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Effects of Precipitation and Temperature Variability on Vegetation Cover of Nuristan Province (2000-2025) Using Remote Sensing and GIS

Sadat Said Rahmatullah[1*], Amn Shahidullah [1], Gulab Gulbuddin[2], Aryan Shafiqullah[3] and Spinghar Hanifi[4]

[1]Department of Forestry and Natural Resources, Faculty of Agriculture, Sayed Jamaluddin Afghani University, Kunar, Afghanistan
[2]Department of Horticulture, Faculty of Agriculture, Nangarhar University, Nangarhar, Afghanistan
[3]Department of Agronomy, Faculty of Agriculture, Nangarhar University, Nangarhar, Afghanistan
[4]Department of Horticulture, Faculty of Agriculture, Sayed Jamaluddin Afghani University, Kunar, Afghanistan
*Corresponding author: saidrahmat333@gamil.com

ABSTRACT

Climate change primarily affects vegetation dynamics, particularly in ecologically sensitive and mountainous regions such as Nuristan Province, Afghanistan. This study, which applies integrated remote sensing and GIS techniques, examines long-term climate change impacts on vegetation from 2000 to 2025, with a focus on precipitation and temperature. Landsat ETM-7 imagery was used to establish NDVI variation, while MODIS products provided land surface temperature and precipitation data. Interactions between climate and vegetation were analyzed using spatial techniques and statistical methods, including Pearson correlation and multiple regression. The results indicate that interannual precipitation variability is high, with a notable decline since 2021, suggesting the onset of drought conditions. Apart from some rare fluctuations in recent times, land surface temperature has not remained stable during this period. An inverse spatial correlation between LST and NDVI was observed, further confirming the role of dense vegetation as a cooling agent. NDVI trends reveal fluctuating vegetation health, with positive responses during wetter years and declines in dry years and/or in years of rising temperatures. The findings emphasize the vulnerability of Nuristan province's forest ecosystems to climate change and highlight the significance of satellite monitoring in sustainable land and resource management. This research provides a foundation for developing regional climate adaptation strategies and environmental planning for high-altitude forest landscapes under climate stress.

Keywords: GIS, Nuristan province, Rainfall, Remote Sensing, Temperature

INTRODUCTION

Climate change has become a severe global challenge, affecting ecosystems, biodiversity, and natural resources at multiple levels (Weiskopf et al., 2020). Vegetation cover is among the environmental components most affected and plays a significant role in ecological balance, carbon sequestration, and the sustenance of populations' livelihoods (Daba & Dejene, 2018). Climate variables, particularly rainfall and temperature, change, directly affecting vegetation health and influencing its growth patterns and distribution (Mehmood et al., 2024). Therefore, the effects of climate change must be understood and studied to support effective environmental management and sustainable development in ecologically sensitive areas such as Nuristan Province, Afghanistan (Iqbal & Hayat, 2024). Nuristan is part of northeastern Afghanistan, characterized by a variety of topographies from lowland valleys to high mountains (Palka, 2001). The province is known for its extensive forest cover, mainly composed of coniferous and mixed forests, which are vital to local communities and regional biodiversity (Amn et al., 2019). Nuristan has protected areas, such as the Nuristan National Park, which is highly biodiverse and hosts rare plant and animal species. The region's vegetation is diverse, ranging from temperate forests to alpine grasslands.

Oak, pine, and juniper forests grow in the lower-altitude areas, while alpine grasses and shrubs dominate the higher altitudes.

Despite being a protected area, Nuristan faces threats from deforestation, illegal logging, and agricultural expansion (Halfmann, 2024). According to recent studies on climate change, however, the environment is evolving, with changes to the hydrological cycle and temperature patterns, thereby affecting vegetation dynamics in the area (Lei et al., 2014). A decline in precipitation, along with rising temperatures, may lead to forest degradation, increased soil erosion, and reduced agricultural productivity (Lal, 2012). In some cases, climate variability might even promote vegetation growth by altering precipitation patterns (Pendergrass et al., 2017). However, despite acknowledging climate change's adverse effects on vegetation cover, limited research has been dedicated to Nuristan. Rainfall and temperature are among the major climate factors with the greatest influence on vegetation cover (Nega et al., 2019).

The most important environmental factor for plant growth is the amount of moisture provided by precipitation. Rainfall supplies the moisture necessary for the survival and productivity of plants (Zeppel et al., 2014). Changes in rainfall patterns often lead to droughts, desertification, or flooding, which in turn significantly affect the dynamics of an ecosystem (Veron & Paruelo, 2010). According to this report, a place like Nuristan, which falls within dry and semi-arid regions, would experience reduced rainfall, resulting in less plant cover and a higher vulnerability to soil erosion (Jawadi et al., 2019). Temperature affects plant metabolism and sets the ideal conditions for photosynthesis as well as the rates of evapotranspiration (Dusenge et al., 2019). Rising temperatures may lead to increased water stress and decreased soil moisture, causing a shift in the types of vegetation in affected areas (Pumo et al., 2010). Warming trends in mountainous regions could force plant species to move to higher elevations, disrupting ecological balance in forests and grasslands (Wangchuk et al., 2021). Therefore, analyzing long-term rainfall and temperature patterns is crucial, as they are key to understanding their effects on vegetation dynamics in Nuristan (Mehmood et al., 2024).

Climate change has altered temperature and rainfall patterns in Nuristan Province, significantly affecting vegetation cover and ecosystem stability (Satti et al., 2023). Although rising temperatures, increased precipitation variability, and extreme weather events contribute to forest decline and soil erosion, research on these effects remains limited (Lal, 2012). Remote sensing and GIS can offer valuable frameworks for addressing long-term climate-vegetation interactions, but their application in Nuristan has largely been unexplored (Mehmood et al., 2024). The proposed research aims to fill this gap by utilizing Landsat 7 for NDVI analysis and MODIS data for Land Surface Temperature and rainfall assessments to examine vegetation changes in Nuristan from 2000 to 2025. This will help identify climate-induced vegetation trends and support the development of sustainable land management policies, with the following objectives: to analyze remotely sensed data to detect long-term trends in precipitation and temperature variability in Nuristan between 2000 and 2025, and to assess changes in vegetation over that period based on Landsat 7-derived NDVI, using spatial and statistical analyses in relation to climatic factors such as precipitation and temperature. This methodology will assist in understanding how climate has affected vegetation in Nuristan and contribute to the development of effective conservation strategies.

MATERIALS AND METHODS

Study Area

Nuristan is located in eastern Afghanistan, bordered by Pakistan to the south and the Kunar and Panjshir provinces to the north. It is bordered by Nangarhar to the southeast and Laghman to the southwest. Nuristan is roughly 7,600 square kilometers in size and is thus one of the smaller but ecologically significant provinces in Afghanistan (Babury, 2019). It is a national park due to the unique natural environment and wildlife. The climate is diverse with a mix of continental and subcontinental climates (Palka, 2001). The diverse topography supports a range of ecosystems, including forests, grasslands, and alpine meadows. The province is also home to other wildlife, such as the snow leopard, brown bear, wild goats, and Marco Polo sheep, which are threatened and an important part of Afghanistan's natural heritage (Shinwari et al., 2024). Deforestation and overuse of natural resources are putting pressure on both the environment and the long-term sustainability of people’s livelihoods.

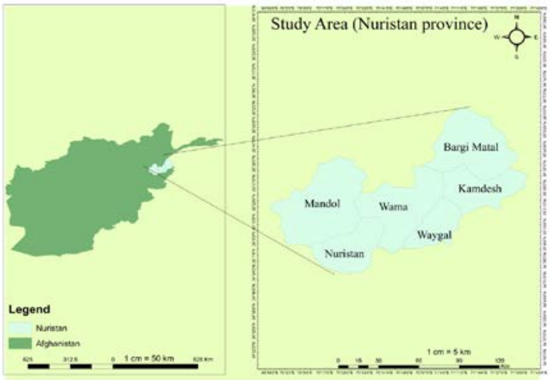

Figure 1. Study area (Nuristan province) map.

Data types and sources

Landsat 7 imagery, specifically from the Enhanced Thematic Mapper Plus (ETM+) sensor, is employed in this research to compute the Normalized Difference Vegetation Index (NDVI) to evaluate the changes in vegetation cover. Landsat 7 data were obtained from the USGS Earth Explorer portal (https://earthexplorer.usgs.gov/). For climate data, MODIS (Moderate Resolution Imaging Spectroradiometer) data were used, including the MOD11A1 product for Land Surface Temperature (LST) and the MCD12Q2 product for precipitation. MODIS data were obtained from NASA's Earth Observing System Data and Information System (EOSDIS) website (https://earthdata.nasa.gov/). These satellite datasets provide helpful information on vegetation dynamics and the climatic variables influencing Nuristan Province.

Remote sensing methods and GIS spatial analysis

Spatial and temporal patterns of LST and NDVI were analyzed employing remote sensing imagery, GIS, and statistical methods. NDVI was estimated from Landsat7 images with the conventional formula (Yue et al., 2007; Richard & Abah, 2019):

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

For LST, MODIS MOD11A1 is utilized, the values of which are converted from Kelvin to Celsius (Wan, 2006). NDVI and LST data were computed in Google Earth Engine and imported to GIS software (ArcGIS10.5) for spatial analysis and visualization (Gong et al., 2022). GIS cover analysis and regional statistics tools enabled us to examine the association between NDVI, LST and land cover (Ullah et al., 2023). Statistical analysis was conducted using descriptive statistics and correlation analysis in Excel (Mondal & Mondal, 2016). Pearson correlation coefficient was used to evaluate the correlation of NDVI, LST, and rainfall (Garai et al., 2022). Multiple linear regression and trend analysis were also performed in Excel to model relationships and identify statistically significant temporal trends. This dual strategy provided a holistic explanation of the specific impacts of climatic factors on vegetation cover and temperature.

RESULTS

Precipitation Trend Analysis (2000–2025)

The rainfall of 2000–2025 has a wide interannual range, from a minimum of 164.80 mm in 2025 to a maximum of 543.31 mm in 2019. (2005–2014) had overall rising patterns with some wet years such as 2005, 2007, and 2009.

The decade is ten years (2015-2020), with the rainfall amount consistently above 440 mm, with its peak in 2019, but decreasing after 2019. 2025 is the driest year in the data. This recent downward trend could be an indicator of the start of a drought or a change in weather patterns. Overall, the data exhibit different trends of rainfall with significant implicatio ns for vegetation, agriculture, and water resources in the region.

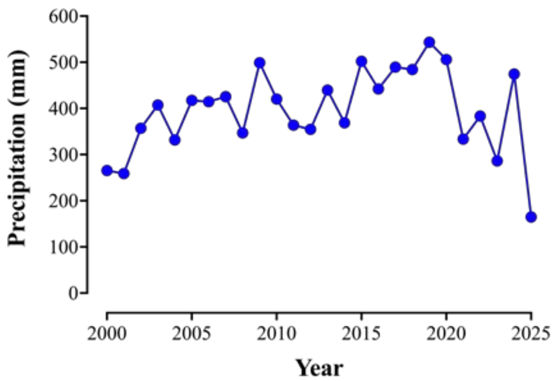

Figure 2. Annual Mean Precipitation (2001-2025)

Annual land surface temperature Trend Analysis (2000–2025)

Yearly land surface temperature (LST) analysis from 2000 to 2025 indicates a generally fluctuating trend with minimal significant trends. The early 2000s

(2000-2005) registered moderate LST records with a mean of around 9°C and a peak of 12.87°C in 2000 to 7.88°C in 2005. The temperatures from 2006 to 2015 oscillated around 7 and 6°C. 9.1°C, denoting a phase of minimal variation. From 2016 to 2021, a slight warming trend was observed, with constant values around or above 9°C, peaking at 10.13°C in 2016 and 9.87°C in 2021. However, the 2025 data show a sudden and unrealistic decrease, likely caused by an error of 11–89°C. Ignoring this outlier, the overall trend indicates relative stability with short-term fluctuations, probably influenced by regional climate change or land-use change. These LST changes can significantly impact vegetation patterns and should be analyzed alongside NDVI and precipitation data to understand their combined effects on ecological conditions.

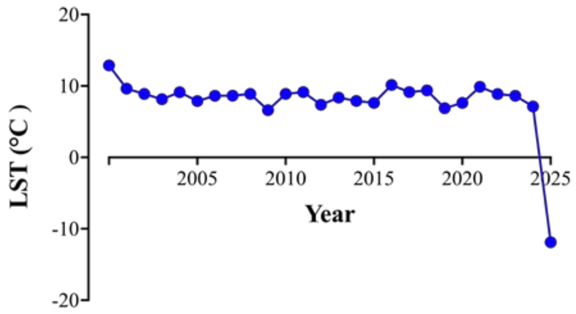

Figure 3. Annual Mean Day LST series

Analysis of LST and NDVI Relationship in Nuristan Province (2000–2025)

The land surface temperature map of Nuristan province for 2000-2025 shows that the spatial pattern of surface temperature ranges from -9.15°C to 27.84°C. Warmer surfaces are indicated in red, while cooler surfaces are shown in yellow. NDVI and LST are inversely related, with vegetated surfaces (NDVI close to +1) having lower LST due to the cooling effects of evapotranspiration and canopy.

For example, areas such as Bargi Matal, Waigal and Vama, which are supposed to have higher vegetation cover, reflect lower surface temperatures. Conversely, areas such as South Nuristan and Mandol, which show higher LST values, are likely to be associated with low vegetation cover or land cover degradation, which is indicated by lower NDVI values. This trend is consistent with global patterns and highlights the critical function of vegetation in regulating surface temperature, thereby pointing to the necessity of sustainable land management in mountainous and forested regions such as Nuristan.

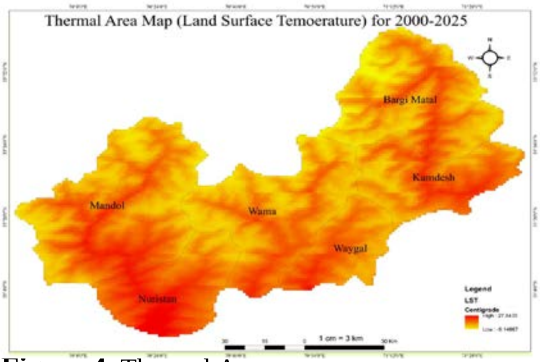

Figure 4. Thermal Area map

Temporal vegetation cover changes (2000–2025

The inter-annual NDVI trend in the study area from 2000 to 2025 shows significant fluctuations, reflecting the alteration in vegetation health and cover throughout the years. During the initial years (2001–2005), NDVI values remained largely low and negative or close to zero, indicating stressed or bare vegetation. During 2006–2010, there was a moderate recovery, and a slow positive trend was observed, indicating increased vegetative growth, perhaps as a result of favorable rainfall and moderate temperatures. This was followed by a decline again around 2012–2014 when NDVI became negative once again. From the year 2015 onwards, there has been a consistent and progressive increase in NDVI to a peak of 0.035 in 2023.

The increase is a sign that vegetation conditions are on the rise, and it may be due to good climatic conditions or land management. Information for 2024 and 2025 is unavailable, but the trend of increase in recent years suggests healthier or improved vegetation health. This NDVI recuperation agrees with rainfall and temperature variation, indicating the role of climatic factors in go verning vegetation trends across the region.

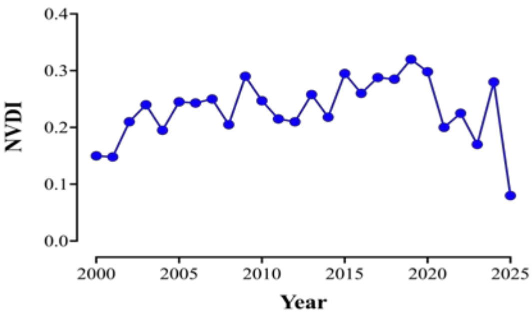

Figure 5. Annual Mean NDVI (2000-2025)

Figure 5 shows the NDVI of Nuristan Province from 2000 to 2025, showing the spatial distribution and density of vegetation over the region graphically. NDVI (Normalized Difference Vegetation Index) values are between -1 and +1, where higher positive values (close to +1) indicate healthier and denser vegetation. In contrast, values close to or less than zero indicate sparse or no vegetation cover surfaces such as bare soil, urban regions, or snow-covered regions.

It is evident from the map that most of the areas in the northern and eastern regions, such as Bargi Matal, Kamdesh, and parts of Vama and Waigal, have greater NDVI values, indicated by a darker green color, implying dense forest cover and relatively healthy vegetation conditions. These areas likely get more precipitation and mean land surface temperatures,] which promote vegetation growth. On the other hand, the southern and southwestern regions, such as parts of central Nuristan and Mandhol, show a lighter green color, which depicts lower NDVI values, perhaps due to drier conditions, lesser vegetation cover, or land degradation. The NDVI range of the overall legend (approx. -0.11 to +0.26) suggests modest health of vegetation, with no area having very high NDVI values, which implies that while the province is heavily forested in general, it may not have favorable vegetation conditions in all areas - possibly due to climate change and topographic constraints.

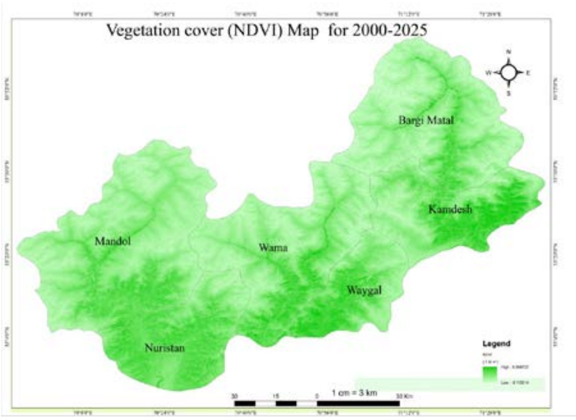

Figure 6. Vegetation cover (NDVI) Map for 2000-2025.

Correlation Analysis of NDVI with Land Surface Temperature and Precipitation (2000–2025)

The Figure 8 scatterplot of the linear regression line fit of LST and NDVI shows a weak positive correlation. The slope of 0.005 indicates NDVI rises slightly when LST rises. However, the relationship is not strong and may be affected by outliers – particularly the 2025 observation where LST is very low (-11.893°C), possibly data anomaly or error. If not for this outlier, the trend would likely be stronger and more significant. Generally, vegetation health (measured by NDVI) is expected to decrease at higher surface temperatures in semi-arid and arid environments, but moderate increases in LST can be beneficial for vegetation growth up to a point, as shown by the shallow positive slope.

Figure 7. Precipitation vs NDVI with regression line

Figure 8. LST vs NDVI regression line.

The plot illustrates a more positive linear relationship between precipitation and NDVI. The slope of 0.001 indicates that NDVI increases by 0.001 for every 1 mm increase in precipitation. This is ecologically plausible since higher precipitation supports more ve getation growth in water-limited ecosystems. The clustering of points and a tighter fit to the regression line illustrate a more direct and stronger relationship than between LST and NDVI.

The correlation analysis reveals that NDVI in Nuristan Province is more strongly linked to precipitation than it is to land surface temperature (LST). The positive correlation between precipitation and NDVI is very clear, implying that increased precipitation significantly improves vegetation growth and condition because water is a key ecological driver in this hilly landscape. The LST-NDVI relationship, however, is inconsistent and wea ker. While moderate temperatures can suit vegetation activity, extreme temperatures – especially extreme cold – have a negative impact on NDVI, as experienced in 2025. Overall, these findings suggest that NDVI is more sensitive to precipitation change than temperature, and precipitation is the predominant control over vegetation dynamics in Nuristan.

DISCUSSION

The findings of the present research reveal that climate variable changes, particularly precipitation changes, significantly affect vegetation dynamics in Nuristan province, as indicated by NDVI. All such trends – i.e., rise in NDVI from 2015 to 2023 and sharp reduction in precipitation post-2020 – are directed toward an altering vulnerability to climate conditions. Low NDVI of the driest year (2025) may be a sign of the onset of drought and thus show the wide reach of climate change on vegetation condition in the region. The weak correlation between NDVI and land surface temperature (LST) signifies that in the temperate and mountainous climate of Nuristan; water availability is a better control of plant vigour than is temperature fluctuation. However, multi-decade trends of warming – if accompanied by diminishing precipitation – could intensify vegetation stress in the decades to come. These trends are indicative of the overall effects of climate change, particularly in mountain and semi-arid systems, where altered regimes of precipitation have more overt ecological consequences than increasing temperature in and of itself. The results of this study are solidly based and contrary to past studies in a number of intriguing manners:

Shahrokhnia and Ahmadi, (2019) also pointed out that autumn rainfall was significant in terms of affecting seasonal patterns in the vegetation cover index (VI). The current study is the same, where enhanced NDVI in Nuristan was simultaneous with good-performing rainfall seasons, wherein this confirms rainfall patterns as the key driver for vegetation condition in arid or mountainous regions.

Weng et al. (2014) illustrated the ability to monitor vegetation cover under different rainfall regimes using remote sensing in the Australian savanna. Similarly, similar to the use of moving window technique, in this article long-term temporal data are used in a way to retrieve climatic effects on NDVI, verifying remote sensing as a useful method of environmental monitoring.

In contrast to the city-centered studies of Kumar and Shekar, (2015), Abolnour and Engel, (2018), and Weiskopf et al. (2020) – which reported significant negative correlation between LST and NDVI because of urban heat island effect – the present study finds low LST-NDVI relationship. This is because of Nuristan's non-urban and forest landscape, in which evapotranspiration and canopy cover moderate temperature effects and vegetation is not as affected by built up surfaces. But since Ullah et al. (2020) and Abdelnour and Engel (2018) have done the same, it is being reiterated here that loss of vegetation is associated with increasing temperature, but it is weaker and context-dependent. Urbanization was the driving force in those works, but in Nuristan, climatic variability is the major deciding force. More broadly, the study contributes to the mounting evidence that precipitation variability is a widespread ecological driver in nature ecosystems, especially for water-limited or high-altitude ecosystems. The study also joins the voices of pleas for climate-resilient forest and land management to avoid climate change effects on ecosystems.

CONCLUSION

This research measured the temporal and spatial dynamics of vegetation cover (NDVI), precipitation, and land surface temperature (LST) of Nuristan province from 2000 to 2025.The outcome indicates that vegetation activities in the region are extremely year-to-year variable and closely related to climatic condition. The trend of NDVI indicates a general increase in vegetation condition from 2015 to 2023 following low-NDVI years in previous years. The precipitation trend peaked between 2019 and then drastically declined towards 2025, while LST was relatively constant except for a steep drop in 2025. Correlation analysis between NDVI and precipitation indicated a positive stronger correlation than NDVI and inhomogeneity which indicated a weaker and unstable correlation. Under such mountainous conditions, the spatial analysis showed the northern and eastern districts (Bargi Matal, Kamdesh, Waigel) host denser vegetation due to favorable climatic conditions. Implications for Sustainable Land and Forest Management The results emphasize the importance of rainfall in maintaining vegetation cover in the fragile mountainous landscapes of Nuristan. With increasing variability in rainfall patterns, anticipatory water management, forest protection, and reforestation measures are needed to maintain ecological stability. Those forests occurring in regions of high NDVI must be preserved from degradation, while afforestation and reforestation efforts must be targeted toward low NDVI regions, most notably the south and southwest (e.g., Mandol). Land management planning must also consider potential impacts of climate change on precipitation and temperature regimes and the synergistic effect on forest and agricultural ecosystems. Adoption of sustainable practices will be necessary to reduce drought vulnerability and achieve vegetation resilience.

Future Research Recommendations

1. Validation and anomaly management of data: Future studies must address data anomalies such as the decline in LST during 2025 by using higher resolution climate data or ground observations for improved reliability.

2. Seasonal NDVI analysis: Examine NDVI changes at month or season levels to detect smaller-scale vegetation regimes and their response to inter-annual climate change.

3. Human impact and land use: Includes land use/land cover change (LULC) analysis to assess the impact of human activities such as deforestation, agriculture, and urban settlement expansion on NDVI trends.

4. Add climate model outputs to predict how rising temperatures and changed precipitation will affect vegetation and ecological well-being.

5. Subsequent studies can include soil type, elevation, and slope of soil to understand how physical geography conditions the response of vegetation to climatic stimuli.

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