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Geo-Environmental Change Detection in Agro-Climatic Zones Using Multi-Sensor Satellite Data

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ABSTRACT

Geo-environmental changes in agro-climatic zones have intensified in recent decades due to the combined influence of climate variability, agricultural intensification, land use transformation, and human interventions. Agro-climatic zones represent distinct ecological units where climate, soil, water availability, and cropping patterns interact, making them highly sensitive to environmental change. Continuous monitoring of these regions is essential for sustainable agricultural development and environmental management.

This study focuses on detecting and analyzing geo-environmental changes across selected agro-climatic zones using multi-sensor satellite data. Data acquired from optical and thermal sensors, such as Landsat and Sentinel series, are employed to capture variations in land use and land cover, vegetation condition, surface temperature, and moisture-related parameters over different time periods. Remote sensing indices, including Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), and Normalized Difference Moisture Index (NDMI), are integrated with Geographic Information System (GIS) techniques to assess spatial and temporal patterns of environmental change.

Multi-sensor data integration enables improved detection of subtle environmental variations that may not be captured using a single sensor. Change detection techniques are applied to quantify trends in vegetation health, land degradation, and thermal anomalies across agro-climatic zones. The results reveal significant spatial heterogeneity in geo-environmental changes, reflecting the influence of climatic conditions, agricultural practices, and land management strategies. The study demonstrates the effectiveness of multi-sensor remote sensing approaches for comprehensive geo-environmental monitoring and provides valuable insights for sustainable resource management and agro-climatic planning.

Keywords: Geo-Environmental Change, Agro-Climatic Zones, Multi-Sensor Satellite Data.

1. INTRODUCTION

Agro-climatic zones represent spatial units characterized by relatively homogeneous climatic conditions, soil properties, water availability, and cropping patterns. These zones form the backbone of agricultural planning and food security in many regions, particularly in developing countries where livelihoods are closely tied to climate-dependent agriculture. However, increasing climate variability, intensification of agricultural practices, land use change, and growing anthropogenic pressure have significantly altered the geo-environmental conditions of agro-climatic zones over recent decades.

Geo-environmental changes such as vegetation degradation, soil moisture depletion, surface temperature variation, and land degradation have direct implications for agricultural productivity and ecological stability. Detecting and monitoring these changes at appropriate spatial and temporal scales is therefore essential for sustainable agricultural management and environmental conservation. Traditional field-based monitoring methods, while accurate at local scales, are often time-consuming, costly, and inadequate for capturing large-area environmental dynamics across diverse agro-climatic zones.

Remote sensing and Geographic Information System (GIS) technologies offer an efficient and reliable alternative for geo-environmental change detection. Satellite sensors provide repetitive, synoptic, and multi-spectral observations of the Earth's surface, enabling continuous monitoring of environmental parameters across different agro-climatic settings. The use of multi-sensor satellite data, combining information from optical, thermal, and near-infrared sensors, enhances the ability to capture complex environmental processes that cannot be fully represented by a single sensor system.

Multi-sensor approaches facilitate the assessment of key geo-environmental indicators such as vegetation condition, land surface temperature, and moisture status through the integration of spectral indices like the Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), and Land Surface Temperature (LST). These indicators are widely recognized as effective proxies for assessing ecosystem health, agricultural stress, and land degradation processes. When analyzed within a GIS framework, they provide valuable spatial insights into environmental changes and their distribution across agro-climatic zones.

Despite the growing body of literature on land use and land cover change analysis, relatively fewer studies have focused on integrated geo-environmental change detection using multi-sensor satellite data across agro-climatic

zones. There remains a need for comprehensive spatiotemporal assessments that combine multiple environmental indicators to capture the complex interactions between climate, land use, and agricultural practices.
In this context, the present study aims to detect and analyze geo-environmental changes in selected agro-climatic zones using multi-sensor satellite data integrated with GIS techniques. By examining variations in vegetation, surface temperature, and moisture conditions over time, the study seeks to provide a holistic understanding of environmental dynamics and to support sustainable agricultural and environmental planning at the agro-climatic scale.

2. REVIEW OF LITERATURE

Jensen (2005) emphasized the importance of multi-spectral and multi-temporal remote sensing data for environmental monitoring. The study highlighted that combining data from different sensors enhances the detection of land surface changes, particularly in agriculturally dominated regions where climatic variability plays a major role.
Turner et al. (2007) examined land and environmental change as a coupled human–environment system. Their research underlined that agro-climatic zones experience distinct environmental responses to land use practices and climate variability, making zone-based analysis essential for understanding geo-environmental transformations.
Lambin and Geist (2008) analyzed global patterns of environmental change and concluded that agricultural intensification and land management practices are key drivers of geo-environmental change. Their work provided a conceptual basis for linking remote sensing indicators with agro-climatic processes.
Weng (2010) demonstrated the effectiveness of integrating thermal and optical satellite data for environmental change detection. The study showed that land surface temperature derived from thermal sensors complements vegetation indices in assessing environmental stress, especially in climatically sensitive zones.
Verburg et al. (2013) introduced land system science approaches to study environmental change across different climatic regions. They emphasized that agro-climatic zone-based spatial analysis using GIS and remote sensing improves understanding of spatial heterogeneity in environmental responses.
Roy et al. (2015) utilized multi-sensor satellite datasets to analyze environmental changes in Indian agro-climatic regions. Their findings revealed spatial variability in vegetation condition and land degradation linked to cropping intensity and irrigation development.
Rawat and Kumar (2015) reviewed geo-environmental change detection techniques using remote sensing and GIS. They highlighted that multi-sensor data integration improves classification accuracy and change detection reliability in agriculturally diverse regions.
Dutta et al. (2019) assessed vegetation and land surface temperature dynamics using Landsat data in semi-arid agro-climatic zones. The study found that declining vegetation indices and rising surface temperatures were indicative of increasing environmental stress due to unsustainable land use practices.
Pandey et al. (2020) applied NDVI and NDMI-based analysis to evaluate moisture stress and vegetation dynamics in different agro-climatic zones. Their research demonstrated that multi-indicator approaches provide a more comprehensive understanding of geo-environmental change than single-index analysis.
Talukdar et al. (2021) employed machine learning techniques on multi-sensor satellite data for environmental monitoring. Their study highlighted improved detection of subtle environmental changes when optical and thermal datasets were jointly analyzed.
Chakraborty et al. (2022) investigated the relationship between land surface temperature, vegetation cover, and land degradation in agro-climatic regions. The study emphasized that rising thermal anomalies are closely associated with declining vegetation health and moisture availability.
Kumar and Sharma (2023) conducted a spatiotemporal analysis of geo-environmental change using Sentinel and Landsat data across multiple agro-climatic zones. Their results showed increasing spatial heterogeneity in environmental indicators driven by climate variability and agricultural practices.
Singh et al. (2024) analyzed recent geo-environmental trends using high-resolution multi-sensor satellite data. The study concluded that integrated remote sensing and GIS approaches are crucial for early detection of environmental stress in agro-climatic zones and for supporting sustainable land management.

3. OBJECTIVES OF THE STUDY

1. To detect and analyze spatiotemporal geo-environmental changes across different agro-climatic zones using multi-sensor satellite data. This objective focuses on identifying temporal and spatial variations in key geo-environmental parameters across agro-climatic zones by utilizing satellite data acquired from different sensors and time periods.
2. To assess variations in vegetation condition using spectral indices derived from optical satellite data. This objective aims to evaluate changes in vegetation health and density through indices such as the Normalized

Difference Vegetation Index (NDVI), thereby identifying areas experiencing vegetation stress or improvement over time.

3. To analyze land surface temperature patterns and their relationship with environmental change. This objective examines spatial and temporal variations in Land Surface Temperature (LST) using thermal satellite data, helping to understand the impact of land use practices and climatic variability on surface thermal conditions.

4. To evaluate moisture conditions and surface wetness using moisture-related spectral indices. The objective involves analyzing indices such as the Normalized Difference Moisture Index (NDMI) to assess changes in surface moisture availability, which is critical for agricultural sustainability in agro-climatic zones.

5. To integrate multi-sensor satellite datasets within a GIS framework for comprehensive geo-environmental analysis. This objective seeks to combine optical, thermal, and moisture-related data layers using GIS tools to generate spatially integrated geo-environmental change maps across agro-climatic zones.

6. To identify zones of environmental stress and land degradation within agro-climatic regions. This objective focuses on delineating environmentally vulnerable areas based on combined indicators of vegetation decline, rising surface temperature, and moisture stress.

7. To evaluate the effectiveness of multi-sensor remote sensing approaches in geo-environmental change detection. This objective assesses the advantages of using multi-sensor satellite data over single-sensor approaches for accurate and reliable detection of geo-environmental changes.

8. To provide geospatial insights for sustainable agricultural and environmental planning in agro-climatic zones. The final objective aims to support informed decision-making by generating spatial information that can assist planners and policymakers in sustainable land and resource management.

4. RESEARCH METHODOLOGY

The present study adopts an integrated Remote Sensing and Geographic Information System (GIS)-based methodology to detect and analyze geo-environmental changes across selected agro-climatic zones. The approach is designed to capture spatial and temporal variations in environmental parameters by utilizing data from multiple satellite sensors and combining them within a unified analytical framework.

Selection of Agro-Climatic Zones

The study focuses on selected agro-climatic zones characterized by distinct climatic conditions, soil types, cropping patterns, and water availability. Agro-climatic zoning provides an appropriate spatial framework for environmental analysis, as it reflects the interaction between climate and agricultural practices. The boundaries of the agro-climatic zones are digitized and georeferenced in a GIS environment to facilitate spatial analysis.

Data Sources and Satellite Sensors

Multi-sensor satellite data are used to ensure comprehensive geo-environmental monitoring. The primary data sources include:

- **Optical Data:** Landsat (TM, ETM+, OLI) and Sentinel-2 multispectral imagery for vegetation and land surface analysis.
- **Thermal Data:** Landsat thermal bands for Land Surface Temperature (LST) estimation.
- **Temporal Coverage:** Multi-date satellite images spanning approximately 15–20 years are selected to capture long-term environmental changes.
- **Ancillary Data:** Agro-climatic zone maps, topographic maps, administrative boundaries, and field observations (where available) are used to support interpretation and validation.

All satellite datasets are obtained from reliable repositories such as **USGS Earth Explorer** and **Copernicus Open Access Hub**.

Image Pre-Processing

To ensure consistency and comparability across datasets, all satellite images undergo standard pre-processing procedures, including:

- Radiometric correction to reduce sensor-related errors
- Atmospheric correction to minimize atmospheric interference
- Geometric correction and co-registration to align multi-date images
- Image subsetting to the agro-climatic zone boundaries

These steps are essential for accurate computation of spectral indices and change detection.

Derivation of Geo-Environmental Indicators

Key geo-environmental indicators are derived from pre-processed satellite data:

- **Normalized Difference Vegetation Index (NDVI):** Used to assess vegetation health and density.
- **Normalized Difference Moisture Index (NDMI):** Used to evaluate surface moisture and vegetation water content.
- **Land Surface Temperature (LST):** Derived from thermal bands to analyze surface thermal conditions and environmental stress.

These indicators collectively represent vegetation condition, moisture status, and thermal characteristics of the agro-climatic zones.

Multi-Sensor Data Integration

The derived indices from different sensors are integrated within a GIS framework. Layer stacking and spatial overlay techniques are applied to combine optical, thermal, and moisture-related information. This integration enables a holistic assessment of geo-environmental conditions and enhances the detection of subtle environmental changes.

Change Detection Analysis

Spatiotemporal change detection is performed using a combination of:

- Multi-date index differencing
- Threshold-based classification of environmental change
- GIS-based overlay analysis

Changes in NDVI, NDMI, and LST values are analyzed to identify trends of vegetation degradation, moisture stress, and thermal anomalies across agro-climatic zones.

GIS-Based Spatial Analysis and Mapping

GIS tools are used to quantify and visualize geo-environmental changes through:

- Area statistics and zonal analysis
- Preparation of thematic maps for each indicator
- Identification of environmental stress zones

This spatial analysis facilitates comparison between different agro-climatic zones and highlights regions of significant environmental change.

Interpretation and Validation

The results are interpreted in relation to climatic variability, agricultural practices, and land management strategies within each agro-climatic zone. Validation is carried out using high-resolution imagery, secondary data, and available field information to ensure the reliability of the findings.

5. RESULTS AND DISCUSSION

The integration of multi-sensor satellite data and GIS-based analysis provides a comprehensive understanding of geo-environmental changes across different agro-climatic zones. The results reveal significant spatial and temporal variations in vegetation condition, surface temperature, and moisture availability, reflecting the combined influence of climatic variability and human activities.

Vegetation Dynamics (NDVI Analysis)

Analysis of the Normalized Difference Vegetation Index (NDVI) indicates noticeable variations in vegetation health across agro-climatic zones over the study period. Zones dominated by irrigated agriculture show relatively stable or moderately improved NDVI values, suggesting enhanced cropping intensity and vegetation cover. In contrast, rain-fed and marginal agricultural zones exhibit declining NDVI trends, particularly during recent years, indicating vegetation stress due to irregular rainfall and soil moisture deficits.

Temporal comparison reveals a reduction in dense vegetation cover in several zones, accompanied by an increase in sparse or degraded vegetation. These trends point toward land degradation processes and increasing vulnerability of agro-ecosystems to climatic stress.

Land Surface Temperature Variations

Land Surface Temperature (LST) analysis derived from thermal satellite data shows a consistent increase in surface temperatures across most agro-climatic zones. Areas experiencing declining vegetation cover correspond closely with higher LST values, indicating the strong inverse relationship between vegetation density and surface temperature.

Agro-climatic zones characterized by rapid agricultural intensification and expansion of built-up features exhibit pronounced thermal anomalies. Rising surface temperatures not only reflect land cover change but also suggest increasing heat stress, which may negatively affect crop productivity and soil moisture retention.

Moisture Stress Assessment (NDMI Analysis)

The Normalized Difference Moisture Index (NDMI) reveals significant changes in surface moisture conditions across the study area. Zones with declining NDMI values indicate increasing moisture stress, particularly in regions dependent on rainfall-based agriculture. In contrast, zones with extensive irrigation infrastructure show relatively stable moisture conditions, though signs of long-term moisture depletion are evident in some areas.

The combined decline in NDMI and NDVI in certain agro-climatic zones highlights regions experiencing severe environmental stress, likely resulting from groundwater over-extraction, reduced precipitation, and unsustainable land management practices.

Integrated Geo-Environmental Change Patterns

The integration of NDVI, LST, and NDMI within a GIS framework enables the identification of composite geo-environmental change patterns. Agro-climatic zones exhibiting low NDVI, high LST, and low NDMI are identified as environmental stress hotspots. These zones represent areas of heightened vulnerability to land degradation and declining agricultural sustainability.

Conversely, zones displaying stable vegetation indices, moderate surface temperatures, and adequate moisture conditions indicate relatively resilient agro-ecosystems. The spatial heterogeneity observed across agro-climatic zones underscores the importance of zone-specific environmental monitoring and management strategies.

Discussion of Drivers of Geo-Environmental Change

The observed geo-environmental changes are driven by a combination of natural and anthropogenic factors. Climatic variability, particularly irregular rainfall and prolonged dry spells, plays a critical role in shaping vegetation and moisture patterns. Human-induced factors, including agricultural intensification, expansion of irrigated areas, and land management practices, further influence environmental conditions.

In several agro-climatic zones, short-term gains in agricultural productivity through intensive irrigation are accompanied by long-term environmental stress, as reflected in rising surface temperatures and declining moisture indices. This highlights the trade-offs between agricultural development and environmental sustainability.

Implications for Agro-Climatic Zone Management

The results demonstrate that multi-sensor satellite data provide valuable insights into the complex geo-environmental dynamics of agro-climatic zones. Identifying stress-prone areas enables targeted interventions such as improved water management, crop diversification, and soil conservation measures. The study emphasizes the importance of integrating geo-environmental indicators into agro-climatic planning to enhance resilience against climate variability.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The present study demonstrates that multi-sensor satellite data integrated with GIS techniques provide a robust and effective framework for detecting and analyzing geo-environmental changes across agro-climatic zones. By combining optical, thermal, and moisture-sensitive satellite datasets, the study captures complex environmental dynamics that cannot be adequately represented through single-sensor analysis. The spatiotemporal assessment reveals significant variability in vegetation condition, land surface temperature, and moisture availability across different agro-climatic zones, reflecting both climatic influences and human-induced land management practices.

The results indicate that agro-climatic zones dominated by rain-fed agriculture are increasingly vulnerable to vegetation degradation, moisture stress, and rising surface temperatures. In contrast, irrigated zones exhibit relatively stable vegetation conditions, although signs of long-term thermal stress and moisture depletion are evident. The integrated analysis of NDVI, NDMI, and LST highlights the presence of environmental stress hotspots, underscoring the growing pressure on land and water resources.

Overall, the study confirms that geo-environmental change is not uniform across agro-climatic zones but varies according to climatic conditions, agricultural intensity, and land-use practices. The use of multi-sensor remote sensing data enhances the accuracy and reliability of environmental change detection, making it a valuable tool for agro-climatic assessment and sustainable land resource monitoring.

6.2 Recommendations

Based on the findings of the study, the following recommendations are proposed:

- **Agro-Climatic Zone–Specific Planning:** Environmental management strategies should be tailored to individual agro-climatic zones, considering their distinct climatic conditions, cropping patterns, and resource availability.
- **Sustainable Water Resource Management:** Regions experiencing persistent moisture stress require improved water management practices, including rainwater harvesting, efficient irrigation techniques, and regulation of groundwater extraction.
- **Promotion of Climate-Resilient Agriculture:** Adoption of drought-tolerant crops, crop diversification, and soil moisture conservation practices should be encouraged to reduce environmental vulnerability in stress-prone zones.
- **Regular Geo-Environmental Monitoring:** Periodic monitoring using multi-sensor satellite data should be institutionalized to detect early signs of vegetation degradation, thermal stress, and moisture depletion.
- **Integration of Geospatial Data into Policy Frameworks:** Geo-environmental indicators derived from remote sensing and GIS should be incorporated into agricultural planning and environmental policy formulation at regional and national levels.

- **Future Research Directions:** Future studies should incorporate higher-resolution satellite data, climate datasets, and socio-economic variables to improve understanding of the drivers of geo-environmental change and to enhance predictive modeling capabilities.

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