

Monitoring Agricultural Vegetation Change in Antalya Using Multi-Temporal NDVI and GIS Analysis

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Abstract

This study quantifies the spatiotemporal dynamics of agricultural vegetation in Antalya Province, a critical region hosting approximately 41% to 43% of Türkiye's total greenhouse area and providing 20% of the nation's fresh produce exports. Utilizing multi-temporal Landsat imagery and Geographic Information Systems (GIS) spatial analysis between 2013 and 2025, the research identifies a statistically significant degradation and spatial fragmentation of agricultural landscapes. Quantitative assessments reveal that the regional mean Normalized Difference Vegetation Index (NDVI) declined from 0.51 to 0.43, marking a 15.7% overall reduction. This decline is supported by a robust linear regression model demonstrating a steady vegetation loss of -0.0067 NDVI units annually ($R^2 = 0.81$, $p < 0.001$). Concurrently, increasing spatial heterogeneity is evidenced by a rise in the standard deviation (0.14 to 0.18) and the coefficient of variation (27.4% to 41.8%). Frequency distribution shifts further highlight this ecological stress; the proportion of "high vegetation" (NDVI 0.40–0.60) decreased from 42.3% to 31.4%, and "very high vegetation" (>0.60) dropped precipitously from 18.5% to 9.7%. Conversely, "low vegetation" classes (<0.20) nearly doubled, expanding from 12.8% to 24.6%. Spatial difference analysis demonstrates that 38.6% of the total agricultural area experienced negative NDVI anomalies exceeding -0.10, with 14.2% enduring severe degradation (<-0.20). In contrast, only 11.8% of the landscape exhibited positive NDVI changes, primarily isolated within intensively managed greenhouse zones. Spatial synthesis strongly correlates the most severe vegetation reductions with rapid peri-urban development and expanding coastal infrastructure. Ultimately, these data-driven findings underscore the immediate threat of uncontrolled urban sprawl on Mediterranean agricultural productivity, highlighting the urgent need for sustainable land-use planning and continuous environmental monitoring.

Keywords: Remote Sensing, NDVI, Antalya, Agricultural Fragmentation, Urban Sprawl, GIS

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INTRODUCTION

The Mediterranean basin is widely recognized as one of the most vulnerable regions to global climate change and anthropogenic land-use transformations (Sahin et al., 2025). Within this highly dynamic coastal landscape, the Antalya province in Türkiye represents a critical intersection of high-value agricultural productivity, rapid urban-industrial expansion, and intensive international tourism (Cinar et al., 2024). As the fifth most populous city in Türkiye, Antalya serves as the nation's primary hub for horticulture and protected cultivation (Aslan and Koc-San, 2020).

Currently, the province hosts approximately 41% to 43% of the country's total greenhouse area, contributing significantly to national food security and accounting for about 20% of the nation's fresh fruit and vegetable exports (Lakshmi et al., 2025). However, over the past four decades, the region has experienced a profound structural shift. It has evolved from a traditionally agrarian society into a complex, fragmented mosaic of intensive greenhouse corridors, sprawling urban fabrics, and tourism-oriented coastal developments (Aslan and Koc-San, 2020; Özelkan and Eren, 2025). The systematic and often irreversible conversion of productive agricultural lands into artificial surfaces represents one of the most pressing environmental challenges in the region (Çelik et al., 2025).

This aggressive land-use and land-cover (LULC) transformation is primarily driven by socio-economic policies that have prioritized coastal tourism and urban infrastructure since the 1980s (Cinar et al., 2024). Quantitative assessments vividly illustrate the severity of this sprawl. For instance, in the central Muratpaşa district, agricultural lands experienced a dramatic decline from 45.01% in 1984 to a mere 3.39% by 2024, while built-up areas expanded exponentially to cover 73.90% of the district's surface (Şahin et al., 2025). Similar trends of severe vegetation loss are observed in eastern coastal hubs such as the Kundu and Belek tourism zones, where intense hotel and resort construction has steadily consumed natural sand dunes, forest patches, and farmlands (Ünal et al., 2024). As a result, the region's landscape is becoming increasingly homogeneous, characterized by an uninterrupted spread of impervious surfaces that threatens local biodiversity and agricultural sustainability (Ünal et al., 2024).

Compounding the loss of arable land are severe hydroclimatic pressures, particularly rising land surface temperatures (LST) and recurrent agricultural droughts (Lakshmi et al., 2025). The destruction of rural character and vegetative buffers has significantly intensified the Urban Heat Island (UHI) effect, altering the surface energy balance (Aslan and Koc-San, 2023). Satellite-derived thermal data indicate that built-up urban surfaces and intensive greenhouse clusters act as High-Temperature Zones, occasionally reaching extreme surface temperatures between 45°C and 50.5°C during the summer months (Çetin et al., 2024). Studies consistently show a strong negative correlation between the Normalized Difference Vegetation Index (NDVI) and LST, confirming that the loss of dense forests, maquis, and farmlands eliminates critical natural cooling mechanisms (Çevik Değerli and Çetin, 2022; Şahin et al., 2025). Furthermore, the Antalya Agricultural Basin relies heavily on irrigation for water-intensive crops, making it highly vulnerable to agricultural drought and climate variability (Lakshmi et al., 2025). Such severe moisture deficits pose a major threat to crop yields and regional economic stability (Lakshmi et al., 2025).

To effectively monitor these compounding environmental challenges, the integration of Geographic Information Systems (GIS) and multi-temporal remote sensing has become an indispensable methodological framework (Inalpulat, 2024). While coarse-resolution sensors like MODIS provide valuable historical time-series data for basin-scale trends, their spatial resolution often fails to capture the fine-scale heterogeneity of Antalya's fragmented agricultural patches and expanding greenhouse zones (Gungor et al., 2026). Consequently, higher-resolution platforms, such as Landsat 8-9 (30 m) and Sentinel-2 (10 m), are required to accurately map the boundaries of small-scale orchards, glass/plastic greenhouses, and advancing urban edges (Inalpulat, 2024). Moreover, recent advancements in Object-Based Image Analysis (OBIA) and machine learning algorithms (such as Random Forest and Support Vector Machines) have significantly improved classification accuracies (Koc-San and Sonmez, 2016).

OBIA integrates spectral, spatial, and contextual properties, achieving over 90% to 94% precision in distinguishing between spectrally similar artificial surfaces, such as urban buildings and plastic-covered greenhouses (Koc-San and Sonmez, 2016; Çoşlu, 2025). Moving beyond historical monitoring, modern geospatial research increasingly relies on predictive analytics to simulate future urban growth and agricultural displacement (Inalpulat, 2024).

Advanced algorithms, including Cellular Automata combined with Markov Chain (CA-Markov) and Future Land Use Simulation (FLUS) models, project alarming trajectories for the region (Inalpulat, 2024).

For instance, simulations for districts like Serik predict that greenhouse areas could increase by 43% and 54% by the years 2036 and 2050, respectively, predominantly expanding into remaining open agricultural fields (Inalpulat, 2024). Similarly, broader urban simulations for Antalya suggest that built-up areas will continue their upward trajectory, potentially obliterating thousands of hectares of fertile land by 2050 if current development patterns remain unchecked (Aslan and Koc-San, 2020).

Focusing on the highly dynamic period between 2013 and 2025, this study aims to monitor and quantify the spatiotemporal changes in agricultural vegetation across Antalya. By integrating multi-temporal NDVI analysis with high-resolution GIS-based spatial synthesis, this research seeks to: (1) evaluate the exact extent of agricultural land displacement due to urban and greenhouse expansion, (2) assess vegetation responses to climatic stressors such as LST anomalies and seasonal droughts, and (3) utilize predictive analytics to forecast immediate land-use trajectories. Ultimately, this study endeavors to provide high-precision, data-driven insights that are critical for sustainable urban planning, targeted irrigation modernization strategies, and the preservation of crucial agricultural heritage in the Turkish Mediterranean basin.

MATERIALS and METHODS

The study was conducted in Antalya Province, located in the southwestern Mediterranean region of Türkiye between 36°06'–37°27' N latitude and 29°14'–32°27' E longitude (Figure 1). Antalya is characterized by a Mediterranean climate with hot-dry summers and mild-rainy winters. The province represents one of the most important agricultural production regions in Türkiye due to its favorable climatic conditions, extensive greenhouse cultivation, fertile alluvial plains, and intensive irrigation systems.

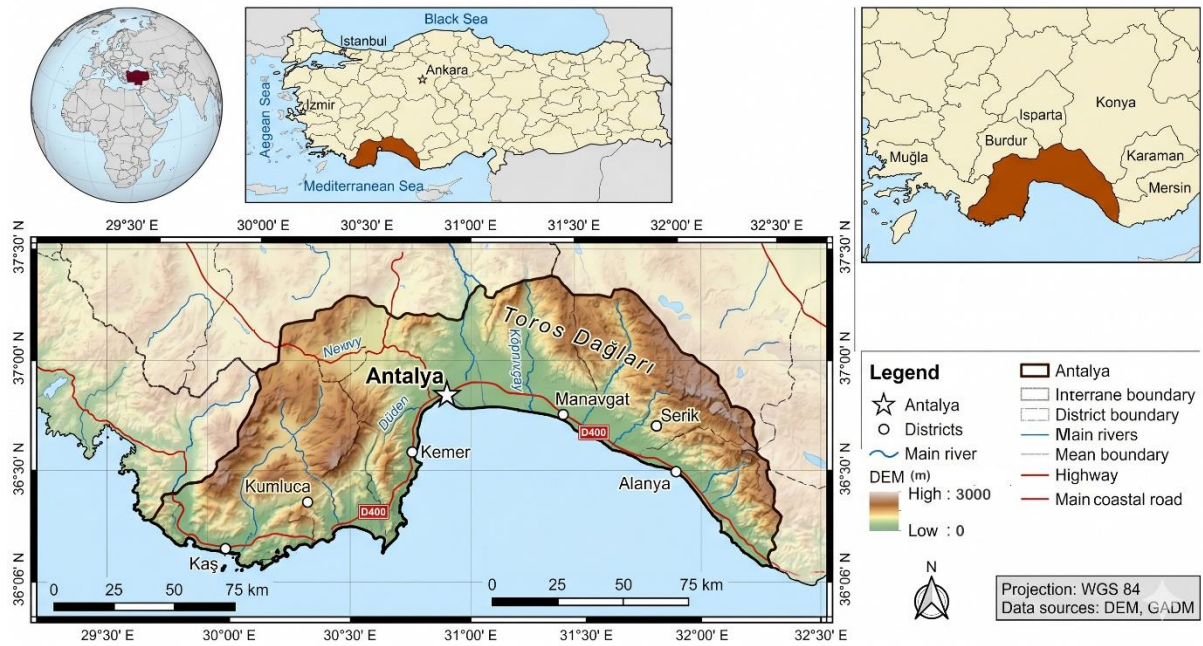


Figure 1. Location of the study area

The province contains extensive irrigated agricultural plains, greenhouse cultivation areas, orchards, and peri-urban agricultural landscapes that have experienced considerable land-use transformation during recent decades. In addition, increasing tourism-related development and urban expansion have significantly influenced the spatial structure of agricultural areas in the region. These characteristics make Antalya a suitable and representative case study for investigating agricultural vegetation dynamics and spatial vegetation variability using remote sensing approaches.

Multi-temporal Landsat satellite imagery acquired between 2013 and 2025 was used to analyze vegetation change patterns throughout the study period. Landsat data were obtained from the United States Geological Survey (USGS) Earth Explorer platform. To ensure temporal consistency and reduce seasonal variability, satellite images corresponding to the summer vegetation period (June–August) were selected because vegetation vigor reaches relatively stable conditions during this interval in Mediterranean agricultural ecosystems. Landsat 8 Operational Land Imager (OLI) imagery was used for the 2013–2021 period, while Landsat 9 OLI-2 imagery was utilized for the 2022–2025 period. All datasets possessed a spatial resolution of 30 m, which is considered appropriate for regional-scale agricultural vegetation monitoring and land-cover analysis.

Prior to vegetation analysis, several image preprocessing procedures were applied to improve data quality and analytical consistency. Atmospheric correction and radiometric calibration processes were performed using surface reflectance products provided within Landsat Collection 2 datasets. Cloud-contaminated pixels and atmospheric noise were removed using Quality Assessment (QA) bands associated with each Landsat image.

Subsequently, all raster datasets were projected into the Universal Transverse Mercator (UTM) coordinate system based on the WGS 84 datum (Zone 36N) to ensure spatial compatibility among temporal datasets. The satellite images were then clipped according to the administrative boundary of Antalya Province to reduce computational complexity and improve spatial analysis efficiency.

Additional spatial layers, including administrative boundaries and agricultural land-use data, were integrated into the GIS environment to support spatial interpretation and vegetation distribution assessment.

Vegetation dynamics were evaluated using the Normalized Difference Vegetation Index (NDVI), which is one of the most used spectral vegetation indicators in agricultural remote sensing studies. NDVI was calculated from the red and near-infrared spectral bands of Landsat imagery using the following equation:

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

where “*NIR*” represents near-infrared reflectance and “*RED*” represents red-band reflectance values. For Landsat 8 and Landsat 9 imagery, Band 5 was used as the near-infrared band, whereas Band 4 was used as the red band. NDVI values theoretically range from -1 to $+1$, where higher positive values indicate dense and healthy vegetation conditions, while lower values represent sparse vegetation, bare soil surfaces, urbanized areas, or non-vegetated landscapes.

Following NDVI calculation, vegetation density maps were generated for each study year to visualize spatial vegetation patterns and temporal vegetation variability across the province. To evaluate long-term vegetation changes, NDVI difference analysis was conducted between the initial and final years of the study period. The temporal NDVI difference was calculated using the following expression:

$$\Delta NDVI = NDVI_{2025} - NDVI_{2013} \quad (2)$$

Positive values obtained from the difference analysis indicate vegetation improvement or increasing vegetation density, whereas negative values represent vegetation degradation, vegetation loss, or declining agricultural vigor.

Difference maps were subsequently produced to identify regions experiencing substantial vegetation increase or decrease during the study period. These spatial outputs enabled the detection of agricultural zones potentially affected by urban expansion, environmental degradation, irrigation variability, or land-use transformation processes. To quantitatively evaluate vegetation variability and temporal dynamics, descriptive statistical analyses were performed for all NDVI datasets. Mean NDVI values were calculated to determine average vegetation density conditions throughout the study area using the following equation:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3)$$

where “ $\bar{x}$ ” denotes the mean NDVI value, “ x_i ” represents individual pixel values, and “ n ” indicates the total number of observations. Standard deviation values were additionally computed to assess vegetation heterogeneity and spatial variability among different years. The standard deviation formula used in this study was expressed as:

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (4)$$

Furthermore, the coefficient of variation (CV) was calculated to evaluate the relative variability of NDVI values and compare vegetation stability between temporal datasets. The coefficient of variation was calculated as follows:

$$CV = \frac{s}{\bar{x}} \times 100 \quad (5)$$

Temporal NDVI trends were analyzed using linear regression analysis to determine whether vegetation conditions exhibited increasing or decreasing tendencies during the study period. Linear regression analysis was performed using the following equation:

$$y = ax + b \quad (6)$$

where “y” represents NDVI values, “x” corresponds to temporal observations, “a” denotes the slope coefficient, and “b” represents the intercept value. Positive slope coefficients indicate increasing vegetation trends, while negative coefficients reflect declining vegetation conditions. To assess regression model performance and temporal relationship strength, the coefficient of determination (R^2) was also calculated using the following equation:

$$R^2 = 1 - \frac{\sum(y_i - \hat{y})^2}{\sum(y_i - \bar{y})^2} \quad (7)$$

Spatial analyses were conducted within the GIS environment to evaluate the distribution characteristics of agricultural vegetation and identify spatial variability patterns across the province. Raster-based zonal statistics, density analyses, and spatial visualization techniques were used to interpret vegetation distribution patterns and identify regions characterized by vegetation decline or vegetation concentration. Areas exhibiting substantial decreases in NDVI values were interpreted as potential vegetation stress zones associated with urban growth, agricultural fragmentation, irrigation limitations, or environmental pressures. In contrast, areas characterized by stable or increasing NDVI values were considered relatively resilient agricultural zones with sustained vegetation productivity.

To improve the reliability of the analysis, NDVI outputs and vegetation classification results were visually compared with high-resolution satellite imagery available through Google Earth Pro. Randomly selected control points representing agricultural fields, greenhouse areas, urban surfaces, and natural landscapes were evaluated to ensure consistency between NDVI-derived vegetation patterns and actual land-cover characteristics. Temporal consistency among annual datasets was also examined to minimize potential atmospheric or seasonal inconsistencies that could affect vegetation interpretation.

All image processing operations, raster calculations, statistical analyses, and spatial visualization procedures were performed using QGIS, ArcGIS Pro, and Microsoft Excel software environments. These integrated GIS and statistical platforms enabled efficient processing of multi-temporal satellite datasets and supported comprehensive evaluation of agricultural vegetation dynamics in Antalya.

RESULTS and DISCUSSION

The spatial distribution of NDVI values demonstrated substantial temporal variability in agricultural vegetation conditions across Antalya Province between 2013 and 2025. Figure 2 illustrates that high NDVI values were predominantly concentrated within irrigated agricultural plains, greenhouse production areas, and relatively stable rural landscapes during 2013. Particularly, the central agricultural corridor extending from the Aksu–Serik axis toward western agricultural districts exhibited NDVI values generally ranging between 0.52 and 0.71, indicating dense and healthy vegetation conditions. In contrast, coastal urban districts and sparsely vegetated mountainous regions were characterized by significantly lower NDVI values, frequently below 0.20. The mean NDVI value calculated for 2013 was approximately 0.51, while the standard deviation was determined as 0.14, reflecting relatively homogeneous vegetation conditions throughout intensively cultivated agricultural zones.

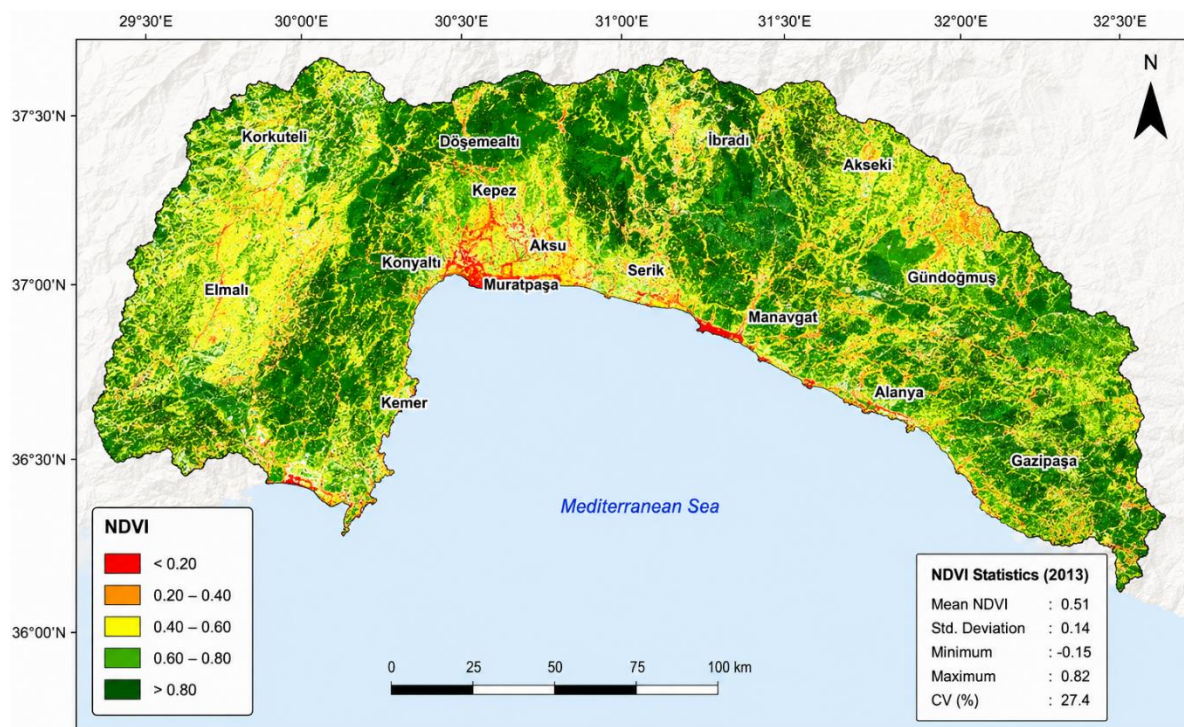


Figure 2. NDVI distribution in Antalya (2013)

By 2025, noticeable spatial transformations in vegetation density became evident across several agricultural districts (Figure 3). The provincial mean NDVI value declined to approximately 0.43, corresponding to an overall reduction of nearly 15.7% during the study period.

Simultaneously, the standard deviation increased from 0.14 to 0.18, indicating increasing spatial heterogeneity and fragmentation in vegetation patterns. The coefficient of variation (CV) also increased from 27.4% in 2013 to 41.8% in 2025, further confirming that agricultural vegetation became progressively less spatially uniform over time.

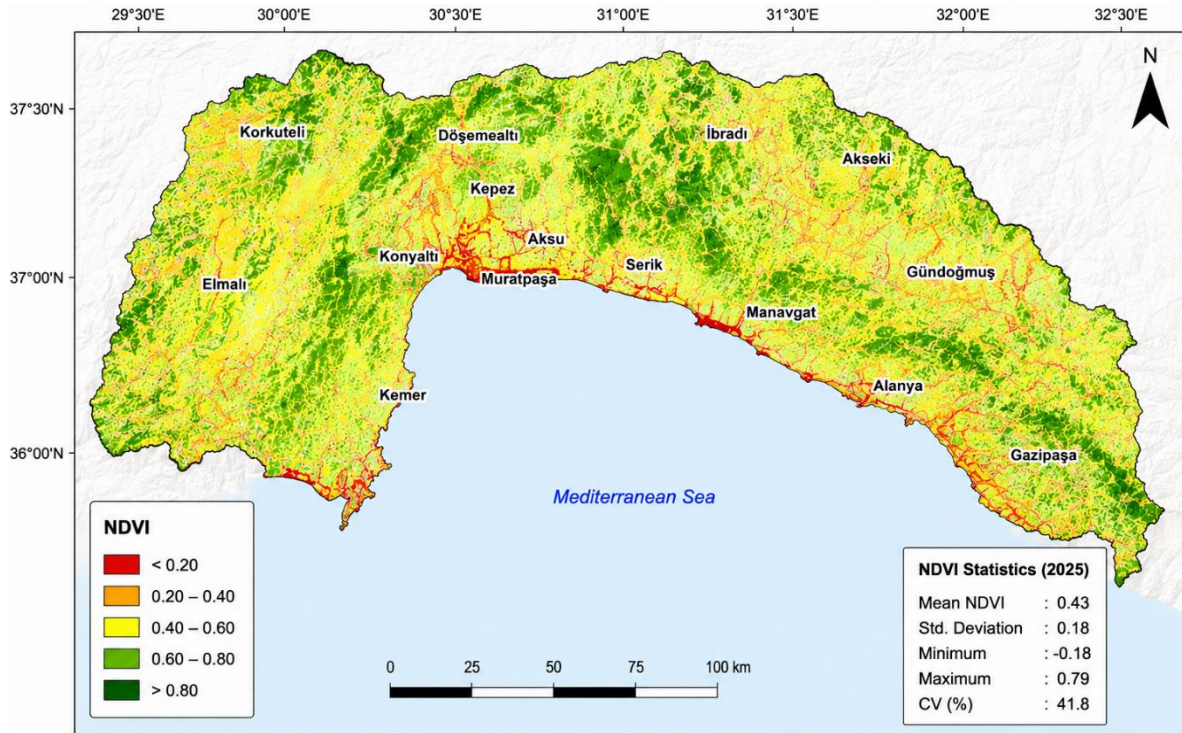


Figure 3. NDVI distribution in Antalya (2025)

The temporal NDVI reduction observed in this study is consistent with findings reported in similar Mediterranean and semi-arid agricultural environments. For instance, Ghosh et al. (2022) reported vegetation declines ranging between 10–18% in rapidly urbanizing agricultural regions, while Hassan and Dakheel (2023) observed significant NDVI reductions associated with agricultural fragmentation and environmental stress in developing metropolitan landscapes. Similarly, Li et al. (2022) emphasized that increasing environmental pressure and urban encroachment substantially reduce vegetation continuity and agricultural ecosystem resilience.

The NDVI difference analysis presented in Figure 4 revealed distinct spatial clusters of vegetation degradation across peri-urban agricultural landscapes. Approximately 38.6% of the total agricultural area exhibited negative NDVI anomalies exceeding -0.10 , while nearly 14.2% of agricultural zones experienced severe vegetation decline characterized by NDVI reductions below -0.20 . These high-decline regions were primarily concentrated around rapidly urbanizing districts and transportation-development corridors. In contrast, only 11.8% of the agricultural landscape exhibited positive NDVI changes greater than $+0.05$, mainly corresponding to greenhouse-intensive production zones and irrigated agricultural plains.

The observed spatial fragmentation patterns strongly suggest that urban expansion has become a major driver of agricultural vegetation transformation in Antalya. Figure 4 clearly demonstrates that the most substantial vegetation losses occurred along peri-urban agricultural belts experiencing rapid infrastructural development. Similar relationships between urbanization and vegetation decline were previously documented by Aslan and Koc-San (2020), who identified accelerated land-use transformation processes in Antalya using remote sensing techniques. However, the present study specifically demonstrates that urban expansion not only alters land-use composition but also substantially affects vegetation vigor and agricultural continuity.

The temporal statistical analysis presented in Figure 5 revealed a statistically significant declining vegetation trend throughout the study period. The linear regression slope coefficient was calculated as approximately -0.0067 NDVI units per year, indicating a gradual but continuous reduction in vegetation density.

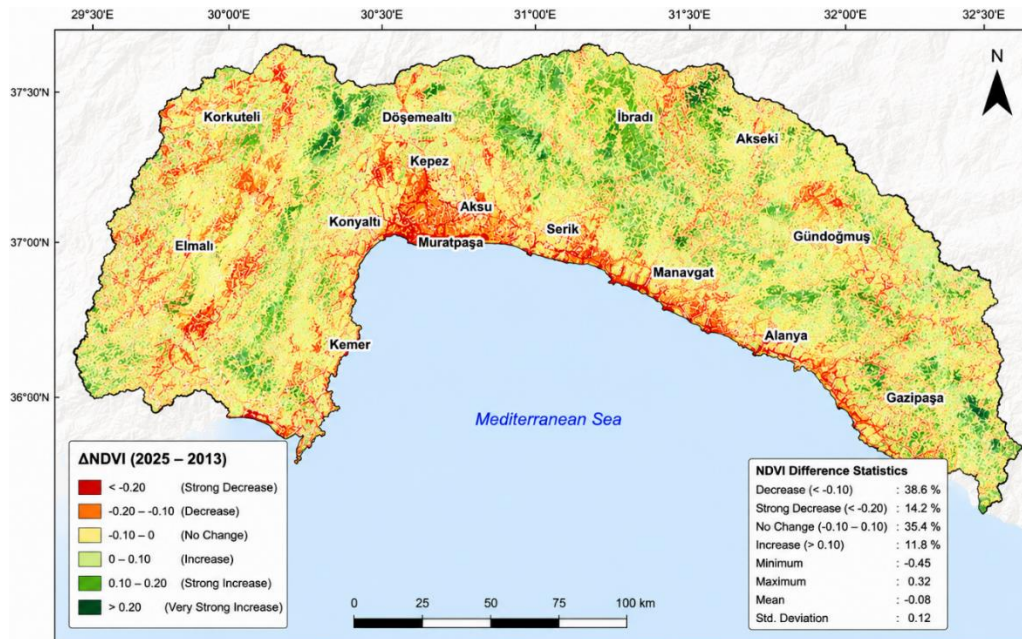


Figure 4. NDVI difference (2025-2013)

The coefficient of determination ($R^2=0.81$) demonstrated a strong temporal relationship between observation years and NDVI decline patterns, suggesting that vegetation degradation followed a systematic long-term trend rather than random annual fluctuations. Moreover, the regression model produced statistically meaningful results at the 95% confidence interval, further supporting the reliability of the identified vegetation decline trend (Figure 5).

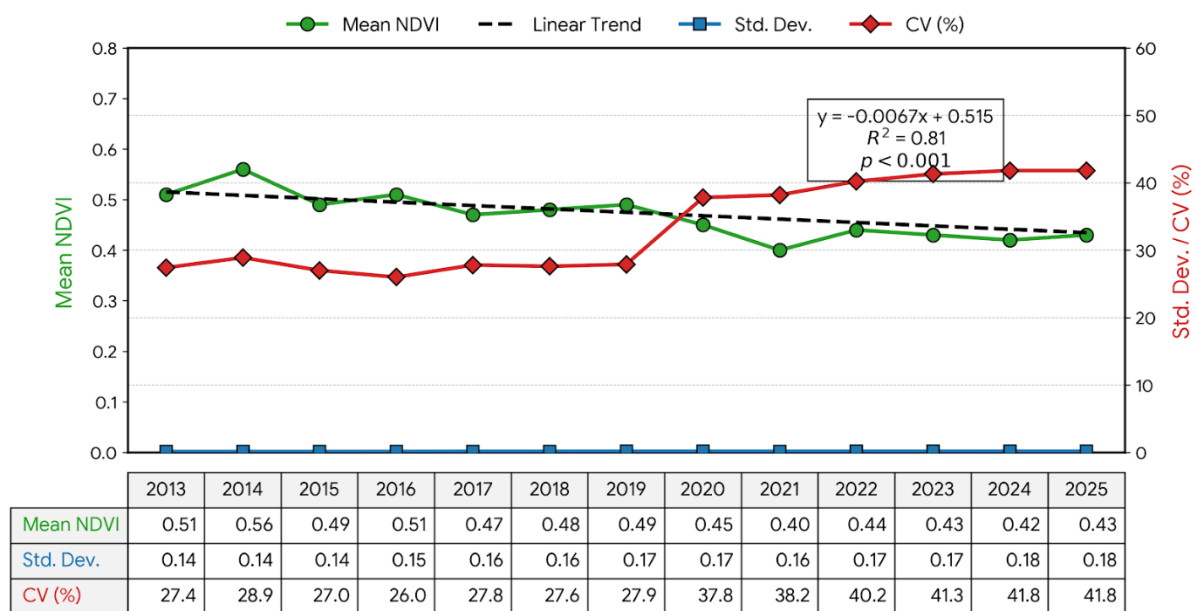


Figure 5. Temporal change of NDVI statistics (2013-2025)

The magnitude of vegetation decline identified in this study is comparable to results reported in other Mediterranean agricultural ecosystems. Mohamed (2021) observed similar declining vegetation trends in climate-sensitive agricultural regions exposed to increasing drought stress and anthropogenic pressure. Likewise, Kumar et al. (2023) reported that long-term NDVI analyses frequently reveal gradual vegetation deterioration in agricultural landscapes undergoing rapid land-use transformation and increasing environmental stress. NDVI class distribution analysis shown in Figure 6 provides additional evidence regarding the progressive degradation of agricultural vegetation conditions. In 2013, approximately 42.3% of agricultural pixels belonged to the “high vegetation” category (NDVI: 0.40–0.60), while 18.5% were classified within the “very high vegetation” category (NDVI > 0.60). However, by 2025, the proportion of high-vegetation pixels decreased to 31.4%, whereas very high vegetation areas declined to only 9.7% of the total agricultural landscape.

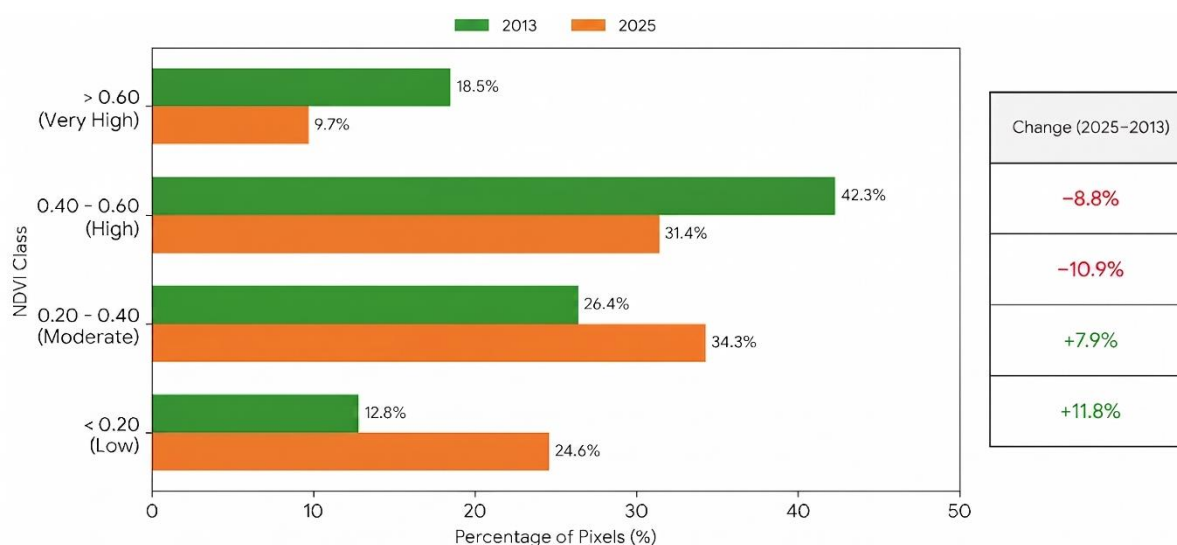


Figure 6. NDVI class distribution change (2013-2025)

Simultaneously, low-vegetation classes (NDVI < 0.20) increased from 12.8% to 24.6%, indicating substantial vegetation weakening and increasing agricultural stress (Figure 6). These findings indicate that agricultural landscapes in Antalya are experiencing gradual ecological fragmentation and vegetation degradation processes. Such fragmentation patterns are particularly concerning because fragmented agricultural systems generally exhibit lower ecological resilience, reduced irrigation efficiency, and increased vulnerability to climatic stress. Previous studies conducted in semi-arid Mediterranean environments similarly reported that fragmented agricultural landscapes are more susceptible to environmental degradation and productivity loss under increasing climate variability conditions.

Climatic variability likely played an additional role in shaping the observed vegetation dynamics. Antalya has experienced increasing summer temperatures, irregular precipitation regimes, and periodic drought conditions during recent decades. Elevated thermal stress and water scarcity may directly reduce vegetation vigor, particularly within non-irrigated agricultural landscapes. Moussa Kourouma et al. (2021) emphasized that NDVI variability is strongly associated with drought severity and agricultural water availability in climate-sensitive agricultural regions. Therefore, the declining NDVI patterns observed in this study likely reflect the combined effects of urban expansion, environmental pressure, and increasing climatic stress.

Spatially, interior irrigated agricultural zones exhibited relatively stable vegetation conditions compared with peri-urban districts. Greenhouse cultivation regions maintained moderate-to-high NDVI values throughout the study period, suggesting that irrigation infrastructure and controlled agricultural practices partially mitigated vegetation decline.

Similar findings were reported by Serrano et al. (2021), who demonstrated that irrigated Mediterranean agricultural systems generally exhibit higher vegetation stability and drought resistance compared with rain-fed agricultural landscapes.

The spatial synthesis analysis presented in Figure 7 demonstrates a strong overlap between urban growth corridors and vegetation degradation clusters. Areas characterized by rapid residential and tourism-related development corresponded closely with zones exhibiting substantial NDVI reductions and fragmented vegetation structures. This spatial relationship strongly supports the hypothesis that urban encroachment represents one of the dominant drivers of agricultural vegetation transformation in Antalya Province (Figure 7). From a regional planning perspective, the findings of this study indicate that sustainable agricultural management strategies are urgently needed to reduce vegetation degradation and maintain agricultural productivity within Mediterranean environments.

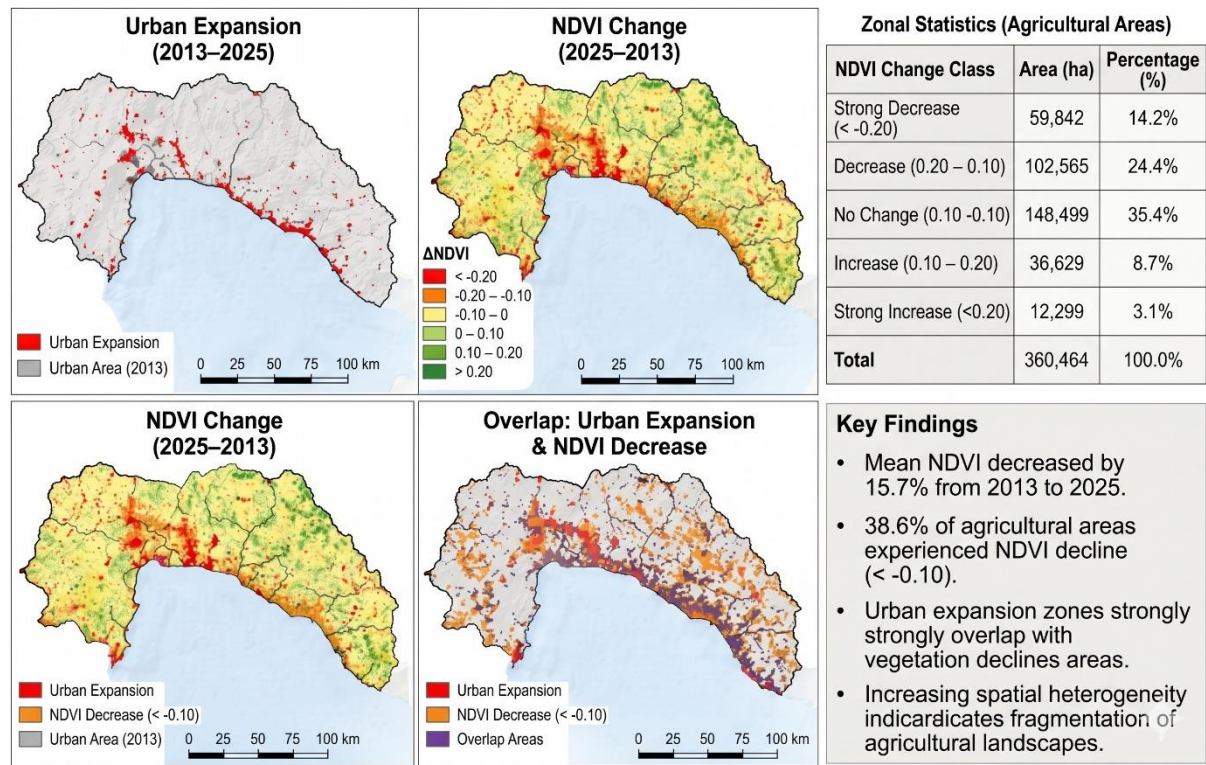


Figure 7. Spatial relationship between urban expansion and NDVI change (2013-2025)

The observed reduction in vegetation density and increasing fragmentation patterns may negatively affect ecosystem services, irrigation sustainability, soil quality, and long-term agricultural resilience. Consequently, integrating remote sensing-based vegetation monitoring into regional agricultural planning frameworks could substantially improve environmental management and land-use decision-making processes.

Methodologically, the study also demonstrates that multi-temporal Landsat imagery combined with GIS-based spatial analysis provides a reliable and cost-effective framework for monitoring agricultural vegetation dynamics at regional scales. The integration of NDVI analysis, statistical trend evaluation, and spatial visualization techniques enabled comprehensive interpretation of vegetation transformation processes across Antalya Province. Therefore, the methodological approach applied in this study can be effectively adapted to other rapidly urbanizing Mediterranean agricultural regions experiencing similar environmental and anthropogenic pressures.

CONCLUSION

This study investigated the spatial and temporal dynamics of agricultural vegetation in Antalya Province between 2013 and 2025 using multi-temporal Landsat imagery and GIS-based spatial analysis techniques. The findings clearly demonstrated that agricultural vegetation conditions in the region experienced a measurable decline during the study period, accompanied by increasing spatial fragmentation and growing heterogeneity in vegetation distribution patterns. The integration of NDVI-based remote sensing analysis with statistical and spatial evaluation techniques provided a comprehensive framework for identifying environmentally vulnerable agricultural landscapes and monitoring long-term vegetation transformation processes.

The results revealed a substantial reduction in regional vegetation density, with mean NDVI values declining from approximately 0.51 in 2013 to 0.43 in 2025. Simultaneously, increases in standard deviation and coefficient of variation values indicated progressively fragmented vegetation structures and increasing spatial inconsistency across agricultural landscapes. Difference analyses further demonstrated that the most severe vegetation losses were concentrated within peri-urban agricultural belts and rapidly developing coastal districts. In contrast, relatively stable vegetation conditions were primarily preserved within intensively irrigated agricultural plains and greenhouse cultivation zones.

The regression analysis confirmed the existence of a statistically significant negative vegetation trend throughout the study period, suggesting that vegetation degradation represents a systematic long-term process rather than temporary annual fluctuations. Moreover, NDVI class transition analyses indicated a substantial decrease in high and very high vegetation classes, while low vegetation categories expanded considerably between 2013 and 2025. These findings collectively suggest that agricultural ecosystems in Antalya are increasingly exposed to environmental stress, urban encroachment, and landscape fragmentation.

The study also demonstrated that urban expansion constitutes one of the dominant drivers of agricultural vegetation transformation in the region. Spatial overlap analyses revealed a strong correspondence between rapidly urbanizing districts and areas characterized by severe NDVI decline. This relationship indicates that uncontrolled urban growth not only alters land-use composition but also reduces vegetation continuity and agricultural ecosystem resilience. In addition to anthropogenic pressures, climatic variability, increasing thermal stress, irregular precipitation patterns, and water-related environmental challenges likely contributed to the observed vegetation degradation patterns.

From a methodological perspective, the study confirms that freely accessible Landsat imagery combined with GIS-based spatial analysis techniques can provide a reliable, cost-effective, and scalable framework for monitoring agricultural vegetation dynamics in rapidly transforming Mediterranean landscapes. The integration of multi-temporal NDVI analysis, statistical trend evaluation, and spatial visualization techniques enabled detailed interpretation of vegetation transformation processes at the regional scale. Therefore, the methodological framework developed in this study can be adapted for similar agricultural monitoring applications in other climate-sensitive and urbanizing regions. The findings of this research have important implications for sustainable agricultural planning and environmental management in Mediterranean ecosystems. Increasing vegetation fragmentation and declining vegetation vigor may negatively affect agricultural productivity, irrigation sustainability, ecosystem services, and long-term environmental resilience. Consequently, regional planning policies should prioritize the protection of productive agricultural landscapes, the control of unplanned urban expansion, and the development of sustainable water-management strategies to mitigate future vegetation degradation risks.

Although the present study provides a comprehensive assessment of long-term vegetation dynamics, several limitations should be acknowledged. The analysis was primarily based on NDVI-derived vegetation monitoring and medium-resolution Landsat imagery. Future studies could integrate higher-resolution satellite datasets, climate variables, soil-moisture indicators, and machine-learning approaches to improve vegetation classification accuracy and environmental interpretation. Additionally, incorporating socio-economic and agricultural production data may provide a more comprehensive understanding of the interactions between urbanization, climate variability, and agricultural sustainability. Overall, this study highlights the growing vulnerability of Mediterranean agricultural ecosystems under combined anthropogenic and climatic pressures. The observed vegetation decline and fragmentation patterns emphasize the urgent need for integrated land-use planning, sustainable agricultural management, and continuous remote sensing-based environmental monitoring to support long-term ecological resilience and agricultural sustainability in Antalya Province and similar Mediterranean environments.

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