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Seasonal Vegetation Trends in Biomes of Türkiye: A Decade-Long (2014-2023) Analysis Using NDVI Time Series

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Research Article

Abstract − This study analyzes Türkiye's biomes' seasonal vegetation trend from 2014 to 2023 using the Normalized Difference Vegetation Index (NDVI) and Google Earth Engine (GEE). Focusing on Mediterranean Forests, Woodlands & Scrub; Temperate Broadleaf & Mixed Forests; Temperate Grasslands, Savannas & Shrublands; and Temperate Coniferous Forests biomes, it aims to illuminate vegetative trends and inform conservation strategies in line with the European Green Deal. Using Landsat 8 Operational Land Imager (OLI) satellite imagery and GEE's computational capabilities, the study efficiently processes large datasets, revealing distinctive vegetative responses to climatic conditions across biomes. Key findings include the resilience of Mediterranean vegetation to drought, stable growth in temperate broadleaf and mixed forests, dynamic seasonal shifts in grasslands, and consistent photosynthetic activity in coniferous forests. The study highlights the importance of continuous monitoring and suggests future research integrating remote sensing and ground observations for ecosystem management under climate change.

Keywords – *NDVI, biomes, Türkiye, vegetation trend, google earth engine*

Türkiye Biyomlarında Mevsimsel Bitki Örtüsü Trendleri: NDVI Zaman Serileri ile Son On Yılın (2014-2023) Analizi

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Araştırma Makalesi

Öz − Bu çalışma, Normalize Edilmiş Fark Bitki Örtüsü İndeksi (NDVI) ve Google Earth Engine (GEE) kullanarak 2014-2023 yılları arasında Türkiye biyomlarının mevsimsel bitki örtüsü eğilimini analiz etmeyi amaçlamaktadır. Çalışma, Akdeniz Ormanları, Ağaçlık ve Çalılıklar; Ilıman Geniş Yapraklı ve Karışık Ormanlar; Ilıman Otlaklar, Savanlar ve Çalılıklar; ve Ilıman İğne Yapraklı Ormanlara ait biyomlara odaklanmaktadır. Biyomlar içerisinde bitkisel eğilimlerin incelenmesi ve Avrupa Yeşil Mutabakatı doğrultusunda koruma stratejilerinin incelenmesi temel hedeflerdendir. Landsat 8 Operational Land Imager (OLI) uydu görüntülerini ve GEE'nin veri işleme yeteneklerini kullanan bu çalışma, büyük veri kümelerini analitik bir şekilde işleyerek biyomlar boyunca iklim koşullarına verilen farklı bitkisel tepkileri ortaya çıkarmaktadır. Çalışmanın temel bulgular arasında Akdeniz bitki örtüsünün kuraklığa karşı dayanıklılığı, ılıman geniş yapraklı ve karışık ormanlarda istikrarlı büyüme, otlaklarda dinamik mevsimsel değişimler ve iğne yapraklı ormanlarda tutarlı fotosentetik aktivitelerden söz edilebilir. Çalışma, ekolojik açıdan oldukça önemli bu alanların sürekli izlemenmesinin önemini vurgulamakta ve iklim değişikliği altında ekosistem yönetimi için uzaktan algılama ve yer gözlemlerini entegre eden gelecekteki araştırmaları önermektedir.

Anahtar Kelimeler – *NDVI, biyom, Türkiye, vejetasyon trendi, google earth engine*

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1. Introduction

The study of the Earth's vegetative cover, which is central to understanding the complex interactions within the biosphere, has been revolutionized by the advent of Earth observation technologies. These technologies allow comprehensive monitoring of vegetation dynamics over time, from local to global scales. Central to this advancement is the Normalized Difference Vegetation Index (NDVI), which has been established as an essential metric for assessing vegetation health and productivity due to its effective use of red and near-infrared spectral data (Tucker, 1979). The robustness and simplicity of NDVI have made it a cornerstone for analyzing vegetation trends, allowing researchers to detect both subtle and significant changes within ecosystems, ranging from gradual shifts to sudden declines caused by environmental stressors (Eastman et al., 2013; Meneses-Tovar, 2011).

Biomes, representing large ecosystems with distinct climates and unique species adaptations, are critical to Earth's biodiversity and ecological integrity (Woodward, 2008). Originating in the work of ecologists such as Frederic E. Clements and Victor Shelford, the concept of a biome encompasses a variety of life forms shaped by climatic conditions and is distinct from more localized habitats and ecosystems (Clements & Shelford, 1939). The critical role of biomes in regulating climate, particularly forest biomes with their diverse species and carbon buffering capacity, underscores the importance of their conservation amidst threats from human-induced degradation such as logging, agriculture, and urbanization (Atangana et al., 2014; Hunter et al., 2021). As biomes face unprecedented challenges, preserving their unique ecological dynamics and biodiversity is critical to maintaining global environmental health and climate stability, underscoring the need for sustainable management and concerted conservation efforts.

The study of NDVI changes over various temporal scales has been the focus of numerous remote sensing and environmental monitoring studies. Research has predominantly focused on monthly, seasonal, or annual variations over extended periods to capture the dynamics of vegetation health and productivity. Much of this research relies on Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI datasets (Beck et al., 2006; Funk et al., 2009; Kouadio et al., 2014; Eisfelder et al., 2023), although other satellite platforms such as Landsat (Panuju & Trisasongko, 2012; Guha & Govil, 2021) and Sentinel (Filgueiras et al., 2019; Karlsen et al., 2021) have also provided valuable insights. Despite the commonality in methodological approaches, the novelty of these studies often lies in their geographic focus, ranging from local to global scales and delving into specific ecological units such as biomes (Soudani et al., 2012; Hmimina et al., 2013; Bao et al., 2015). The literature reveals a notable gap in the context of Türkiye, a region of considerable botanical diversity and home to multiple terrestrial biomes. Although a wealth of NDVI-based research exists, most of these studies are limited to local scales, with only one national-scale study using MODIS data identified (Evrendilek & Gulbeyaz, 2008). This lack of comprehensive, large-scale analyses within Türkiye's borders is striking, given the ecological importance of the country and the potential insights such studies could provide into vegetation dynamics across its diverse biomes.

Motivated by the need to fill the gap in existing research, this study aims to conduct a seasonal (spring, summer, fall, and growing season covering all seasons) NDVI trend analysis from 2014 to 2023 across the different biomes of Türkiye, a country known for its significant biodiversity within Europe. Specifically, the objectives of this research are:

- Examination of Türkiye's seasonal NDVI values and trends in the last ten years (2014-2023),
- Evaluation of seasonal NDVI values and trends within the country at the biome subscale, and
- Assessment of the suitability of the GEE platform for use in large-scale vegetation studies.

This research utilizes medium-high resolution Landsat 8 Operational Land Imager (OLI) satellite imagery and the computational power of the Google Earth Engine (GEE) cloud platform to generate NDVI data sets. The study focuses on four major biomes: Mediterranean Forests, Woodlands & Scrub; Temperate Broadleaf & Mixed Forests; Temperate Grasslands, Savannas & Shrublands; and Temperate Coniferous Forests. Through this comprehensive analysis, we aim to contribute to the understanding of vegetation trends in these areas and demonstrate the utility and efficiency of the Google Earth Engine in supporting environmental studies and policy-making processes.

2. Material and Methods

2.1. Study Area

The administrative boundaries of Türkiye define the study area and cover approximately 780.000 square kilometers in the northern hemisphere, specifically between 36° to 42° north latitude and 26° to 45° east longitude (Figure 1). This geographic location, closer to the equator than the North Pole, places the country within the temperate climate zone, fostering a rich ecological habitat conducive to a diverse range of flora and fauna. Türkiye boasts a remarkable biodiversity, with approximately 11.000 indigenous plant species, 35% endemic, highlighting the country's unique botanical importance (Aksoy et al., 2014). Remarkably, the floristic diversity within Türkiye's borders rivals that of the entire European continent, underscoring its ecological and conservation significance (Gemici et al., 1992). This diverse ecological backdrop serves as the foundation for our study, providing a unique opportunity to examine NDVI trends across its diverse biomes.

Türkiye is home to four terrestrial biomes, each with a unique blend of ecological characteristics and rich biodiversity. The boundaries of all these biomes were digitized and mapped in Figure 1 from Ecoregions 2017 data prepared by Resolve (Dinerstein et al., 2017). The Mediterranean Forest, Woodland & Scrub biome is at the forefront, recognized by the World Wide Fund for Nature (WWF) as the most widespread terrestrial biome in the country. This biome thrives in a climate of dry summers and wet winters, although certain areas may experience more evenly distributed rainfall throughout the year (URL-1). It is essential for its rich biodiversity, contributing to 10% of the world's plant species, and boasts diverse vegetation types such as forests, woodlands, shrublands, and grasslands. The varied landscape often forms a "mosaic habitat," a complex tapestry of different vegetation types woven together by the influences of soil type, topography, exposure to the elements, and fire history (Cody, 1986). Next, the Temperate Broadleaf & Mixed Forests biome represents a crucial ecological domain within Türkiye, characterized by the WWF as a temperate zone rich in broadleaf and coniferous trees. This biome is characterized by a variety of plant species, each of which is uniquely adapted to temperate conditions (URL-2). The Temperate Grasslands, Savannas, and Shrublands biome presents a landscape dominated by grasses and shrubs. Its climate ranges from semi-arid to semi-humid, and it differs from tropical grasslands in its distinct annual temperature patterns and species diversity (URL-3). Finally, the Temperate Coniferous Forest biome, characterized by warm summers and cool winters, has a variable plant composition. Some regions are dense with deciduous trees, while others are rich in evergreen deciduous trees or host a mixture of both, reflecting Türkiye's vast ecological diversity (URL-4).

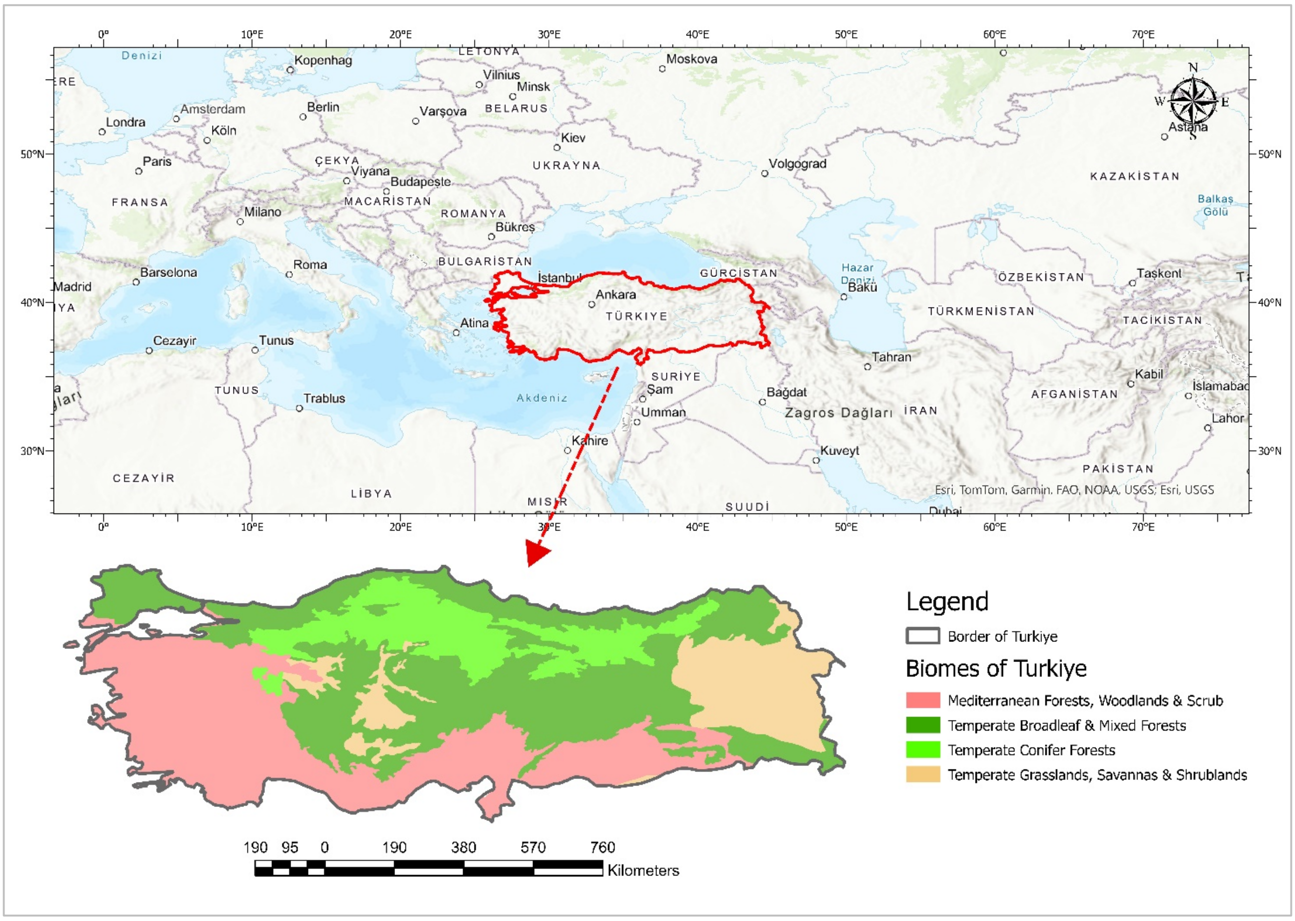

Figure 1. Study area and its biomes derived from Ecoregions 2017 Resolve dataset (Dinerstein et al., 2017)

2.2. Temporal NDVI Production Stages in Google Earth Engine

The analytical component of this research was conducted using GEE, a state-of-the-art cloud- and web-based geographic information system platform. The choice of GEE was strategic, primarily because of its versatility and ability to adapt the model developed in this study for analogous research endeavors with minimal adjustments and the ability to share the model as needed (Amani et al., 2020; Aktürk, 2023; Akturk et al., 2023). GEE is unique because it provides various datasets in various formats, including raster, vector, and tabular, accessible through its extensive libraries. This accessibility allows researchers to quickly acquire large datasets, bypassing the limitations traditionally associated with hardware and software by leveraging Google's robust server infrastructure for data analysis. While the procedural steps taken in this study mirror those typically used to generate standard NDVI products, the methodology was tailored to take advantage of the unique capabilities of the GEE platform, resulting in a customized NDVI analysis specifically designed for the objectives of this study (Figure 2).

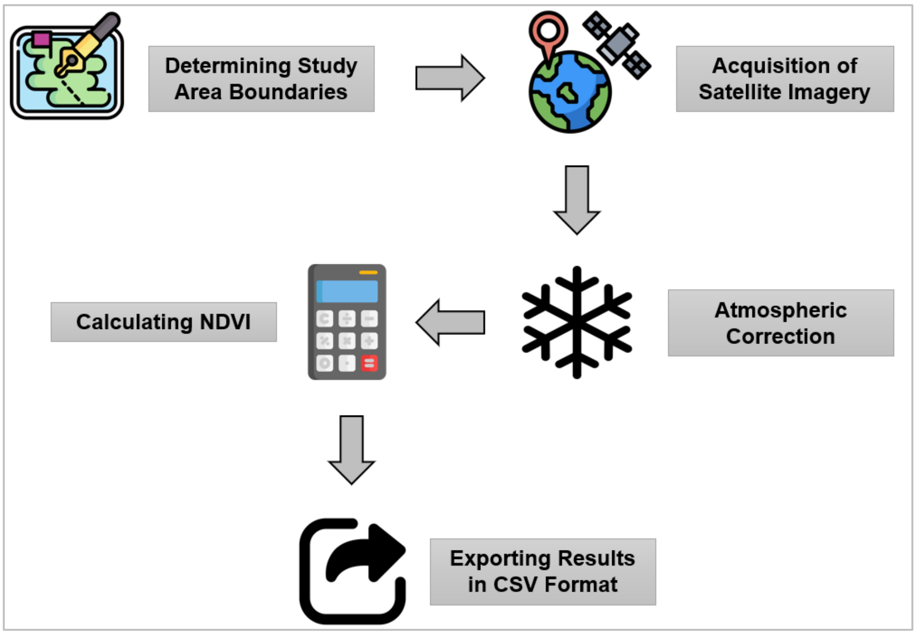

Figure 2. Procedural steps to generate NDVI with GEE in this study

The initial phase of NDVI production involves defining the study area, a critical step that significantly affects the efficiency of subsequent analysis in GEE. Defining the study area boundaries at the outset is essential to streamline the analysis process, as performing analysis on an undefined or overly broad area can unnecessarily increase processing time. To this end, the study used the Global Administrative Unit Layers (GAUL) 2015, a dataset provided by the Food and Agriculture Organization (FAO) that contains detailed administrative boundaries at the country, province, or district level and is accessible through the GEE library (URL-5). However, given the specific focus of this study on the biomes within Türkiye, the boundaries for the RESOLVE Ecoregions 2017 product (Dinerstein et al., 2017), also available in the GEE library, were used. This choice ensures that the analysis accurately targets the ecological boundaries of interest, thereby optimizing the efficiency and relevance of the NDVI production process.

After defining the study area, the next step is to select the appropriate satellite imagery provider. GEE provides access to an extensive library, including the Landsat and Sentinel series. While the Sentinel series has a higher spatial resolution of 10 meters, providing finer detail, the Landsat series is often chosen for its extensive temporal coverage. For this study, the Landsat 8 Collection 2 Tier 1 and Real-Time data imagery, with a spatial resolution of 30 meters, was selected to cover the study period from 2014 to 2023 with only one satellite. The decision was influenced by the availability of high-quality Landsat datasets that benefit from radiometric calibration in the Tier 1 images, ensuring the data's reliability. All available images within approximately 90-day intervals during the spring (March-May), summer (June-August), and fall (September-November) seasons were used for each year within the study period to capture the dynamic changes in vegetation.

Following the selection of Landsat 8 Collection 2 Tier 1 and Real-Time imagery for its superior radiometric quality, the study addresses the challenge of atmospheric distortions, such as clouds and fog, that can obscure the actual reflectance values captured by satellite imagery. Atmospheric correction is critical to mitigate the effects of atmospheric scattering and absorption on reflectance data obtained from satellite or airborne sensors (Pacifici et al., 2014). This study uses the ‘Landsat Simple Composite’ algorithm within GEE to counteract these atmospheric effects and derive the most accurate NDVI values. This algorithm creates a composite from a collection of Landsat scenes by selecting pixels with minimal cloud cover and computing percentile values for each band from the selected pixels. This approach reduces atmospheric clutter, improving the reliability of NDVI calculations and providing a clearer picture of vegetation health and dynamics (Qiu et al., 2023).

After defining the study area, selecting the appropriate satellite imagery, and making the necessary atmospheric corrections, the process moves on to calculating the NDVI. This calculation is critical in assessing vegetation health and involves the analysis of images from the near-infrared (NIR) and red spectral bands. Based on the selection of satellite images, spectral band numbers can vary to calculate NDVI. It can be calculated with the following Equation (1) for Landsat 8:

$$\boldsymbol{NDVI} = \frac{\boldsymbol{NIR}\ (\boldsymbol{Band}\ 5) - \boldsymbol{Red}\ (\boldsymbol{Band}\ 4)}{\boldsymbol{NIR}\ (\boldsymbol{Band}\ 5) + \boldsymbol{Red}\ (\boldsymbol{Band}\ 4)} \tag{1}$$

After the NDVI is calculated using the specified formula for Landsat 8, the resulting data is formatted as a raster in GEE. This data can then be exported to various platforms, including Google Drive, the cloud, or directly within GEE, depending on the needs of the study. Since this research focuses on analyzing NDVI trends over time across Türkiye's biomes, it is essential to extract more granular information beyond the raster images. In order to achieve this, the study calculates the average NDVI values for each biome and disaggregates the data by year and season. This process allows for a detailed temporal analysis of vegetation health and dynamics. These averaged NDVI values are then exported from GEE in .csv format to analyze trends across biomes.

3. Results

This section of this study presented the seasonal average NDVI values for different biomes within Türkiye over a decade, providing a nuanced understanding of vegetation dynamics in these ecologically diverse areas. The data are presented in Table 1, and the trend graph in Figure 3, where each biome is analyzed to reveal NDVI trends and patterns that may have implications for environmental monitoring and ecological management.

Table 1. Seasonal mean NDVI values of biomes over the years. In the table, the Mediterranean Forests, Woodlands & Scrub biome is abbreviated as Bio1 (Blue), the Temperate Broadleaf & Mixed Forests biome is abbreviated as Bio2 (Red), the Temperate Grasslands, Savannas & Shrublands biome is abbreviated as Bio3 (Grey), and the Temperate Coniferous Forests biome is abbreviated as Bio4 (Green). The 'Growth Season' values are obtained by averaging all seasons.

Year	Spring Season				Summer Season				Fall Season				Growth Season			
	Bio1	Bio2	Bio3	Bio4	Bio1	Bio2	Bio3	Bio4	Bio1	Bio2	Bio3	Bio4	Bio1	Bio2	Bio3	Bio4
2014	0,396	0,340	0,219	0,338	0,359	0,368	0,264	0,423	0,327	0,301	0,190	0,350	0,365	0,358	0,256	0,398
2015	0,423	0,384	0,213	0,375	0,377	0,385	0,280	0,451	0,339	0,310	0,210	0,362	0,379	0,375	0,267	0,421
2016	0,410	0,352	0,217	0,378	0,359	0,379	0,312	0,443	0,326	0,284	0,180	0,331	0,360	0,359	0,277	0,412
2017	0,386	0,318	0,170	0,304	0,375	0,387	0,281	0,444	0,334	0,299	0,188	0,340	0,364	0,360	0,252	0,400
2018	0,427	0,400	0,306	0,401	0,375	0,389	0,309	0,444	0,331	0,300	0,205	0,337	0,375	0,380	0,284	0,421
2019	0,401	0,367	0,202	0,363	0,382	0,386	0,273	0,457	0,343	0,305	0,195	0,349	0,375	0,365	0,251	0,416
2020	0,414	0,357	0,183	0,371	0,374	0,387	0,296	0,441	0,330	0,301	0,202	0,338	0,371	0,362	0,263	0,405
2021	0,417	0,371	0,285	0,374	0,364	0,371	0,248	0,427	0,323	0,292	0,184	0,342	0,368	0,361	0,240	0,405
2022	0,376	0,325	0,198	0,330	0,366	0,383	0,277	0,454	0,339	0,303	0,196	0,353	0,363	0,371	0,252	0,429
2023	0,412	0,351	0,263	0,348	0,382	0,399	0,292	0,458	0,349	0,319	0,210	0,363	0,383	0,380	0,274	0,432

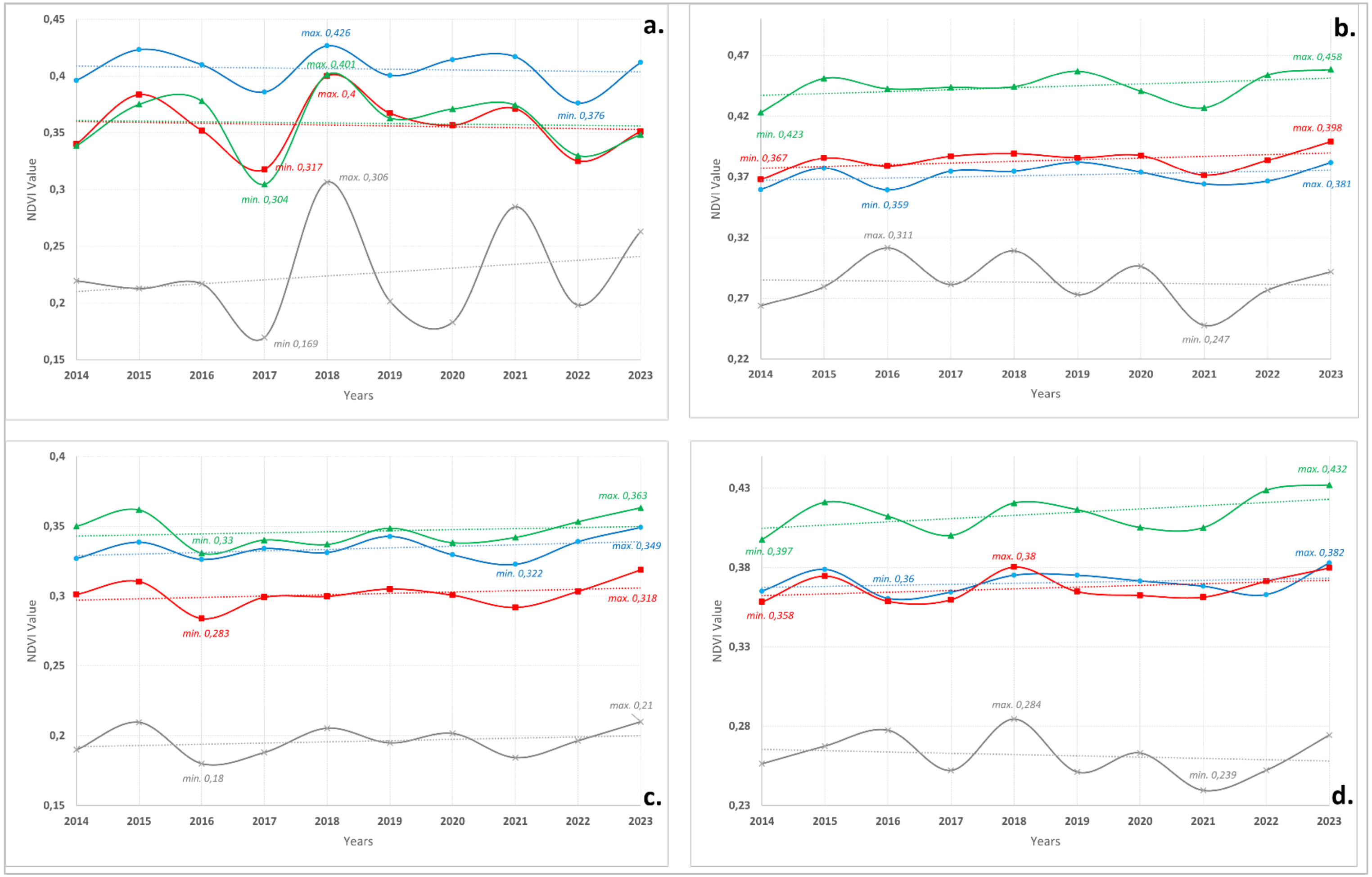

Figure 3. Seasonal mean NDVI trend graph of biomes over the years. Seasons are numbered in the graphic as Spring (a), Summer (b), Fall (c), and Growth Season (d). The Mediterranean Forests, Woodlands & Scrub biome (Blue), the Temperate Broadleaf & Mixed Forests biome (Red), the Temperate Grasslands, Savannas & Shrublands biome (Grey), and the Temperate Coniferous Forests biome (Green)

The data presented in Table 1 and Figure 3 shows that the Mediterranean Forests, Woodlands, & Scrub biome (Bio1) reached their peak NDVI value of 0.426 during spring. Subsequently, there was a significant decrease in the average NDVI values during the summer and spring seasons. Throughout the growing season, the average NDVI values for Bio1 were lower than those observed for the Temperate Coniferous Forests biome (Bio4) but comparable to the Temperate Broadleaf & Mixed Forests biome (Bio2). Specifically, the years 2016, 2021, and 2022 recorded the lowest NDVI values for this biome, while the highest values were recorded in 2018 and 2023.

In this study, the Mann-Kendall trend analysis was used to assess the presence and direction of NDVI and related vegetation trends within this biome and others that exhibit non-linear patterns. This nonparametric test, commonly used in environmental studies, helps to identify trends within time series data (McLeod, 2005). The heat map in Figure 4 shows the p-values for the Mann-Kendall trend analysis across all biomes and seasons, indicating no statistically significant trend for Bio1 in any season. However, when evaluating the general averages, there are slight increases in seasons rather than spring.

Results for the Temperate Broadleaf & Mixed Forests biome (Bio2) indicate that the peak in NDVI values occurs during the summer season, while the lowest values are typically recorded in the fall. Throughout the growth season, Bio2 exhibits NDVI values that are not only similar to those of Bio1 but also slightly higher, indicating a consistent trend in vegetative vigor. Despite these observations, the NDVI trend for Bio2 does not show a statistically significant change, mirroring the trend observed in Bio1. However, a numerical increase in NDVI values is evident over the decade under study.

The Temperate Grasslands, Savannas, & Shrublands biome (Bio3) results are notably distinct, consistently exhibiting the lowest average NDVI values among the studied biomes. The NDVI values of this biome reach their peak during the summer months while exhibiting markedly lower averages during the spring and fall seasons. Notably, the spring season of 2017 showed the lowest NDVI value of 0.169 for Bio3, representing the minimum recorded across all biomes and seasons within the scope of this study. Like other biomes, the longitudinal NDVI trends for Bio3 do not demonstrate statistically significant changes. However, the biome exhibits the highest degree of variability in NDVI values over the years, highlighting its dynamic response to seasonal climatic fluctuations.

The Temperate Coniferous Forests biome (Bio4) shows the highest average NDVI values during the growth season, which illustrates its robust vegetative health. The biome reached a peak NDVI average of 0.458 in the summer of 2023, representing the highest recorded value among all evaluated seasons and biomes. While Bio4 exhibits NDVI averages in the spring that are comparable to those of Bio2 and in the fall similar to Bio1, its summer values are distinctively higher than those of all other biomes. This pronounced differentiation highlights the unique ecological robustness of Bio4 during the warmer months. As with other biomes, no discernible statistical trend in NDVI values is evident for Bio4 throughout the study period. Nevertheless, a comprehensive examination of the data indicates that, except for the spring season, there has been a discernible upward trajectory in the mean NDVI values across the remaining seasons.

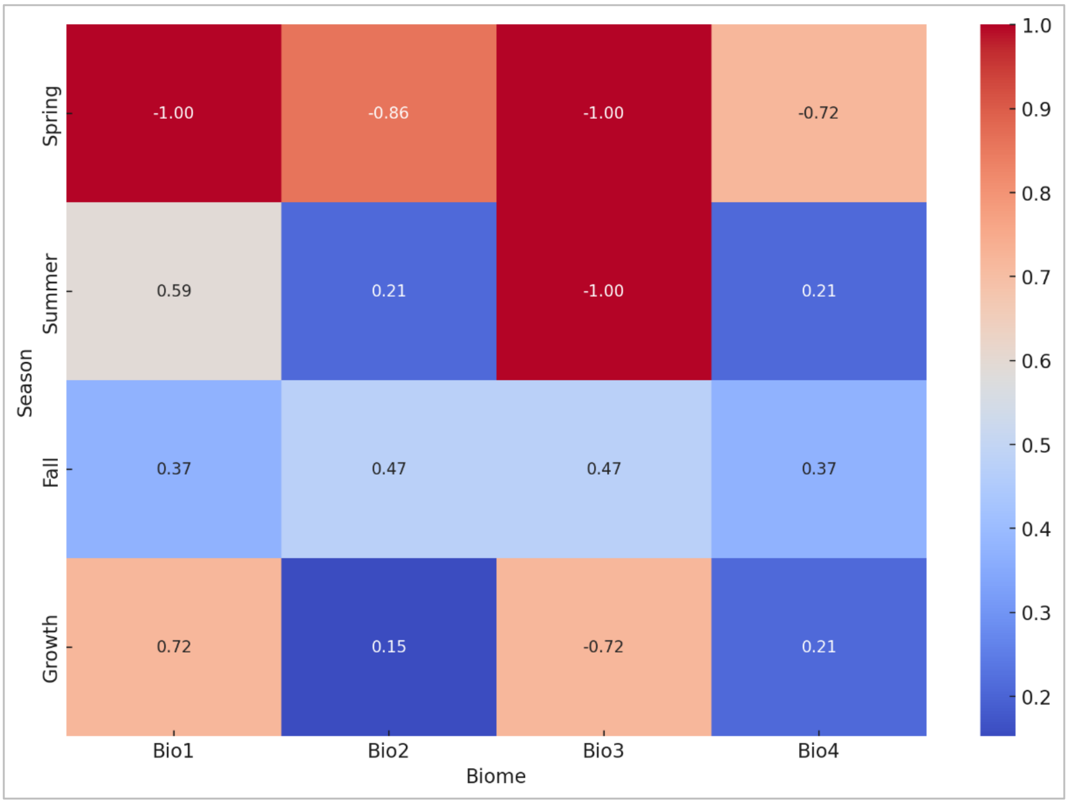

Figure 4. p-values for the Mann-Kendall trend analysis across all biomes and seasons

4. Conclusion

4.1. Mediterranean Forests, Woodlands & Scrub Biome (Bio1)

The Mediterranean Forests, Woodlands, & Scrub biome (Bio1), characteristic of the Mediterranean climate with its hot, dry summers and mild, wet winters, have exhibited varying NDVI values over the past decade, reflecting its distinct seasonal patterns and vegetation types. The biome is typically dominated by sclerophyllous vegetation - plants with stiff leaves adapted to dry conditions. Due to their evolutionary traits to conserve water, these species may not exhibit as robust a spring NDVI response as species in more temperate biomes. Nevertheless, the spring period showed the highest NDVI values, indicating the active growth phase following winter precipitation. However, variability during this period, highlighted by declines in spring NDVI in 2017 and 2022, underscores the sensitivity of vegetation in this biome to interannual climate variability, potentially exacerbated by phenomena such as late frosts or reduced precipitation. 2018 stands out with the highest recorded spring NDVI value of 0.427, indicating a solid growth season this year, possibly due to optimal rainfall and temperature conditions that supported the photosynthetic activity of the biome's flora.

In contrast to the spring, the summer and fall seasons show slight increases in NDVI trends, contributing to a stable and slightly increasing trend in the overall 'Growth Season.' This could be attributed to the biome's adaptive strategies, where plants use deep water reserves despite the summer drought or show delayed growth that continues into the fall, taking advantage of the mild conditions before winter.

Observations over the past decade reveal a biome that, while showing variability in the spring, shows overall stability and even slight increases in vegetative health and productivity in later seasons. This resilience and adaptability are likely due to the intrinsic drought tolerance mechanisms of sclerophyllous plants and the seasonality of the Mediterranean climate, which provides a regenerative rainy season to offset the stresses of the dry summer period.

Scientifically, these results highlight the importance of seasonal and interannual analyses in assessing the health of Mediterranean-type ecosystems. The capacity of these systems to recover, despite fluctuations, indicates the robustness of their vegetation and the critical need for their conservation, given their role in supporting biodiversity and sequestering carbon in a climate subject to increasing variability and change.

4.2. Temperate Broadleaf & Mixed Forests Biome (Bio2)

The Temperate Broadleaf & Mixed Forests biome (Bio2) exhibits NDVI values indicative of the seasonal dynamics and vegetative health inherent in this ecologically diverse biome. Throughout the ten-year study, the spring and summer seasons consistently exhibited higher NDVI values than the fall, indicating robust growth during the warmer months. This biome, composed of a mix of deciduous and evergreen trees, exhibits higher variability in NDVI during the spring, reflecting the sensitive response of deciduous trees to the onset of the growing season. This is evidenced by the notable decline in spring NDVI from 2016 to 2017, suggesting a possible delay in the onset of spring growth or a response to atypical climatic events during this period. However, this decline was followed by a significant rebound in spring 2018. NDVI peaked at 0.4, indicating an exceptional growing season, likely due to favorable weather conditions that increased photosynthetic activity and overall forest health. While spring NDVI has shown a slight decreasing trend over the past decade, summer and fall NDVI have increased. These contrasting seasonal trends may reflect the different growth and senescence cycles of the biome's mixed vegetation. The vigorous spring growth of deciduous trees may be more susceptible to annual climate variability. At the same time, the sustained photosynthetic activity of evergreens contributes to increased NDVI values in summer and stability in fall. The overall 'growing season' NDVI trend shows a slight increase, suggesting an overall improvement in the vegetative vigor of the biome. This could indicate a biome experiencing positive changes, such as an extended growing season or successful forest management practices that improve growing conditions.

In addition, the spring NDVI values in this biome are very similar to those observed in the Temperate Grasslands, Savannas & Shrublands biome, possibly due to similar climatic conditions affecting the onset of growth in these biomes. The summer data also show similar characteristics to the first biome, further emphasizing the interrelated nature of these ecosystems. In summary, NDVI trends within the Temperate Broadleaf & Mixed Forests biome over the study period illustrate the sensitivity and subsequent resilience of the vegetation of this biome. The data reflect a capacity for recovery and adaptation, underscoring the importance of understanding the temporal and spatial patterns of NDVI values to inform conservation and management strategies for these temperate forest ecosystems.

4.3. Temperate Grasslands, Savannas & Shrublands Biome (Bio3)

The Temperate Grasslands, Savannas & Shrublands biome (Bio3) inherently differs from the other biomes regarding vegetation structure and response to climatic conditions. Over the ten years, Bio3 was characterized by significantly lower NDVI values, characteristic of the biome's open landscapes and grass-dominated vegetation, less dense than the tree-dominated biomes. A notable observation from the decade-long NDVI data is the significant increase trend during springs. This trend contrasts with the other biomes and likely reflects the rapid vegetative growth typical of grassland regions after winter dormancy. Favorable spring conditions, including increased moisture and light, stimulate the growth of grasses and forbs, resulting in higher NDVI values. There is also a tendency for a minor increase in the fall, possibly due to the biome's grasses and forbs taking advantage of the cooler yet still growth-supporting conditions often found in the transition period before winter. This increase is less pronounced than in the spring but suggests that fall remains a productive season for the biome's vegetation. Conversely, the summer seasons show a decreasing trend in NDVI, contrary to observations in the other biomes. This decrease could be attributed to the typical stressors affecting grasslands in summer, such as heat waves and drought conditions, which can reduce vegetative vigor and cover. This decline during the summers has affected the overall growing season trend, contributing to a downward trajectory over the ten years.

The fluctuating NDVI values in the spring and summer seasons indicate the high interannual sensitivity of the biome, while the fall season shows more stability. This pattern may be due to the inherent adaptability of grassland vegetation to changing conditions and biome management, including grazing and land use practices, which can significantly affect vegetation cover from year to year. In 2018, the biome reached its highest spring NDVI value of 0.306, reflecting a year of peak productivity across all biomes. This peak may indicate optimal conditions that year, favoring vegetative growth across different ecosystem types. The NDVI data for Bio3 over this period highlight the importance of understanding grassland ecosystems' unique responses and adaptations. The observed trends and peaks, particularly in 2018, underscore the need for adaptive management to ensure the conservation and resilience of these biomes, which are critical for biodiversity, soil stabilization, and their role in the carbon cycle under the stressors of climate change.

4.4. Temperate Coniferous Forests Biome (Bio4)

The Temperate Coniferous Forests biome (Bio4) is characterized by the highest average NDVI values within the nine-month growing season period each year, except for the winter months. This persistent NDVI performance is primarily attributed to the biome's composition of coniferous trees, which retain their needles throughout the year, maintaining a constant level of photosynthetic activity even in the absence of winter foliage. In the spring season, Bio4 has slightly lower NDVI values than the Mediterranean Forests, Woodlands & Scrub biome, which experience more active photosynthesis during regrowth and renewal. Outside of spring, however, Temperate Coniferous Forests have shown an upward trend in NDVI over the past decade throughout the other seasons. This trend has contributed to a significant increase in the overall growing season, indicating the stable and robust nature of the vegetation in this biome throughout the year.

The continuity of high NDVI values reflects the adaptation of conifers to the temperate biome's climate, where they remain evergreen and functionally active, in contrast to deciduous trees that undergo seasonal leaf loss. The notable exceptions to this stable trend occurred in the spring of 2017 and the summer of 2021, where a decrease in NDVI values was observed. These anomalies may be related to specific climatic events or disturbances that temporarily affect the photosynthetic efficiency of the forest canopy. While season by season Bio4 shows similar trends to other biomes, it has a distinctive overall character. It maintains high NDVI values, indicating its resilience and ecological stability. The increase in NDVI values over the years suggests that the Temperate Coniferous Forests may be experiencing favorable climatic conditions or that management practices within these forests effectively maintain and improve forest health.

The sustained photosynthetic capacity of temperate coniferous forests throughout the year is critical for carbon sequestration and habitat stability. The data from this study highlight the importance of these forests in maintaining biodiversity and providing ecosystem services. The observed upward trend in NDVI underscores the resilience of these forests in the face of environmental change and the need for continued monitoring and adaptation of management practices to conserve these critical ecosystems in Türkiye.

4.5. Utilization of GEE for NDVI Analysis

The use of GEE in this study underscored its critical role in facilitating comprehensive NDVI analysis. GEE's extensive libraries, especially satellite image libraries, were instrumental in streamlining the data acquisition and manipulation process, allowing for an efficient examination of vegetation indices across Türkiye's diverse biomes. With GEE's robust computational capabilities hosted on Google's servers, the study benefited from the rapid processing of large datasets. This feature is particularly advantageous for monitoring large areas such as Türkiye. In addition, GEE's user-friendly interface and scripting environment have enabled the customization of analyses to meet specific research needs, with the flexibility to adapt and reuse code with minimal modifications. This adaptability ensures that the methods developed in this study are not only reproducible but can be easily adapted by other researchers for further NDVI investigations. GEE has thus contributed to the advancement of remote sensing research, providing a powerful tool for environmental monitoring and contributing to a collaborative scientific community.

5. Conclusion

This study has provided an in-depth analysis of NDVI trends in four different biomes in Türkiye from 2014 to 2023, providing valuable insights into changes in vegetative health and productivity over time. By carefully examining the seasonal NDVI values, it has been shown that each biome; Mediterranean Forests, Woodlands & Scrub; Temperate Broadleaf & Mixed Forests; Temperate Grasslands, Savannas & Shrublands; and Temperate Coniferous Forests shows unique vegetative responses to climatic variations and disturbances. The resilience of the Mediterranean Forests, Woodlands & Scrub biome to drought, the steady vegetative growth of the Temperate Broadleaf & Mixed Forests, the dynamic seasonal changes of the Temperate Grasslands, Savannas & Shrublands, and the consistent photosynthetic activity of the Temperate Coniferous Forests highlight the complex interplay between climate, vegetative cover, and ecosystem health.

Using GEE was instrumental in achieving the study's goals, demonstrating its effectiveness in processing and analyzing large amounts of remotely sensed data. GEE's extensive libraries and computational power facilitated a streamlined approach to NDVI analysis across Türkiye's vast and varied landscapes. This study highlights the utility of GEE in environmental monitoring. It sets a precedent for its application in large-scale vegetation studies, providing a reproducible and adaptable methodology for future research efforts.

Looking forward, the results of this study underscore the need for continued and improved monitoring of vegetation trends to inform conservation and management strategies in the face of global environmental change. It highlights the potential for further integrating remote sensing data with ground-based observations to refine our understanding of ecosystem dynamics. Future studies could extend this work by incorporating additional biophysical parameters, exploring the effects of climatic anomalies, and applying predictive models to anticipate changes in vegetation health and productivity. Such holistic approaches are essential for the sustainable management of natural resources and conservation of biodiversity, in line with global initiatives such as the European Green Deal to address the pressing challenges of climate change and environmental degradation.

Conflict of Interest

The author(s) declare that they have received no funds and there is no conflict of interest.

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