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Remote Sensing-Based Evaluation of Vegetation Condition and Drought-Related Spatial Dynamics in Bursa Province, Türkiye

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Abstract

This study assessed vegetation condition and drought dynamics in Bursa Province, northwestern Türkiye, using Sentinel-2-derived annual NDVI and VCI products for 2017-2025. Sentinel-2 Surface Reflectance Harmonized imagery was processed in Google Earth Engine, where cloud-contaminated pixels were masked and annual median NDVI composites were generated. VCI was calculated from pixel-based long-term NDVI minimum and maximum values, and annual NDVI and VCI maps were produced for spatial analysis. In addition, annual mean NDVI and VCI values and drought-class area percentages were derived from raster outputs. The results revealed clear interannual variability in vegetation conditions across Bursa. Annual mean NDVI ranged from 0.52 in 2017 to 0.55 in 2021, while annual mean VCI varied between 61.06 and 63.74. The maps also showed that vegetation stress was spatially heterogeneous across the province. Overall, drought and vegetation stress in Bursa did not follow a monotonic trend but fluctuated between relatively favorable and unfavorable years. These findings demonstrate that Sentinel-2-based NDVI and VCI products provide an effective framework for monitoring provincial-scale vegetation variability and drought conditions and can support irrigation planning and water-resources management.

Key Words: *NDVI, semi-arid, Sentinel-2, vegetation condition index, VCI*

Introduction

Drought is one of the most critical environmental hazards affecting terrestrial ecosystems, agricultural production, and water-dependent landscapes (Lesk et al., 2016). Its impacts have become increasingly pronounced under climate change, rising temperatures, and irregular precipitation regimes, particularly in regions characterized by seasonal water stress and strong interannual variability (Yetik and Candoğan, 2025). Because drought develops gradually and affects vegetation, soil moisture, and ecosystem productivity over broad spatial extents, continuous monitoring is essential for sustainable land management, irrigation planning, and regional water-resources management.

Conventional drought assessment has largely relied on meteorological observations (Kesgin et al., 2024). Although station-based measurements are indispensable, they are often limited in spatial representativeness, especially when the objective is to evaluate the spatial heterogeneity of vegetation stress over large administrative units. Remote sensing has therefore become a widely adopted approach for drought monitoring because it provides repetitive, synoptic, and spatially explicit observations of land surface conditions. In this context, Sentinel-2 offers a major advantage due to its high spatial resolution and short revisit period. As noted in a recent review, Sentinel-2 provides 10 m to 60 m spatial resolution and a combined revisit time of 5 days, making it highly suitable for detailed drought-related analyses at regional and sub-regional scales (Varghese et al., 2021).

Among remote sensing indicators, the Normalized Difference Vegetation Index (NDVI) is one of the most widely used measures of vegetation greenness and vigor. NDVI was originally introduced by Tucker (1979), who demonstrated the sensitivity of red and near-infrared band combinations to photosynthetically active vegetation. Because healthy vegetation strongly absorbs red radiation and reflects near-infrared radiation, NDVI provides a simple yet robust measure of vegetation condition. However, absolute NDVI values alone may not fully capture the relative degree of vegetation stress from year to year. For that reason, the Vegetation Condition Index (VCI), introduced by Kogan (1995), has been widely used to express vegetation condition relative to long-term minimum and maximum NDVI conditions, thereby enabling the interpretation of drought severity in a normalized form.

A substantial body of literature has demonstrated the usefulness of NDVI- and VCI-based drought assessment in different climatic and ecological settings. Varghese et al. (2021) reviewed the potential of Sentinel-2 for drought studies and emphasized its value for detecting drought-driven land surface changes through vegetation, soil moisture, evapotranspiration, and water-related indicators. In Türkiye, Dikici and Aksel (2021) evaluated NDVI and VCI over the Asi Basin and reported that both indices are informative for agricultural drought assessment, while also highlighting the importance of regional interpretation. Similarly, Dikici (2022) analyzed drought conditions in the Seyhan Basin using vegetation indices and meteorological drought indicators, showing that NDVI and VCI remain practical and effective tools for basin-scale drought monitoring. More recently, Uyar (2025) applied a Google Earth Engine workflow integrating Sentinel-2, Landsat 8, and MODIS data for the 2017-2023 period, using annual NDVI and VCI maps to assess drought conditions and vegetation dynamics. These studies collectively indicate that satellite-based vegetation indices are operationally effective for evaluating drought intensity and vegetation response across time.

Despite the increasing number of remote sensing drought studies, province-scale assessments based on high-resolution Sentinel-2 data remain limited for northwestern Türkiye. Bursa constitutes a particularly relevant case because it includes heterogeneous topographic, climatic, and land-cover conditions, ranging from forested mountainous areas to lowland agricultural and peri-urban landscapes. Such spatial diversity makes Bursa an appropriate study area for evaluating interannual vegetation variability and drought patterns using spatially explicit satellite indicators. A province-wide analysis is also useful for identifying years with relatively favorable vegetation conditions as well as years marked by broader vegetation stress.

In this context, the present study aims to assess vegetation health and drought dynamics in Bursa Province using Sentinel-2-derived NDVI and VCI for the 2017-2025 period. Annual NDVI and VCI maps were generated to characterize the spatial distribution of vegetation condition and to identify interannual changes across the province. The study is expected to contribute to regional drought monitoring and to demonstrate the applicability of cloud-based satellite image processing for practical environmental assessment, including irrigation-related planning and water-resources evaluation.

Materials and Methods

Study Area

This study was carried out for Bursa Province, located in northwestern Türkiye (Figure 1). Bursa is characterized by marked topographic, climatic, and land-cover heterogeneity, including mountainous forested areas, lowland agricultural plains, peri-urban zones, and water-related landscapes. Such spatial complexity makes the province suitable for examining interannual vegetation variability and drought conditions at the provincial scale. In the present study, the administrative boundary of Bursa was used as an analysis extent, and all satellite-based processing, mapping, and raster-based statistical evaluations were constrained to this boundary.

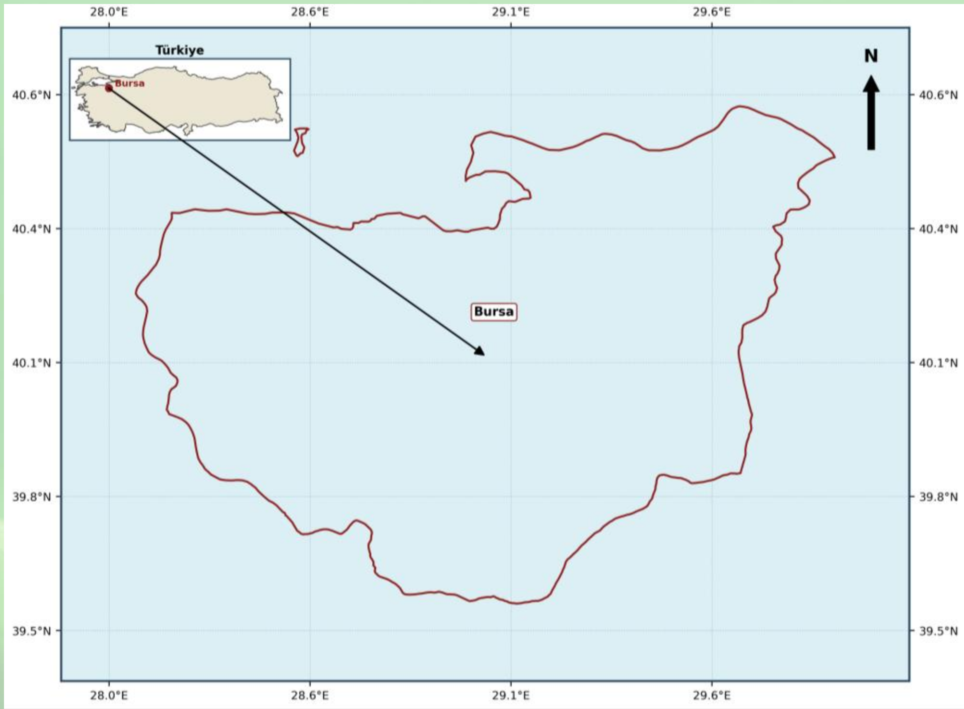

Figure 1. Study site.

Satellite Data and Processing Environment

The analysis was based on Sentinel-2 Surface Reflectance Harmonized imagery accessed through Google Earth Engine. Google Earth Engine provides a cloud-based platform for large-scale geospatial processing and enables the efficient handling of satellite image archives for time-series analysis (Gorelick et al., 2017). Sentinel-2 imagery was preferred because of its relatively high spatial resolution and short revisit interval, which make it particularly suitable for regional drought and vegetation monitoring studies (Drusch et al., 2012; Varghese et al., 2021). The study period covered the years from 2017 to 2025, and the red (Band 4) and near-infrared (Band 8) bands were used in the calculation of vegetation indices.

Image Pre-processing and Annual Composite Generation

All Sentinel-2 scenes intersecting the Bursa boundary were filtered in Google Earth Engine for the 2017-2025 period. In order to reduce atmospheric contamination and cloud-induced noise, a cloud and cloud-shadow masking procedure was applied using the Scene Classification Layer (SCL). Pixels classified as cloud shadow, cloud-contaminated areas, cirrus, and snow were excluded from the analysis. After masking, annual composites were generated for each year. To reduce the influence of residual outliers and unstable observations, the annual NDVI product for each year was derived using a median compositing approach. This procedure resulted in one annual NDVI raster for each year between 2017 and 2025.

NDVI and VCI Calculation

Vegetation condition was evaluated using the Normalized Difference Vegetation Index (NDVI), one of the most widely used indicators of vegetation greenness and vigor in remote sensing studies. NDVI was originally proposed by Tucker (1979) and is defined in Equation 1.

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

where NIR represents Sentinel-2 Band 8 and Red represents Sentinel-2 Band 4. Higher NDVI values indicate denser and healthier vegetation, whereas lower values generally correspond to sparse vegetation, stressed vegetation, or non-vegetated surfaces.

In addition to NDVI, the Vegetation Condition Index (VCI) was used to assess the relative vegetation stress condition of each pixel. VCI was developed by Kogan (1995) and expresses the position of a current NDVI value within its long-term range. In this study, VCI was calculated for each annual NDVI raster using pixel-based minimum and maximum NDVI values derived from the full 2017-2025 period according to the Equation 2.

$$VCI = [(NDVI - NDVI_{\min}) / (NDVI_{\max} - NDVI_{\min})] \times 100 \quad (2)$$

This normalization enables drought severity to be interpreted relative to the local historical variability of vegetation conditions. The resulting VCI values were classified into five drought-related categories: 0-20 (extreme drought), 20-40 (severe drought), 40-60 (moderate drought), 60-80 (light drought), and 80-100 (no drought).

Raster Export, Mapping, and Statistical Evaluation

Annual NDVI and VCI outputs were exported from Google Earth Engine as GeoTIFF files at 10 m spatial resolution. These raster products were subsequently imported into QGIS for cartographic layout preparation. To maintain visual consistency among years, the same legend structure and color classification scheme were applied across all annual maps.

Beyond visual interpretation, a raster-based statistical evaluation was also conducted. For each annual NDVI and VCI raster, mean values were calculated using all valid pixels within the Bursa boundary. In addition, the proportional extent of each VCI class was computed for every year. Particular emphasis was placed on the percentage of pixels with VCI < 40, representing the combined extent of extreme and severe drought conditions, and the percentage of pixels with VCI >= 80, representing areas with no drought condition. These statistics were used to quantitatively compare interannual changes in vegetation health and drought severity across the province.

Methodological Framework

The overall methodological framework of the study consisted of defining the Bursa provincial boundary as the area of interest, acquiring and preprocessing Sentinel-2 imagery in Google Earth Engine, generating annual NDVI composites, calculating pixel-based VCI values from the long-term NDVI range, exporting annual raster outputs, and evaluating both map-based and raster-derived statistical results (Figure 2). In this way, the study integrated spatial visualization with numerical assessment in order to characterize vegetation dynamics and drought conditions in Bursa during the 2017-2025 period.

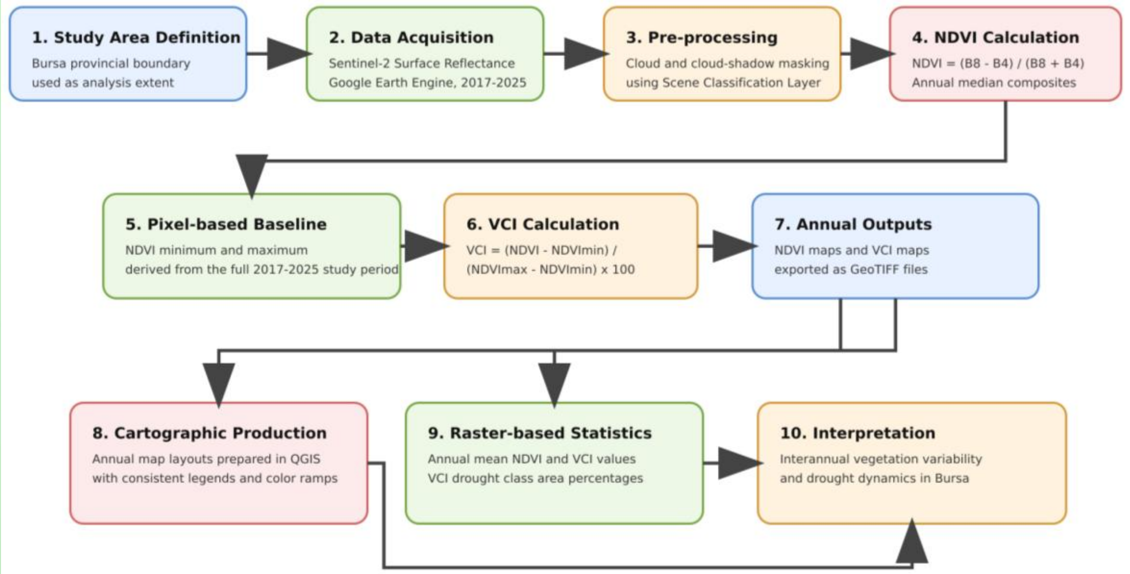

Figure 2. Methodological workflow of the study.

Results and Discussion

The annual NDVI and VCI maps produced for Bursa Province for the 2017-2025 period reveal clear interannual variability in vegetation condition and drought severity, even though the overall provincial-scale signal remains within a moderate range. Taken together, the map series and raster-derived statistics indicate that the study period was characterized not by a monotonic deterioration, but by alternating years of relative vegetation recovery and renewed stress. This pattern is consistent with the nature of vegetation-based drought indicators, which are generally effective in capturing broad spatio-temporal changes in plant condition, but which also reflect the combined influence of climate, phenology, land-cover composition, and local ecological variability (Kogan, 1995; Varghese et al., 2021).

Interannual Variation in NDVI

The annual NDVI maps presented in Figure 3 indicate moderate but meaningful year-to-year fluctuations in the vegetation condition of Bursa Province. Annual mean NDVI values ranged from 0.52 in 2017 to 0.55 in 2021, showing that the highest vegetation greenness during the study period occurred in 2021, followed by relatively favorable conditions in 2022 (0.54) and 2023 (0.54). In contrast, the lowest mean NDVI values were observed in 2017 (0.52), 2019 (0.53), and 2024 (0.53), suggesting that these years experienced comparatively reduced vegetation vigor at the provincial scale.

Figure 3 also shows that this variability was spatially structured rather than uniform. In most years, the northern and northeastern sectors of the province tended to preserve relatively higher NDVI values, while lower values were more evident in the central, western, and southern parts of the province. The general visual pattern suggests that topography, vegetation density, and local land-cover composition influenced the annual NDVI response. The comparatively greener appearance of 2021-2023 in Figure 3 is fully consistent with the statistical summary, whereas the paler and more fragmented NDVI patterns visible in 2017 and again in 2024-2025 reflect weaker vegetation conditions. These findings are in line with the broader literature on Sentinel-2-based drought and vegetation monitoring. Varghese et al. (2021) emphasized that Sentinel-2 is particularly suitable for drought-related vegetation analysis because its spatial and temporal resolution allows the detection of relatively fine-scale land-surface changes. Similarly, West et al. (2018) showed that Sentinel-2-derived NDVI can reflect moisture-related vegetation response more effectively than coarser multispectral systems in several environments, particularly when vegetation cover is sufficiently developed. In this context, the annual NDVI maps of Bursa appear to provide a stable and interpretable representation of province-scale vegetation dynamics.

Studies conducted in Türkiye also support the interpretation of the present NDVI results. In Bursa, Dedeoğlu et al. (2019) demonstrated that Sentinel-2A-derived vegetation indices were sensitive to spatial differences in land productivity conditions, indicating that Sentinel-2-based spectral metrics can successfully reflect land-surface variability at the provincial scale. Similarly, Karabulut et al. (2021) showed that Sentinel-2A NDVI time series effectively captured crop phenology in Kırklareli, confirming the value of NDVI for monitoring vegetation dynamics under Turkish environmental conditions. Civelek et al. (2025) also showed that NDVI thresholds derived from Sentinel-2 imagery and implemented in Google Earth Engine were effective for identifying wheat and barley cultivated areas in Çanakkale. Although these studies were not designed specifically as drought investigations, they collectively confirm that Sentinel-2-derived NDVI products are highly responsive to vegetation development and spatial variability under Turkish agro-ecological conditions. Therefore, the Bursa NDVI maps can be considered not only visually consistent but also methodologically comparable with previous Sentinel-2-based vegetation studies from Türkiye.

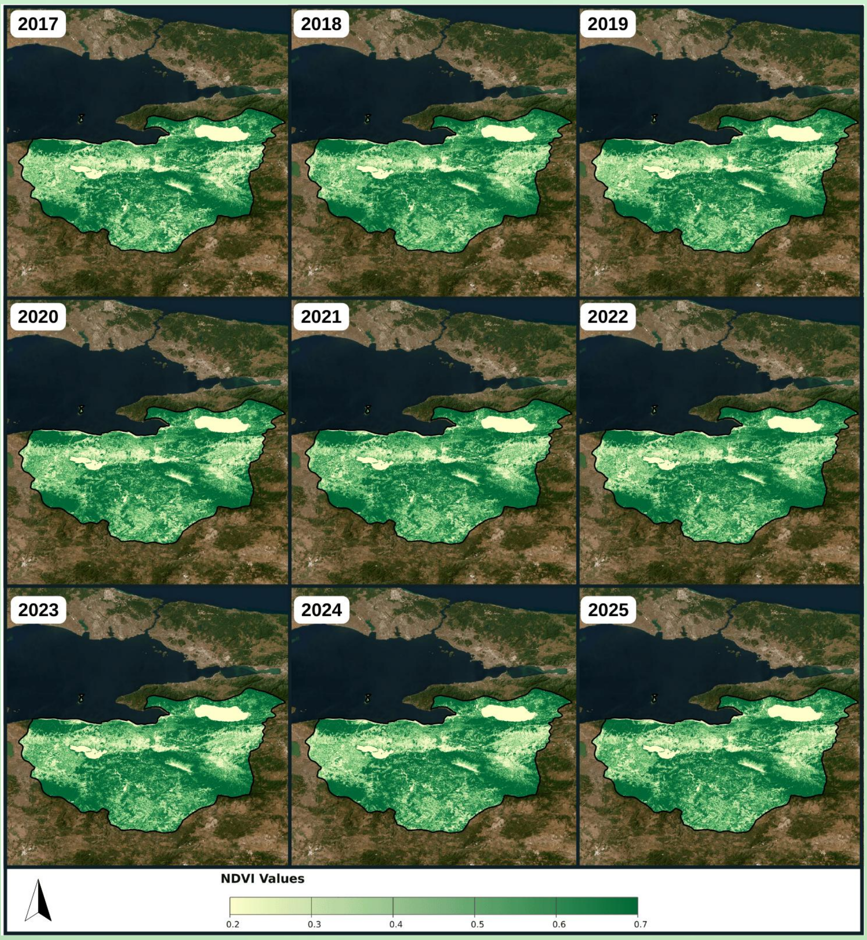

Figure 3. Annual NDVI maps of Bursa Province derived from Sentinel-2 imagery for the 2017-2025 period.

However, the provincial NDVI signal should be interpreted carefully. Because the present analysis covers the entire administrative area of Bursa rather than a cropland-only mask, the results reflect integrated vegetation behavior across forests, agricultural lands, shrub-dominated areas, mixed natural covers, and other land uses. As a result, NDVI changes in this study should be interpreted primarily as province-wide vegetation condition changes, rather than as crop-specific productivity changes. This distinction is important, because in heterogeneous landscapes the same annual NDVI value may reflect different ecological processes in different parts of the province.

Interannual Variation in VCI and Drought Classes

The annual VCI maps presented in Figure 4 further clarify the drought-related dimension of the observed vegetation changes. Annual mean VCI values ranged from 61.06 in 2017 to 63.74 in 2021. These values indicate that, at the province-wide average, Bursa generally remained within the moderate to relatively favorable vegetation-condition range throughout the study period. In other words, the annual signal does not suggest persistent province-wide extreme drought; instead, it indicates fluctuating but mostly moderate vegetation stress conditions. This interpretation is supported by the class-based area statistics derived from the VCI raster. The proportion of the province affected by the combined extreme and severe drought classes (VCI < 40) was highest in 2017 (21.23%), declined substantially in 2018 (15.25%), remained relatively low in 2021 (15.13%), and then increased again in 2024 (19.51%) and 2025 (19.66%). Accordingly, 2021 can be regarded as the most favorable year in the series from the perspective of combined NDVI and VCI behavior, whereas 2017 stands out as the most stressed year. The renewed increase in drought-affected areas during 2024-2025 suggests a deterioration following the relatively favorable 2021-2023 phase.

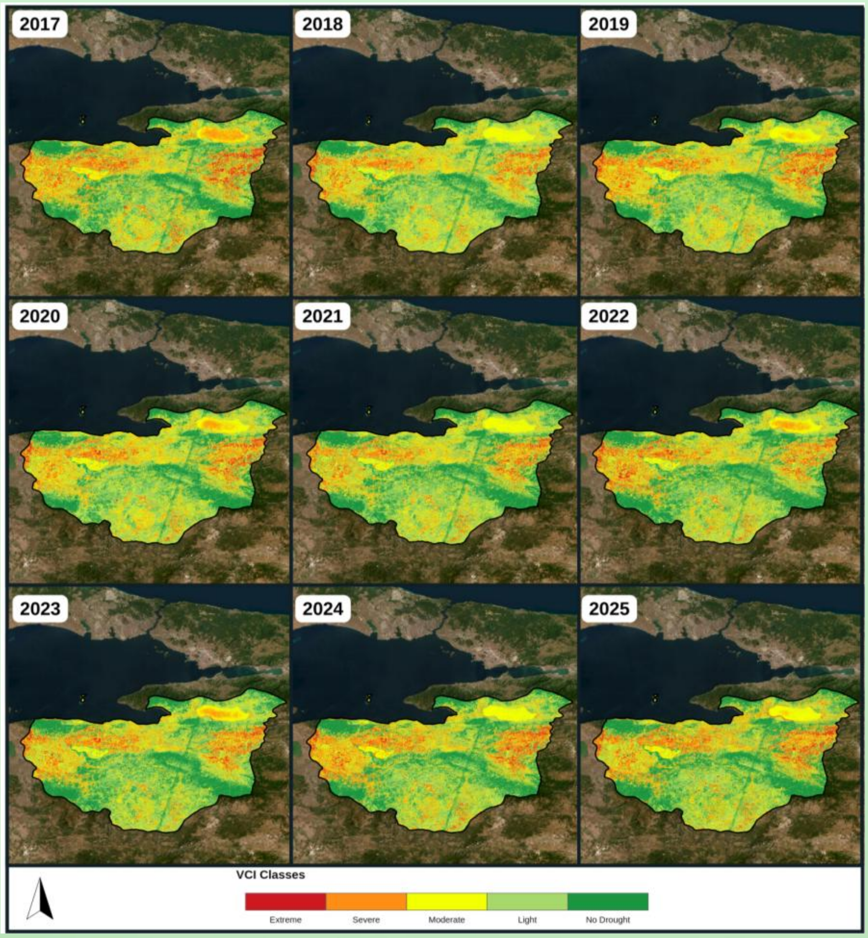

Figure 4. Annual VCI maps of Bursa Province for the 2017-2025 period.

Figure 4 also reveals pronounced spatial heterogeneity in drought intensity. In 2017, orange and red zones were more widespread, indicating broader vegetation stress across substantial parts of the province. In contrast, 2021 exhibits a visibly larger proportion of green-toned areas, consistent with its high mean VCI and low drought-affected area percentage. The 2024 and 2025 maps in Figure 4 show a return of more fragmented but spatially expanded stress zones, indicating that vegetation stress re-emerged after the 2021-2023 recovery interval. Thus, the maps and statistics jointly indicate that the Bursa case is best described as a sequence of interannual fluctuations rather than a simple linear trend.

An important feature of the 2025 result is the coexistence of relatively high drought-affected area and a high proportion of the no-drought class. The percentage of VCI >= 80 reached 28.75% in 2025, which is the highest value in the series, while VCI < 40 simultaneously remained high at 19.66%. This indicates strong spatial polarization in vegetation conditions, meaning that favorable and unfavorable conditions co-occurred across different parts of the province. Therefore, the 2025 pattern should not be interpreted as a uniformly good year or a uniformly bad year; rather, it reflects marked within-province heterogeneity. The predominance of moderate, light, and no-drought classes over the extreme class is also notable. Across the full study period, the extreme drought class remained relatively limited to an area extent, ranging from 2.66% to 4.60%, whereas moderate, light, and no-drought classes accounted for the majority of the mapped area. This outcome resembles findings reported in other VCI-based regional studies. For example, Li et al. (2022) reported that frequent droughts may still be dominated by mild and moderate classes rather than extreme classes when analyzed over broad spatial extents. In the Bursa case, this means that vegetation stress was recurrent, but predominantly moderate in severity at the annual provincial scale.

The general usefulness of NDVI and VCI observed in the present study is consistent with previous drought-monitoring research in Türkiye and elsewhere. Dikici and Aksel (2021), in the Asi Basin, reported that both NDVI and VCI are informative for agricultural drought assessment, while also noting that their performance may vary according to basin characteristics and land-cover composition. Similarly, Dikici (2022), in the Seyhan Basin, concluded that VCI provides a practical means of evaluating vegetation stress relative to long-term vegetation behavior and is therefore valuable for drought monitoring. The present Bursa analysis supports this interpretation. While NDVI maps clearly showed broad differences in annual greenness, VCI added a normalized measure of stress severity and made it easier to identify years such as 2017, 2024, and 2025 as relatively unfavorable in comparison with 2021-2023. A broader national-scale perspective is provided by Şorman et al. (2018), who analyzed meteorological and agricultural drought variation across Türkiye using VCI together with SPEI. Their results showed that VCI is capable of capturing spatially variable drought behavior across different climatic regions of the country. This is directly relevant to Bursa, because the spatial heterogeneity visible in Figure 4 is consistent with the expectation that vegetation stress in Türkiye is regionally differentiated rather than spatially uniform. More recently, Lakshmi et al. (2025) reported substantial spatial variability in remotely sensed drought indicators across the Antalya Basin and emphasized that vegetation-based drought products are particularly useful for identifying where stress intensifies or weakens over time. The Bursa results show a very similar behavior at the provincial scale: stress does not increase uniformly, but fluctuates spatially and temporally.

At the same time, the present findings highlight an important methodological issue also discussed in the literature: the effect of heterogeneous land cover on VCI interpretation. Faridatul and Ahmed (2020) showed that in heterogeneous environments, traditional VCI may overestimate drought-affected areas because non-vegetated or weakly vegetated surfaces naturally have low NDVI values and may therefore be mapped as stressed zones. This point is directly relevant to Bursa, because the province includes forest, urban, bare, water-related, and mixed land-cover types in addition to agricultural areas. Accordingly, the results presented here should be interpreted as provincial vegetation-condition patterns rather than purely agricultural drought patterns. In this respect, the use of the full provincial boundary is acceptable for a general vegetation-stress assessment, but a cropland mask would be preferable if the objective were strictly agricultural drought mapping.

Interpretation of Temporal Pattern

When the annual NDVI and VCI statistics are read together, the temporal behavior of Bursa during 2017-2025 can be summarized in three phases. The first phase is represented by 2017, which appears as the most stressed year of the series, with the lowest NDVI mean, the lowest VCI mean, and the highest drought-affected area. The second phase covers 2018-2020, during which the province generally recovered from the 2017 condition but still exhibited noticeable year-to-year oscillation. The third phase includes 2021-2023, when vegetation conditions improved and drought-affected areas declined, followed by a renewed weakening in 2024-2025.

This temporal sequence does not support a straightforward statement that drought continuously increased throughout the entire period. Instead, it supports a more defensible interpretation: drought and vegetation stress in Bursa fluctuated considerably from year to year, with 2021-2023 representing a comparatively favorable interval and 2017 together with 2024-2025 representing more stressed conditions. This is an important distinction for scientific reporting. In annual vegetation-index studies, broad fluctuations may be more meaningful than attempting to infer a monotonic trend from a relatively short series.

The annual scale adopted in this study should also be considered when interpreting the results. As emphasized by Lakshmi et al. (2025), annual aggregation can smooth short-term extremes and may therefore underestimate the intensity of seasonally concentrated drought episodes. In the present case, annual median NDVI composites were intentionally selected to produce stable, comparable maps across years. This approach is suitable for annual spatial comparison, but it may suppress drought signals that are short in duration yet severe during critical growing periods. For that reason, the present results are best interpreted as annual vegetation-condition summaries rather than direct measurements of seasonal agricultural drought intensity.

Conclusion

This study assessed vegetation condition and drought dynamics in Bursa Province for the 2017-2025 period using Sentinel-2-derived annual NDVI and VCI maps. The results showed that vegetation stress in Bursa did not follow a simple monotonic trend; instead, the period was characterized by clear interannual fluctuations.

Among the analyzed years, 2021 represented the most favorable conditions, with the highest NDVI and VCI means and one of the lowest proportions of drought-affected area. In contrast, 2017 was identified as the most stressed year, while 2024 and 2025 indicated renewed deterioration after the relatively favorable 2021-2023 interval. Accordingly, the temporal pattern of Bursa is better described as alternating phases of recovery and stress rather than continuous drought intensification. The spatial results also demonstrated that vegetation stress was not uniform across the province. Some parts of Bursa consistently showed more favorable vegetation conditions, whereas others were more prone to moderate or severe stress. This indicates that local environmental and land-cover differences likely influenced the spatial drought response. Methodologically, the study confirms that Sentinel-2 imagery processed in Google Earth Engine provides an effective and practical basis for provincial-scale vegetation and drought assessment. Nevertheless, because the analysis covered the entire provincial boundary, the results reflect integrated vegetation response across multiple land-cover types rather than a purely agricultural drought signal. In addition, annual composites provide robust year-to-year comparison but may smooth short-term seasonal stress events.

Overall, the findings indicate that Bursa experienced moderate but spatially heterogeneous vegetation stress during 2017-2025, with the most favorable conditions in 2021 and the most unfavorable conditions in 2017, followed by renewed weakening in 2024-2025. The study demonstrates that annual NDVI and VCI products derived from Sentinel-2 imagery can provide a coherent basis for monitoring vegetation variability and drought conditions at the provincial scale and can serve as supportive information for irrigation management and water-resources planning.

Declarations

Ethical Approval Certificate
Not applicable.

Author Contribution Statement
Ali Kaan Yetik: Data collection, investigation, formal analysis, and writing the original draft

Fund Statement
No financial support was received for this study.

Conflict of Interest
The authors declare no conflict of interest.

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