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Monitoring of perennial plantations using satellite data.

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Abstract: This study develops a modern monitoring methodology based on the use of satellite data to assess the ecological condition of perennial tree plantations in the Quva district of the Fergana region. The research analyzes average NDVI indicators from 2014 to 2023 using satellite imagery from Sentinel-2 and Landsat 8, revealing a consistent decline in forest health over the years. Remote sensing technologies, particularly the Google Earth Engine platform, were employed to generate vegetation indices, which facilitated the visualization and assessment of zonal maps, degraded areas, and their dynamics. The study provides practical recommendations for environmental management, forest planning, and nature conservation. This research underscores the necessity of integrating digital technologies into the monitoring of perennial forests in the context of Uzbekistan and serves as a significant scientific and practical tool for ensuring ecological security.
Keywords: remote sensing, satellite imagery, forest monitoring, NDVI, GEE, vegetation indices, Landsat, Sentinel, geographic information systems

Introduction

In recent years, global environmental challenges—particularly climate change, biosphere degradation, the increasing emission of carbon into the atmosphere, and the scarcity of natural resources—have compelled humanity to adopt new approaches to environmental observation, management, and conservation. The need for continuous monitoring of ecologically significant biogeocenoses such as forests and perennial tree plantations has grown significantly. These ecosystems play a crucial role in regulating climate, absorbing carbon, preventing soil erosion, preserving biodiversity, and ensuring overall ecological stability vital for human well-being. However, due to anthropogenic pressures, mismanagement of land resources, wildfires, and technogenic risks, these forests are rapidly diminishing, and their natural condition is deteriorating. Therefore, the implementation of precise, continuous, prompt, and objective monitoring systems has become an integral part of national ecological strategies [1,2].

In Uzbekistan, several critical state policy documents have been adopted to address these pressing issues. Among them are the Presidential Decree No. PF–46 dated December 30, 2021, which approved the “Green Space” National Program for 2022–2026; Presidential Resolution No. PQ–186 dated April 11, 2022, outlining the “Comprehensive Measures for Environmental Protection and Rational Use of Natural Resources for 2022–2025”; and Presidential Resolution No. PQ–103 dated March 31, 2023, on the “Improvement of Monitoring and Digitalization Systems for Land Resources.” These documents emphasize the state's intention to integrate digital technologies, satellite-based control mechanisms, and the use of GIS and remote sensing technologies into environmental monitoring frameworks.

Today, the monitoring of land resources — especially forests and perennial plantations — using modern technologies is regarded as one of the key directions in ensuring environmental security, sustainable development, and effective climate policy. The use of satellite data, particularly the analysis of vegetation indices such as NDVI, EVI, and SAVI, enables the assessment of vegetation health, detection of spatial and temporal changes, identification of degraded zones, and the development of scientifically grounded management decisions. This marks a qualitative leap from traditional observation methods to a more advanced level of environmental monitoring.

The main objective of this research is to thoroughly investigate the theoretical and practical foundations of monitoring the condition of perennial tree plantations using satellite data. It aims to analyze modern technologies and methodologies, and to propose region-specific applications and recommendations tailored to the context of Uzbekistan. The research tasks include: studying advanced remote sensing techniques, developing a methodology to assess forest conditions through vegetation indices, analyzing real-time changes based on satellite imagery for Uzbekistan, mapping and evaluating monitoring results using GIS, and formulating integrated recommendations for decision-making systems [3,4].

This topic is not only scientifically and practically relevant, but it also aligns closely with the strategic directions of national policy. Forest monitoring is not merely observation—it is a rational response to global change, a modern mechanism for sustainable resource management, and a critical scientific approach toward maintaining ecological balance and enhancing human well-being.

Results And Discussion

The assessment of perennial tree plantation conditions holds a critical place in environmental monitoring systems. These natural resources are considered one of the primary biotic systems that ensure ecological stability, preserve biodiversity, mitigate climatic extremes, and absorb carbon compounds. In Uzbekistan, perennial plantations are mainly concentrated in foothill areas, riverbanks, and irrigated zones, where they play a crucial role in preventing soil erosion, maintaining the microclimate, improving the ameliorative state of lands, and ensuring the ecological well-being of the population. However, these ecosystems are increasingly at risk due to anthropogenic pressures, climate change, improper management, and a shortage of technological resources.

Today, satellite-based monitoring systems offer the capability to manage this process in a digital, systematic, and reliable manner. Remote sensing technologies, which involve the observation of the Earth's surface through electromagnetic waves from space, are considered the most efficient and globally scalable methods for monitoring forest conditions. The main objectives of such monitoring include: identifying the spatial extent of perennial plantations, analyzing their qualitative indicators, evaluating and forecasting dynamic changes, detecting early signs of ecological degradation, and providing scientific justification for management decisions.

A comprehensive monitoring system typically consists of several key technological blocks: satellite data collection, data preprocessing, statistical analysis, mapping, forecasting, and formulation of management decisions. Satellite systems used in this process include Landsat (NASA), Sentinel (ESA), MODIS, WorldView, and PlanetScope. These systems offer a range of spectral, spatial, and temporal resolutions, making them adaptable for different monitoring tasks [5,6].

For instance, Landsat 8 provides multispectral imagery with a spatial resolution of 30 meters and a revisit time of 16 days. Sentinel-2 offers imagery with resolutions ranging from 10 to 20 meters and a revisit time of approximately 5 days, making it especially suitable for vegetation monitoring. Based on these datasets, vegetation indices such as NDVI (Normalized Difference Vegetation Index) are calculated. The NDVI is computed using the following formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Here:

NIR refers to near-infrared radiation (e.g., Sentinel-2: Band 8),

RED refers to the red spectral band (Band 4).

An NDVI value greater than 0.2 generally indicates the presence of vegetation, while values in the range of 0.4 to 0.7 are characteristic of healthy forested areas.

In addition to NDVI, other vegetation indices are also employed, including the Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), Green Chlorophyll Index (GCI), among others. The main advantages of NDVI are its simplicity, widespread use in global studies, and its ability to provide dynamic temporal analysis of vegetative changes.

The use of satellite imagery for monitoring perennial tree plantations offers several technical advantages:

1. Coverage of large geographic areas;
2. Temporal comparison capability;
3. Objective and automated analysis;
4. Comparison with archived datasets;
5. Possibility of quarterly or even monthly updates.

Furthermore, various software tools are available for image processing and analysis, including ArcGIS, QGIS, Google Earth Engine (GEE), SNAP, ENVI, and ERDAS Imagine [7,8,9].

Among these, Google Earth Engine is considered one of the most versatile and free platforms. It allows for the calculation of NDVI, EVI, and other indices; linear regression analysis; zonal statistics; and cartographic visualization.

Based on the case of Kuva district in the Fergana region, a ten-year NDVI trend (2014–2023) was analyzed. In 2014, the average NDVI value for Kuva district was approximately 0.69, while by 2023 it had declined to 0.48 (table 1). This trend indicates a significant reduction in vegetation density and health of tree plantations over the past decade.

Table 1.

Perennial plantations in the Kuva district: NDVI and Degradation.

№	Years	Average NDVI (Kuva)	Degraded area (ha)
1	2014	0.69	1100
2	2015	0.68	1300
3	2016	0.65	1600
4	2017	0.63	1900
5	2018	0.6	2300
6	2019	0.58	2700
7	2020	0.56	3100
8	2021	0.54	3500
9	2022	0.51	3900
10	2023	0.48	4300

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In addition to NDVI trends, satellite imagery is also used to generate degradation zone maps.

These maps are produced through image classification techniques, followed by correlation analyses with biophysical variables such as Rainfall Estimate (RFE), Land Surface Temperature (LST), evapotranspiration, and soil moisture. This integrated analytical approach enables the precise delineation of zones characterized as healthy, vulnerable, degraded, or recovering vegetation areas.

By combining multispectral remote sensing data with climatic and hydrological indicators, the monitoring framework enhances the accuracy of forest condition assessment. Such spatially explicit degradation maps serve as critical tools for identifying priority areas for ecological restoration, supporting sustainable forest management, and informing regional land-use policies [10,11].

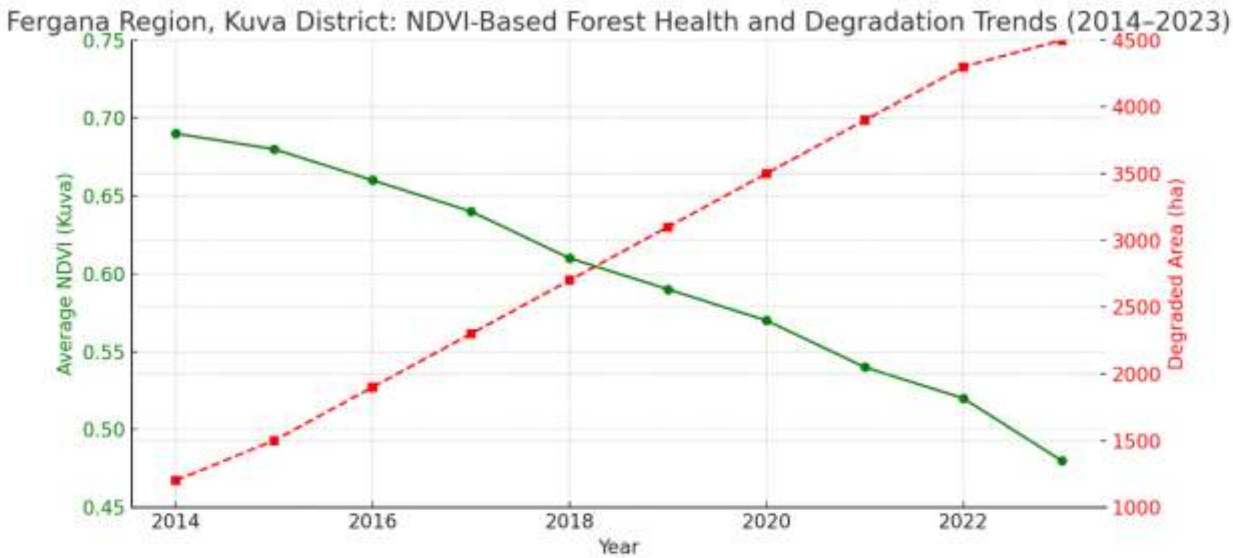

Figure 1. Fergana Region, Kuva District: NDVI and Degradation by Forest Condition (2014-2023).

From a technical standpoint, satellite monitoring also presents certain limitations. For instance, images obtained from optical satellites such as Sentinel-2 can become unusable due to high cloud cover, necessitating pre-processing steps such as cloud masking and filtering. On the other hand, radar imagery (e.g., Sentinel-1) allows for cloud-independent analysis and is particularly useful in persistently cloudy regions. However, radar images are generally less sensitive than optical vegetation indices (like NDVI) in accurately detecting forest density and vegetation health.

To overcome these limitations, it is recommended to integrate satellite data with UAV (drone)-based ground-truthing methods. This hybrid approach enables more precise calibration and validation of remotely sensed data, thus enhancing the accuracy of forest monitoring assessments.

From a practical perspective, the monitoring of perennial tree plantations has significant ecological, economic, and managerial implications. Through systematic observation, it becomes possible to:

- Identify ecologically sensitive areas for conservation,
- Detect degraded zones that require reforestation or restoration,
- Map fire-prone areas for preventive measures, and
- Develop decision-support systems for the sustainable management of land and forest resources.

Such outcomes demand the development of scientifically sound models, policy frameworks, and actionable recommendations that are tailored to regional conditions such as those found in Uzbekistan [12,13].

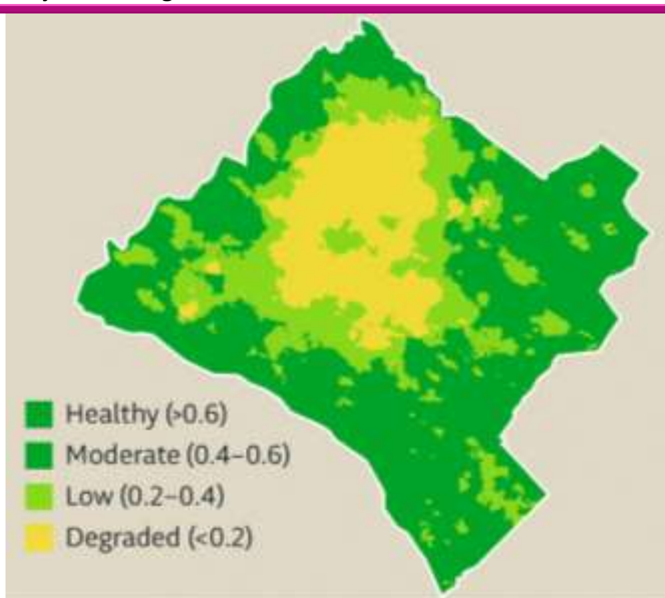

Figure 2. Zonal NDVI map of the Kuva district (2014-2023).

To implement this system effectively in the context of Uzbekistan, it is essential to develop the necessary technical infrastructure, institutional frameworks, and a well-trained workforce. At present, certain monitoring components exist within platforms managed by Uzhydromet, the Ministry of Ecology, and the Cadastre Agency. However, these systems suffer from weak inter-agency information exchange, limited software compatibility, and a shortage of qualified personnel. Therefore, it is crucial to adopt the experiences of advanced countries such as Canada, the United States, and Finland by creating a unified, integrated geospatial information platform, establishing regional satellite monitoring centers, and securing funding for scientific projects.

In parallel, the development of academic and pedagogical capacity is imperative. Specialized master's programs, online courses, and laboratories should be introduced to train experts in satellite data analysis, remote sensing technologies, vegetation indices, geostatistical modeling, and Python-based applications of Google Earth Engine (GEE).

The use of satellite data for monitoring perennial tree plantations is a strategic priority for Uzbekistan in ensuring environmental security, efficient resource management, climate resilience, and sustainable development. This direction encompasses technical, scientific, methodological, and organizational approaches. The integration of modern technologies—such as NDVI, GEE, UAVs, and SAR—enables the protection of forests, the identification of degraded areas, the formulation of reforestation strategies, and the digital transformation of land management systems. For the monitoring system to function effectively, it is equally important to invest in robust information platforms, human resource development, and financial infrastructure [14,15].

Conclusion

The results of the study conducted in the Kuva district demonstrate that the use of satellite data for monitoring perennial tree plantations is becoming an integral component of modern ecological analysis and management systems. Through vegetation indices such as NDVI, it is possible to assess the condition of vegetation cover over time, identify degraded areas, and map their spatial extent, thereby providing a reliable information base for decision-making in environmental management. The findings reveal a consistent decline in the health of perennial plantations in Kuva over the past decade, with a noticeable decrease in average NDVI values and an expansion of degraded zones, underscoring the urgent need for remedial actions.

The methodological approaches applied in this study — including the use of satellite imagery, the Google Earth Engine platform, advanced vegetation indices, and GIS technologies — confirm the feasibility of implementing a systematic, scientifically grounded, and continuous monitoring framework. Additionally, the study highlights the necessity of enhancing technical infrastructure, improving the qualifications of specialists, and integrating ground-truth data with satellite-based information in order to increase monitoring effectiveness. In conclusion, under the specific conditions of Uzbekistan — particularly in regions like the Fergana Valley that are under intensive anthropogenic pressure — satellite-based monitoring represents a strategic and essential tool for the conservation, restoration, and sustainable management of tree-based ecosystems.

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