MODIS-Terra for Long-Term Environmental Monitoring: Insights into Drought Dynamics in Morocco

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Abstract

Effective drought monitoring is fundamental in the context of climate change, especially in regions where agriculture and urban systems are highly vulnerable. This study evaluates drought trends in Morocco's Rabat-Salé-Kénitra and Casablanca-Settat regions using MODIS-Terra satellite data spanning 2003 to 2023. The study analyzes Evapotranspiration (ET), Leaf Area Index (LAI), and Normalized Difference Vegetation Index (NDVI) to understand patterns of water stress, vegetation dynamics, and ecosystem health. MODIS products MOD16A2, MOD15A2, and MOD13A3 were used to derive ET, LAI, and NDVI, respectively. The analysis reveals an upward trend in ET, a fluctuating LAI, and a decline in NDVI, indicative of increasing drought stress. These findings underscore the urgency of adaptive water resource management and sustainable land-use strategies to bolster ecosystem resilience in Morocco's coastal urban zones.

Keywords: MODIS-Terra, Evapotranspiration, Leaf Area Index, Normalized Difference Vegetation Index, Drought Monitoring, Climate Change.

1. Introduction

Anthropogenic climate change is reshaping global environmental systems, manifesting in altered precipitation patterns, elevated temperatures, and increased frequency and intensity of drought events (Vicente-Serrano et al., 2012; IPCC, 2021). These impacts are especially pronounced in arid and semi-arid zones such as Morocco, where hydrological resources are inherently limited and highly sensitive to climatic perturbations (Trambauer et al., 2014; López-Moreno et al., 2016; Lehner et al., 2006).

Drought-induced stress affects key sectors such as agriculture, water management, and natural ecosystems. Therefore, regional and national-level drought surveillance is indispensable for mitigating long-term socio-economic and environmental consequences. Remote sensing technologies—particularly satellite-based observations—offer an efficient, scalable, and consistent approach to track landscape changes over extensive temporal and spatial domains. Among these tools, NASA's Terra satellite equipped with the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor provides a robust platform for environmental monitoring. It delivers a suite of high-frequency, moderate-resolution products tailored for ecological and hydrological assessments (Justice et al., 2002; Running et al., 2004).

This research focuses on two Moroccan coastal regions: Rabat-Salé-Kénitra and Casablanca-Settat. These regions are vital not only due to their population density and economic activity but also because of their susceptibility to environmental degradation stemming from fluctuating climatic conditions and increased anthropogenic demand. Featuring Mediterranean climates, both regions have witnessed increasingly erratic rainfall and rising temperatures over the past decades, compounding their vulnerability to drought and land degradation (Badr et al., 2016).

The study capitalizes on two decades of MODIS-Terra satellite observations (2003–2023) to investigate spatiotemporal patterns in three drought-relevant indices: ET, LAI, and NDVI. Each indicator serves as a proxy for different facets of environmental dynamics—ET represents atmospheric water demand and surface moisture loss; LAI captures vegetation structure and canopy density; NDVI indicates vegetative health and photosynthetic activity. The integration of these metrics provides a comprehensive framework for evaluating drought trajectories and informing resource management strategies geared toward environmental sustainability and resilience.

2. Study Area

Shifts in global climate conditions have significantly disrupted atmospheric systems, resulting in modified rainfall patterns, elevated temperatures, and an increased frequency of extreme weather phenomena, notably droughts (Vicente-Serrano et al., 2012; IPCC, 2021). These changes have particularly severe repercussions for arid and semi-arid countries such as Morocco, where limited freshwater availability and sensitive ecosystems make the regions more vulnerable to climatic extremes (Trambauer et al., 2014; López-Moreno et al., 2016).

This study concentrates on two strategically important coastal zones in Morocco—Rabat-Salé-Kénitra and Casablanca-Settat (Figure 1)—recognized for their dense urban infrastructure, agricultural productivity, and economic activities. These areas lie along the Atlantic coastline and are subject to a Mediterranean climate, characterized by seasonal rainfall, yet increasingly affected by irregular precipitation and drought occurrences.

Remote sensing technologies, particularly satellite-based tools, have proven to be highly effective for continuous monitoring of environmental changes across vast regions and over long timeframes, combining affordability with temporal and spatial reliability (Zhou et al., 2012; AghaKouchak et al., 2015). This research draws on MODIS-Terra data collected over a 20-year period to assess drought evolution using three principal environmental indicators: Evapotranspiration (ET), Leaf Area Index (LAI), and Normalized Difference Vegetation Index (NDVI). By analyzing the spatial and temporal distribution of these parameters, the study aims to advance understanding of ecological stress processes and inform effective environmental planning and sustainable management strategies.

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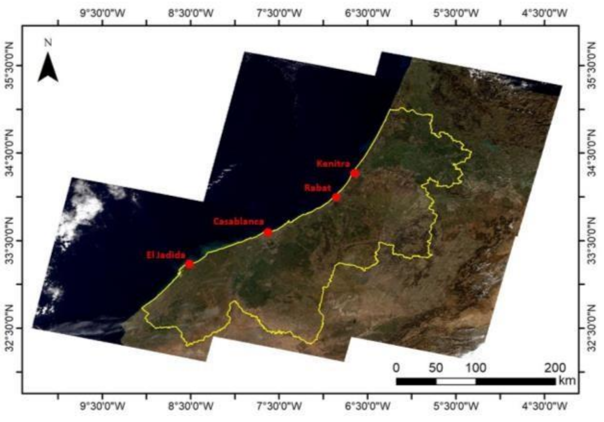

Figure 1: Study area

3. Methodology

To explore long-term transformations in vegetation patterns and hydrological dynamics from 2003 to 2023, this study utilized a multi-sensor, multi-temporal remote sensing approach based on MODIS-Terra datasets. Three core MODIS products were employed, each corresponding to distinct environmental indicators associated with drought assessment:

- MOD16A2 (Evapotranspiration - ET): This 8-day composite product, available at a 500-meter resolution, provides estimates of actual evapotranspiration. The data combine surface meteorological variables, land use, and vegetation conditions, making the product effective in monitoring water loss and atmospheric water demand (Mu et al., 2011).
- MOD15A2 (Leaf Area Index - LAI): This dataset, also compiled as 8-day composites with 500-meter spatial detail, estimates both the Leaf Area Index and the fraction of absorbed photosynthetically active radiation (FPAR). LAI is widely used to evaluate plant canopy density and vegetative health (Yang et al., 2006).
- MOD13A3 (Normalized Difference Vegetation Index - NDVI): This product provides monthly composites at a 1-kilometer spatial resolution, capturing variations in vegetation greenness and vigor. NDVI is a recognized index for tracking photosynthetic activity and plant stress in response to drought (Huete et al., 2002).

Three representative years—2003, 2013, and 2023—were selected to provide snapshots of decadal environmental shifts and facilitate temporal comparisons. These benchmark years were chosen to reflect medium- and long-term patterns in drought development.

A combination of geospatial analysis and statistical evaluation was applied to detect trends and variations across the selected indices. Only data pixels containing full temporal coverage across all three years were used to ensure methodological consistency and spatial reliability.

This comparative approach enabled the identification of critical areas experiencing pronounced vegetative decline or increasing evapotranspiration, thereby supporting the prioritization of mitigation efforts. The integration of these remote sensing indicators helps inform adaptive management strategies to address drought risk and enhance regional environmental resilience.

4. Results

4.1. Baseline Environmental Status (2003)

4.1.1. Evapotranspiration (ET). The color distribution shows large patches of green and yellow, especially in the northern and central parts. This indicates lower ET values in these areas (Figure 2.a).

Southern regions show more orange and red, indicating higher ET values, likely due to less vegetative cover and higher temperatures or soil moisture depletion.

Interpretation:
The overall lower ET values in the north could reflect either a more moderate climate or greater vegetative cover, which reduces water loss.

The higher ET values in the south may reflect more arid conditions typical of Morocco's climate.

4.1.2. Leaf Area Index (LAI). The map primarily displays yellow to orange shades, indicating moderate to low LAI values (Figure 2.b). There are some patches of green, particularly in the northern regions, which suggest areas of denser vegetation.

High LAI Zones: There are a few isolated spots with higher LAI values (green areas), which may correspond to forested or well-irrigated agricultural areas.

Low LAI Zones: The southern and western parts of the map show more orange and red hues, signifying sparse vegetation, possibly due to arid conditions or less vegetative cover during this period.

4.1.3. Normalized Difference Vegetation Index (NDVI). *High NDVI values (green):* Predominantly concentrated in the northern areas and central zones, which suggests these regions had a healthier and denser vegetation cover during this year (Figure 2.c).

Low NDVI values (red): More noticeable along the western and southwestern coastal regions, where vegetation might be sparse or the land is used for urbanization or agriculture (Figure 2.c).

Range: The NDVI values in 2003 range between -0.1914 and 0.9169, with a significant portion of the area falling in the low to medium NDVI categories, indicating regions with limited vegetation cover or seasonal variability.

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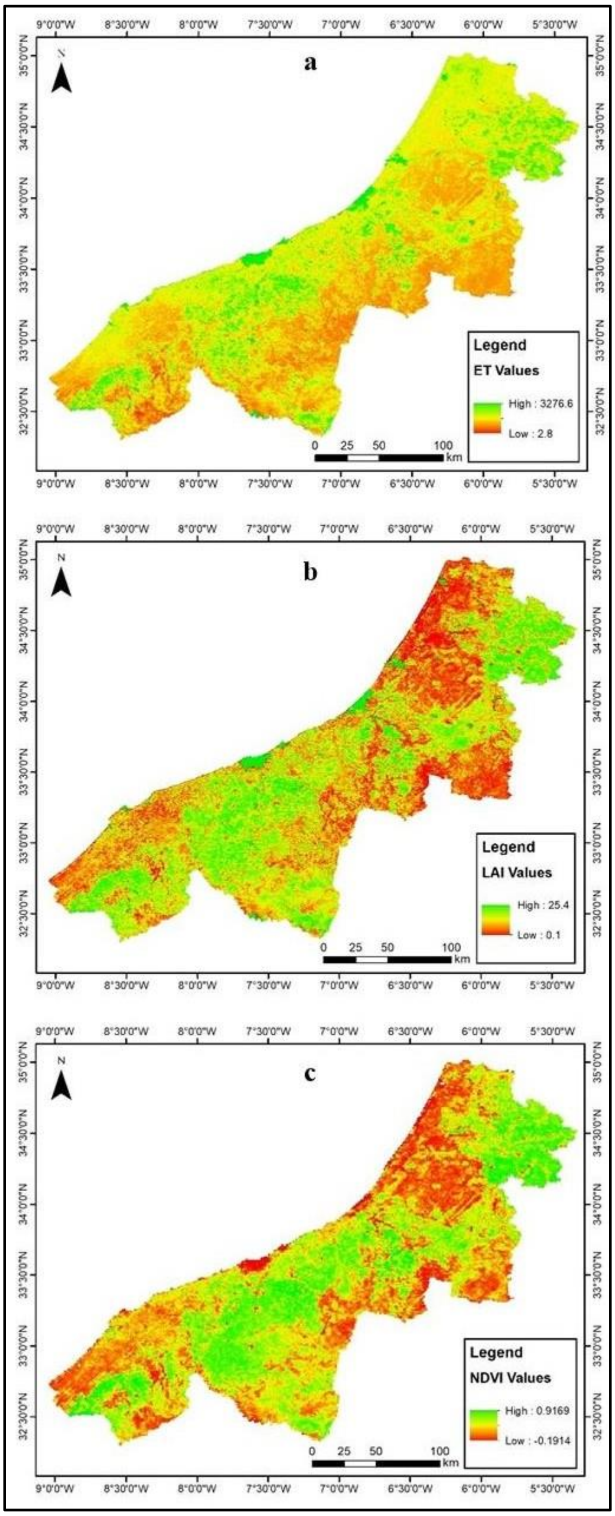

Figure 2: Environmental Indicators in 2003.

4.2. Midpoint Variability and Vegetative Response (2013)

4.2.1. Evapotranspiration (ET). There is a noticeable increase in orange and red areas compared to 2003. Northern regions that were previously green and yellow now show more orange, indicating increased ET (Figure 3.a).

Pockets of green remain, indicating some areas have maintained low ET values.

Interpretation:
The increase in ET values across the region suggests a general rise in water loss, which could be attributed to increasing temperatures, reduced vegetation, or both.

Some coastal areas still show lower ET values, potentially indicating the influence of cooler maritime climates or specific land use changes (e.g., afforestation or conservation efforts).

4.2.2. Leaf Area Index (LAI). Compared to 2003, the 2013 map exhibits a slight shift towards more green areas, indicating an overall increase in vegetation density. The green regions have expanded, particularly in the central and northern areas (Figure 3.b).

High LAI Zones: There are more extensive areas of high LAI (green zones), suggesting better vegetation health or increased vegetation cover, possibly due to improved agricultural practices, afforestation, or natural vegetation recovery.

Low LAI Zones: The southern and coastal regions still exhibit lower LAI values (orange to red), but these areas appear less extensive than in 2003, indicating some improvement in vegetative cover.

4.2.3. Normalized Difference Vegetation Index (NDVI). *High NDVI values (green):* Expanded slightly compared to 2003, particularly in the central areas. This may indicate an improvement in vegetation health or growth due to changes in agricultural practices, reforestation, or climate conditions (Figure 3.c).

Low NDVI values (red): Remain consistent in the coastal regions, particularly to the southwest. However, there seems to be an expansion of areas with higher NDVI values, suggesting possible vegetation recovery or agricultural development (Figure 3.c).

Range: The NDVI values slightly shifted between -0.1279 and 0.9189. The change in lower NDVI value might suggest a slight reduction in barren areas or urban zones.

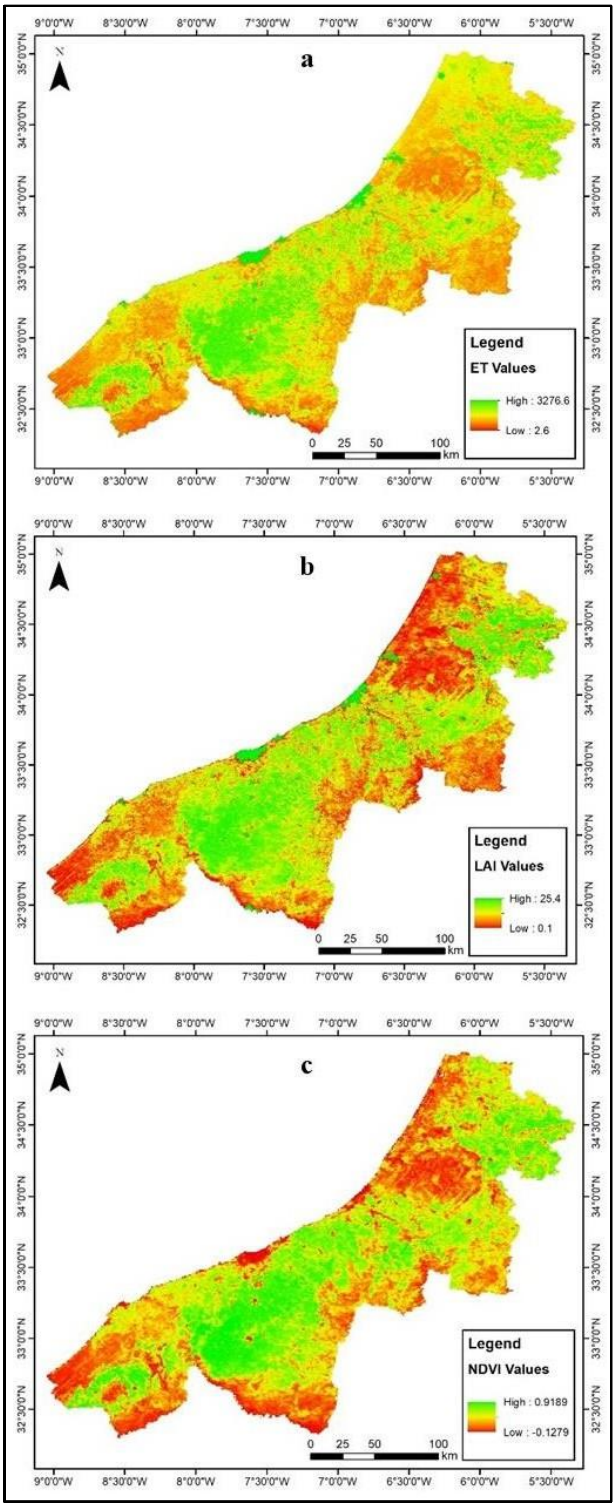

Figure 3: Environmental Indicators in 2013.

4.3 Recent Conditions and Drought Intensification (2023)

4.3.1. Evapotranspiration (ET). The 2023 map shows even more red and orange across almost the entire region. The north, which had relatively lower ET values in 2003 and 2013, now shows higher ET values (Figure 4.a).

The patches of green have shrunk significantly, indicating a general rise in ET across the board.

Interpretation:
The continued increase in ET values over the last two decades reflects intensifying conditions that are conducive to higher water loss. This could be due to rising temperatures from climate change, reduced precipitation, or loss of vegetation.

The increase in ET values may also point toward greater stress on agricultural systems, with more water required for crops and natural vegetation.

4.3.2. Leaf Area Index (LAI). The 2023 map shows a further increase in green areas, indicating higher LAI values overall. There is a noticeable reduction in red and orange zones, reflecting improved or denser vegetation (Figure 4.b).

High LAI Zones: The high LAI zones have become even more widespread compared to 2013, suggesting significant vegetative growth. This could be attributed to various factors such as climate change effects, changes in land use, or better water management practices.

Low LAI Zones: The low LAI areas have decreased further, indicating that even regions that were previously sparse in vegetation have experienced some recovery or improvement.

4.3.3. Normalized Difference Vegetation Index (NDVI). *High NDVI values (green):* Still present, but not as extensive as in 2013. There appears to be some reduction in the greener zones, which could indicate deforestation, degradation of vegetation, or urban expansion (Figure 4.c).

Low NDVI values (red): Areas with low NDVI seem to have expanded, especially toward the central and coastal zones, which might suggest urbanization, land use change, or degradation of vegetation due to environmental factors like drought (Figure 4.c).

Range: The NDVI values in 2023 range from -0.1355 to 0.9009. This shows a slight decrease in the overall vegetation index, hinting at a potential reduction in vegetation density or health over time.

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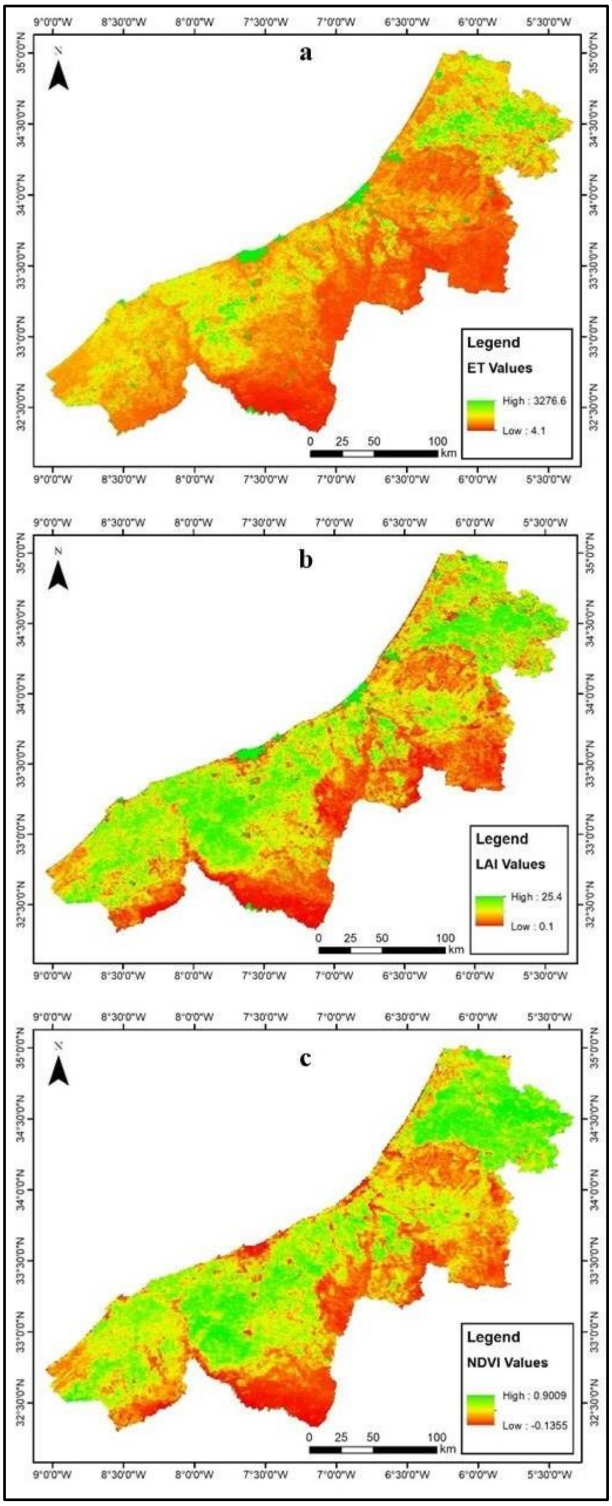

Figure 4: Environmental Indicators in 2023.

4.4. Comparative Analysis

4.4.1. Evapotranspiration (ET). Over the span of 20 years (2003 to 2023), the general trend is a rise in ET values, indicated by the shift from green/yellow (low ET) to orange/red (high ET).

Environmental Implications:

The rising ET values suggest increased environmental stress, likely driven by climate change, leading to higher temperatures and lower moisture availability.

This pattern is consistent with the regional climate trends in North Africa, where warming and drought events have been more frequent in recent decades.

Potential Agricultural Impact:
Higher ET rates mean more water is being lost from the soil and vegetation. This would likely demand more irrigation to sustain agriculture, especially in southern regions where the orange and red dominate.

Crop yields in areas like Casablanca and Rabat may be affected unless adaptive measures are put in place, such as the adoption of drought-resistant crops or improved irrigation techniques.

4.4.2. Leaf Area Index (LAI). *2003 to 2013:* The region saw an increase in vegetation density, particularly in the central and northern areas. The expansion of high LAI zones suggests a positive trend in vegetation cover, possibly due to afforestation or improved agricultural practices.

2013 to 2023: This trend continued, with further increases in vegetation density and a reduction in low LAI zones. The overall vegetation health appears to have improved, which could be due to better environmental management or favorable climatic conditions.

Positive Vegetation Trends: The data from 2003 to 2023 suggests a steady improvement in vegetation cover across the Rabat and Casablanca regions. The increase in LAI values over time indicates healthier and denser vegetation, which could have positive implications for agriculture, biodiversity, and climate resilience in the area.

Regional Variations: While there is an overall improvement, some areas, particularly in the south and along the coast, still show lower LAI values, which may require targeted interventions for further improvement.

This analysis highlights the importance of monitoring LAI as a key indicator of ecosystem health and the effectiveness of land management practices over time.

4.4.3. Normalized Difference Vegetation Index (NDVI). *2003-2013:* There is a noticeable improvement in vegetation cover and density during this decade. The central and northern regions show an increase in green zones, which may be attributed to environmental restoration projects, favorable climate conditions, or agricultural expansion. The coastal zones, however, remain largely barren or urbanized.

2013-2023: There is a slight regression in vegetation health and density, as seen in the reduction of green areas and the expansion of red and yellow zones. This could be due to several factors, including:

- *Urbanization:* The regions of Rabat and Casablanca have undergone significant development over the past decade, leading to a decrease in natural vegetation.
- *Climate Change:* Changes in precipitation patterns or increased droughts could have contributed to vegetation stress or decline.

- *Land Use Changes:* The expansion of agricultural lands, industrial areas, or infrastructure projects could have reduced natural vegetation cover.

This analysis suggests that while the regions experienced a period of improvement in vegetation health, the recent decade shows signs of environmental pressure and degradation, which might warrant sustainable land-use practices or environmental restoration efforts to prevent further decline.

5. Discussion

The observed trends reveal a clear and continuous rise in evapotranspiration (ET) across both Rabat-Salé-Kénitra and Casablanca-Settat over the 20-year study period, particularly in the southern and interior sub-regions. This increasing ET is likely driven by multiple interlinked factors including regional warming, prolonged dry seasons, and the diminishing density of vegetation cover. These findings align with previous studies conducted in comparable arid and semi-arid regions in North Africa and the Mediterranean basin, where elevated temperatures and reduced precipitation have been identified as key contributors to rising ET rates (Miralles et al., 2014; García-Ruiz et al., 2011).

Analysis of the Leaf Area Index (LAI) reveals a more complex temporal pattern. From 2003 to 2013, there was a moderate increase in LAI values, which could be associated with afforestation programs, the adoption of advanced irrigation systems, or the cultivation of high-biomass agricultural crops. These observations mirror regional patterns reported in the Sahel and Southern Europe, where similar increases in vegetative indices have been linked to agricultural intensification and reforestation initiatives (Fensholt et al., 2012; Vicente-Serrano et al., 2020). However, the 2013–2023 period is marked by a significant reversal of this trend, characterized by declining LAI. This decline is likely the result of accelerated urban sprawl, soil degradation, and a reduction in annual precipitation (Vicente-Serrano et al., 2013).

NDVI data exhibits a trajectory comparable to that of LAI. Between 2003 and 2013, there was a slight but noticeable increase in vegetation greenness and productivity, particularly in central and northern portions of the study regions. This period of relative recovery could be attributed to localized climate variability, reforestation efforts, or expanded agricultural practices. However, the following decade (2013–2023) indicates a downward trend, with pronounced NDVI declines in peri-urban zones and regions exposed to environmental stress. These trends are consistent with observations from the Iberian Peninsula, Tunisia, and Western Algeria, where sustained droughts and anthropogenic land use changes have contributed to NDVI reductions (Begué et al., 2011; Jarlan et al., 2014; Vicente-Serrano et al., 2012).

An additional noteworthy observation is the occasional divergence between LAI and NDVI trends across certain sub-regions. This may reflect differing phenological characteristics among plant types. For instance, certain annual crops might exhibit a rapid canopy development, thereby increasing LAI, while their chlorophyll content—and thus NDVI—remains low due to nutrient or water limitations. Similar interpretations have been proposed by Gouveia et al. (2016) in their analysis of Mediterranean vegetation under drought stress.

Altogether, these results highlight the critical value of combining multiple remote sensing indicators to achieve a holistic and nuanced understanding of ecosystem dynamics under climate change. The patterns observed in Morocco's coastal regions reflect a broader trend of environmental degradation affecting North Africa, and underscore the urgency of implementing integrated land and water management strategies. Effective mitigation will require adaptive interventions at multiple levels—from local land stewardship to national climate resilience planning.

6. Conclusion

This study demonstrates clear and measurable trends in environmental stress and drought conditions across the Rabat-Salé-Kénitra and Casablanca-Settat regions, using two decades of MODIS-Terra satellite data. The steady increase in evapotranspiration indicates intensifying atmospheric demand for water, while declines in both LAI and NDVI suggest deteriorating vegetation health and biomass density, particularly in recent years. These findings reflect the combined effects of climatic variability—marked by rising temperatures and irregular precipitation—and human pressures such as urban expansion and land-use change.

The integration of remote sensing-based indicators like ET, LAI, and NDVI provides a valuable framework for long-term monitoring and environmental assessment. These tools offer scalable and timely insights into ecosystem dynamics, supporting early warning systems and decision-making processes. As drought risks intensify, there is an urgent need for data-driven, multi-sectoral strategies that strengthen the resilience of both natural systems and the communities that depend on them.
In light of these insights, it is crucial to adopt proactive measures including reforestation, sustainable agriculture, urban green planning, and improved water governance. By leveraging satellite technology and interdisciplinary research, Morocco can enhance its adaptive capacity and safeguard the ecological and socio-economic vitality of its coastal urban regions.

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