

**Short thesis for the degree of doctor of philosophy (PhD)**

**Spatiotemporal Dynamics of Drought and Desertification in Northern  
Algeria: A Multi-Scale Analysis Using Remote Sensing and Ensemble  
Machine Learning, From Regional Aridification to Local Land-Cover  
Transformation in the Algerian Steppe.**

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## 1. Introduction:

“The nation that destroys its soil destroys itself.” This statement by Franklin D. Roosevelt in 1937 underscores the fundamental relationship between land resources and societal well-being. Land degradation is a complex environmental process characterized by the deterioration of the quality, productivity, and ecological functioning of land resources, including the soil, water, and biological components of terrestrial ecosystems (Safriel, 2007). Globally, pressure on land resources has increased substantially over the past century as a result of rapid population growth, agricultural intensification, urban expansion, and unsustainable land management practices. As a consequence, land degradation now affects approximately 40% of the Earth's terrestrial surface and is estimated to generate annual economic losses of around US\$490 billion. When combined with desertification and drought, total annual losses may reach US\$878 billion. (Nkonya et al., 2011). These processes directly affect the livelihoods and economic well-being of nearly two billion people worldwide, with more than 250 million individuals experiencing severe impacts in developing countries. Beyond their socioeconomic consequences, land degradation threatens biodiversity, disrupts essential ecosystem services, and undermines long-term environmental sustainability.

Desertification represents a specific and accelerated form of land degradation that occurs primarily in dryland environments. These regions are characterized by low and highly variable precipitation, fragile ecosystems, and a high susceptibility to environmental disturbances (Amiraslani & Caiserman, 2018; Ziadat et al., 2021). Since the late 1960s, African drylands have experienced some of the most severe and prolonged drought episodes in recorded history, leading to the formal recognition of desertification as a global environmental challenge during the United Nations Conference on Desertification. Subsequently, the United Nations Convention to Combat Desertification defined desertification as “land degradation in arid, semi-arid, and dry sub-humid areas resulting from climatic variations and human activities.” (Djeddaoui et al., 2017; Seely & Wöhl, 2004; Sivakumar, 2007). In drylands, climatic variability interacts with anthropogenic pressures such as overgrazing, agricultural expansion, and unsustainable resource exploitation, creating reinforcing feedback loops that accelerate soil degradation, vegetation loss, and ecosystem instability (Feng et al., 2015).

Among the drivers of land degradation, drought stands out as one of the most widespread and economically damaging climate extremes. Approximately 70% of global drylands experience recurrent drought conditions, particularly across semi-arid regions of Africa, Asia, and South America (Haile et al., 2020; Mathbout et al., 2021). According to the World Meteorological Organization, drought is defined as a prolonged period of abnormally low precipitation that leads to water shortages and negatively impacts ecosystems, agriculture, water supply, and human livelihoods (Bazza et al., 2018; Wilhite & Glantz, 1985). Drought triggers and intensifies desertification processes, particularly in regions where climatic variability is compounded by unsustainable land management practices. The interplay between drought and desertification creates a reinforcing ecological cycle: drought accelerates vegetation decline and soil exposure, which in turn reduces soil moisture retention and increases susceptibility to wind and water erosion. Consequently, each successive drought exerts a progressively greater ecological impact because the system's natural buffering capacity has already been weakened.

Northern Africa is widely recognized as one of the most climate-sensitive regions globally, with growing evidence that climate change is increasing both the frequency and severity of drought events (Derdous et al., 2021). Algeria exhibits a pronounced climatic gradient, ranging from the humid Mediterranean coast to the hyper-arid Sahara Desert. Annual precipitation follows this gradient, varying from less than 100 mm in the southern Sahara to approximately 400–1000 mm along the

northern coastal regions (Malika et al., 2018). The semi-arid steppe region, situated between these two climatic extremes, constitutes a critical ecological transition zone. Covering more than 20 million hectares, it represents the largest rangeland system in North Africa and is particularly vulnerable to drought-induced land degradation (Elouissi et al., 2021). Nearly 44% of the Algerian steppe is classified as highly to very highly susceptible to desertification.

This vulnerability is driven by rapid demographic growth, overgrazing, agricultural expansion, and changing land-use practices, which collectively exert increasing pressure on these fragile ecosystems. Historically, Algeria has experienced severe drought episodes, notably during 1943–1948 and the 1980s–1990s, which significantly disrupted ecosystems, water resources, and agricultural systems. In recent decades, desertification has progressively expanded northward, threatening the ecological stability, agricultural productivity, and socioeconomic sustainability of northern Algeria (Fellag et al., 2021).

Land use and land cover (LULC) change represents a critical pathway through which human activities drive land degradation (X. Hu et al., 2021; Roy et al., 2022). Agricultural expansion, deforestation, overgrazing, and urbanization fundamentally alter vegetation structure, soil properties, hydrological processes, and land–atmosphere interactions (Y. Hu et al., 2023; Leng et al., 2020; Ma et al., 2023). These transformations can either exacerbate or mitigate land degradation, depending on the nature of land management practices and the prevailing ecological conditions (AbdelRahman, 2023; Bhattacharyya et al., 2023). In the Algerian context, LULC dynamics are closely associated with large-scale ecological interventions such as the Green Dam afforestation initiative, which was established during the 1970s as a strategic barrier to limit desert encroachment (Ilhame et al., 2025; Merdas et al., 2015). However, the long-term sustainability of this initiative has been challenged by the combined effects of climatic stress, pest outbreaks, and unsustainable pastoral practices. Consequently, understanding the spatiotemporal dynamics of LULC is essential for identifying the anthropogenic drivers of desertification and evaluating ecosystem resilience within vulnerable dryland environments (Hezil et al., 2024; Liiv et al., 2025).

Early detection and continuous monitoring of land degradation processes are fundamental for sustainable land management and informed environmental planning. In this context, remote sensing technologies have emerged as powerful tools for monitoring environmental change across extensive spatial and temporal scales (Higginbottom & Symeonakis, 2014). Satellite observations from sensors such as Landsat, MODIS, and Sentinel enable the systematic assessment of vegetation dynamics, soil moisture conditions, surface temperature variations, and land-cover changes (Hermans & McLeman, 2021; Liu et al., 2018; Rivera-Marin et al., 2022). Multi-indicator remote sensing approaches now enable researchers to integrate complementary datasets for a more comprehensive assessment of land degradation. Vegetation indices provide insights into vegetation health and productivity, while climate-based drought indices capture meteorological stress conditions including the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) (Keyantash & Dracup, 2002; Kim et al., 2023). Composite indicators such as the Vegetation Health Index (VHI), derived from the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) (Bento et al., 2018; Zeng et al., 2023), integrate both moisture and thermal stress signals, providing a more robust representation of drought impacts on vegetation. Additional indicators, including the Normalized Difference Water Index (NDWI) and Land Surface Temperature (LST), further contribute to the detection of moisture stress and thermal anomalies associated with land degradation processes (Kumar et al., 2022; Zolfaghari et al., 2022).

More recently, the integration of remote sensing data with machine learning algorithms such as Random Forest (RF) and Extreme Gradient Boosting (XGBoost) has significantly advanced the assessment and mapping of desertification (Hashemi et al., 2024; Kılıç, 2026; Rao et al., 2022). Unlike conventional statistical approaches, machine learning techniques can capture complex, non-linear relationships among environmental variables, integrate diverse satellite-derived indicators, and generate spatially explicit predictions of land degradation patterns. These data-driven approaches enhance assessment accuracy, facilitate the identification of key environmental drivers across heterogeneous landscapes, and enable the detection of early warning signals associated with desertification processes (Appiagyei et al., 2023; Mihi et al., 2022). Despite these methodological advances, comprehensive studies that simultaneously integrate long-term drought dynamics, land use/land cover transformation, vegetation responses, and machine-learning-based desertification modelling remain relatively limited in Northern Algeria (Derdour et al., 2023a; Kreri et al., 2026). Most existing assessments rely on single-index approaches or analyses conducted at isolated spatial scales, limiting their ability to capture the complex, non-linear, and multi-causal nature of land degradation processes (Berdugo et al., 2020). Understanding the interaction between climatic variability and anthropogenic pressures is particularly important in this region, where fragile dryland ecosystems are highly vulnerable to land-use transformation and the increasing frequency and severity of drought events (Derdour et al., 2023b; Vicente-Serrano et al., 2015; Wang et al., 2022).

To address this critical research gap, this dissertation investigates the spatiotemporal dynamics of drought and desertification across Northern Algeria through an integrated multi-scale analytical framework. The primary objective is to examine the drivers, dynamics, and spatial patterns of land degradation by combining drought variability analysis, vegetation response assessment, land use/land cover (LULC) change detection, and machine-learning-based desertification modelling using multi-source remote sensing datasets. Specifically, the research seeks to elucidate how climatic variability and human-induced land-use changes interact to influence vegetation condition and desertification processes across the dryland ecosystems of Northern Algeria.

### **1.1. The specific objectives of this research are as follows:**

- To assess long-term drought variability and vegetation responses across Northern Algeria at the regional scale, using satellite-derived indicators, particularly NDVI anomalies, to evaluate spatiotemporal patterns of vegetation dynamics and drought impacts.
- To analyze the relationship between meteorological drought and vegetation stress in Northwestern Algeria at the sub-regional scale, by integrating meteorological drought indices, such as the Standardized Precipitation Index (SPI), with remote sensing-based indicators, including the Vegetation Health Index (VHI).
- To investigate land use/land cover (LULC) dynamics in the Green Dam region at the local scale, and to evaluate land degradation processes within this ecologically sensitive desert-steppe transition zone of Northern Algeria.
- 4. To develop a machine-learning-based framework for mapping and assessing desertification severity across Northern Algeria, utilizing multi-indicator remote sensing datasets and advanced classification algorithms.
- 5. To examine land degradation processes across Northern Algeria by integrating climatic and anthropogenic drivers, with the aim of identifying the spatial patterns, controlling factors, and underlying mechanisms of land degradation and desertification.

This dissertation is guided by the following primary research question: *How do drought dynamics, climate variability, and human land-use changes interact to shape the spatiotemporal patterns of land degradation and desertification across the dryland ecosystems of Northern Algeria?* This question is operationalized through the following sub-questions:

- How has drought variability influenced regional vegetation dynamics across Northern Algeria using satellite-derived NDVI anomalies?
- How do meteorological drought conditions relate to vegetation stress in Northwestern Algeria, and can SPI and VHI effectively capture these interactions?
- To what extent have land-use and land-cover changes across the Green Dam region driven land degradation at the desert–steppe transition zone?
- What spatial patterns and severity levels of desertification can be identified across Northern Algeria through the application of machine learning to multi-indicator remote sensing data?
- How do drought dynamics, climate drivers, and human drivers interact to influence land degradation across Northern Algeria, and what spatial patterns and mechanisms emerge from this interaction?

This dissertation adopts a hierarchical multi-scale analytical framework encompassing three levels: a regional scale (Northern Algeria), a sub-regional scale (Northwestern Algeria), and a local scale (the Green Dam region in Djelfa Province). This structure directly addresses a key research gap identified in the literature, namely the absence of integrated multi-scale analytical frameworks for Northern Algeria.

At the regional scale, Northern Algeria provides the broad climatic context necessary for understanding large-scale patterns of land degradation. At the sub-regional scale, Northwestern Algeria captures the critical transition between Mediterranean and arid zones, where desertification processes are particularly dynamic. At the local scale, the Green Dam region enables a focused examination of desert–steppe transition dynamics, particularly in areas where ecological restoration initiatives have been implemented.

By explicitly linking processes across these scales, the dissertation enables an examination of how regional climatic patterns are expressed within sub-regional hydrological systems and, in turn, influence local land degradation dynamics at the desert–steppe interface.

The findings of this research contribute to a more comprehensive and grounded understanding of land degradation dynamics in Northern Algeria by integrating remote sensing indicators, drought analysis, land use/land cover (LULC) change detection, and machine learning approaches within a unified analytical framework. The results provide critical insights for policymakers and land managers in three main areas: (1) more effective strategies for combating desertification, (2) improved sustainable land management practices, and (3) enhanced ecosystem resilience in vulnerable dryland environments.

Methodologically, the dissertation demonstrates the robustness and added value of combining multi-source satellite observations, meteorological reanalysis data, and ensemble machine learning techniques to overcome the limitations of conventional index-based assessments. From an applied perspective, the identification of drought hotspots, rapidly degrading landscapes, and environmentally vulnerable zones can support environmental agencies in prioritizing restoration interventions,

strengthening drought early-warning systems, and reducing anthropogenic pressure on fragile steppe ecosystems.

Ultimately, this work contributes to the development of evidence-based, spatially explicit strategies for sustainable dryland management and climate adaptation in data-scarce arid and semi-arid regions.

## **1.2. Scientific Contributions and Novelty:**

This dissertation makes four principal contributions to advancing the understanding of land degradation dynamics in Northern Algeria. First, it develops a hierarchical multi-scale analytical framework that integrates regional, sub-regional, and local assessments within a unified methodological structure, enabling the examination of degradation processes across interconnected spatial scales. Second, it combines drought indicators, vegetation dynamics, land use/land cover change analysis, and machine learning techniques to provide a comprehensive assessment of desertification processes and their underlying drivers.

Third, the study identifies the dominant environmental controls of desertification through the application of interpretable ensemble-learning models, offering new insights into the relative importance of vegetation condition, surface moisture availability, soil exposure, thermal stress, and topographic factors. Finally, it provides a spatially explicit assessment of future desertification vulnerability, generating information that can support evidence-based land management, environmental planning, and climate adaptation strategies in Northern Algeria and other dryland regions facing similar environmental challenges.

## **2. Materials and Methods:**

This dissertation employs an integrated, multi-scale analytical framework to investigate drought, land degradation, and desertification processes across Northern Algeria. All analyses were conducted using open-source geospatial platforms and statistical programming environments. Multi-source satellite datasets (MODIS and Landsat), meteorological data (CHIRPS and ERA5), and topographic information derived from SRTM were integrated to provide a comprehensive representation of environmental conditions across multiple spatial and temporal scales.

The methodological framework comprised three main components: (1) the calculation of drought and vegetation indicators, including SPI, NDVI, VCI, TCI, VHI, and associated anomaly analyses; (2) supervised land use/land cover (LULC) classification using the Maximum Likelihood Classifier (MLC), combined with future scenario modelling through the Land Change Modeler (LCM); and (3) the development of a machine learning framework based on Random Forest (RF) and Extreme Gradient Boosting (XGBoost) algorithms to map desertification severity using 16 multi-source environmental predictors. Model performance and transferability were rigorously evaluated through spatial cross-validation procedures to ensure robust and reliable predictions.

### **2.1. Study Area Description:**

#### **2.1.1. Regional Scale: Northern Algeria:**

The primary study area encompasses Northern Algeria, covering 375,815 km<sup>2</sup> across 40 administrative provinces (wilayas). This region spans a pronounced climatic gradient from the humid Mediterranean coast (400–1000 mm annual precipitation) through sub-humid highlands to the semi-arid steppe bordering the Sahara (<250 mm annually).

Elevation ranges from sea level to 2,301 m, creating complex topographic controls on hydrological processes and vegetation distribution. The region hosts diverse land cover types, including

Mediterranean forests, agricultural lands, degraded steppes, and urban settlements, making it highly representative of dryland vulnerability to both climatic variability and anthropogenic pressures.

2.1.2. Sub-regional Scale: Northwestern Algeria:

The secondary study area focuses on Northwestern Algeria (approximately 500 km east–west extent), situated between 2°10'10" W–3°10'11" E and 34°18'54"–36°48'12" N. This transitional zone captures the critical interface between Mediterranean and arid climatic regimes. Mean annual precipitation varies markedly from approximately 240 mm in interior basins (e.g., Tafna) to over 700 mm in coastal mountainous areas.

The vegetation gradient mirrors this climatic transition, shifting from Mediterranean forest communities (e.g., *Pinus halepensis*, *Quercus spp.*) in the north to open steppe vegetation (e.g., *Macrochloa tenacissima*, *Artemisia herba-alba*) in the interior zones. Three major hydrological basins dominate the region: the Chelif Basin (the largest watershed in Algeria), the transboundary Tafna Basin, and the Macta Basin, which includes Ramsar-designated wetland ecosystems.

2.1.3. Local Scale: Green Dam Region (Djelfa Province):

The tertiary study area is the Moudjbara perimeter in southeastern Djelfa Province (~10,000 ha; 34°31'–34°41' N, 3°19'–3°23' E), representing a strategic desert–steppe transition zone. This area was among the first afforested with *Pinus halepensis* under the Green Dam initiative (1972).

The climate is semi-arid, with mean annual rainfall of approximately 300 mm, characterized by cold winters (mean minimum temperature ~0.1°C) and hot summers (mean maximum temperature ~33.8°C). Soils are predominantly shallow rendzinas with moderate organic matter content (5–8%). Land cover is heterogeneous, including natural Aleppo pine stands, artificial plantations, degraded steppe formations, croplands, and expanding urban areas surrounding Djelfa city.

2.2. Data Sources and Preprocessing:

2.2.1. Satellite Remote Sensing Data:

A multi-sensor satellite data archive was assembled to characterize vegetation dynamics, surface environmental conditions, and land use/land cover change across all spatial scales considered in this study (Table 1).

Table 1. Summary of satellite datasets utilized in the dissertation.

| Data Type                | Product              | Source      | Spatial Resoluti<br>on | Temporal Resolutio<br>n | Key Variables    | Analytical Purpose                       |                  |
|--------------------------|----------------------|-------------|------------------------|-------------------------|------------------|------------------------------------------|------------------|
| Vegetation Indices       | MOD13Q1 V6.1         | NASA/MO DIS | 250 m                  | 16-day                  | NDVI, EVI, MSAVI | Vegetation dynamics,                     | drought response |
| Derived Vegetation       | MOD13Q1 (NDVI-based) | NASA/MO DIS | 250 m                  | 16-day                  | FVC              | Vegetation cover quantification          |                  |
| Land Surface Temperature | MOD11A2 V6.1         | NASA/MO DIS | 1 km                   | 8-day                   | LST (day/nigh t) | Thermal stress, evapotranspiration proxy |                  |

|                            |                         |            |         |                        |                            |                                        |             |
|----------------------------|-------------------------|------------|---------|------------------------|----------------------------|----------------------------------------|-------------|
| Surface Reflectance        | MOD09A1                 | NASA/MODIS | 500 m   | 8-day                  | Blue, Red, NIR, SWIR bands | NDWI, BSI, TGS                         | derivation  |
| BRDF-Corrected Reflectance | MCD43A4                 | NASA/MODIS | 500 m   | Daily                  | Albedo, spectral bands     | Surface balance, exposure              | energy soil |
| Long-term LULC             | Landsat MSS/TM/ETM+/OLI | USGS       | 30–60 m | Multi-date (1972–2019) | Spectral bands             | Historical land cover change detection |             |

All MODIS products were preprocessed within Google Earth Engine to ensure computational efficiency, consistency, and reproducibility. Quality assurance (QA) bands were systematically applied to mask clouds, cloud shadows, and atmospheric artifacts through binary flag operations. Radiometric scaling factors provided by NASA were used to convert digital numbers into physically meaningful reflectance and temperature values.

For desertification mapping, annual median composites were generated for the reference years 2002, 2012, and 2022 to minimize seasonal variability and the influence of outliers. For drought analyses, monthly NDVI and LST composites were produced to ensure temporal consistency with the meteorological datasets.

Landsat imagery used for land use/land cover (LULC) analysis underwent radiometric calibration to top-of-atmosphere reflectance, followed by atmospheric correction using the FLAASH algorithm within ENVI 5.3. All scenes were selected under cloud-free conditions and standardized to a common acquisition period (July–August) to minimize phenological variability.

The imagery was subsequently reprojected to the UTM Zone 31N coordinate system (WGS84 datum) and clipped to the study area boundaries using ArcGIS 10.8.1, ensuring spatial consistency across all analyses.

### 2.2.2. Meteorological Drought:

The Standardized Precipitation Index (SPI) was calculated at 3-, 6-, and 12-month timescales using accumulated CHIRPS precipitation data. SPI values were standardized on a pixel-by-pixel basis using long-term precipitation means and standard deviations, enabling the classification of moisture conditions along a continuum ranging from extremely wet to extremely dry.

### 2.2.3. Vegetation and Thermal Stress:

Vegetation condition and thermal stress were assessed using the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI), which normalize MODIS-derived NDVI and Land Surface Temperature (LST) values relative to their historical ranges during the 2003–2023 period. These indices were subsequently integrated into the composite Vegetation Health Index (VHI) using equal weighting ( $\alpha = 0.5$ ), enabling the simultaneous representation of both moisture-related and thermal stress conditions affecting vegetation.

### 2.2.4. Anomaly-Based Indicators:

To capture departures from long-term environmental conditions, seasonal anomalies (November–June) were calculated for NDVI (percentage deviation), precipitation, and temperature (absolute deviation) relative to a 30-year climatological baseline (1990–2020). Negative NDVI anomalies were subsequently classified into five drought severity categories to assess the intensity and spatial extent of vegetation stress.

### **2.3. Land Use/Land Cover Classification and Change Analysis:**

Land use/land cover (LULC) maps for the Green Dam region were generated for five temporal snapshots (1972, 1989, 1999, 2009, and 2019) using the Maximum Likelihood Classifier (MLC) implemented in ArcGIS. Five land-cover classes were defined: degraded steppes, croplands, urban areas, dense plantations/natural forests, and open plantations.

Classification accuracy was assessed using confusion matrices based on more than 150 randomly distributed validation points per map. The results yielded Overall Accuracy values exceeding 75% and Kappa coefficients greater than 0.64 for all time periods, indicating satisfactory classification performance and reliability.

Land use/land cover change detection and intensity analyses were conducted using the Land Change Modeler (LCM) within Idrisi TerrSet and the OpenLand package in R. Future LULC scenarios for 2029 were simulated using a Multi-Layer Perceptron Artificial Neural Network (MLP-ANN) coupled with a Markov chain model. The modelling framework incorporated explanatory variables including the Digital Elevation Model (DEM), distance to roads, and proximity to urban areas to improve the representation of land-use transition dynamics.

Anthropogenic pressures were further quantified using historical demographic and livestock census data, together with projected population and livestock estimates extending to 2030.

### **2.4. Machine Learning Modelling Framework:**

Desertification severity was mapped using two ensemble machine learning algorithms: Random Forest (RF) and Extreme Gradient Boosting (XGBoost). These models were selected for their robustness in handling high-dimensional, non-linear environmental datasets and their ability to capture complex interactions among predictor variables.

#### **2.4.1. Training and Calibration:**

A hybrid sampling strategy yielded 1,945 spatially stratified ground-truth samples distributed across five desertification severity classes (Non, Slight, Moderate, High, and Severe). The models were trained using 16 multi-source predictors, including vegetation indices (NDVI, EVI, FVC), surface moisture indicators (NDWI), soil exposure metrics (BSI, TGSI, Albedo), thermal variables (LST), drought indices (SPI, VHI), and topographic variables. All predictors were standardized using Z-score normalization to ensure comparability across variables.

Model hyperparameters were optimized using stratified 10-fold cross-validation, resulting in configurations such as a learning rate of 0.1 and maximum tree depth of 7 for XGBoost, and 200 trees for the Random Forest model.

#### **2.4.2. Validation and Uncertainty:**

Model performance was evaluated using an independent hold-out validation dataset and spatial cross-validation (SCV) to reduce bias associated with spatial autocorrelation. Feature importance was

derived using Gini impurity measures for the Random Forest (RF) model and gain-based metrics for the Extreme Gradient Boosting (XGBoost) model.

Spatial uncertainty was quantified by mapping the standard deviation of RF class probabilities and by conducting a pixel-wise agreement analysis between RF and XGBoost outputs, enabling the identification of areas of classification consistency and ambiguity.

#### **2.4.3. Provincial Zonal Statistics and Future Projection:**

To translate pixel-based classifications into policy-relevant insights, zonal statistics were computed across the 40 provincial boundaries for 2002 and 2022. Desertification maps were post-processed to enforce monotonic temporal transitions, and the net change in high and severe degradation classes was calculated to identify rapidly degrading hotspots.

A forward projection to 2030 was developed by linearly extrapolating 2002–2022 trends of the 16 environmental predictors. The resulting datasets were constrained within physically plausible bounds and subsequently fed into the trained Random Forest (RF) classifier to generate an illustrative future scenario of desertification severity. This projection was explicitly framed as exploratory, acknowledging the inherent limitations of linear extrapolation.

### **3. Results:**

#### **3.1. Thesis Statement 1:**

**Regional-scale NDVI anomaly analysis reveals increasing drought frequency and severity across Northern Algeria after 2015, with vegetation responses showing weakened coupling to precipitation and increased sensitivity to thermal stress.**

The analysis of growing-season NDVI anomalies (2011–2022) demonstrates that Northern Algeria has experienced a clear shift toward recurrent vegetation stress, particularly during 2016, 2021, and 2022, when over 76% of the study area was affected by drought conditions. While NDVI anomalies generally track rainfall deficits, Spearman correlation analysis reveals only weak positive relationships ( $r_s = 0.10\text{--}0.37$ ), whereas temperature anomalies exhibit consistently negative correlations (up to  $r_s = -0.47$ ).

These results indicate that thermal stress, driven by elevated evapotranspiration and land-surface heating, is increasingly amplifying drought impacts and decoupling vegetation productivity from direct precipitation inputs. The diminishing amplitude of post-drought NDVI recovery cycles further suggests a progressive erosion of the ecosystem's buffering capacity under sustained hydroclimatic pressure.

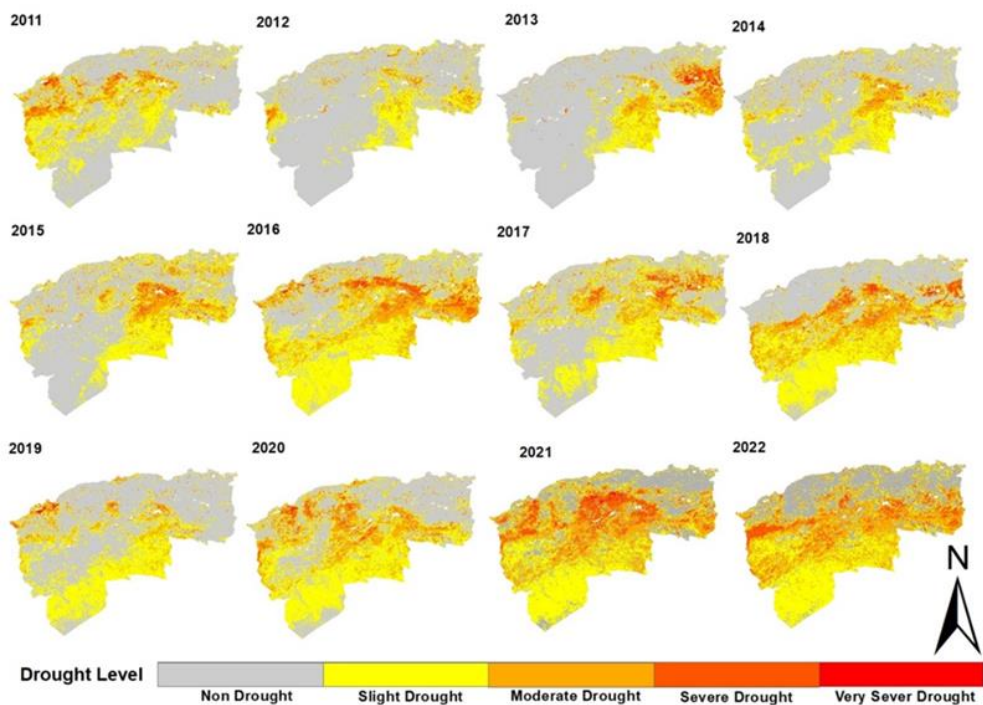


**Figure 1.** The spatial distribution of drought in northern Algeria.

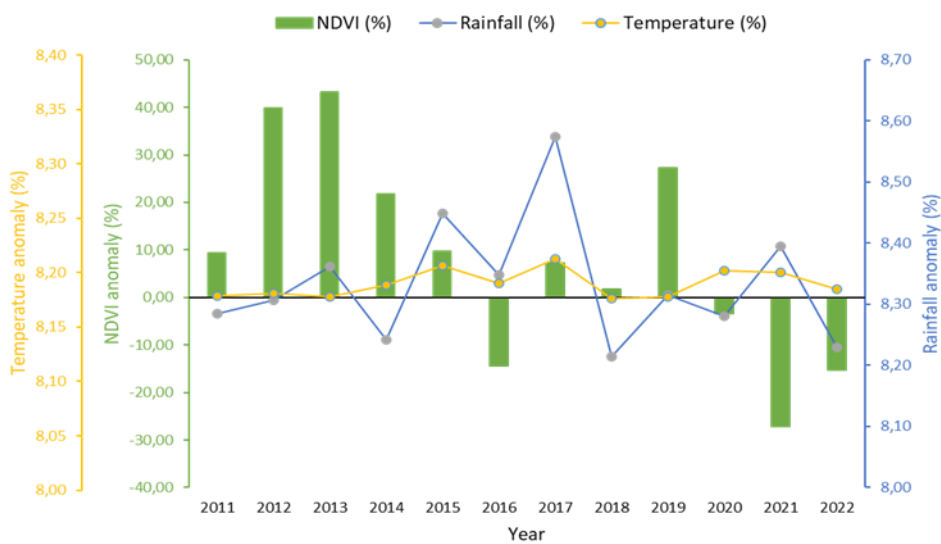


**Figure 2.** Temporal variations in NDVI, rainfall, and temperature anomalies.

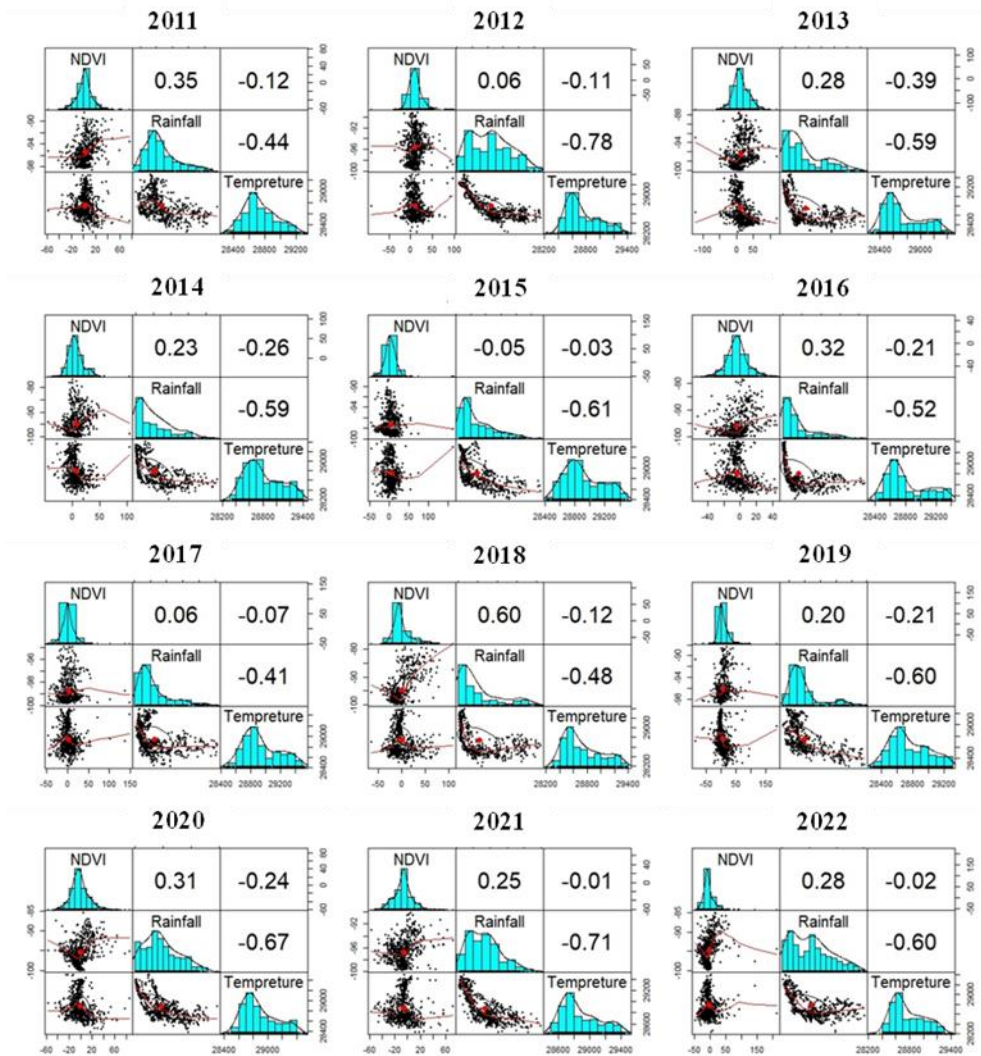


**Figure 3.** Spearman correlation coefficients ( $r_s$ ) of NDVI, rainfall, and temperature anomalies in Northern Algeria.

### 3.2. Thesis Statement 2:

**Multi-index drought assessment in Northwestern Algeria confirms a hydroclimatic regime shift toward persistent dryness after 2015, with interior steppe provinces emerging as persistent vulnerability hotspots driven by coupled meteorological and thermal stress.**

The integration of SPI (3-, 6-, and 12-month timescales), VCI, TCI, and VHI for the 2003–2023 period reveals a statistically significant drying trend, with no discernible evidence of persistent wetting across the region. The post-2015 period marks a structural transition from a relatively wetter hydroclimatic regime toward sustained seasonal water stress, a pattern that is particularly evident in SPI-6 and SPI-12 trajectories.

Vegetation and thermal condition indices further indicate that interior provinces, including Saïda Province, Tiaret Province, Sidi Bel Abbès Province, and Mascara Province, consistently exhibit lower VCI and TCI values, reflecting the combined effects of moisture deficits and elevated thermal stress.

Correlation analysis demonstrates that SPI-6 exhibits the strongest relationship with VHI ( $r = 0.509$ ,  $p = 0.019$ ), confirming that vegetation health within this semi-arid transition zone responds most strongly to accumulated seasonal precipitation anomalies rather than to short-term rainfall variability.

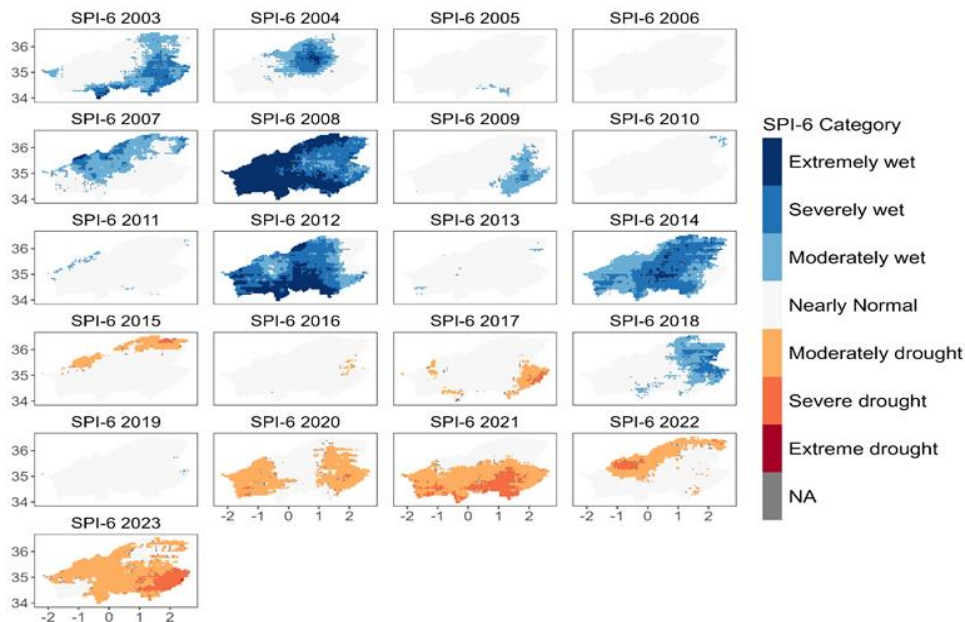


**Figure 4.** Spatial distribution of SPI6 in Northwest Algeria

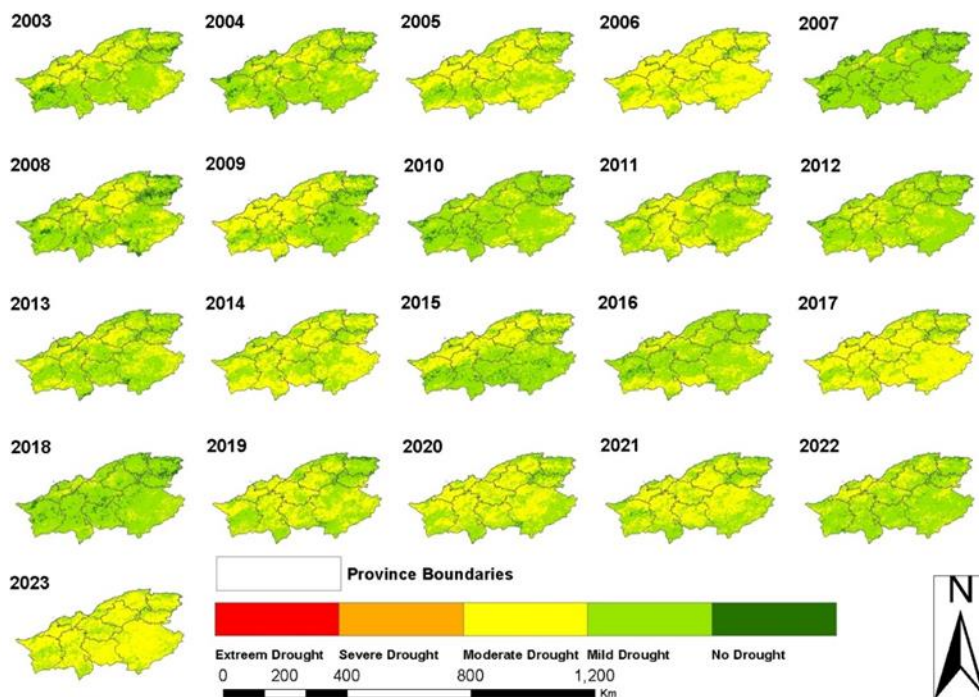


**Figure 5.** Spatial Distribution of Drought Severity in Northwest Algeria.

### 3.3. Thesis statment 3:

**Land-use dynamics in the Green Dam region (Djelfa) reveal a non-linear trajectory of plantation expansion, partial recovery, and subsequent collapse, driven by the combined effects of anthropogenic pressure and climatic stress.**

My research demonstrated that multi-temporal land use/land cover (LULC) classification (1972–2019) revealed the dynamic evolution of the Green Dam landscape. Afforestation efforts reached their peak during the 1972–1989 period, converting approximately 10,300 ha of degraded steppe into open plantations. However, this expansion proved neither ecologically nor socially sustainable over the long term. Open plantation cover declined by 19.9% between 1989 and 1999, experienced a temporary recovery of 33.6% between 1999 and 2009, and subsequently decreased by 43% between 2009 and 2019.

Intensity analysis, combined with demographic and livestock data, indicated that rapid population growth and projected livestock numbers exceeding five million head by 2030 have consistently surpassed the ecological carrying capacity of the steppe ecosystem. Furthermore, Land Change Modeler projections suggest the continued conversion of open plantations into degraded steppe landscapes by 2029, highlighting the structural instability of large-scale monoculture afforestation initiatives in water-limited ecotones when implemented without integrated, community-based land management strategies.

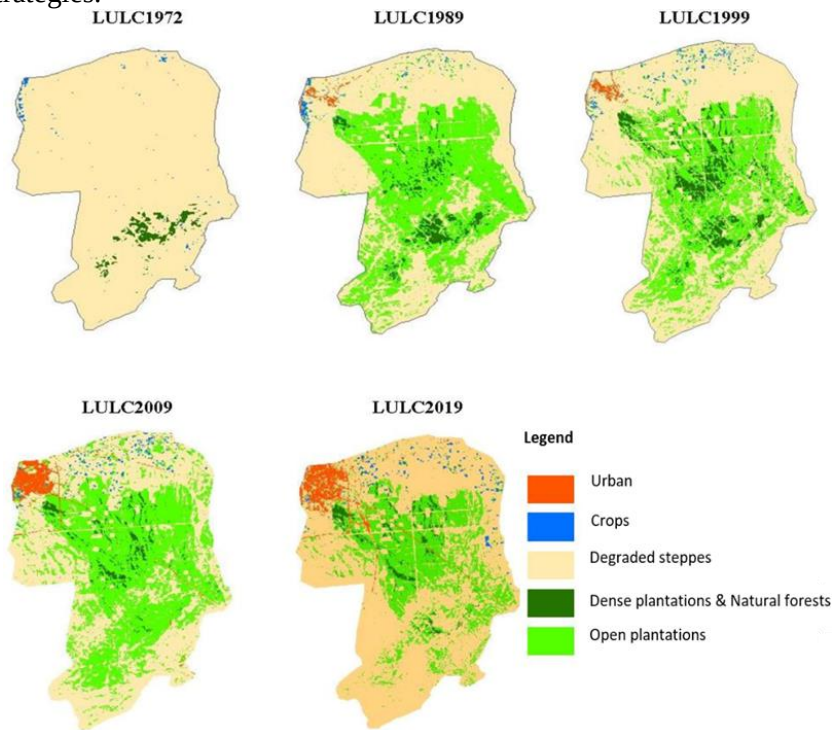


**Figure 6.** LULC classified maps of the Moudjbara region for the five studied years (1972, 1989, 1999, 2009, and 2019).

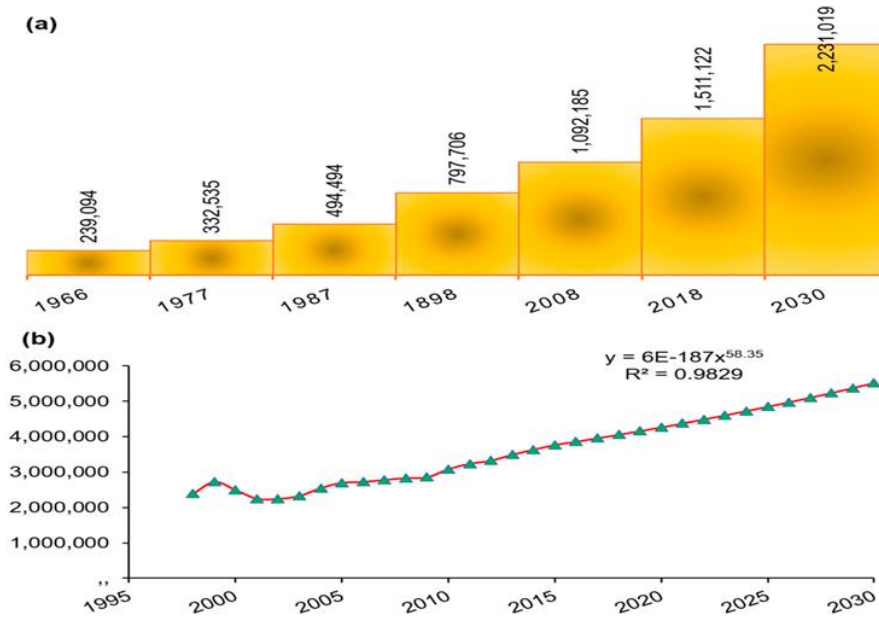


**Figure 7.** Evolution of the size of the human population, and the number of livestock (sheep and goats). Future prediction for the year 2030 was calculated using the mean annual growth rate (3.3%) of the period 2008–2018 in the case of population size, and the power function in the case of livestock number.

#### 3.4. Thesis statment 4:

**Machine learning classifiers (RF, XGBoost) achieve >90% accuracy in mapping desertification severity across Northern Algeria, with NDWI, albedo, NDVI, and topographic variables identified as dominant environmental drivers.**

I demonstrated that ensemble tree-based models trained on 1,945 ground-truthed samples and 16 multi-source predictors consistently achieved an overall accuracy of 0.94 and macro-averaged F1-scores of 0.94 on independent validation datasets. The results further showed that spatial cross-validation confirmed strong model generalization capacity, with only minimal performance degradation ( $\pm 0.035$ ) after accounting for spatial autocorrelation effects.

Feature importance analyses from both algorithms converged on NDWI, albedo, NDVI, FVC, and slope as the most influential determinants of desertification severity, highlighting the critical roles of surface moisture availability, vegetation cover, soil exposure, and topographically controlled water redistribution processes. Classification uncertainty was lowest within the extreme classes (non-desertified and severe desertification) and highest within ecotonal transition zones, reflecting the inherently continuous and gradual nature of land degradation gradients.

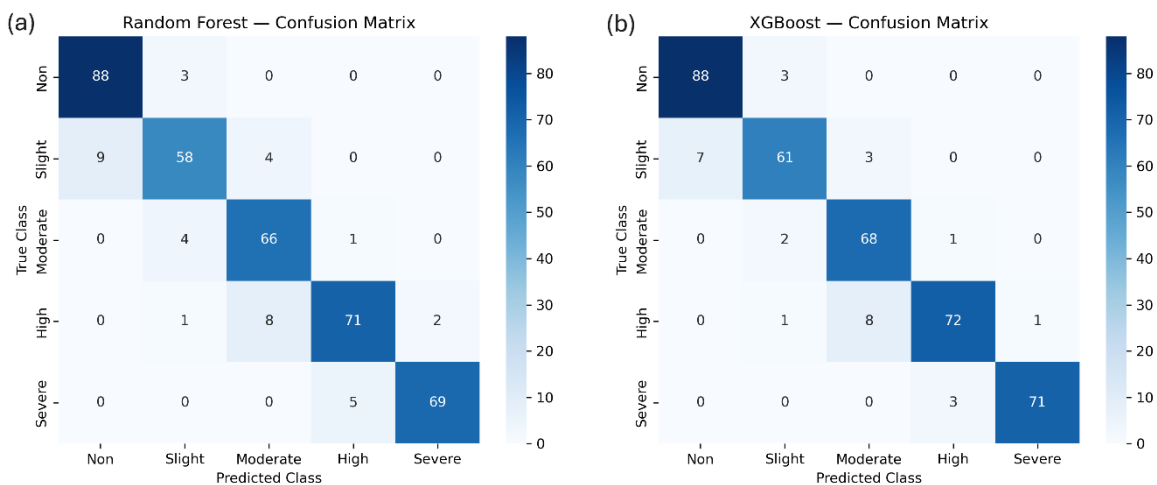


**Figure 8.** Confusion matrices for XGBoost and Random Forest models on the hold-out validation set.

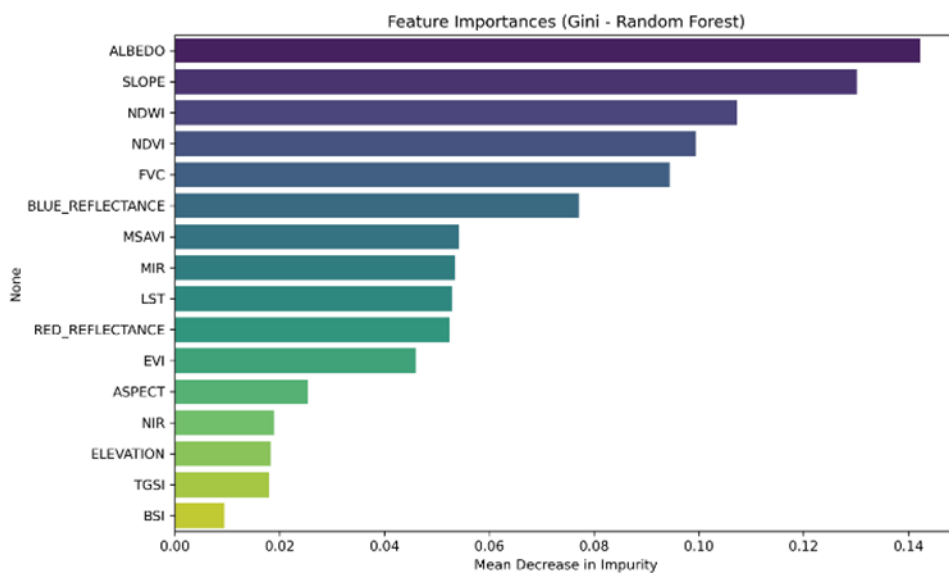


**Figure 9.** Relative importance of environmental predictors in the Random Forest classification model.

### 3.5. Thesis statment 5:

**Provincial zonal statistics identify Tlemcen, Sidi Bel Abbès, and Naâma as the most rapidly degrading provinces, providing actionable spatial targets for targeted land management interventions.**

My study demonstrated that the application of Random Forest (RF)-derived desertification maps to administrative boundaries across 40 provinces for the 2002–2022 period reveals substantial spatial heterogeneity in degradation rates. While the southern pre-Saharan zones exhibit the greatest absolute extent of severe desertification, zonal change analysis identified Tlemcen Province, Sidi Bel Abbès

Province, and Naâma Province as experiencing the most rapid net expansion of high and severe degradation classes.

This pattern suggests a progressive northward migration of degradation pressures from arid margins toward traditionally semi-arid agricultural and pastoral landscapes. In contrast, coastal and northern mountainous provinces exhibit negligible net change, confirming that degradation hotspots are primarily concentrated within transitional steppe–plateau ecotones, where climatic stress and anthropogenic land-use pressures interact synergistically to accelerate land degradation processes.

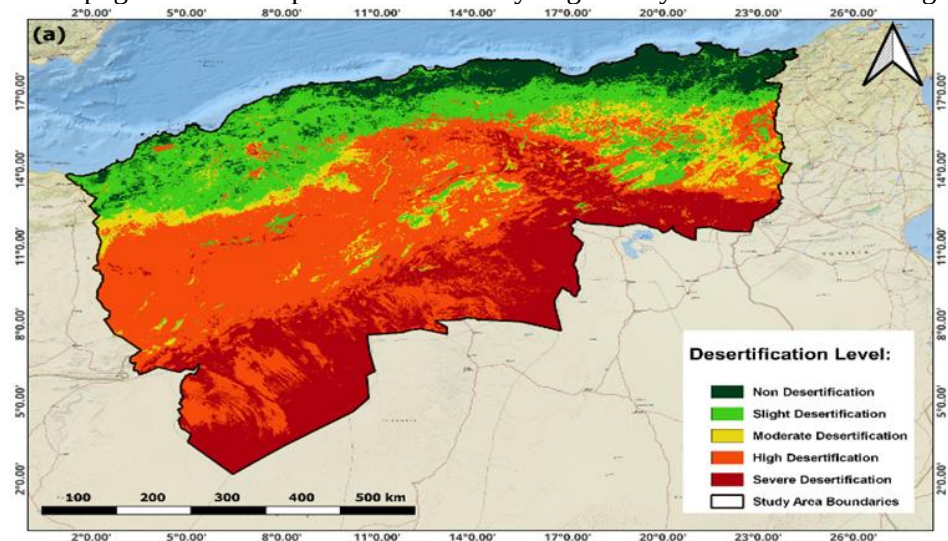


**Figure 10.** Spatial distribution of desertification severity in Northern Algeria 2002.

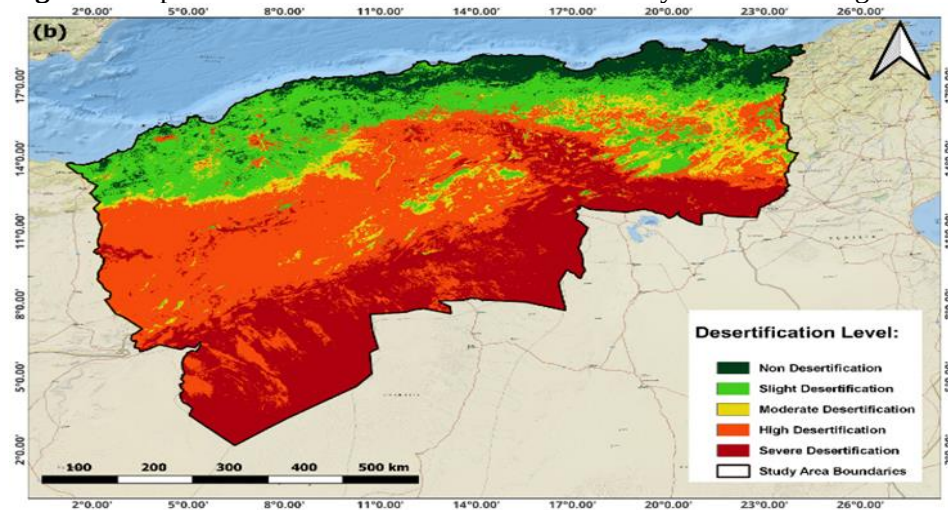


**Figure 11.** Spatial distribution of desertification severity in Northern Algeria 2022.

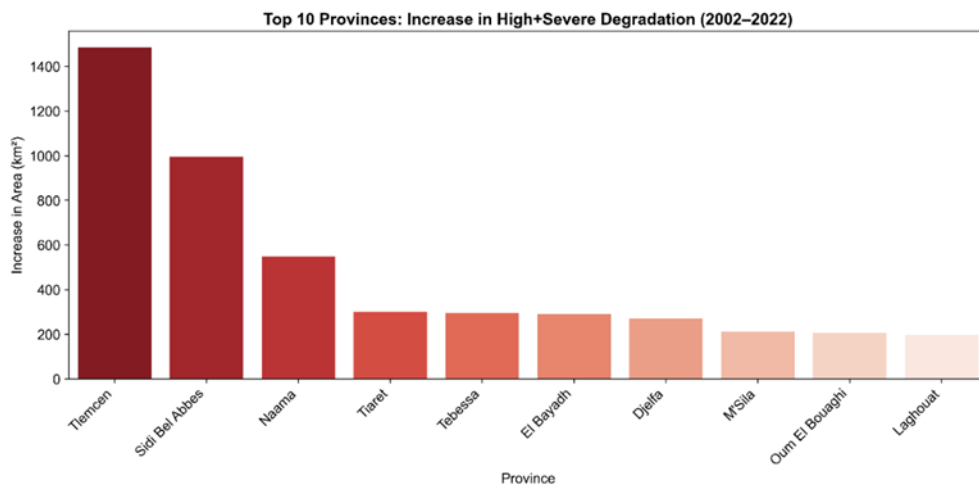


**Figure 12.** Provincial zonal statistics: Top 10 regions exhibiting the highest net increase in high and severe desertification area (2002–2022).

### 3.6. Thesis statment 6:

**Future scenario projection to 2030 indicates continued northward expansion of moderate-to-severe desertification classes, particularly across transitional steppe zones, underscoring the urgency of proactive land management.**

I found that linear extrapolation of 2002–2022 trends in environmental predictors projects a continued northward expansion of desertification severity by 2030. The model forecasts substantial transitions from moderate to high and severe desertification classes across Djelfa Province, M'Sila Province, Médéa Province, and the western high plains, with the severe desertification boundary potentially advancing 30–50 km northward in several sectors.

These projections suggest a progressive reduction in the ecological buffer separating productive northern agricultural systems from Saharan margins, highlighting the growing vulnerability of transitional landscapes under current climatic and land-use trajectories. Although the projection should be interpreted as an illustrative scenario rather than a deterministic forecast, it provides a valuable high-level spatial planning tool for prioritizing soil conservation measures, regulated grazing practices, and assisted natural regeneration within at-risk steppe ecotones.

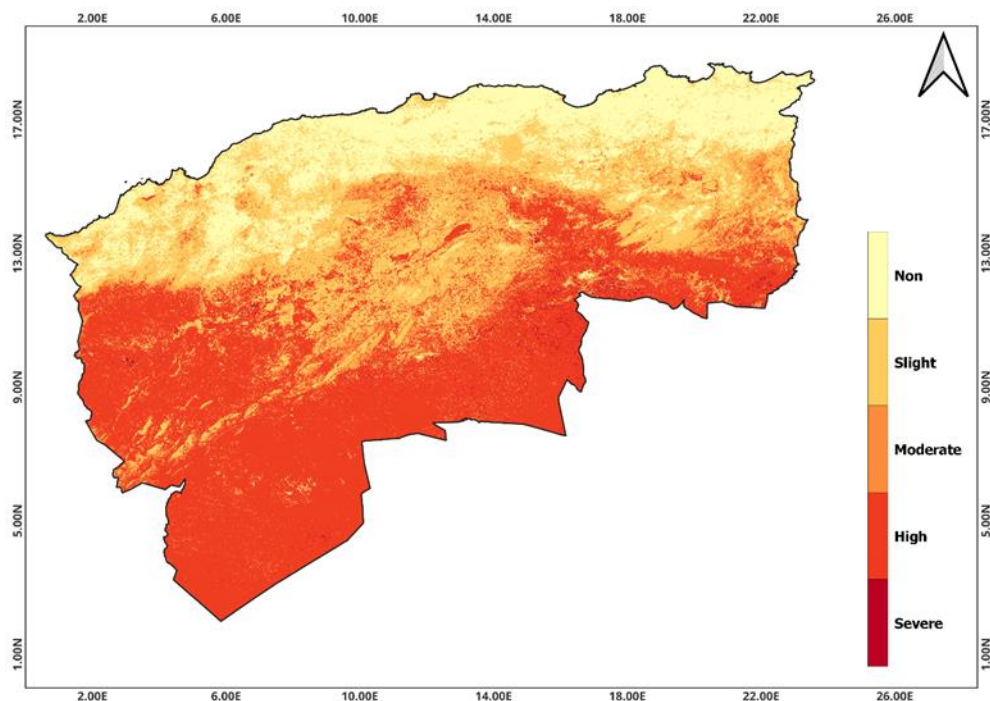


**Figure 13.** Spatial distribution of desertification severity classes projected to 2030 in Northern Algeria.

#### 4. Conclusion:

This dissertation investigated the spatiotemporal dynamics of land degradation, drought, and desertification across Northern Algeria through an integrated, multi-scale analytical framework. The central research question; *How do drought dynamics, climate variability, and human land-use changes interact to shape the spatiotemporal of land degradation and desertification patterns across the dryland ecosystems of Northern Algeria?*, was addressed by demonstrating that desertification is not driven by a single environmental or anthropogenic factor. Rather, it emerges from the complex and non-linear interaction between intensifying hydroclimatic stress, particularly the post-2015 trend toward increasing aridity and thermal stress, and unsustainable human pressures, including overgrazing, demographic expansion, and maladaptive land management practices.

The findings identified the interior steppe provinces as persistent hotspots of environmental vulnerability and demonstrated that the long-term effectiveness of the Green Dam afforestation initiative has been constrained by both ecological and socio-economic factors. Furthermore, the study confirmed that machine learning approaches, particularly Random Forest and XGBoost, provide robust and reliable tools for desertification assessment, enabling the identification of degradation patterns, key environmental drivers, and areas requiring priority intervention. Collectively, the research contributes a validated multi-scale analytical framework that is transferable to other data-scarce dryland regions facing similar environmental challenges.

The results have important practical implications for environmental management and policy. They highlight the need to strengthen drought early-warning systems based on seasonal indicators such as SPI-6, promote restoration strategies centered on native steppe vegetation and ecosystem resilience, and support participatory governance approaches that integrate local communities into land management decision-making. The identification of rapidly degrading provinces, particularly Tlemcen Province, Sidi Bel Abbès Province, and Naâma Province, provides a scientific basis for prioritizing restoration efforts, grazing regulation, and soil conservation measures.

Despite these contributions, several limitations should be acknowledged. Future projections were based on linear extrapolation of historical environmental trends and should therefore be interpreted as

illustrative scenarios rather than deterministic forecasts. In addition, the absence of direct soil moisture observations limited the ability to fully characterize drought propagation processes and soil–vegetation interactions. Addressing these limitations through the integration of in situ observations, higher-resolution datasets, and advanced predictive modelling approaches represents an important direction for future research on land degradation and desertification in Northern Algeria and other dryland environments.

## 5. Future research:

Future research should address the methodological limitations identified in this dissertation by integrating direct soil moisture observations to improve the calibration and representation of drought propagation processes. The development of hybrid machine learning frameworks that explicitly incorporate socio-economic drivers alongside biophysical variables would further enhance the ability to capture the complex interactions underlying land degradation dynamics.

In addition, comprehensive field-based validation campaigns within ecotonal transition zones are needed to better constrain model uncertainty in highly heterogeneous landscapes and to strengthen the ecological interpretation of model outputs. Furthermore, coupling the empirical modelling frameworks developed in this study with climate scenario projections, such as Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), would substantially improve the predictive capacity of long-term land degradation risk assessments. Such integration would enable a more robust evaluation of future environmental trajectories and provide valuable insights into the potential impacts of alternative climatic and socio-economic development pathways on dryland ecosystems.

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Candidate: Ramzi Benhizia  
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### List of publications related to the dissertation

#### Foreign language scientific articles in international journals (2)

1. **Benhizia, R.**, Phinzi, K., Hateffard, F., Aib, H., Szabó, G.: Drought Monitoring Using Moderate Resolution Imaging Spectroradiometer-Derived NDVI Anomalies in Northern Algeria from 2011 to 2022.  
*Environments*. 11 (5), 1-17, 2024. EISSN: 2076-3298.  
DOI: <http://dx.doi.org/10.3390/environments11050095>  
IF: 3.7
2. **Benhizia, R.**, Kouba, Y., Szabó, G., Négyesi, G., Ata, B.: Monitoring the Spatiotemporal Evolution of the Green Dam in Djelfa Province, Algeria.  
*Sustainability*. 13 (14), 1-15, 2021. ISSN: 2071-1050.  
DOI: <http://dx.doi.org/10.3390/su13147953>  
IF: 3.889

### List of other publications

#### Foreign language Hungarian book chapters (1)

3. Barkat, A., Szabó, G., **Benhizia, R.**, Mester, T., Rahal, Z.: Groundwater Quality Assessment of Oued Souf Valley Using GIS.  
In: , Debreceni Egyetemi Kiadó, Debrecen, 39-46, 2024.

#### Foreign language scientific articles in international journals (5)

4. Ata, B., Kozma, G., **Benhizia, R.**, Péntes, J.: Energy consumption, economic growth, and renewable energy effects on CO2 emissions in Iran: an ARDL-PCA analysis.  
*Carbon Balance Manage*. [Epub ahead of print], 2026. EISSN: 1750-0680.  
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5. Aib, H., Czédli, H., Baranyai, E., Sajtos, Z., Dönczö, B., Parvez, M. S., Berta, C., Varga, Z., **Benhizia, R.**, Nyeste, K. J.: Fish Scales as a Non-Invasive Method for Monitoring Trace and Macroelement Pollution.  
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9. **Benhizia, R.**, Saidi, F. A., Aib, H., Ata, B.: Spatiotemporal Dynamics of Drought Conditions in Constantine, Algeria (2002-2022): Insights from MODIS-Derived Indices.  
In: Az elmélet és a gyakorlat találkozása a térinformatikában = Theory meets practice in GIS : Debreceni Egyetem Térinformatikai Konferencia és Szakkiállítás/ szerk. Abriha-Molnár Vanda Éva, Debreceni Egyetemi Kiadó, Debrecen, 309-317, 2024. ISBN: 9789634906193





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In: Book of Proceeding 2nd International Sustainable Development Congress. Ed.: Asad Layek, Asad Layek, Antalya, 434-462, 2021. ISBN: 9786057403445

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**Total IF of journals (publications related to the dissertation): 7,589**

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