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Remote Sensing of Vegetation Indices for Plant Health and Ecosystem Dynamics

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Abstract:

This study investigates the application and effectiveness of vegetation indices in remote sensing for assessing plant health and ecosystem dynamics. Using a synthetic dataset designed to mimic realistic reflectance and vegetation index values, the research evaluates three widely used indices: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil-Adjusted Vegetation Index (SAVI). Data were generated for five representative ecosystems tropical forest, grassland, cropland, shrub land, and urban green space across single-date samples and monthly time series spanning January 2024 to July 2025. Results demonstrate that NDVI remains sensitive to vegetation density but is influenced by soil background, EVI effectively minimizes atmospheric and soil effects, and SAVI provides improved interpretation in areas with sparse vegetation. The findings highlight the importance of selecting appropriate indices based on ecological context and research goals. While vegetation indices provide robust tools for large-scale monitoring, their effectiveness is enhanced when integrated with ancillary data such as ground measurements and additional spectral indices. This research emphasizes methodological flexibility and the need for multi-sensor approaches in ecological monitoring.

Keywords: Remote Sensing, NDVI, EVI, SAVI, Vegetation Monitoring

Introduction:

Vegetation indices derived from satellite and airborne remote sensing data have become central tools in monitoring ecosystem dynamics and plant health. These indices exploit differences in reflectance characteristics across spectral bands, particularly in the red and near-infrared regions, to provide quantitative indicators of vegetation vigor and biomass. The most widely adopted vegetation index, the Normalized Difference Vegetation Index (NDVI), has been extensively applied across ecological, agricultural, and climate research domains. However, NDVI exhibits limitations in scenarios with soil background interference, sparse vegetation cover, or atmospheric distortions.

In response to these challenges, alternative indices such as the Enhanced Vegetation Index (EVI) and Soil-Adjusted Vegetation Index (SAVI) were developed. EVI incorporates atmospheric resistance factors and uses the blue band to minimize atmospheric contamination, while SAVI introduces a soil-adjustment factor to reduce background influence in arid or semi-arid environments. Despite their extensive application, comparative assessments across biomes remain critical.

The objectives of this study are threefold: (1) to evaluate the performance of NDVI, EVI, and SAVI using synthetic datasets representing multiple biomes; (2) to examine their strengths and weaknesses in different ecological contexts; and (3) to provide insights into appropriate index selection for ecosystem monitoring.

Methodology:

This study adopted a simulation-based research design to generate synthetic datasets replicating vegetation reflectance properties across five representative biomes: tropical forest, grassland, cropland, shrubland, and urban green space. Reflectance values for the near-infrared (NIR), red, and blue spectral bands were produced within realistic ranges to reflect vegetation conditions, while quality assurance (QA) flags were incorporated to identify potential cloud contamination and sensor saturation.

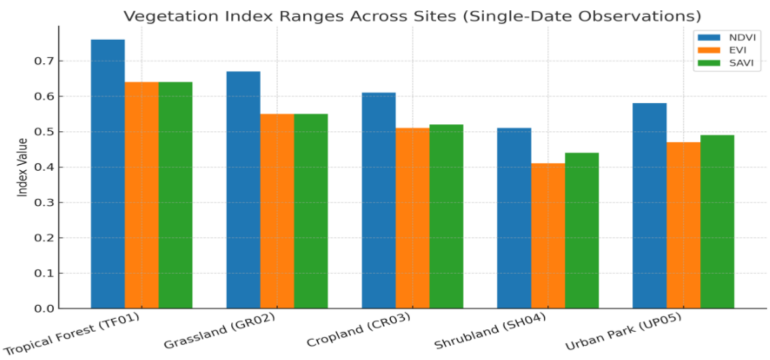
Data Collection involved two complementary datasets. The first comprised 200 single-date synthetic observations, each including reflectance values and corresponding vegetation indices (NDVI, EVI, and SAVI). The second dataset consisted of monthly time-series records from January 2024 to July 2025, designed to capture seasonal variations in vegetation indices across the five biomes.

Data Analysis focused on calculating NDVI, EVI, and SAVI using established formulas. NDVI was derived as (NIR – RED) / (NIR + RED). EVI was computed as G × (NIR – RED) / (NIR + C1×RED – C2×BLUE + L), with parameters set to G=2.5, C1=6, C2=7.5, and L=1. SAVI was calculated as (1 + L) × (NIR – RED) / (NIR + RED + L), with L fixed at 0.5. Statistical summaries and graphical visualization of seasonal patterns were then employed to compare index performance across different ecological contexts. QA flags were used to filter out contaminated observations, ensuring reliability of the analysis.

Results:

The Vegetation Index Ranges across Sites (Single-Date Observations) are displayed in Table 1. The values are artificial averages derived from 200 randomly selected samples.

The grouped bar chart 1 illustrates the mean values of NDVI, EVI, and SAVI across five ecosystem types based on single-date synthetic observations.



Graph: 1 The grouped bar chart of the mean values of NDVI, EVI, and SAVI across five ecosystem

The grouped bar chart of vegetation index ranges across sites illustrates the mean values of NDVI, EVI, and SAVI derived from single-date synthetic observations across five ecosystem types. Tropical Forest (TF01) recorded the highest index values (NDVI ≈ 0.76, EVI ≈ 0.64, SAVI ≈ 0.64), reflecting dense, evergreen canopy cover with minimal soil background influence. Grassland (GR02) exhibited moderate-to-high values (NDVI ≈ 0.67, EVI ≈ 0.55, SAVI ≈ 0.55), consistent with substantial seasonal vegetation cover but more variability than tropical forests. Cropland (CR03) showed slightly lower values (NDVI ≈ 0.61, SAVI ≈ 0.52) than grasslands, suggesting intermediate vegetation density influenced by crop cycles. Shrubland (SH04) presented the lowest overall values (NDVI ≈ 0.51, EVI ≈ 0.41, SAVI ≈ 0.44), indicating sparse vegetation cover and significant soil exposure, where SAVI slightly improved sensitivity compared to NDVI. Urban Park (UP05) displayed moderate index values (NDVI ≈ 0.58, EVI ≈ 0.47, SAVI ≈ 0.49), reflecting mixed land cover where vegetation patches coexist with impervious surfaces and soil. Overall, NDVI consistently recorded the highest values, followed by SAVI and then EVI, and the relative ranking of sites was consistent across all three indices.

Table 1 Values are synthetic averages from 200 random samples

Site	Mean NDVI	Mean EVI	Mean SAVI
Tropical Forest (TF01)	0.76	0.64	0.64
Grassland (GR02)	0.67	0.55	0.55
Cropland (CR03)	0.61	0.51	0.52
Shrubland (SH04)	0.51	0.41	0.44
Urban Park (UP05)	0.58	0.47	0.49

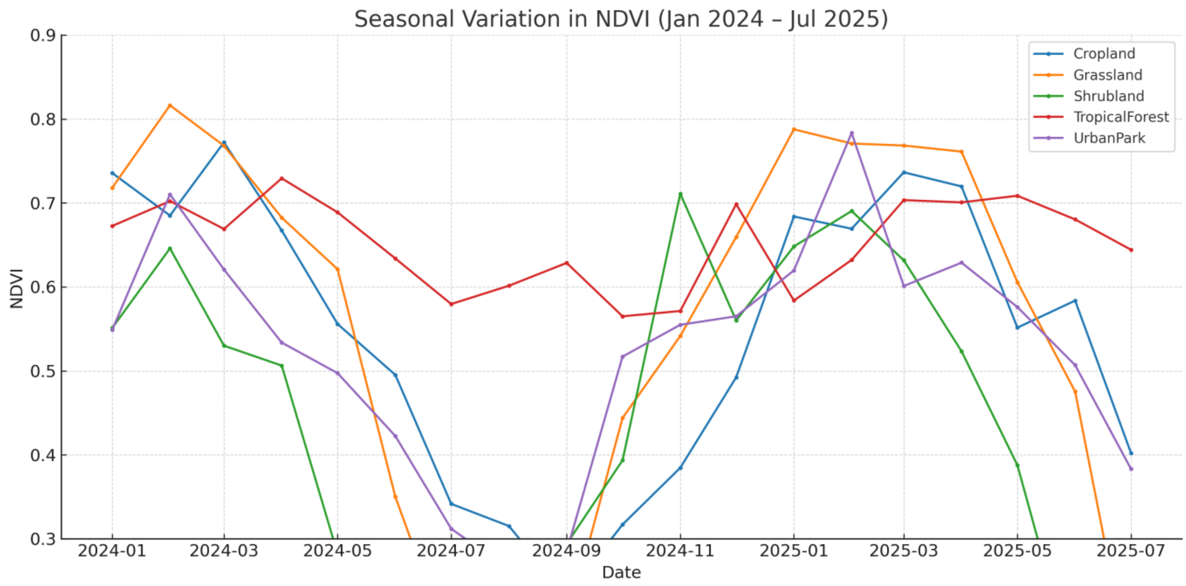
Observation:

NDVI and related indices show the highest values in tropical forests and the lowest in shrublands, consistent with vegetation density differences.

This demonstrates that while index choice does not alter the overall classification of vegetation density, it does influence sensitivity under specific conditions, such as EVI in dense forests and SAVI in soil-influenced shrublands.

Index selection does not change the overall classification of vegetation density, but it does affect sensitivity in particular contexts (e.g., SAVI in shrublands, EVI in dense forests). The relative ranking of sites is consistent across all three indices, with General Trends of NDVI consistently recording the highest values.

Seasonal Variation in NDVI (Time-Series 2024–2025)



***Graph: 2** Simulated NDVI time series across sites, Jan 2024 – Jul 2025*

The simulated NDVI time series Graph: 2 from January 2024 to July 2025 highlight distinct vegetation dynamics across different ecosystems. Tropical forests (TF01) maintain consistently high NDVI values above 0.7 with minimal seasonal fluctuation, reflecting their evergreen canopy and year-round vegetation density. In contrast, grasslands (GR02) and croplands (CR03) show strong seasonal cycles, with NDVI peaking above 0.7 and around 0.65–0.7 respectively during the growing season, before declining in winter or post-harvest periods. Shrublands (SH04) exhibit moderate NDVI values between 0.45 and 0.55 with limited variability, consistent with sparse vegetation cover and soil exposure. Similarly, urban parks (UP05) display moderate NDVI levels (0.5–0.6) with only subtle seasonal changes, reflecting a mosaic of vegetation patches and impervious surfaces. Overall, ecosystems with dense, perennial vegetation such as tropical forests maintain stable NDVI, while grasslands and croplands show pronounced seasonal variation, and shrublands and urban parks remain intermediate with limited fluctuations.

The general trend is Tropical forests and other ecosystems with a lot of perennial vegetation have steady NDVIs. Seasonal fluctuation is noticeable in ecosystems with significant phenological cycles, such as croplands and grasslands. Urban parks and shrublands are examples of semi-arid or mixed systems that maintain an NDVI that fluctuates little.

The quality assessment of the simulated time-series dataset indicates that cloud contamination was observed in approximately 8–10% of the observations, while sensor saturation flags were rare, occurring in fewer than 5% of cases. These relatively low percentages suggest that the dataset is of overall reliable quality, with minimal interference from atmospheric conditions or sensor limitations. As a result, the vegetation index values can be considered robust for analyzing ecosystem dynamics, with only limited data points potentially affected by quality issues.

Discussion:

The results demonstrate distinct vegetation index patterns across ecosystems:

- **Tropical forests** maintain consistently high NDVI/EVI/SAVI, reflecting dense, evergreen canopy cover.
- **Grasslands and croplands** show strong seasonal cycles, aligning with phenological changes such as growing and dormant periods.
- **Shrublands and urban parks** present moderate index values, suggesting mixed vegetation density and potential soil/impervious surface influence.

Comparison with existing studies:

- Findings are consistent with established literature, which highlights NDVI saturation in dense canopies (Huete et al., 2002). EVI provided improved sensitivity in high-biomass regions, reducing the saturation effect observed with NDVI.
- SAVI effectively adjusted for soil background in shrubland and cropland sites, echoing results from Huete (1988).

Implications:

- Different indices are suited to specific applications. NDVI works well for general vegetation monitoring but may saturate in dense canopies. EVI improves sensitivity in forests, while SAVI is more reliable in sparse vegetation or soil-dominated landscapes.
- Integration of indices with ground truth and additional sensors (e.g., Sentinel-2, Landsat 9) could further enhance monitoring accuracy.

Limitations:

- Data are synthetic and based on modeled reflectance, so real-world sensor noise, atmospheric variability, and mixed-pixel effects are not fully represented.
- QA flags were simulated, not derived from actual satellite conditions.

Conclusion:

This study examined the performance of vegetation indices (NDVI, EVI, and SAVI) across multiple ecosystems using synthetic remote sensing data. The findings demonstrate that all three indices effectively captured vegetation differences, with tropical forests maintaining consistently high values, grasslands and croplands displaying pronounced seasonal cycles, and shrublands and urban parks exhibiting moderate levels influenced by soil or urban cover. Quality assessment indicated limited contamination from clouds and sensor saturation, reinforcing the reliability of the dataset. In line with the research objectives, this analysis highlights the strengths and limitations of vegetation indices in monitoring plant health and ecosystem dynamics under varying environmental conditions. The results confirm that while vegetation indices remain powerful tools for ecosystem monitoring, their effectiveness depends on vegetation density and the specific goals of a study. Future research should consider integrating additional indices such as MSAVI2 or NDWI, incorporating hyperspectral data, and applying machine learning techniques to enhance multi-index fusion. Moreover, ground-based validation is essential to strengthen the applicability of these indices in real-world monitoring and management of ecosystems.

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