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Short-Term Significant Response to Climate Change: Treeline Shift and Critical Bare Land Contraction in the Western Taurus Mountains

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Abstract: Global climate change, characterized by rising temperatures and a reduction in the duration of snow cover, is shifting favorable growth conditions for plant species to higher elevations, consequently inducing an upward migration of the treeline. This study focused on determining the short-term elevational change of the treeline in high-altitude regions. The study area selected was a region in the Western Taurus Mountains above 1,000 meters, characterized by minimal anthropogenic disturbance. Multi-temporal satellite imagery from the years 2004, 2014, and 2024, combined with the NDVI spectral index, was utilized to analyze the changes in forest cover and the spatial dynamics of the treeline. The results confirm a significant altitudinal shift of the treeline between the periods examined, consistent with existing literature. Specifically, the treeline experienced an upward displacement of approximately 24 meters over the 20-year period, which can be associated with changes in climatic components. Furthermore, bareland areas, which are critical habitats for high-altitude adapted herbaceous species, particularly endemic flora, showed a tendency towards contraction during this process. The findings demonstrate the high sensitivity of high-altitude ecosystems to climatic variations, even over the short term, and illustrate the spatial changes in land cover. This research provides a holistic and practical methodology for monitoring rapid changes in high-mountain ecosystems and offers results that will serve as a foundation for future ecosystem monitoring studies.

Keywords: Alpine zone, climate change effects, high-altitude region, remote sensing, treeline uplift.

İklim Değişikliğine Kısa Vadeli Önemli Tepki: Batı Toros Dağları'nda Ağaç Sınırlarının Kayması ve Kritik Çıplak Arazi Daralması

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Öz: Küresel iklim değişikliği, sıcaklıkların artması ve kar örtüsü süresinin kısalması nedeniyle bitki türleri için uygun büyüme koşullarının daha yüksek rakımlara taşınmasına yol açarak ağaç üst sınırının yukarı doğru göç etmesine neden olmaktadır. Bu çalışma, yüksek rakımlı bölgelerde kısa vadede meydana gelen ağaç üst sınırındaki değişimini belirlemeye odaklanmıştır. Çalışma alanı olarak, insan müdahalesinin minimum olduğu, batı Toros dağlarının 1000 m ve üzerindeki rakımda bir bölge seçilmiştir. Araştırmada 2004, 2014 ve 2024 yıllarına ait multi-temporal uydu görüntüleri ve NDVI spektral indexi ile birleştirilerek vejetasyon örtüsündeki değişim ve ağaç üst sınırının mekânsal dinamikleri analiz edilmiştir. Çalışma sonuçları, ağaç üst sınırının söz konusu dönemler arasında literatüre paralel olarak belirgin bir değişim gösterdiği doğrulamıştır. Bu kapsamda, 20 yıllık süreçte iklim bileşenlerindeki değişimle ilişkilendirilebilecek şekilde ağaç üst sınırındaki kayma, yüksek rakıma doğru yaklaşık 24 metre olarak tespit edilmiştir. Ayrıca yüksek rakıma adapte olmuş otsu bitki türleri ve özellikle endemik bitkilerin yaşadığı çıplak alanlar bu süreçte daralma eğilimine girmiştir. Elde edilen bulgular, yüksek rakımlı ekosistemlerin kısa vadeli bile olsa iklim değişimlerine karşı yüksek duyarlılığa sahip olduğunu ve arazi örtüsünün mekânsal değişimler sergilediğini göstermektedir. Çalışma, yüksek dağ ekosistemlerinde hızlı değişimlerin izlenmesine yönelik bütüncül ve pratik bir yöntem sunmakta ve gelecek dönemlerde yapılacak ekosistem izleme araştırmalarına temel oluşturacak nitelikte sonuçlar sağlamaktadır.

Anahtar kelimeler: Ağaç üst sınırı kayması, alpin bölge, iklim değişikliği etkileri, uzaktan algılama, yüksek rakımlı bölge.

INTRODUCTION

Global climate change has exerted increasingly pronounced impacts on ecosystems over the last century (Bakure et al., 2022). The accumulation of greenhouse gases in the atmosphere and associated temperature increases, driven by anthropogenic activities, are causing shifts in climate systems at both global and regional scales (Filonchyk et al., 2024). These changes are particularly evident in high-altitude regions. High-mountain ecosystems

possess more limited growth conditions and highly sensitive ecological balances compared to lower-altitude areas. Consequently, they are rapidly affected by factors such as rising temperatures, shortened snow cover duration, and changes in precipitation regimes (Broadbent et al., 2024). Biogeographically, land cover in high-mountain regions is shaped by environmental variables, including temperature, precipitation, and topographical characteristics (Klinge et al., 2018). The treeline (tree upper limit) is recognized as one of the most sensitive ecosystem indicators in these regions (Schickhoff et al., 2015). The treeline represents a natural boundary where plant communities transition based on climatic limits, and it is prone to upward migration in parallel with warming temperatures and seasonal climatic shifts (Harsch et al., 2009; Wang et al., 2022). These altitudinal shifts impact not only the forest cover components but also vital ecosystem services such as soil erosion, hydrological cycling, and biodiversity (Ivashchenko et al., 2025). Long-term studies conducted in high-altitude areas, particularly in Europe and North America, have demonstrated a significant elevation of treelines, strongly correlated with temperature increases (Körner and Hiltbrunner, 2024; Corimanya et al., 2025). For instance, dendrochronological analysis in the valleys of the Western Italian Alps reported a treeline shift of 115 m during the 1901–2000 period (Leonelli et al., 2011). Similarly, in the Eastern Alps, an approximate 140 m vertical shift in treeline position has been observed since the 19th century, linked to an increase in mean temperature (Körner & Hiltbrunner, 2024). Research in the Eastern Black Sea and Taurus Mountains has indicated that treelines have advanced by 50-150 m over the last 20–30 years, primarily associated with increases in mean temperature (Arekhi et al., 2018). A study in the Altai Mountains documented an upward treeline migration of 150 m, attributed to an increase in mean temperature of approximately 1,3-1,7 °C (Cazzolla et al., 2019). Furthermore, in the Carpathian Mountains, a major Eurasian mountain system, satellite imagery and climate modeling have shown a strong relationship between treeline position and climatic variables, predicting continued upward migration due to rising temperatures (Mkrtchian & Mueller, 2025). Therefore, monitoring the impacts of climate change in high-altitude areas is critical for understanding ecosystem dynamics and developing sustainable management strategies.

The increase in global temperatures observed over the past two decades clearly indicates an acceleration of anthropogenic climate change. Since the early 2000s, the global mean surface temperature has increased at a rate of approximately 0.2–0.3 °C per decade, and the most recent decades have been the warmest period in the modern observational record (IPCC, 2023). This trend represents a critical climatic pressure directly influencing treeline dynamics in high-mountain ecosystems. However, the Mediterranean Basin is warming approximately 20% faster than the global average and is therefore identified as a "climate change hotspot" (UNEP, 2025). Several studies indicate that sea surface temperatures in the Mediterranean increased at a rate of approximately 0.37–0.41 °C per decade during the 1982–2022 period, exceeding the global average warming rate (Pisano et al., 2020; Darmaraki et al., 2019). Considering this rate, the Mediterranean climate zone has experienced an increase of approximately 0.7–0.8 °C over the past 20 years. The fact that the region is warming faster than the global average suggests that risks such as drought, heatwaves, ecosystem stress, and biodiversity loss are likely to intensify in the future (Lionello & Scarascia, 2020). Therefore, monitoring treeline shifts in high-mountain ecosystems of the Mediterranean Basin, particularly in the Western Taurus Mountains, is of critical importance for understanding the regional manifestations of global climate change.

The Western Taurus Mountains are a significant geographical area situated in southwestern Türkiye-Antalya, noted for combining the Mediterranean climate zone with high-mountain ecosystems. The higher elevations of the mountains typically exceed 1,000 m above sea level and encompass both forest and maquis-type natural vegetation. The topographical complexity and climatic heterogeneity of the region facilitate the co-existence of diverse land cover types and allow for differential ecosystem responses to climate change (Zou et al., 2025). Due to these characteristics, the mountain ecosystem in the part of the Western Taurus Mountains were selected as an appropriate research area for monitoring short-term climate change impacts and evaluating land cover dynamics within high-altitude ecosystems.

Monitoring short-term climate change impacts in high-altitude regions, such as the selected study area, necessitates the use of multi-temporal remote sensing techniques to accurately quantify the spatial and temporal dimensions of land cover change (Behera et al., 2025). Satellite imagery is frequently favored in the literature as a data source, providing extensive coverage and enabling the tracking of long-term changes (Kamel, 2020; Yılmaz & Selim, 2024). Multi-temporal satellite datasets are a potent tool for both land cover classification and the determination of positional changes in the treeline (García-Güemes et al., 2020; Al-Taei et al., 2023; Ullah et al., 2025; Karakuş and Kahraman, 2025). Specifically, satellite data from platforms such as Landsat, Sentinel, and MODIS facilitate the comparison of land cover alterations across different time intervals, enhancing the comprehension of ecosystem dynamics (Selim et al., 2025). Moreover, the generation of spectral indices from satellite imagery allows for the acquisition of more detailed information regarding specific land cover classes (Arfa & Minaei, 2024; Selim & Selim,

2025). In this context, the integration of satellite imagery and spectral indices enables the assessment of both the direct impacts of climate change on land cover and the resulting indirect ecosystem responses. It has been established through the use of satellite imagery and spectral indices that measured temperature increases over the last two decades have resulted in an upward shift of the forest boundary, a contraction of maquis, grassland, and meadow areas, and the displacement of certain plant communities (Zhang & An, 2024; Liu et al., 2024). This underscores the vulnerability of high-mountain ecosystems to climate change and highlights the importance of proactive ecosystem management measures. This specific study, focused on the Antalya section of the Western Taurus Mountains, therefore provides crucial data for understanding how the high-altitude ecosystems of Türkiye's Mediterranean region are responding to short-term treeline changes.

This study aims to evaluate the treeline dynamics in a section of the Western Taurus Mountains using Landsat satellite imagery and the Normalized Difference Vegetation Index (NDVI) spectral index for the years 2004, 2014, and 2024. The research identifies the temporal change trends of the treeline across these specified years. This approach provides a holistic methodological framework for detecting treeline changes in high-altitude areas where human intervention is minimal or indirectly low, and where changes are predominantly driven by climatic factors. In particular, global warming trends observed over the last two decades, with the Mediterranean Basin warming approximately 20% faster than the global average, have intensified the upward migration of treelines in sensitive ecosystems (IPCC, 2023; Lionello & Scarascia, 2020). The contraction of bare land and the expansion of forest boundaries in the Western Taurus Mountains can therefore be interpreted as direct ecological responses to accelerated regional climate change. Beyond generating scientific knowledge, this study produces actionable insights that can be utilized for local and regional land management and landscape planning. By detecting ecosystem dynamics in high-mountain regions, the findings can aid in the development and understanding of critically important strategies such as erosion control, water resource management, biodiversity conservation, and species protection, thus offering guidance to decision-makers and planners. Consequently, monitoring changes in the treeline within sensitive ecosystems, such as the Western Taurus Mountains, is a crucial prerequisite for developing sustainable land-use policies. In this context, the study provides scientific data of fundamental importance for future ecosystem monitoring research, due to its holistic approach. Furthermore, the study offers an innovative perspective by quantitatively demonstrating the effects of treeline change in high-altitude ecosystems and focusing on faster change dynamics, in contrast to much of the existing long-term literature.

MATERIAL AND METHOD

Study area: This study was conducted in a section of the Taurus Mountains located in the Mediterranean Region at elevations above 1,000 meters. The area provides a suitable environment for research due to its high-altitude topography and ecosystem characteristics that are sensitive to climate change. Moreover, the study site is largely freefrom anthropogenic influences, allowing for the investigation of forest cover dynamics and the upward shift of the treeline within the context of natural processes. The study area is situated in the western section of the Taurus Mountains, Antalya, within the Mediterranean climate zone, above 1,000 m elevation. To precisely define the boundaries of the research area, the following corner coordinates were used: northwest (36°22'34.30" N, 29°57'38.60" E), northeast (36°27'1.82" N, 30°2'36.58" E), southeast (36°22'23.24" N, 30°2'24.89" E), and southwest (36°22'22.00" N, 29°57'45.76" E) (Figure 1). These coordinates encompass the study site and provide a clear spatial framework for the analysis.

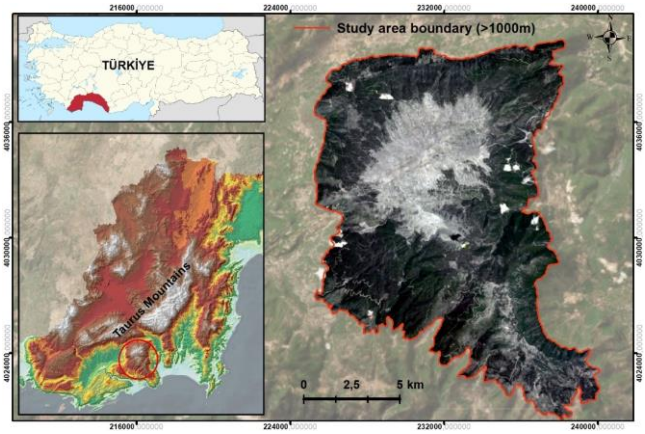


Figure 1. Study area location

The section of the Western Taurus Mountains, known as the Beydağları, has a lower elevation limit of 1,000 meters above sea level, while its highest peak reaches 2,350 meters. The region exhibits a typical Mediterranean mountain climate, characterized by hot, dry summers and relatively cool, wet winters. Compared to lower elevations, the diurnal temperature range increases during summer due to altitude, and frost and snowfall are more likely in winter. At lower elevations, mixed forests dominated by *Pinus brutia*, *Pinus nigra*, and oak species are observed. In higher elevations, above the forest line, the landscape is dominated by rocky or limestone substrates, grasslands, and bare land (Deniz & Sümbül, 2004). The study area mountain primarily consist of limestone geology, and these mountainous formations often display karstic features such as dolines and limestone pavements. This geological structure promotes

rapid surface water infiltration, limited water availability, and locally variable soil depths (Darıcı & Bayrakdar, 2024). The study area generally exhibits a heterogeneous composition of Mediterranean maquis, mixed pine–oak forests, and montane forest mosaics. The presence of topo climatic variables such as slope aspect, gradient, and elevation contributes to high microhabitat diversity and spatial variability (Zhang et al., 2022).

Data sets: In this study, multi-temporal satellite imagery and the Normalized Difference Vegetation Index (NDVI) are employed to investigate treeline dynamics in a high-elevation, minimally disturbed area. Landsat satellite images from 2004, 2014, and 2024 were analyzed to assess the temporal position and change trends of the treeline. Digital Elevation Model (DEM) data (SRTM) were utilized for topographic analyses, providing a fundamental data source for determining the altitudinal position of the treeline, examining elevation distribution, and quantifying vertical shifts in treeline location. Additionally, slope, aspect, and other topo-climatic factors were evaluated to understand their influence on treeline dynamics and land cover changes. NDVI analysis enabled the differentiation of vegetated and non-vegetated areas, which was subsequently used to delineate the treeline accurately.

Methodology: The methodology of the study consists of four main stages: (1) data pre-processing, (2) calculation of NDVI and thresholds, (3) data correction, noise reduction, and transformation, and (4) determination of treeline positions and shift magnitudes.

Stage I: First, cloud-free Landsat 5 TM, Landsat 7 ETM+, and Landsat 8/9 OLI-TIRS images for the years 2004, 2014, and 2024 were obtained from the USGS EarthExplorer platform. To ensure comparability and avoid seasonal biases, all selected images correspond to the same phenological period, specifically early to mid-September (03 September 2004; 11 September 2014; 17 September 2024). This deliberate choice minimizes the influence of snow cover duration or vegetation growth stage differences, thereby confirming that the detected treeline shifts are driven by long-term climatic processes rather than short-term seasonal variability. These images underwent a series of pre-processing steps, including atmospheric correction to remove cloud effects, atmospheric scattering, and absorption; radiometric conversion, in which digital numbers (DN) were converted to reflectance and radiance values using sensor calibration coefficients; and geometric correction, ensuring that all images were projected onto the same coordinate system (UTM Zone 36N, WGS84) and pixel alignment was achieved. These pre-processing steps were performed to ensure geometric consistency and spectral comparability across different years.

Stage II: In this stage, NDVI maps were generated separately for each of the three years to assess vegetation density (Equation 1). Threshold values were then applied to distinguish vegetated areas from non-vegetated areas.

$$NDVI = \frac{NIR-Red}{NIR+Red} \quad \text{(equation 1)}$$

Although the literature generally reports that areas with NDVI < 0.2 are classified as non-vegetated (Hashim et al., 2019), this threshold can vary depending on the physical, ecological, and climatic characteristics of the terrain and should be reassessed for each study area (Hao et al., 2012; Drori et al., 2020). Accordingly, the threshold was recalibrated for the study area. During the calibration process, the NDVI threshold was systematically adjusted in incremental steps above and below the commonly cited 0.2 value, and the resulting classifications were visually compared against the actual land cover patterns. Through this iterative testing, it was observed that a threshold of < 0.22 provided the most consistent and accurate separation between vegetated and non-vegetated surfaces. This value minimized misclassification errors, particularly in transitional zones near the treeline, and ensured that the detected shifts reflected real ecological changes rather than artifacts of threshold selection. Therefore, the adjusted threshold of 0.22 was adopted in the analysis.

Stage III: In this stage, data refinement procedures were applied to the NDVI maps for which thresholds had been defined using reclassification. First, raster data were converted to vector format to enable the delineation of a continuous treeline. The vector data were then filtered to isolate the continuous treeline above 1,000 m and to remove noise, eliminating small, vegetated patches located outside this elevation range. For each year, these treeline vectors were checked against the corresponding satellite imagery and subjected to a smoothing procedure. This step aimed to reduce irregularities and noise along the boundary, producing a more realistic, consistent, and spatially continuous treeline. During smoothing, Bézier interpolation was applied to minimize pixel-induced fluctuations and to represent the ecological gradual transition of treelines. While Bézier curves visually smooth boundaries, their use here is not merely aesthetic; they provide a mathematically continuous, parameterized representation of ecological limits, which better reflects the gradual nature of vegetation transitions (Shimagaki & Barton, 2023). Importantly, the interpolation was performed after vectorization, meaning that the treeline was first delineated based on NDVI classification and then refined. Thus, Bézier interpolation does not invent new boundaries but reduces artificial noise caused by pixel resolution, ensuring that the ecological boundary remains consistent with the original satellite observations. Although the DEM (SRTM) has moderate resolution, the interpolation was not applied to alter elevation data but only to refine the treeline vector, thereby preserving the ecological validity of the boundary.

Stage IV: In the final stage, the treelines for the three years were overlaid with DEM data, and zonal statistics were applied to determine the magnitude of vertical shifts. The mean elevation of the pixels intersected by the continuous treeline in the DEM was calculated to obtain the average treeline elevation for each year. Subsequently, the difference in treeline elevation between the three years was calculated to quantify the vertical shift in meters.

$$\Delta h = h_{2024} - h_{2014} \quad \text{(Treeline shift between 2024 and 2014)}$$
$$\Delta h = h_{2014} - h_{2004} \quad \text{(Treeline shift between 2014 and 2004)}$$
$$\Delta h = h_{2024} - h_{2004} \quad \text{(Treeline shift between 2024 and 2004)}$$

Following these procedures, the treeline lines for the respective years, the changes in the area encompassed by the treeline, the mean treeline elevations, and the quantified treeline shifts were evaluated holistically. The results were interpreted in the context of the study area and discussed within the broader framework of global climate change, providing a comprehensive conclusion to the study.

RESULTS

This study, conducted in a mountain ecosystem within the western section of the Taurus Mountains in Antalya Province, aims to monitor short-term changes in the treeline and provides a holistic approach to assessing the ecological impacts of global climate change at the regional scale. Accordingly, the study focuses on the short-term dynamics of treeline shifts in a section of the Western Taurus Mountains that is minimally affected by direct or indirect human activity. As noted in the first stage of the methodology, the pre-processed satellite images used in the analysis are presented in Figure 2.

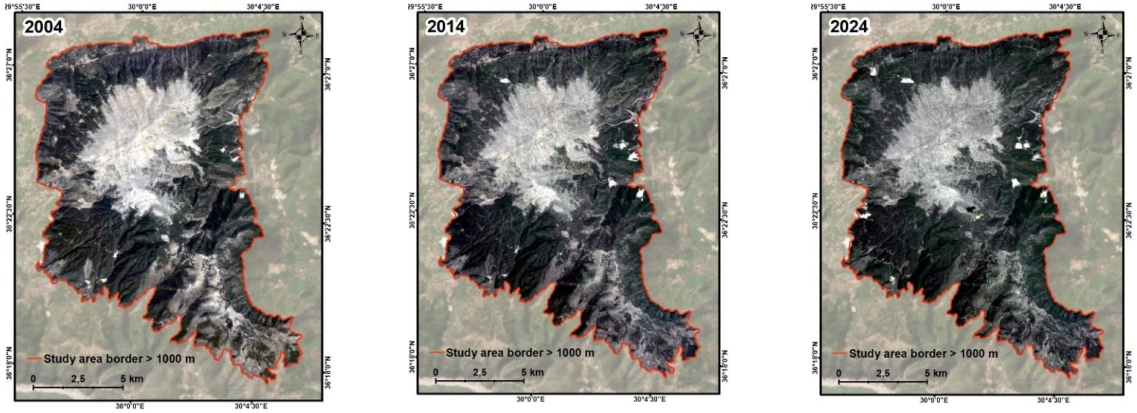


Figure 2. Composite Landsat satellite images from three distinct periods.

As observed from the satellite imagery, two land cover classes, vegetation and bare land, predominate within the scope of the study area. According to FAO (2000), vegetation refers to biotic surface cover, including natural or semi-natural trees, shrubs, grasses, and herbaceous plants, while bare land encompasses areas with little or no vegetation, such as exposed soil, rocky surfaces, bare rocks, sand, gravel, deserts, and other unvegetated surfaces. Accordingly, the study was conducted focusing on these two classes: vegetation and non-vegetation. The total area above 1,000 meters elevation within the study region is 18,500 hectares.

The NDVI maps generated for the study period indicate an increase in vegetation cover between 2004 and 2024. Notably, in the ridge ecosystems located in the southern part of the study area, vegetation density appears to have intensified toward the ridge crests (Figure 3).

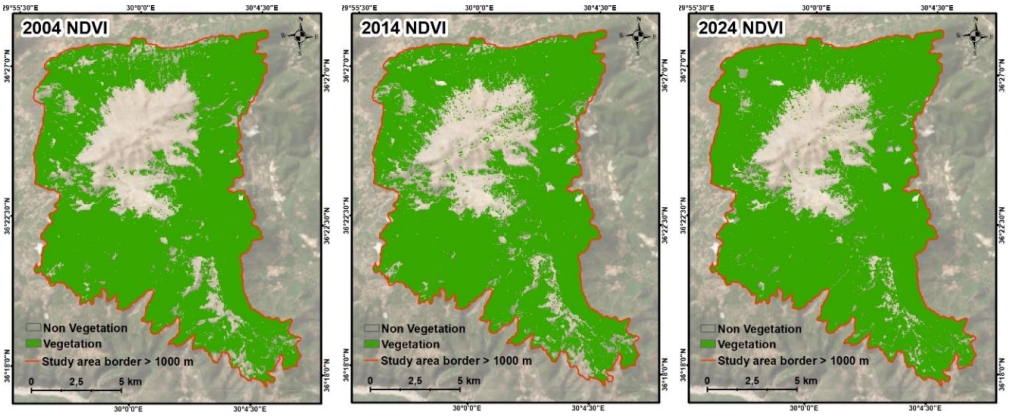


Figure 3. Multi-temporal NDVI maps for the study area.

Similarly, a comparison of the 2004 and 2014 NDVI images indicates that the open areas in the northwestern part of the study region tended to become increasingly vegetated over time. Table 1 presents the areas covered by vegetation and non-vegetation for the three years, along with the corresponding changes observed in each class.

Table 1. Land cover changes based on NDVI results.

	Vegetation (ha)	Non-Vegetation (ha)	Total (ha)
2004	13,494	5,006	18,500
2014	13,605	4,895	18,500
2024	13,802	4,698	18,500

The data for the 2004–2024 period indicate a steady increase in vegetation cover in the mountain ecosystems of the Western Taurus Mountains at elevations above approximately 1,000 meters, rising from 13,494 ha to 13,802 ha. Correspondingly, non-vegetation areas decreased from 5,000 ha to 4,698 ha. This trend confirms the expansion of vegetation in the high-mountain belt, with trees and shrubs extending their coverage. The increase in the vegetation class is consistent with processes such as changes in temperature regimes associated with elevation, a reduction in snow cover duration, upward expansion of vegetation at the ecotone, and natural regeneration. The reduction in non-vegetation areas indicates that bare soils, rocky surfaces, and sparsely vegetated slopes are progressively being colonized by plants. Overall, vegetation cover increased by approximately 2.28% between 2004 and 2024.

In parallel with the increase in vegetation, the upper altitudinal limit at which trees can grow also showed an upward shift over the 20-year period (Figure 4). Although this region represents the climatic boundary where trees can no longer grow continuously due to limiting conditions such as low temperatures, short growing seasons, and prolonged snow cover, a partial upward shift in the treeline was observed within the scope of this study.

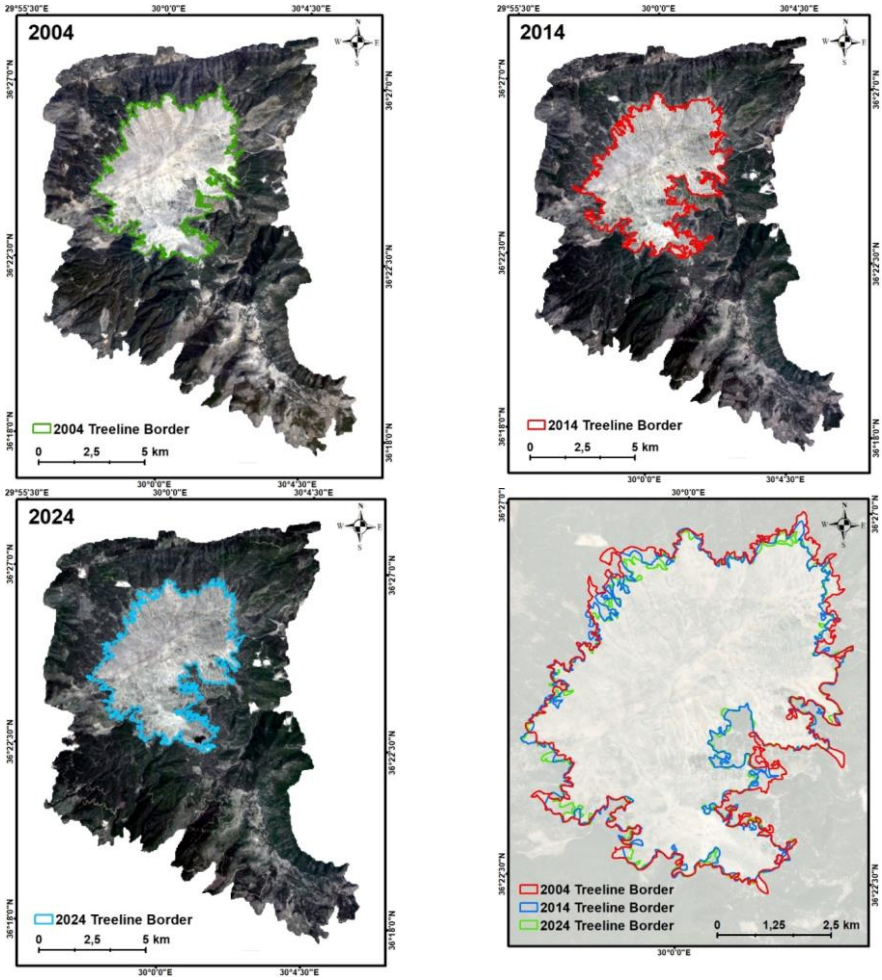


Figure 4. Alterations in the treeline position

The treeline, which was determined to have an average elevation of 1,819.98 m in 2004, rose to 1,839.92 m in 2014 and further to 1,843.54 m in 2024. This corresponds to an approximate upward shift of 20 m between 2004 and 2014, and about 4 m between 2014 and 2024, resulting in a total mean increase of 23.50 m over the 20-year period (Table 2).

Table 2. Temporal changes in treeline shift.

	Non-vegetation (ha)	Mean Altitude (m)	Mean Shift (m)
2004	3,546	1,819.97	-
2014	3,259	1,839.92	19.95
2024	3,208	1,843.54	23.57

The treeline change observed between 2004 and 2014 progressed at a considerably faster rate compared to the period between 2014 and 2024, after which the upward shift appears to have slowed gradually. During the first decade of observation, treeline advancement was more pronounced, coinciding with a period of relatively strong warming and stable precipitation regimes that favored vegetation expansion at higher elevations. In contrast, the subsequent decade exhibited a noticeably slower rate of treeline migration, which aligns with a moderation in temperature increases and the emergence of more irregular precipitation patterns and drought stress (Statsclimat, 2026). This temporal divergence highlights the sensitivity of mountain ecosystems to short-term climatic variability, indicating that treeline dynamics are shaped not only by long-term warming trends but also by fluctuations in regional hydroclimatic conditions. The observed differences therefore correspond closely with the climatic records of the study area and underscore the capacity of ecosystems to respond in distinct ways under varying climatic pressures. Based on the data obtained from this study, the treeline in the study area experienced an average increase of approximately 1.17 m/year between 2020 and 2024. However, these values should be interpreted with caution, as they reflect an approximate trend given the spatial resolution of Landsat imagery and the vertical uncertainty associated with the SRTM digital elevation model. Therefore, the results primarily indicate a general upward tendency of the treeline during the last two decades, rather than an exact annual rate of change. The results scientifically demonstrate a significant shift in the spatial distribution of the high-altitude vegetation boundary (treeline) and non-vegetated areas (barelands) within the examined mountainous region. As vegetation expands upward from lower elevations, barelands at higher altitudes have undergone a process of compression and reduction. Consequently, the upward movement of the treeline has led to a contraction of the habitat available for endemic species adapted to cold climates within the Alpine Zone. This represents a notable risk for plant species specialized to high-altitude environments. In this context, the study provides quantitative evidence of short-term treeline shifts in a Mediterranean mountain ecosystem and offers valuable data that can inform decision-making for ecosystem management.

DISCUSSION

Treeline shifts in both global and Mediterranean mountain regions are primarily driven by increasing temperatures, lengthening growing seasons, and reduced snow cover duration, largely independent of direct anthropogenic impacts (Holtmeier & Broll, 2005). Global climate change exerts profound impacts on high-altitude ecosystems, where rising temperatures and altered precipitation regimes trigger ecological responses such as treeline migration (Harsch et al., 2009; Klinge et al., 2018). These shifts represent adaptive reactions of ecosystems to climatic stressors, with short-term responses including accelerated upward movement of treelines and long-term consequences such as changes in biodiversity, soil stability, and hydrological cycles (Broadbent et al., 2024; Ivashchenko et al., 2025). In the Mediterranean Basin, which is warming faster than the global average, treeline dynamics are particularly sensitive, reflecting both immediate and cumulative ecosystem responses to climate change (Lionello & Scarascia, 2018; Pisano et al., 2020). The principal driver of treeline advancement is climate change. In high-altitude areas, elevated temperatures during the growing season and earlier snowmelt facilitate the colonization of higher, colder zones by trees and shrubs. Elevated atmospheric CO_2 concentrations can also indirectly promote plant growth (Grace et al., 2002; Schickhoff et al., 2015). This upward shift constrains the habitats of cold-adapted, often endemic, herbaceous species characteristic of the Alpine Zone, compressing them into smaller, isolated summit areas and increasing their risk of local extinction. Concurrently, grassland and tundra ecosystems are progressively replaced by forests or shrublands, altering hydrological cycles, soil structure, and the foraging and shelter patterns of local fauna (Kumar & Khanduri, 2024). Moreover, darker forest canopies absorb more solar radiation than lighter-colored snow and grasslands, potentially accelerating regional warming (Schwaab et al., 2015). Given the multiple ways in which treeline shifts affect ecosystem dynamics and ecological processes, monitoring these changes and implementing appropriate management measures is essential. Short- and long-term monitoring programs are critical for this purpose. In this study, short-term treeline dynamics in the region were examined, and a total upward displacement of approximately 24 m was detected over a 20-year period. This value was not calculated as a fixed annual increment; rather, it represents the average of the total displacement, yielding an annual mean of about 1.17 m/year. It should therefore be emphasized that this average is a methodological indicator, while in reality the rate of treeline movement may vary across individual years. Nevertheless, the obtained average value is consistent with findings reported in the literature. For instance, Baglioni et al. (2025) documented an average rise of 2.1 m/year in Italian mountains, Mkrtchian & Mueller (2025) reported upward shifts ranging from 10 to 40 m in the Carpathians.

In this context, the long-term average identified in our study aligns well with the values reported from other regions, supporting the broader evidence of climate-driven treeline shifts. A global study monitoring treelines across 243 mountainous regions, covering approximately 1 million km², reported an average upward shift of 1.2 m/year, with rates reaching 3.1 m/year in tropical regions, and noted an overall acceleration of treeline movement across all areas (He et al., 2023). Researchers emphasize that treelines remain sensitive to climate change independent of human influence, with upward shifts reducing tundra areas, threatening alpine species, and potentially affecting water availability in dependent regions (He et al., 2023). A global meta-analysis evaluating 166 treeline sites since 1,900 found upward movement at 52% of locations, with varying magnitudes across regions (Harsch et al., 2009). Remote-sensing-based studies of 24 major mountain ranges between 1990 and 2020 reported mean treeline migration rates of 0.7 m/year in temperate and boreal zones and 1.7 m/year in temperate continental climates, highlighting the loss or degradation of alpine species' habitats and the need for monitoring treeline dynamics (Zhang & An, 2024). Similarly, studies have documented a 150 m treeline rise in the Altai Mountains over the past 52 years (Cazzola et al., 2019), approximately 115 m upward shift in the Alps during 1901–2000 (Leonelli et al., 2011), and an average annual treeline rise of 3.7 m in a Himalayan national park (Bhatta et al., 2025).

These studies collectively demonstrate that treeline advances are heterogeneous and strongly influenced by regional factors including climate, topography, precipitation regimes, snow accumulation, local ecosystem characteristics, and global climate change (Frei et al., 2023; He et al., 2023; Bhatta et al., 2025). Such shifts can reduce or eliminate sensitive habitats such as alpine meadows, tundra, and mountain grasslands, constrict the living spaces of high-altitude plant and animal communities, and impact numerous ecological variables including microclimate, soil properties, and hydrological balance (Leonelli et al., 2011; Zhang & An, 2024).

The findings reported in the literature clearly corroborate the results obtained in the present study. Considering recent global analyses, the average annual treeline shift is approximately 1.2 m/year, with minimum and maximum rates of 0.3 m/year and 10 m/year, respectively; however, these rates vary depending on multiple factors (Harsch et al., 2009; Leonelli et al., 2011; He et al., 2023). In this context, the observed upward shift of the treeline by approximately 24 m over the past two decades in the mountain ecosystem of a section of the Western Taurus Mountains can be considered a moderate change compared to global trends. Nevertheless, this upward movement may have several ecological consequences. In sensitive ecosystems such as the Western Taurus Mountains, treeline shifts can induce significant short- and long-term changes. Primarily, they reduce the habitats of alpine meadows, endemic herbaceous plants, and cold-adapted shrub communities at high elevations, as these habitats become compressed and progressively smaller as trees advance. This poses a particular threat to the micro-endemic species of the Taurus Mountains, many of which are adapted to narrow elevational bands and cannot find suitable soil, moisture, or temperature conditions at higher altitudes (Lu et al., 2025). Similarly, high-altitude fauna may experience habitat loss and population decline if they cannot migrate to higher elevations (Greenwood & Jump, 2014). Treeline advancement also alters soil properties and carbon cycling. As trees encroach on previously open areas, shading, organic matter accumulation, and soil moisture change, reshaping microbial communities and nutrient cycling. Forest expansion can further modify fire regimes, hydrological cycles, and water retention capacity (Ivashchenko et al., 2025). Over the long term, upward treeline shifts may transform ecosystem competitive dynamics: trees can suppress herbaceous and shrub communities, potentially leading to a decline in open-area biota characteristic of the Taurus Mountains (Illerbrun & Roland, 2011). Thus, the treeline in the study area has shifted upward by approximately 24 m over the last two decades, although the magnitude of this shift varied between the two decadal periods examined, indicating temporally heterogeneous rates of treeline advance. The pronounced difference in the magnitude of treeline displacement between these two decades suggests that the upward movement of the treeline in the Taurus Mountains is largely associated with temperature increases linked to climate change. However, the observed variability in the rate of treeline advance cannot be attributed solely to rising temperatures. Variations in precipitation regimes and soil moisture availability, differences in the duration and thickness of snow cover, microclimatic constraints imposed by topographic heterogeneity, and ecological lag processes (biotic inertia) related to tree establishment in newly suitable habitats may have collectively influenced the temporal dynamics of treeline shifts (Hooshyarkhah et al., 2026).While the ecological implications of treeline shifts are widely acknowledged, their precise quantification and reliable determination of annual rates remain methodologically challenging. This is because treeline dynamics are influenced not only by temperature increases but also by topography, slope aspect, snow cover persistence, land-use history, soil characteristics, and local plant competition (Liang et al., 2016; Rita et al., 2023). Consequently, observed treeline advancement or retreat must be carefully evaluated in relation to true ecological

shifts versus potential errors arising from remote sensing resolution, classification, and image interpretation, as well as validated with field observations/representing a limitation of this and similar studies.

In this and many other studies, Landsat imagery with a 30 m spatial resolution and ASTER Global DEM were used. First, the 30 m resolution may not capture the highly heterogeneous treeline ecotone in mountainous areas with sufficient detail. The treeline often represents a mosaic transition zone shaped by micro-topographic variations of just a few meters; thus, pixel size can hinder the accurate detection of young trees, sparse shrubs, or low-density forest patches. This "mixed pixel" issue can lead to classification errors and cause the treeline to appear artificially higher or lower than its actual position (Xu et al., 2020). Furthermore, the relatively low vertical and slope accuracy of ASTER GDEM may limit the precision of topographic thresholds used for treeline delineation (Uuemaa et al., 2020). Landsat's 16-day revisit cycle, combined with cloud cover and snow, can reduce usable data frequency in mountainous areas, complicating annual or short-term treeline monitoring. Limited spectral bands may also reduce the accuracy of distinguishing between woody and herbaceous vegetation (Hemati et al., 2021). Taken together, these limitations underscore that accurate assessment of treeline shifts requires integration with complementary datasets, such as field observations, high-resolution orthophotos, and LiDAR.

CONCLUSION

In this study, conducted in a mountainous area above 1,000 m in the western section of the Taurus Mountains, Antalya, within the Mediterranean climate zone, short-term dynamics of treeline shifts were analyzed using remote sensing data and spectral indices. Results show that during the last 20 years, the treeline has advanced upslope by about 24 m. Given that the study area is largely free from direct anthropogenic impacts, this upward shift is primarily attributed to ecological and climatic processes and appears to be strongly linked to global climate change. In parallel with global temperature increases, the Mediterranean Basin has also experienced accelerated warming, and the treeline migration observed in the study area can be interpreted as a short-term ecological response to these climatic pressures. This local upward shift not only reflects the immediate sensitivity of mountain ecosystems to rising temperatures but also aligns with broader global patterns of climate-driven vegetation dynamics. This result represents a significant contribution to the literature on treeline dynamics both within Mediterranean mountain ecosystems and at the global scale.

The study also emphasizes, in line with existing literature, that treeline shifts are influenced not solely by rising temperatures but also through interactions with multiple environmental and biotic factors, including topography, slope aspect, soil properties, snow cover duration, and plant competition. Nonetheless, the observed average increase of 1.17 m/year suggests that temperature and climate change act as dominant drivers of treeline position in this region. These findings are important for quantitatively demonstrating the short-term effects of warming on mountain ecosystems within the Mediterranean climate zone and provide valuable data for validating ecosystem models and climate change scenarios.

Ecologically, the upward movement of the treeline reduces the habitat available to high-altitude plant species, particularly endemic species. As trees advance, these habitats become increasingly compressed, intensifying pressure on biodiversity within the mosaic-structured transition zones. The high sensitivity of the Taurus Mountains' micro-endemic plant species further accentuates the ecological significance of treeline shifts. In addition, the expansion of tree and shrub cover associated with treeline migration can alter soil properties and redistribute carbon within the ecosystem; factors such as shading, organic matter accumulation, and soil moisture may induce significant changes in microbial communities and nutrient cycling. In this context, the observed upward treeline movement has the potential to reshape not only vegetation distribution but also the functioning and ecological interactions within mountain ecosystems.

From a methodological perspective, the reliability of the findings derived from Landsat imagery and ASTER GDEM was carefully evaluated. The 30-meter spatial resolution and limited spectral bands constrained the accurate detection of sparsely forested areas and mosaic-structured transition zones, while the limited accuracy of ASTER GDEM in slope and elevation measurements affected the precision of topographic thresholds used to delineate the treeline. Nevertheless, the observed trends are consistent with field observations and similar studies reported in the literature. This consistency confirms that remote sensing-based analyses are suitable for detecting short-term treeline shifts in mountainous and heterogeneous ecosystems, while also highlighting the critical importance of field validation and integration of higher-resolution datasets.

In conclusion, the upward treeline movement observed in the Taurus Mountains represents a tangible indicator of the short-term impacts of global climate change. This study provides a valuable reference for monitoring treeline dynamics and assessing ecological consequences in Mediterranean mountain ecosystems. The results are not only important for tracking vegetation and

ecosystem processes but also for validating climate change models, developing conservation strategies, and planning biodiversity management. Therefore, future research should combine long-term monitoring with multiple remote sensing datasets to more comprehensively and reliably understand the ecological and climatic implications of treeline shifts.

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REFERENCES

Al-Taei, A.I., Alesheikh, A.A., & Darvishi Boloorani, A. (2023). Land use/land cover change analysis using multi-temporal remote sensing data: a case study of Tigris and Euphrates Rivers Basin. *Land*, ***12***(5), 1101. https://doi.org/10.3390/land12051101

Arekhi, M., Yesil, A., Ozkan, U.Y., & Balik Sanli, F. (2018). Detecting treeline dynamics in response to climate warming using forest stand maps and Landsat data in a temperate forest. *Forest Ecosystems*, ***5***(1), 23. https://doi.org/10.1186/s40663-018-0141-3

Arfa, A., & Minaei, M. (2024). Utilizing multitemporal indices and spectral bands of Sentinel-2 to enhance land use and land cover classification with random forest and support vector machine. *Advances in Space Research*, ***74***(11), 5580-5590. https://doi.org/10.1016/j.asr.2024.08.062

Bakure, B.Z., Hundera, K., & Abara, M. (2022). Review on the effect of climate change on ecosystem services. In *IOP Conference Series: earth and environmental science*, ***1016***(1), 012055. IOP Publishing. https://doi.org/10.1088/1755-1315/1016/1/012055

Baglioni, L., Morresi, D., Garbarino, M., Urbinati, C., Lingua, E., Marzano, R., & Vitali, A. (2025). Forestlines in Italian mountains are shifting upward: detection and monitoring using satellite time series. *Biogeosciences*, ***22***(17), 4349-4366. https://doi.org/10.5194/bg-22-4349-2025

Behera, M.D., Yadhukrishna, K.G., Raj, A., Srivastava, I.S., Das, P., Kashyap, A., & Joshi, R. (2025). Spatio-temporal assessment of surface dynamics of high-altitude wetlands using Earth-Observation Datasets. In *Sustainable Development Perspectives in Earth Observation* (pp. 287-303). Elsevier. https://doi.org/10.1016/B978-0-443-14072-3.00022-8

Bhatta, S., Chandani, K.C., Chauhan, R., Aryal, S., Khadka, D., & Sapkota, R.P. (2025). Geospatial assessment of treeline shifting in response to climate change in Langtang National Park, Central Nepal. *Environmental Challenges*, 101155. https://doi.org/10.1016/j.envc.2025.101155

Broadbent, A.A., Newbold, L.K., Pritchard, W.J., Michas, A., Goodall, T., Cordero, I., ... & Bardgett, R.D. (2024). Climate change disrupts the seasonal coupling of plant and soil microbial nutrient cycling in an alpine ecosystem. *Global Change Biology*, ***30***(3), e17245. https://doi.org/10.1111/gcb.17245

Cazzolla Gatti, R., Callaghan, T., Velichevskaya, A., Dudko, A., Fabbio, L., Battipaglia, G., & Liang, J. (2019). Accelerating upward treeline shift in the Altai Mountains under last-century climate change. *Scientific reports*, ***9***(1), 7678. https://doi.org/10.1038/s41598-019-44188-1

Corimanya, J.L., Jiménez-García, D., Li, X., & Peterson, A.T. (2025). Geographic patterns of upward shifts in treeline vegetation across western North America, 1984-2017. *Biogeosciences*, ***22***(20), 5665-5681. https://doi.org/10.5194/bg-22-5665-2025

Darmaraki, S., Somot, S., Sevault, F., Nabat, P., Cabos Narvaez, W.D., Cavicchia, L., ... & Sein, D.V. (2019). Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics,* ***53***(3), 1371-1392. https://doi.org/10.1007/s00382-019-04661-z

Darıcı, F., & Bayrakdar, C. (2024). Beydağları'nın Jeomorfolojik Özelliklerine Morfometrik Yaklaşım. *Jeomorfolojik Araştırmalar Dergisi*, ***13***(1-22). https://doi.org/10.46453/jader.1458005

Deniz, I.G., & Sümbül, H. (2004). Flora of the Elmalı cedar research forest (Antalya/Turkey). *Turkish Journal of Botany*, ***28***(6), 529-555.

Drori, R., Dan, H., Sprintsin, M., & Sheffer, E. (2020). Precipitation-sensitive dynamic threshold: A new and simple method to detect and monitor forest and woody vegetation cover in sub-humid to arid

areas. *Remote Sensing*, ***12***(8), 1231. https://doi.org/10.3390/rs12081231

FAO. (2000). Food and Agriculture Organization, Land Cover Classification System (LCCS): Classification Concepts and User Manual. 00100 Rome, Italy, ISBN 92-5-104216-0.

Filonchyk, M., Peterson, M.P., Zhang, L., Hurynovich, V., & He, Y. (2024). Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. *Science of The Total Environment*, ***935***, 173359. https://doi.org/10.1016/j.scitotenv.2024.173359

Frei, E.R., Barbeito, I., Erdle, L.M., Leibold, E., & Bebi, P. (2023). Evidence for 40 Years of Treeline Shift in a Central Alpine Valley. *Forests*, ***14***(2), 412. https://doi.org/10.3390/f14020412

Greenwood, S., & Jump, A. S. (2014). Consequences of treeline shifts for the diversity and function of high altitude ecosystems. *Arctic, Antarctic, and Alpine Research*, ***46***(4), 829-840. https://doi.org/10.1657/1938-4246-46.4.829

Hadi, S. J., & Tombul, M. (2018). Comparison of spatial interpolation methods of precipitation and temperature using multiple integration periods. *Journal of the Indian Society of Remote Sensing*, ***46***(7), 1187-1199. https://doi.org/10.1007/s12524-018-0783-1

Hao, F., Zhang, X., Ouyang, W., Skidmore, A.K., & Toxopeus, A.G. (2012). Vegetation NDVI linked to temperature and precipitation in the upper catchments of Yellow River. *Environmental Modeling & Assessment*, ***17***(4), 389-398. https://doi.org/10.1007/s10666-011-9297-8

Harsch, M.A., Hulme, P.E., McGlone, M.S., & Duncan, R.P. (2009). Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology letters*, ***12***(10), 1040-1049. https://doi.org/10.1111/j.1461-0248.2009.01355.x

Hashim, H., Abd Latif, Z., & Adnan, N.A. (2019). Urban vegetation classification with NDVI threshold value method with very high resolution (VHR) Pleiades imagery. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, ***42***, 237-240. https://doi.org/10.5194/isprs-archives-XLII-4-W16-237-2019

Hemati, M., Hasanlou, M., Mahdianpari, M., & Mohammadimanesh, F. (2021). A Systematic Review of Landsat Data for Change Detection Applications: 50 Years of Monitoring the Earth. *Remote Sensing*, ***13***(15), 2869. https://doi.org/10.3390/rs13152869

Hooshyarkhah, B., Johnson, D.L., Spencer, L., Ryait, H.S., & Chegoonian, A. (2026). Spatiotemporal Dynamics of the Alpine Treeline Ecotone in Response to Climate Warming Across the Eastern Slopes of the Canadian Rocky Mountains. *Climate,* ***14***(3), 69. https://doi.org/10.3390/cli14030069

Holtmeier, F.K., & Broll, G. (2005). Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Global ecology and Biogeography*, ***14***(5), 395-410. https://doi.org/10.1111/j.1466-822X.2005.00168.x

Illerbrun, K., & Roland, J. (2011). Treeline proximity alters an alpine plant–herbivore interaction. *Oecologia*, ***166***(1), 151-159. https://doi.org/10.1007/s00442-010-1822-y

IPCC. (2023). IPCC AR6 Synthesis Report: Climate Change 2023, Intergovernmental Panel on Climate Change, https://www.ipcc.ch/report/ar6/syr/ (accessed date: 06.03.2026)

Ivashchenko, K., Romanova, A., Sushko, S., Zhuravleva, A., Kvitkina, A., Khodzhaeva, A., & Ananyeva, N. (2025). Effects of Early-Stage Treeline Shifts on Soil Microbial Biomass and Catabolic Diversity in Reserved and Grazed Subalpine Meadows. *Plants*, ***14***(10), 1541. https://doi.org/10.3390/plants14101541

Kamel, M. (2020). Monitoring of land use and land cover change detection using multi-temporal remote sensing and time series analysis of qena-luxor governorates (QLGs), Egypt. *Journal of the Indian Society of Remote Sensing*, ***48***(12), 1767-1785. https://doi.org/10.1007/s12524-020-01202-8

Karakuş, N., & Kahraman, E. (2025). Uzaktan Algılama Verileriyle Arazi Kullanımı/Arazi Örtüsünün Arazi Yüzey Sıcaklığı Üzerindeki Etkisinin Değerlendirilmesi: Antalya İli Konyaaltı İlçesi Örneği. *Journal of Anatolian Environmental and Animal Sciences*, ***10***(6), 1062-1069. https://doi.org/10.35229/jaes.1804293

Klinge, M., Dulamsuren, C., Erasmi, S., Karger, D.N., & Hauck, M. (2018). Climate effects on vegetation vitality at the treeline of boreal forests of Mongolia. *Biogeosciences*, ***15***(5), 1319-1333. https://doi.org/10.5194/bg-15-1319-2018

Körner, C., & Hiltbrunner, E. (2024). Rapid advance of climatic tree limits in the Eastern Alps explained by on-site temperatures. *Regional Environmental Change*, ***24***(3), 98. https://doi.org/10.1007/s10113-024-02259-8

Kumar, S., & Khanduri, V. P. (2024). Impact of climate change on the Himalayan alpine treeline vegetation. *Heliyon*, ***10***(23). https://doi.org/10.1016/j.heliyon.2024.e40797

Leonelli, G., Pelfini, M., Morra di Cella, U., & Garavaglia, V. (2011). Climate warming and the recent treeline shift in the European Alps: the role of geomorphological factors in high-altitude sites. *Ambio*, ***40***(3), 264-273. https://doi.org/10.1007/s13280-010-0096-2

Liang, E., Wang, Y., Piao, S., Lu, X., Camarero, J.J., Zhu, H., ... & Peñuelas, J. (2016). Species interactions slow warming-induced upward shifts of treelines on the Tibetan Plateau. *Proceedings of*

the National Academy of Sciences, ***113***(16), 4380-4385. https://doi.org/10.1073/pnas.152058211

Lionello, P., & Scarascia, L. (2018). The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, ***18***(5), 1481-1493. https://doi.org/10.1007/s10113-018-1290-1

Liu, L., Chen, J., Shen, M., Chen, X., Cao, R., Cao, X., ..., & Tang, Y. (2024). A remote sensing method for mapping alpine grasslines based on graph-cut. *Global Change Biology*, ***30***(1), e17005. https://doi.org/10.1111/gcb.17005

Lu, X., Zheng, X., Liang, E., Piao, S., Babst, F., Elliott, G. P., ..., & Camarero, J. J. (2025). Patterns, dynamics and drivers of alpine treelines and shrublines. *Nature Reviews Earth & Environment*, ***6***(8), 489-502. https://doi.org/10.1038/s43017-025-00703-9

Mkrtchian, A., & Mueller, D. (2025). Climatic determinants of the Carpathian treeline and its projected upward shifts in response to climate change. *Climatic Change*, ***178***(6), 109. https://doi.org/10.1007/s10584-025-03947-y

Qian, Y., Zhou, W., Yan, J., Li, W., & Han, L. (2015). Comparing Machine Learning Classifiers for Object-Based Land Cover Classification Using Very High Resolution Imagery. *Remote Sensing*, ***7***(1), 153-168. https://doi.org/10.3390/rs70100153

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F.E., ..., & Buongiorno Nardelli, B. (2020). New evidence of Mediterranean climate change and variability from sea surface temperature observations. *Remote Sensing*, ***12***(1), 132. https://doi.org/10.3390/rs12010132

Rita, A., Saracino, A., Cieraad, E., Saulino, L., Zotti, M., Idbella, M., ... & Bonanomi, G. (2023). Topoclimate effect on treeline elevation depends on the regional framework: A contrast between Southern Alps (New Zealand) and Apennines (Italy) forests. *Ecology and Evolution*, ***13***(1), e9733. https://doi.org/10.1002/ece3.9733

Saliba, Y., & Bărbulescu, A. (2024). A comparative evaluation of spatial interpolation techniques for maximum temperature series in the Montreal region, Canada. *Rom. Rep. Phys*, ***76,*** 701. https://doi.org/10.59277/RomRepPhys.2024.76.701

Schickhoff, U., Bobrowski, M., Böhner, J., Bürzle, B., Chaudhary, R.P., Gerlitz, L., ..., & Wedegärtner, R. (2015). Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. *Earth System Dynamics*, ***6***(1), 245-265. https://doi.org/10.5194/esd-6-245-2015

Schwaab, J., Bavay, M., Davin, E., Hagedorn, F., Hüsler, F., Lehning, M., ..., & Bebi, P. (2015). Carbon storage versus albedo change: radiative forcing of forest expansion in temperate mountainous regions of Switzerland. *Biogeosciences*, ***12***(2), 467-487. https://doi.org/10.5194/bg-12-467-2015

Selim, S., & Selim, C. (2025). The role of spectral indices in identifying green spaces for urban and landscape planning: A remote sensing-based approach. *The Future of Cities: Landscape, Planning and Design*, 1-24, IKSAD Publishing House.

Selim, S., Çağlar, S., Kurt, A., & Sönmez, N.K. (2025). Spatio-Temporal Monitoring of Land Use/Land Cover (LULC) Change from Classified Images Supported by Artificial Intelligence (AI) at the Provincial Scale. *Current Approaches in Architecture, Planning and Design*, ***1*** (31-47), Platanus Publishing, Ankara

Shimagaki, K., & Barton, J.P. (2023). Bézier interpolation improves the inference of dynamical models from data. *Physical Review E*, ***107***(2), 024116. https://doi.org/10.1103/PhysRevE.107.024116

Statsclimat. (2026). Comprehensive Climate Report Antalya (Turkiye), https://statsclimat.com/Asia/Turkiye/report_Antalya (Accessed date: 16.03.2026).

Tanır Kayıkçı, E., & Zengin Kazancı, S. (2016). Comparison of regression-based and combined versions of inverse distance weighted methods for spatial interpolation of daily mean temperature data. *Arabian Journal of Geosciences*, ***9***(17), 690. https://doi.org/10.1007/s12517-016-2723-0

UNEP. (2025). Climate Change in the Mediterranean. UN Environment Programme. https://www.unep.org/unepmap/resources/factsheets/climate-change? (Accessed date: 16.03.2026).

Ullah, S., Ullah, N., Tariq, A., Kasi, B. A., Tahir, P., Khan, B., & Kucher, D. E. (2025). Monitoring effects of LULC change dynamics on the environment using time series remote sensing data with Google Earth Engine. *Theoretical and Applied Climatology*, ***156***(6), 345. https://doi.org/10.1007/s00704-025-05590-0

Uuemaa, E., Ahi, S., Montibeller, B., Muru, M., & Kmoch, A. (2020). Vertical Accuracy of Freely Available Global Digital Elevation Models (ASTER, AW3D30, MERIT, TanDEM-X, SRTM, and NASADEM). *Remote Sensing*, ***12***(21), 3482. https://doi.org/10.3390/rs12213482

Wang, Y., Li, D., Ren, P., Ram Sigdel, S., & Camarero, J.J. (2022). Heterogeneous Responses of Alpine Treelines to Climate Warming across the Tibetan Plateau. *Forests*, ***13***(5), 788. https://doi.org/10.3390/f13050788

Xu, D., Geng, Q., Jin, C., Xu, Z., & Xu, X. (2020). Tree Line Identification and Dynamics under Climate Change in Wuyishan National Park Based on Landsat Images. *Remote Sensing*, ***12***(18), 2890. https://doi.org/10.3390/rs12182890

Yılmaz, İ., & Selim, S. (2024). Comparison of Machine Learning-Based and Spectral Index-Supported Image Classification Algorithms Using the Google Earth Engine (GEE) Platform. *Advances*

in Architecture, Planning and Design. ED. Assoc. Prof. Hüseyin Samet Aşıkkutlu, Platanus Publishing House, ***1***(39-58), ISBN:978-625-6982-22-3

Zhang, Q.P., Fang, R.Y., Deng, C.Y., Zhao, H.J., Shen, M.H., & Wang, Q. (2022). Slope aspect effects on plant community characteristics and soil properties of alpine meadows on Eastern Qinghai-Tibetan plateau. *Ecological Indicators*, ***143***, 109400. https://doi.org/10.1016/j.ecolind.2022.109400

Zhang, Y., & An, C. (2024). Satellites reveal global migration patterns of natural mountain treelines during periods of rapid warming. *Forests*, ***15***(10), 1780. https://doi.org/10.3390/f15101780

Zou, L., Tian, F., Liang, T., Fensholt, R., He, T., & Schaepman-Strub, G. (2025). Topographic effects on vegetation greening and area expansion in global alpine zones under climate change. *International Journal of Applied Earth Observation and Geoinformation*, ***142***, 104727. https://doi.org/10.1016/j.jag.2025.104727