Monitoring of Recent Aridification in Türkiye Using MODIS Satellite Data from 2000 to 2021

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Abstract Simulations of future climate indicate that the Mediterranean countries will see increasing temperatures, and decreasing precipitation. In Türkiye, which has a semi-arid and dry sub-humid climate, the coupled effect of warming and drought is expected to lead to a general increase in aridity. We applied indices derived from satellite data to provide continuous monitoring for drought hazards and evaluated recent trends in aridification and drought. Annual averaged temperatures showed a statistically significant rise, although annual rainfall showed no nationwide trend despite strong fluctuations over Türkiye. Significant increasing (decreasing) trends of vegetation (aridification) could be found in the northern, western, and southern regions, despite the rising temperatures and fluctuations in rainfall. One cause of these trends is presumed to be an increase in the nation's proportion of forest, orchard trees, and irrigated farmland. Although decreasing trend of aridification over Türkiye, drought has recurred throughout the 22-year study period in the central and eastern regions. These areas in which the annual averaged satellite-based aridity index exceeds a threshold value correspond closely to regions vulnerable to drought. Satellite-based indices may show particular promise for the major agricultural or pasture areas in central and eastern Türkiye, which are at heightened risk of future drought.

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1. Introduction

The Intergovernmental Panel on Climate Change has noted a troubling increase in the frequency and intensity of extreme meteorological or climatic events, which are causing widespread adverse effects on natural and human systems (IPCC 2021). The Mediterranean region is no exception: the average temperature in this region is rising 20% faster than the global average, and high-temperature events and heat waves have become more frequent and extreme (Cramer et al. 2018; IEMed 2020). In addition, annual precipitation is projected to decrease in the mid and late 21st century by 30% relative to the reference period 1986–2005, one of the largest declines in the world, which will result in significant increases in dry spells and droughts (Dai 2011; IEMed 2020).

According to a global categorization of climatic aridity, the countries of the southern Mediterranean (north coastal Africa) occupy arid or semi-arid regions and the northern Mediterranean countries lie in semi-arid or dry sub-humid regions, especially Spain, Türkiye, and Greece (Kimura and Moriyama 2019a). However, current conditions, as determined by the satellite-based aridity index (SbAI) of Kimura and Moriyama (2014), indicate that hyper-arid and arid regions are increasing in the eastern and southern Mediterranean countries and southern Spain and that the dry sub-humid region has been increasing in southern Europe (Kimura 2020).

With recent climate change in Türkiye, annual temperature is continually increasing and contributing to extreme weather events like heat waves and drought (Sahin et al. 2018; Afshar et al. 2020). The coupled effect of warming and drought is expected to lead to a general increase in aridity and subsequent desertification (UNEP/MAP and Plan Bleu 2020). The monitoring and assessment of the warming and drought using various model simulations and satellite data is strongly needed because Türkiye is relying on rain-fed agriculture, but also irrigated agriculture playing an important role recently (ex., Tramblay et al. 2020).

Some drought monitoring is based on remote sensing. Spectral reflectance has been widely used to calculate indices like the Normalized Difference Vegetation Index (NDVI) and because the calculation procedures are simple. Bakhtiari et al. (2021) indicated that NDVI performed best in assessing land degradation compared with other indices using spectral reflectance. Additionally, they revealed that thermal indices using land surface temperature (LST) were identified as the most influential variable for land degradation assessment. Jones and Vaughan (2010) have also suggested that a thermal index that uses the difference of the LST between day and night is much more useful as an indicator of water deficit. Kimura and Moriyama (2014) proposed SbAI that uses the difference of the LST between day and night. SbAI

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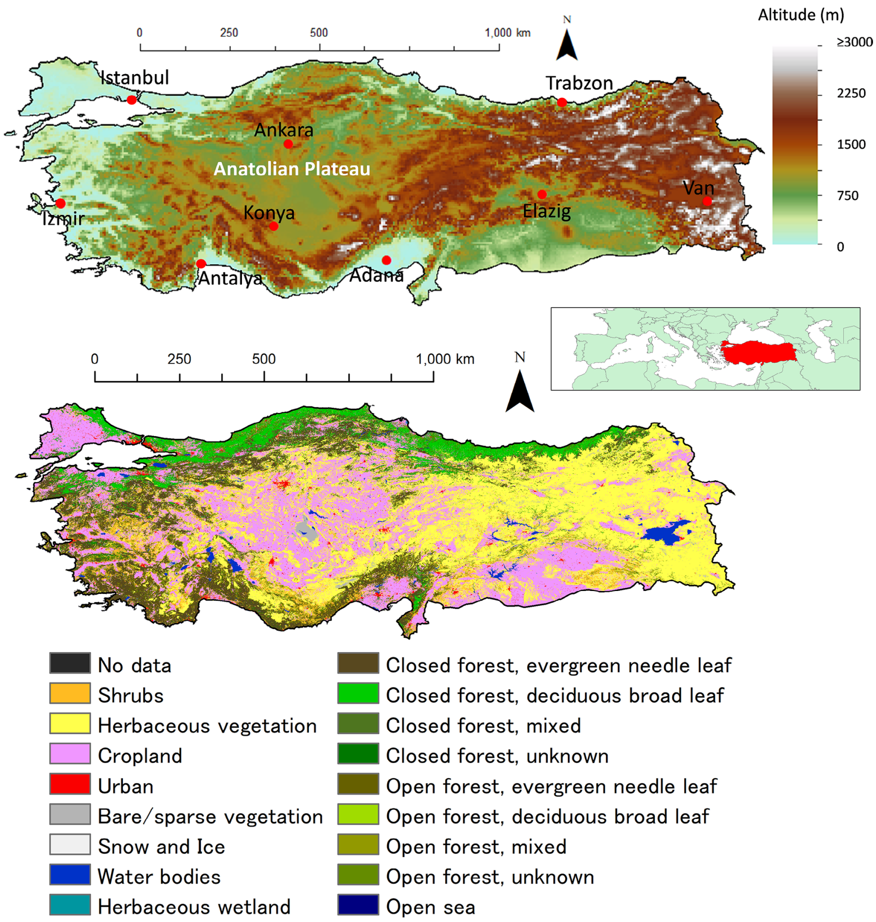

Fig. 1. Distribution of elevation and land use in Türkiye. Topography is from the GTOPO30 dataset at 30 second resolution (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30), and land use is from the Copernicus Global Land Service dataset at 100 m resolution (https://land.copernicus.eu/global/products/lc). Red circles indicate major cities.

has been used to identify degraded lands in China and Mongolia that are source areas of Asian dust (Kimura 2017, 2022). Years in which large increases in degraded land area were identified have been found, using SbAI, to correspond to major droughts in Mongolia (Kimura and Moriyama 2021). SbAI has been also used in studies detecting land degradation and drought in China and Iran (Bakhtiari et al. 2021; Niu et al. 2022).

In this study, we applied these satellite monitoring techniques, NDVI and SbAI, and evaluated recent aridification and drought of Türkiye from 2000 to 2021 for continuous monitoring of drought hazard and risk.

2. Method

2.1 Target area, period and method of analysis

Target area is Türkiye, which is a large country (784,000 km^2) with varied topography at the boundary between Europe and Asia under the influence of widely different air patterns and climates, and it consequently contains a great variety of vegetation types (Fig. 1). The Turkish State Meteorological Service (MGM) states that according to the Köppen climate classification, most parts of Türkiye are under the influence of a Mediterranean climate, whereas continental steppe and cold snowy climates prevail in the central and eastern regions (MGM 2022). Most of the precipitation in the country occurs in the winter season. In some studies, it has been determined that the precipitation in winter and spring seasons tends to decrease in general, whereas a generally increasing trend was observed for summer and autumn rainfall intensity (Altin et al. 2012; MGM 2022).

The period of analysis was from 2000 to 2021, because MODIS has provided daytime and nighttime LST data observed over equivalent locations every day, which have enabled the calculation of SbAI since 2000. NDVI and SbAI were applied to evaluate the annual trend of vegetation amount related to climatic condition, aridification, and drought. To see the effect of climate change on recent Türkiye, annual average temperature and annual rainfall data were used to examine the increasing or decreasing trend from 2000 to 2021. Regarding the trend of NDVI and SbAI, we also discussed about the effect of annual average temperature and annual rainfall.

2.2 Data

This study relied on daily SbAI values, the physical meaning of which is the opposite of heat capacity determined by land surface wetness, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data products MOD09CMG (Vermote 2015) and MOD11C1 (Wan et al. 2015) for broadband albedo and LST which have a 0.05° resolution. Daily satellite data were downloaded from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/). These daily data were averaged to derive annual values for our analysis.

Daily SbAI is defined as follows (Kimura and Moriyama 2014):

$$\mathrm{SbAI} = \frac{\Delta T_{\mathrm{s}}}{R_{\mathrm{s}}}, \tag{1}$$

$$R_{\mathrm{s}} = (1 - r) S_0 \cos\theta_{\mathrm{c}}, \tag{2}$$

$$r = 0.160 r_1 + 0.291 r_2 + 0.243 r_3 + 0.116 r_4 + 0.112 r_5 + 0.081 r_7, \tag{3}$$

where ΔT_s is the difference in land surface temperature between day and night, and R_s is the absorbed solar radiation (calculated shortwave energy balance at land surface which is horizontal solar radiation at land surface minus albedo at land surface without cloud cover) as calculated from broadband albedo r, the solar constant S_0 (1367 W m^{-2}), and the solar zenith angle at the Sun's apex θ_c, and r_{i} are the spectral reflectance of channels 1 through 7. Poor pixels in the Quality Assurance (QA) dataset of day or night LST and in the reflectance products were eliminated from computation. Dry surfaces, with their low thermal inertia, lead to large values of ΔT_s and hence high SbAI (Jones and Vaughan 2010).

Daily NDVI was calculated from 2000 to 2021 on the basis of the near-infrared (NIR) and visible (RED) wavelength channels of the MODIS data product MOD-09CMG.

Annual average temperature and annual rainfall data for Türkiye were downloaded from the World Bank's Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/).

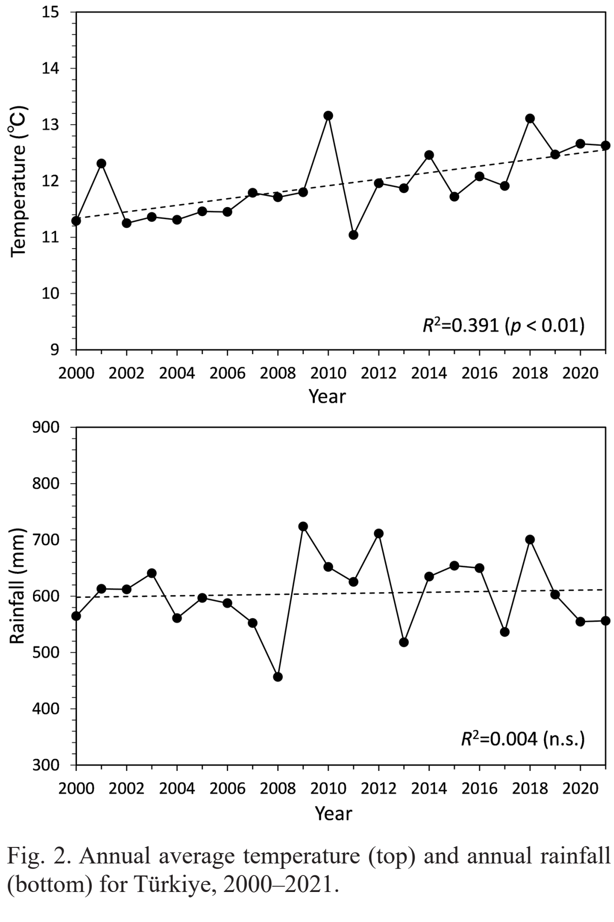

Fig. 2. Annual average temperature (top) and annual rainfall (bottom) for Türkiye, 2000–2021.

3. Results and discussion

3.1 Trend of NDVI

Annual average temperatures in Türkiye showed a statistically significant rise during the study period, although annual rainfall, despite strong fluctuations of ±65 mm, showed no nationwide trend (Fig. 2). Droughts (mainly the meteorological drought affected to agricultural drought) occurred in 2000–2001, 2004, 2008, 2013, 2017, 2020, and 2021 (Kurnaz 2014; Dikici 2020; Global Drought Observatory 2021). Droughts were more likely when the annual rainfall was less than 600 mm (averaged value from 2000 to 2021), but they did not necessarily occur every dry year.

We found a statistically significant increasing trend of NDVI during the study period (Fig. 3), despite the rising temperatures and fluctuations in rainfall (Fig. 2). One cause of this trend is an increase in the nation's proportion of forest, which has grown linearly from 26.2% in 2000 to 28.9% in 2020 as the proportion of agricultural land has fallen from 52.6% in 2000 to 49.1% in 2020 (Günşen and Atmiş 2019; Yücer 2020; World Bank

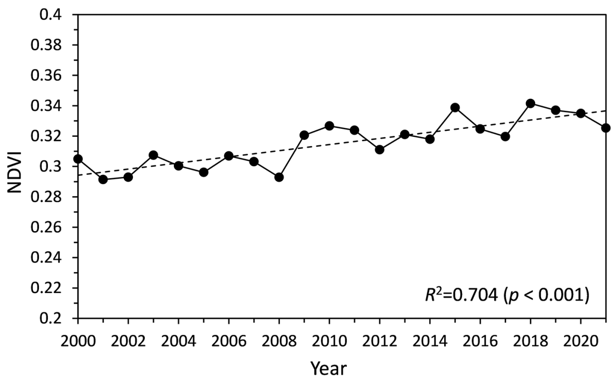

Fig. 3. Annual average NDVI for Türkiye, 2000–2021.

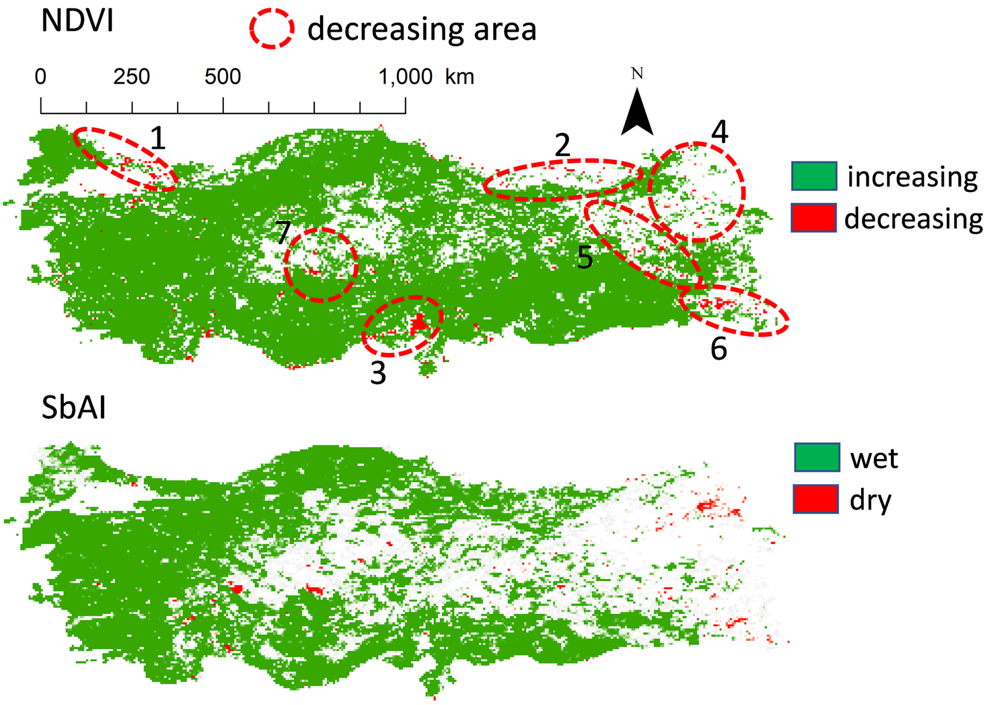

Fig. 4. Spatial distribution of correlation coefficients greater than ±0.42, which are significant with p values less than 5%, for trends in yearly NDVI and SbAI, 2000–2021.

2022). Türkiye is one of the rare countries that is increasing its forest area (FAO 2020). Among Türkiye's major agricultural crops, the cultivated areas of wheat, sugar beet, and barley have decreased, according to Food and Agriculture Organization Statistics (FAOSTAT: https://www.fao.org/faostat/en/). Another cause of increasing trend of NDVI might be related an increased temperature (R^2 = 0.323, $p < 0.01$), not a fluctuated rainfall (R^2 = 0.12, n.s.). However, these relationships should be discussed carefully because the effect of climate variability on vegetation including the forest is more complicated (Keenan 2015; Kramer et al. 2020).

Figure 4 shows a trend analysis of NDVI from 2000 to 2021. Notable areas of increasing NDVI can be seen in the north, west, and south. The land cover map in Fig. 1 shows that north to west is primarily forest and south is cultivated land. The increase in NDVI in south is thought to be caused by planting orchards of drought-resistant species, such as olives, and the development of irrigation farming. For example, irrigated areas under the control of the State Hydraulic Works (DSI) have increased about 61% from 2000 to 2020 (DSI 2020). Notable areas of decreasing NDVI are numbered 1 to 7. Regions 1, 2, and 3 are formerly forested and cultivated areas near urban centers (Istanbul, Trabzon, and Adana in Fig. 1) where urbanization, industrialization, and farmland conversion have taken place (Colak and Rotherham 2006; Telkenaroglu and Dikmen 2017). In the eastern regions 4 to 6, the predominant land use class is herbaceous vegetation (pastureland). The eastern regions are generally highlands and arid regions, which have been always vulnerable to desertification (Kurnaz 2014). Region 7 is around Lake Tuz, which was dried up completely in 2021 (Hansen 2021).

Also shown in Fig. 4 is a trend map of SbAI, which tends to decrease as NDVI increases and vice versa (R^2 = 0.307, $p < 0.01$). However, SbAI do not necessarily correspond to NDVI, because SbAI may be likely related to the actual land surface aridity more directly than NDVI at a physical viewpoint, which is a metric of the reciprocal of heat capacity (Kimura and Moriyama 2019b).

3.2 Trend of SbAI related to drought

A statistically significant trend of decreasing SbAI, or wet trend, corresponds to the increasing trend of NDVI for Türkiye as a whole (Fig. 5). However, SbAI had larger fluctuations than NDVI, which increased more linearly. So, decreasing trend of SbAI might be related to a

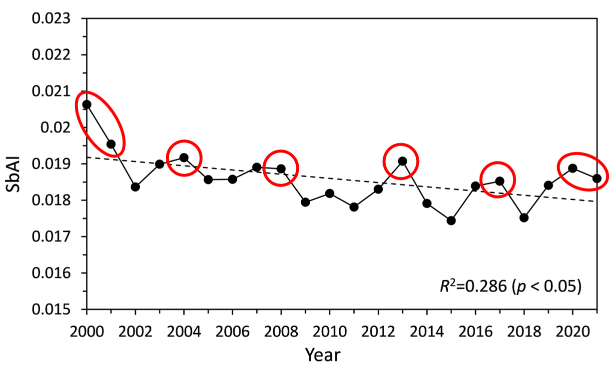

Fig. 5. Annual average SbAI for Türkiye. Red circles indicate years of declared drought.

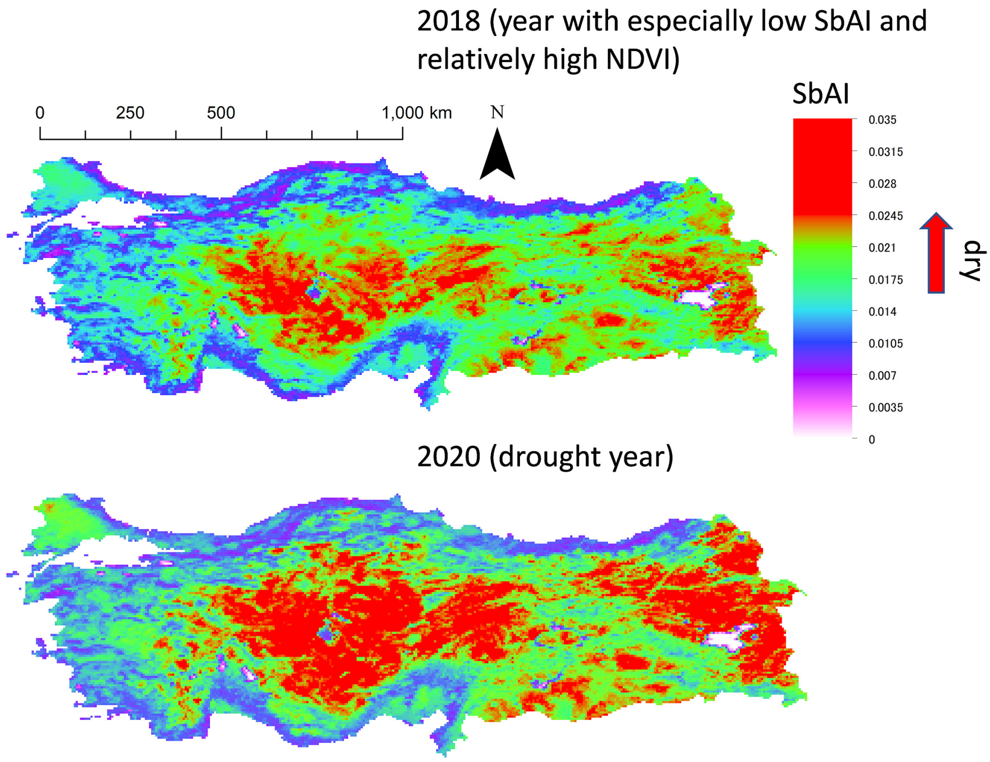

Fig. 6. Spatial distribution of annual average SbAI for 2018 (year with especially low SbAI and relatively high NDVI) and 2020 (drought year). Red colors indicate the area with SbAI > 0.025.

fluctuated rainfall ($R^2 = 0.30$, $p < 0.01$), not an increased temperature ($R^2 = 0.08$, n.s.). Given the recurrence of drought during the study period (red circles), the large fluctuations in SbAI have amplified the vulnerability to drought of some regions.

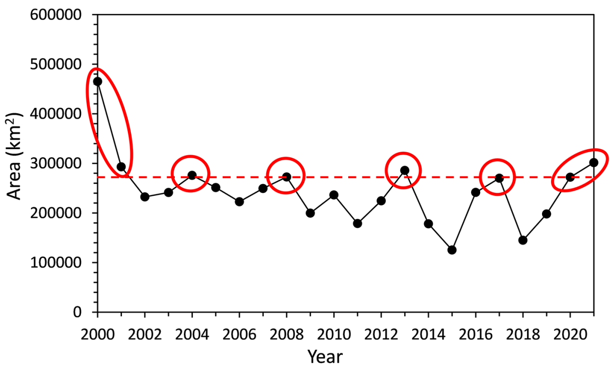

Fig. 7. Total area in Türkiye with annual average SbAI > 0.025, 2000–2021.

Figure 6 compares the distribution of SbAI in a year with especially low SbAI and relatively high NDVI (2018) and a drought year (2020). The threshold value to start monitoring land degradation in arid regions is usually set at SbAI = 0.025 (Kimura and Moriyama 2019b; Kimura 2020). In both years, SbAI was the same in the north, west, and south coastal regions where forest was prevalent. However, the area exceeding SbAI = 0.025 (red colors) was larger in 2020 than in 2018 in the central and eastern regions that are predominantly farmland and pastureland, although a trend of increasing dryness is not apparent in the central region in Fig. 4.

Figure 7 presents the yearly size of arid areas (SbAI > 0.025) in Türkiye. Years in which this area reached or exceeded 280,000 km^2, or 36% of the area of Türkiye (the dashed red line in Fig. 7), were years of drought. The similarity of this record with that of SbAI (Fig. 5) suggests that the area with SbAI > 0.025 in the central and eastern regions is a meaningful indicator of drought in Türkiye. This means that the annual trends of NDVI and SbAI for the whole region do not much affect the drought detection by SbAI > 0.025. These results are also compatible with the desertification model of the Directorate General for Combating Desertification and Erosion (CEM 2022).

4. Conclusion

Numerical simulations of future climate indicate that the countries of the Mediterranean including Türkiye will see enhanced aridification and droughts. In this study, we applied two satellite monitoring techniques (NDVI and SbAI) and evaluated recent aridification and drought of Türkiye from 2000 to 2021. As a result, aridification has not been progressed in most of areas in Türkiye, although drought has recurred throughout the 22-year study period in the central and eastern regions.

The Palmer Drought Severity Index (PDSI), widely used to estimate aridity and drought (Palmer 1965; Dai 2011), is calculated using meteorological data and incorporates the water balance concept. However, there are some disadvantages of using the PDSI, which depends on the density and distribution of meteorological stations, for the purpose of large-scale drought monitoring (Tufaner and Özbeyaz 2020; Niu et al. 2022). The method reported here, based on SbAI, has the advantage that MODIS has provided daytime and nighttime land surface temperature data for consistent locations every day, making continuous monitoring of SbAI possible over large areas, since 2000.

Since this study focused on annualized aridity data, this might obscure the drought's effects on vegetation due to the low NDVI during the winter season. Therefore, the effects of land surface backgrounds during the winter season should be considered in detail for future development of monitoring. Daily monitoring of SbAI makes it feasible to diagnose hot spots or periods of drought on a seasonal or more frequent basis. Because the Earth Observing System satellites that have mounted MODIS instruments are nearing the end of their service lives (NASA 2022), the Second-generation GLobal Imager (SGLI) on the Global Change Observation Mission-Climate (GCOM-C) satellite, with a higher resolution than MODIS, would ensure continuity in such monitoring.

In Türkiye, future spatial and temporal changes in precipitation and the expected increase in temperature will favor extreme weather events that may adversely affect agriculture, forests, and terrestrial ecosystems. Water will become ever more important in the future due to the expected increase in drought coupled with population growth. As Türkiye makes plans for future water demands, continuous monitoring of the aridity index using satellite data can help identify regions vulnerable to drought which, in combination with meteorological data, can aid in managing the hazards of drought.

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