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Soil Parameters Under Varying Land Use Types in -Spatiotemporal Trends of Climatic Southern Iran

Omid Sharifi[1†], *Sepideh Behroozeh*[2†] and *Samira Behroozeh*[3*†]

[1]Department of Agricultural Extension and Education, School of Agriculture, Jiroft University, Jiroft, Iran, [2]Department of Geographical Sciences, School of Humanities, University of Hormozgan, Bandarabbas, Iran, [3]Department of Agricultural Extension and Education, School of Agriculture, Shiraz University, Shiraz, Iran

The study of land use change dynamics in developing countries is particularly important, as it contributes to sustainable land management and the more efficient use of natural resources. Southern Iran, which includes the provinces of Bushehr, Fars, Kerman, Sistan and Baluchestan, and Hormozgan, provides a valuable case study due to its diverse land uses and varying climatic conditions. It is hypothesized that land use changes between 2000 and 2022 in this region have significantly impacted the trends of soil temperature (ST) and soil volumetric water content (SWV), especially in areas where natural covers such as forests and shrublands have been converted to agricultural or barren lands. Trend analysis using the Mann-Kendall Z test and Sen's slope estimator revealed a negative trend in ST across 62.60% of the study area, encompassing most parts of Sistan and Baluchestan, Kerman, Hormozgan, and southeastern Fars. In these regions, soil volumetric water content showed a positive and statistically significant trend. It can be attributed to an increase in sudden and intense rainfall and seasonal precipitation patterns. In 34.79% of the study area, an increasing trend in ST was observed, particularly in Bushehr and sporadically in parts of Fars Province. Similarly, the trend analysis of soil climate variables across different land uses indicated that soil volumetric water content increased by 85.36% in barren lands and by 66.36% in grasslands. In contrast, negative trends were found in forests (94.85%), shrublands (72.79%), and agricultural lands (82.24%). The main reason for this declining trend is the conversion of forests and shrublands to agricultural land. The trend of ST showed a decrease of 69.23% in barren land use, 94.85% in forest use, and 56.73% in grassland use. In these land uses, trees and dense vegetation block direct sunlight, which helps keep ST lower in these areas. In contrast, an increasing trend was observed in shrublands (63.48%) and agricultural lands (82%). Given the rapid pace of land use change, forecasting and analyzing satellite imagery represents a valuable approach for supporting environmental management strategies. Such forecasts provide deeper insights into potential future changes and inform proactive measures to mitigate their adverse impacts.

Keywords: land use, ST, SWV, Southern Iran, trending

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***Correspondence**
Samira Behroozeh,
s.behroozeh@ymail.com

†ORCID:
Omid Sharifi
orcid.org/0000-0002-9647-0036
Sepideh Behroozeh
orcid.org/0009-0007-2600-7533
Samira Behroozeh
orcid.org/0000-0001-5014-3075

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INTRODUCTION

Drought is a common natural disaster and a major ecological, hydrological, agricultural, and economic concern for humanity (Han et al., 2020). The extent of drought has increased in recent decades and is expected to intensify in the future (West et al., 2019). Drought can have numerous detrimental effects on both the environment and the economy (Rulinda et al., 2013). Therefore, monitoring changes in drought conditions for land use restoration (Mahmoudi et al., 2019) has become crucial for various applications (Heydari et al., 2018). Drought, along with land-use and land-cover changes, which are among the most pressing global environmental issues, often results from both natural factors and human activities (Hosseini et al., 2020). Land degradation is a major global environmental issue. The deterioration of the physical, chemical, and biological properties of land threatens food security, ecosystem services, livelihoods, and quality of life (Kumar et al., 2022). Land degradation is emerging as one of the most catastrophic global challenges in the context of contemporary climate change and uncontrolled human activities. Understanding the extent of degradation and its potential causes is crucial for developing effective mitigation measures, as well as sustainable strategies for the responsible use of land resources (Bouma et al., 2019). Climatic and biogeographical indices, such as Soil Water Volume (SWV) and Soil Temperature (ST), are effective tools for assessing the status of land degradation on a large scale in arid lands affected by negative human activities. Land Surface Temperature (LST) is also one of the key physical variables in Earth surface processes, responding sensitively to climatic changes and terrestrial surface characteristics at both global and regional scales (Song et al., 2018). This parameter plays a critical role in controlling physical, chemical, and biological processes as well as mediating interactions between the land and the atmosphere, significantly affecting vegetation, water, and soil conditions (Urqueta et al., 2018). Therefore, changes in vegetation cover can result from fluctuations in LST, which is closely related to vegetation density.

Soil moisture is a vital variable in the hydrological cycle that refers to the amount of water present in the soil and is recognized as a key factor in agriculture and natural resource management (Rasheed et al., 2022). By influencing evaporation and transpiration, drought forecasting, irrigation management, and plant health monitoring, this variable contributes to the optimal growth and development of vegetation (Greiser et al., 2024). Variations in soil moisture can lead to changes in the density and health of vegetation cover, which in turn impacts local ecosystems. Thus, understanding its spatiotemporal distribution is essential and effective for vegetation cover management. Today, various indices and methods are employed to monitor land degradation, with these efforts primarily relying on satellite data, as well as the application of remote sensing and geographic information systems (Cheng et al., 2020). Indices derived from remote sensing data have proven particularly valuable for tracking changes in vegetation cover over time. Recent studies have highlighted the effectiveness of indices related to temperature, precipitation, humidity, evaporation, transpiration, vegetation, and land degradation. These studies have documented the spatial and temporal variations of these indices across different scales, which are instrumental in assessing and predicting future land degradation risks (Badapalli et al., 2021; Burrell et al., 2018; Hamzeh et al., 2017). Soil water volumetric, particularly surface soil water volumetric, plays a crucial role in the management of water and soil resources. Similarly, surface soil temperature, which refers to the temperature measured at the ground surface, has become one of the key parameters for examining spatial changes, as it is a critical indicator of land surface changes. Many researchers in environmental fields such as global climate change, hydrological cycles, agriculture, and urban land cover use ST indices as important and effective remote sensing parameters in their studies (Hereher and El-Kenawy, 2022; Shao et al., 2020). This variable is essential for hydrological modeling, land degradation analysis, ecological studies, and climate change research.

On the other hand, in recent decades, unsustainable practices in the exploitation of natural resources have caused significant damage to natural resource areas (Karimi and Sharif Zade, 2017). As a result of the unplanned and self-interested interaction between human societies and the environment, we are confronted with numerous environmental challenges, including land and forest degradation. These challenges have reached a point where many human settlements in our country are heading toward unsustainability. The nature, magnitude, and intensity of these challenges vary depending on the geographical and human conditions prevailing in different regions (Dehghani et al., 2019). Given that human society currently and in the future will rely on natural resources as the essential foundation for sustainable environmental development and ecological processes (Savari et al., 2019), land degradation not only threatens the ecological health of grasslands and shrublands but also reduces the quality and quantity of forage available for livestock (Souri et al., 2018). Furthermore, it exacerbates environmental anomalies such as floods, air pollution, drought, erosion, and declining groundwater levels (Kavianpour et al., 2015). In this context, vegetation plays a crucial role in maintaining ecosystem balance, water storage and production, as well as providing medicinal, industrial, and food products. It also contributes to economic value at both the micro and macro levels while creating jobs at minimal cost (Karimi and Sharif Zade, 2017). It is recognized as a fundamental factor in traditional livestock production (Dehdari et al., 2014) and as one of the factors for the development of countries (Savari et al., 2019). Additionally, vegetation plays a vital economic and social role in the survival of rural and nomadic livelihoods (Habibyian and Barani, 2019), providing fodder, storing precipitation, moderating climate, producing oxygen (Karimi et al., 2016), feeding livestock, and preventing soil erosion (Sharifiyan Bahraman et al., 2018).

The southern provinces of Iran (Bushehr, Fars, Kerman, Hormozgan, and Sistan and Baluchestan) host a wide range of soil types due to their diverse topographic and climatic conditions. Based on Iran's national soil maps and the FAO global soil database, the dominant soils in these regions include Aridisols, Entisols, and Inceptisols. These soils, which are

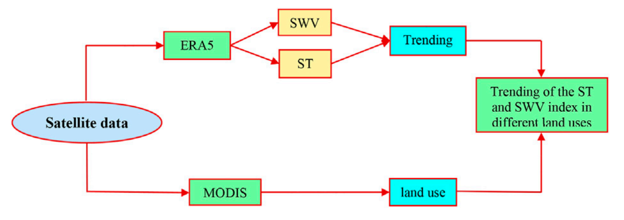

FIGURE 1 | Research methodology flow chart.

primarily formed under arid and semi-arid climates, are characterized by low organic matter content, localized salinity, limited water-holding capacity, and textures ranging from sandy loam in desert and coastal areas to silty and clayey textures in alluvial plains (Mohammadhosseini Sagayesh et al., 2025; Roozitalab et al., 2018). Differences in soil type and structure play a key role in explaining the spatial and temporal variations in soil temperature and volumetric water content across different land use types. For example, shallow sandy soils in barren lands, due to their low water retention capacity, often experience greater temperature fluctuations and respond more rapidly to climatic changes. In contrast, deeper, clay-rich soils commonly found in forest and agricultural lands exhibit distinct thermal and moisture patterns due to their different physical properties (Horel et al., 2022; Onwuka et al., 2021). The thermal and hydrological behavior of soils in response to climate change and land use types is strongly influenced by structural and physical differences in the soil. For instance, shallow sandy soils in barren areas tend to warm up more quickly and retain less moisture, whereas deeper, clay-rich soils in forested and agricultural areas display different responses to temperature and moisture variations (Zhu et al., 2025).

Research indicates the high potential of southern Iran regarding land degradation, as well as the significant application of remote sensing, geographic information systems, and climate models in monitoring land use. Previous studies have paid little attention to assessing the sensitivity of different land uses to drought from the perspective of climatic soil variables in the context of land use restoration. In recent studies, climatic soil indices have been introduced as a simple and effective criterion for monitoring land conditions under various circumstances. Given the importance of this issue, the aim of the present study is to analyze the trends of the variables under investigation (ST and SWV) across different land uses from 2000 to 2022. It is noteworthy that, in terms of location, no such study has been conducted in southern Iran to date.

MATERIALS AND METHODS

The data used in this study includes SWV in cubic meters per cubic meter and ST in degrees Celsius, sourced from the ERA5 climate model at a monthly temporal resolution and a spatial resolution of 10 km for the period 2000–2022. Both SWV and ST data correspond to the topsoil layer (0–7 cm) as provided by the ERA5-Land dataset. These data were processed to estimate the spatiotemporal trends of soil temperature and soil moisture across different land use types in southern Iran. The steps of the research process are presented in **Figure 1**.

Land Use Mapping Preparation

The MCD12Q1 product from the MODIS sensor, with a resolution of 500 m, was used for the period 2000–2022 to examine land use and land cover changes. Provided by NASA, this dataset offers high-quality land cover information with extensive temporal coverage and reliable classification accuracy. Its consistency, accessibility, and suitability for long-term analysis of land cover and climate-related trends across diverse regions made it an appropriate choice for this study. The land use map was prepared with seven land use classes (**Table 1**). Additionally, a 30-m digital elevation model (DEM) from the ASTER sensor was used to analyze the elevation classes of Iran.

Statistical Analysis of Trend Indexes

To calculate the trend of SWV and ST changes in the study area, the non-parametric Mann-Kendall test and Sen's slope estimator were used (Kendall, 1975). The statistics for this test were calculated using **Equation 1** through **Equation 5**.

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}\left(X_j - X_i\right) \tag{1}$$

In **Equation 1**, "S" is the Mann-Kendall test statistic, where "xi" is the value of the i-th data point, "xj" is the value of the j-th data point, "N" is the number of data points, and "sgn (xj − xi)" is the sign function, which is calculated using **Equation 2**.

$$\mathrm{sgn}\left(X_j - X_i\right) = \begin{cases} +1, \text{if}\left(X_j - X_i\right) > 0 \\ 0, \text{if}\left(X_j - X_i\right) = 0 \\ -1, \text{if}\left(X_j - X_i\right) < 0 \end{cases} \tag{2}$$

The variance of the Mann-Kendall statistic is calculated using **Equation 3**.

$$\mathrm{Var}(S) = \frac{1}{18}\left[N(N-1)(2N+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t + 5)\right] \tag{3}$$

In **Equation 3**, "N" is the number of observations, "m" is the number of tied groups, "t_i" is the number of tied values for the i-th group, and "t" represents the total number of tied values. The second term in **Equation 4** is an adjustment for ties or tied values in the data.

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{Var}(S)}, \text{ifs} > 0 \\ 0, \text{ifs} = 0 \\ (S+1)/\sqrt{\mathrm{Var}(S)}, \text{ifs} < 0 \end{cases} \tag{4}$$

A positive "Z" value indicates an increasing trend, while a negative "Z" value indicates a decreasing trend in the time series. Additionally, for testing a monotonic increasing or decreasing trend at the significance level "P", if the "Z" value is greater than "$z_{(1\text{-}p/2)}$" (where "$z_{(1\text{-}p/2)}$" is obtained from the standard normal cumulative distribution table), the null hypothesis is rejected. For this purpose, a significance level of "P = 0.05" is used, with the

TABLE 1 | Description of land use types in the study area derived from the MODIS product (Sulla-Menashe and Friedl, 2018).

Class	land use	Description
1	Barren land	Less than 60% of areas with bare surfaces such as sand, rocks, and soil, and with vegetation cover of less than 10%
2	Agricultural land	At least 60% of the land surface is under cultivation
3	Forest	Deciduous broad-leaved trees (with a canopy height of over 2 m) and a tree cover of more than 60%
4	Rangeland	Mostly covered with annual plants that are less than 2 m in height
5	Shrubland	Mostly covered with perennial woody plants, with a cover between 10% and 60% and a height ranging from 1 to 2 m
6	Water bodies	Includes oceans, seas, lakes, ponds, streams, and rivers
7	Built-up areas	Areas with at least 30% impervious surfaces, including buildings, asphalt, and transportation routes such as highways

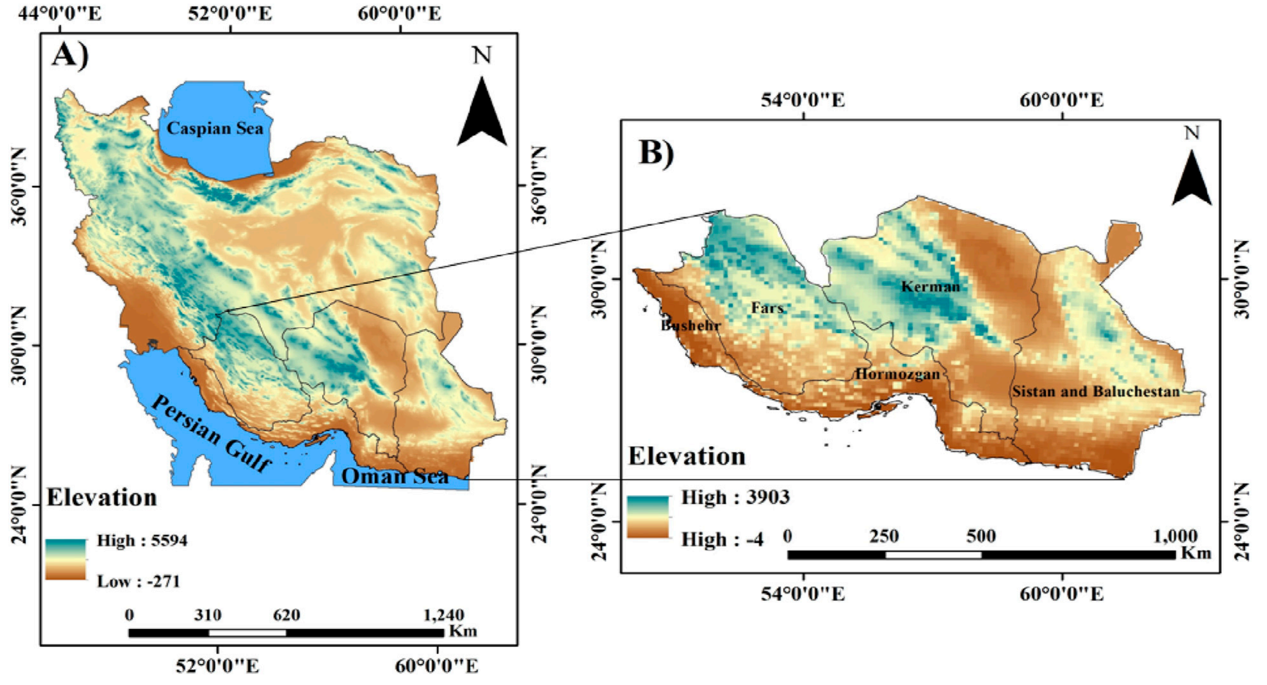

FIGURE 2 | (A) Map of Iran. **(B)** The study area in southern Iran.

standard "Z" values set at "±1.96" in this study. To confirm the accuracy of the trend changes, Sen's slope estimator was used, which is calculated using **Equation 5** (Sen, 1968).

$$\beta = \text{Median}\left[\frac{X_i - X_j}{i - j}\right](\forall j > i) \quad (5)$$

In **Equation 5**, "β" is the slope estimator of the trend line, while "x_i" and "x_j" represent the values of each pixel at times "i" and "j", respectively, where "i" and "j" are the year indices. Positive values indicate an increasing trend, while negative values indicate a decreasing trend. Values equal to zero indicate the absence of a trend (Theil, 1950).

Study Area

The southern provinces of Iran, including Bushehr, Fars, Kerman, Sistan and Baluchestan, and Hormozgan (**Figure 2**), have diverse climatic conditions. These areas are primarily characterized by a hot and dry climate, with very hot and humid summers, where temperatures can exceed 50 °C. In these areas, relative humidity can also reach up to 70 percent. Especially in the provinces of Bushehr and Hormozgan, which are close to the Persian Gulf (Chaudhari et al., 2018). The study area exhibits diverse precipitation patterns that are heavily influenced by climatic and geographical conditions. These precipitation patterns have significant impacts on land use and water resources in these areas, necessitating careful management and appropriate planning for the optimal use of water and soil resources (Karimzadeh Motlagh et al., 2022).

RESULT AND DISCUSSION

Spatiotemporal Trends of Annual Changes in the Variables Under Investigation

The spatiotemporal changes of SWV and ST indicators over 23 years in the southern provinces of the country (Bushehr, Fars,

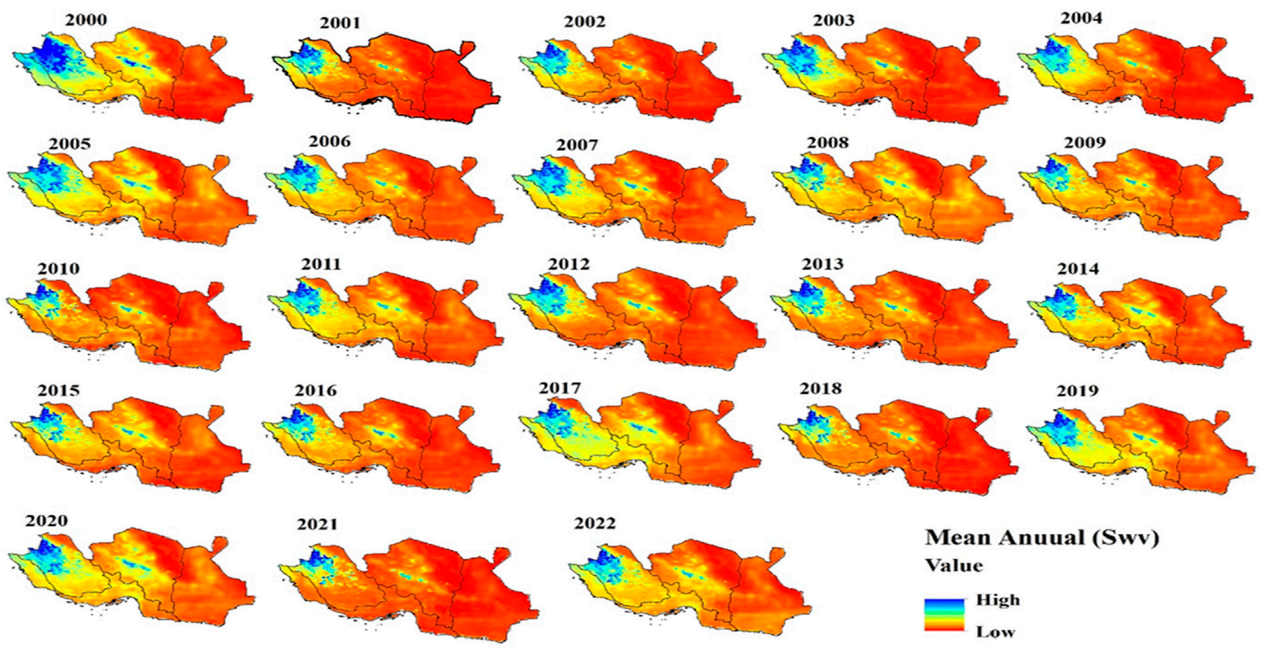

FIGURE 3 | Annual average soil water volumetric from 2000 to 2022 in the study area (southern Iran).

Kerman, Sistan and Baluchestan, and Hormozgan) are shown in **Figures 3**, **4**.

The results of the analysis of the annual average SWV index (**Figure 3**) indicate that the lowest SWV was recorded in 2021. Which includes all the provinces under investigation. This situation is observed in all areas of Sistan and Baluchestan, Hormozgan, a large part of Kerman province, and the southern regions of Fars and Bushehr provinces. The highest value of this index was recorded in 2020, which was generally observed in Bushehr, Fars, Hormozgan, and the western and southwestern parts of Kerman province.

The annual changes in the ST index presented in **Figure 4** for the study area indicate that the trend of changes has been consistent over the years studied. Similarly, the lowest ST was recorded in 2020 in the eastern part of Sistan and Baluchestan, as well as in the northern and northeastern regions of Fars province and the western part of Kerman province. The highest value was observed in 2021 in Hormozgan, Bushehr, southern Fars, Sistan and Baluchestan, as well as in the northeastern and southern parts of Kerman province.

The Trends in Temperature and SWV Indices Changes

The trends of soil climatic parameters, including SWV and ST, from 2001 to 2022 are shown in **Figures 5A–D**; **Table 2** using the Mann-Kendall Z statistic and Sen's slope estimator. Based on **Figure 5A**, the trend of ST index changes has decreased over 60.62% of the region's area. This includes southern, western, and southwestern Kerman, southeastern Fars, a large part of Sistan and Baluchestan, and the northeastern, northern, and northwestern parts of Hormozgan. In 0.08% of the region's area (including certain points in Kerman Province), the decrease is also statistically significant. Meanwhile, in 34.79% of the region, this index shows an increasing trend. A statistically significant increase is observed in 4.51% of the area, notably in Bushehr and scattered parts of Fars Province. The increase in sudden and intense rainfall, as well as seasonal precipitation systems in these areas, has led to higher soil moisture and lower ST. The Sen's slope estimator indicates that this index has an increasing trend in 39.30% of the region and a decreasing trend in 60.70% of the area (**Figure 5C**).

The results of the SWV index changes, as shown in **Figure 5B**, indicate a decreasing trend in 24.09% of the region, including Bushehr Province, northern and northeastern Kerman, and predominantly in Fars Province. In 1.37% of the region's area (including certain points in Fars and Bushehr), the decrease is statistically significant. On the other hand, in 62.77% of the studied area (including Sistan and Baluchestan, Hormozgan, southeastern Fars, and most parts of Kerman Province), the trend of this index has been increasing. Additionally, in 11.76% of the region's area, the SWV index shows a statistically significant increasing trend, which is scattered throughout the provinces of Sistan and Baluchestan, Kerman, and Hormozgan. Furthermore, based on the Sen's slope estimator, there is a decreasing trend in 25.47% of the country's area, while an increasing trend is observed in 74.53% of the country's area (**Figure 5D**). In these areas, SWV showed a positive and statistically significant trend, which can be attributed to the increase in sudden and heavy rainfall events and seasonal precipitation patterns, leading to higher SWV and reduced ST.

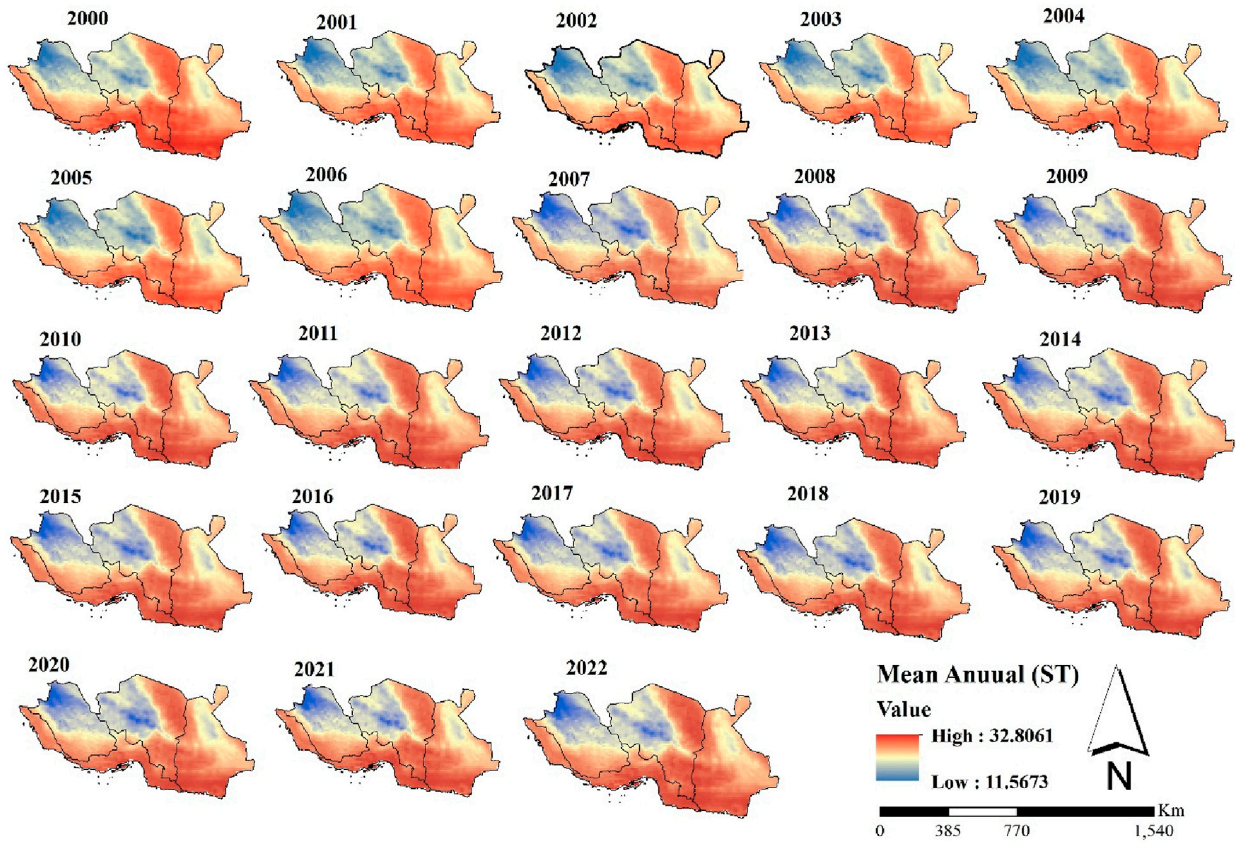

FIGURE 4 | Annual average soil temperature from 2000 to 2022 in the study area (southern Iran).

A noticeable inverse relationship was observed between soil temperature (ST) and soil volumetric water content (SWV) trends across the region. Areas such as Sistan and Baluchestan, Hormozgan, and southern Kerman showed increasing SWV and decreasing ST, likely due to intensified seasonal rainfall enhancing soil moisture and cooling effects. Conversely, regions with declining SWV—like Bushehr and parts of Fars—experienced rising ST. Soil characteristics also play a role: sandy soils in barren lands warm and dry quickly, while clay-rich soils in vegetated areas retain moisture and heat more slowly. These patterns underscore the combined impact of rainfall variability and soil properties on soil-climate interactions.

Trend Analysis of Soil Climatic Variables (SWV, ST) in Different Land Uses

The trends of ST and SWV variables across different land uses are presented in **Figure 6**. The SWV in shrubland use, there is a negative trend of 72.79%, of which 4.19% is statistically significant. In forest land use, there is a negative trend of 94.85%, with 2.28% of this amount being statistically significant. In agricultural land use, there is a negative trend of 82.24%, with 4.58% of this amount being statistically significant. The SWV index in barren land use has shown a positive trend of 85.36%, of which 13.65% is statistically significant. In grassland use, there is a positive trend of 66.36%, with 15.58% of this amount being statistically significant. The concentrated vegetation present in grassland areas also contributes to reducing evaporation and enhancing water infiltration into the soil. Previous research indicates that grasslands play a significant role in water regulation. Compared to bare soil, grasslands significantly increase water infiltration and reduce surface runoff (Zhao et al., 2020). In forest, shrubland, and agricultural land uses, this trend has been decreasing. The primary reason for this decreasing trend is the conversion of forest and shrubland to agricultural land, a finding supported by the study conducted by Xiao et al. (2024). In agricultural land use, unsustainable agricultural practices such as excessive irrigation, improper use of fertilizers, and poor land management techniques also contribute to soil moisture loss and reduced soil efficiency (Sharma et al., 2024). Studies have shown that significant changes in Land Use Land Cover (LULC) have occurred in various regions, with the expansion of agricultural lands and urban areas often coming at the expense of reduced forests and rangelands (Jalayer et al., 2022; Muhammad et al., 2022).

The ST trend in shrubland use, there is a positive trend of 63.48%, of which 14.14% is statistically significant. In agricultural

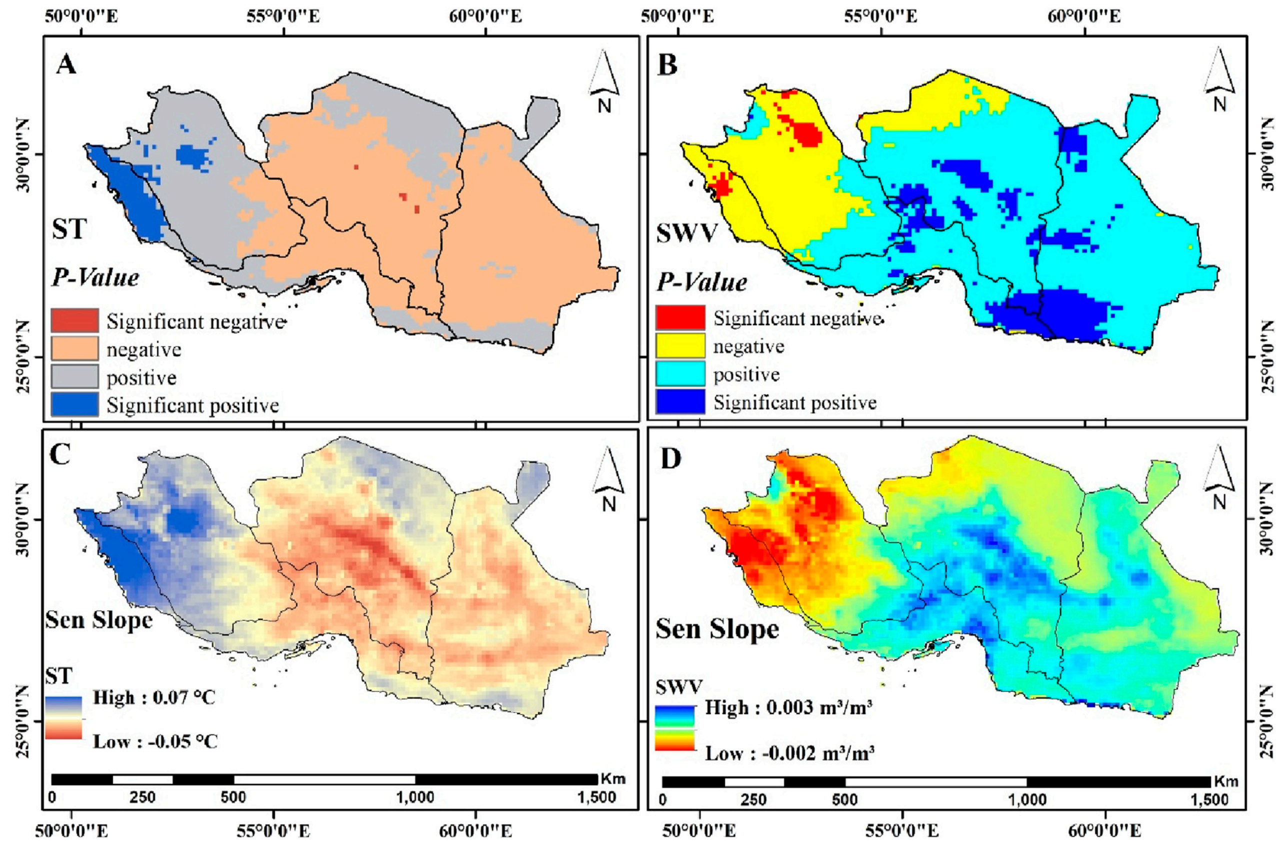

FIGURE 5 | (A) p-value of the ST index in the study area from 2000 to 2022. **(B)** p-value of the SWV index in the study area from 2000 to 2022. **(C)** Sen's slope of the ST index in the study area from 2000 to 2022. **(D)** Sen's slope of the SWV index in the study area from 2000 to 2022.

TABLE 2 | Summary of spatial trends in ST and SWV content (2001–2022) based on Mann–Kendall Z and Sen's slope statistics.

Statistically Significant Area (%)	Area (%)	Trend Direction	Variable
4.51	34.79	Increasing	ST
0.08	60.62	Decreasing	ST
-	39.30	Increasing	Sen's Slope (ST)
-	60.70	Decreasing	Sen's Slope (ST)
11.76	62.77	Increasing	SWV
1.37	24.09	Decreasing	SWV
-	74.53	Increasing	Sen's Slope (SWV)
-	25.47	Decreasing	Sen's Slope (SWV)

land use, there is a positive trend of 82%, with 40.94% of this amount being statistically significant. In agricultural land uses, replacing natural vegetation cover with crops or shrubs reduces the land's ability to retain moisture. The studies by Gürsoy (2021) and Chilagane et al. (2021) indicated that in agricultural land use, activities such as the use of heavy machinery and the destruction of natural cover lead to soil compaction, reducing its ability to absorb and retain water. This leads to reduced evaporation and, consequently, an increase in ST. The results of the study by Borna and Jahan (2015) indicate that in shrublands and agricultural areas, where shorter plants are present compared to forests or grasslands, the rate of evapotranspiration is lower. This results in higher soil surface temperatures, as taller plants and trees play a crucial role in cooling the environment through transpiration.

The ST in barren land use has shown a negative trend of 69.23%, with 0.07% of this amount being statistically significant. In forest land use, there is a negative trend of 94.85%. In grassland use, there is a negative trend of 56.73%, with 0.77% of this amount being statistically significant. In these land uses, trees and dense vegetation block direct sunlight, which helps keep ST lower in these areas. The results of Song et al. (2013) examined the impact of elevation and vegetation density on ST variations. The findings of this study showed that vegetation can reduce ST by blocking direct sunlight, which in turn keeps ST lower in various areas.

CONCLUSION AND IMPLICATIONS

This study highlights the critical influence of land use dynamics on soil-climatic variables across southern Iran's diverse ecological regions. Rather than affecting all areas uniformly, the results

FIGURE 6 | Trending of the ST and SWV index in different land uses during the 2000–2022 period.

revealed that land cover types respond differently to climatic stressors particularly agricultural and shrubland areas, which showed signs of increased soil temperature likely due to vegetation removal and poor soil practices.

In contrast, forested and grassland regions benefited from denser vegetation cover, which likely contributed to maintaining cooler soil conditions and promoting water retention. These insights underscore the importance of preserving natural vegetation and implementing sustainable agricultural practices to combat land degradation.

The analysis of trends based on the Mann-Kendall Z test and Sen's slope estimator revealed that the trend of ST changes over most of the area in Sistan and Baluchestan, Kerman, Hormozgan, and southeastern Fars has been negative, indicating a decrease in ST. The trend analysis of soil climatic variables across different land uses indicated that SWV has shown an increasing trend in barren land, grassland, and forest areas. This increase may be attributed to intensified rainfall events, improved soil water retention due to vegetation density, and more efficient water and soil management practices in these ecosystems.

Additionally, the results indicated a negative trend in ST for barren land, forest, and grassland uses. The trend of ST in shrubland and agricultural land uses was observed to be increasing.

In many areas particularly forests, grasslands, and some parts of barren lands an increasing trend in SWV has been associated with a decreasing trend in ST. This relationship aligns with the findings of recent studies (Behroozeh et al., 2025; Bongasie et al., 2024), which emphasize the role of soil moisture in regulating surface energy fluxes and soil temperature. An increase in SWV enhances the soil's heat capacity and promotes evapotranspiration, which ultimately leads to a reduction in ST. Conversely, a decline in soil moisture often caused by unsustainable land use practices reduces latent heat flux and results in higher soil temperatures. Understanding this inverse dynamic offers new insights into the combined impacts of land use change and climate variability on soil-climate interactions. It also highlights the crucial role of vegetation cover in moderating temperature fluctuations and mitigating the adverse effects of climate change on soil health, especially in arid and semi-arid regions.

These findings make a unique contribution to the field of natural resource management and climate studies, as this is the first study to examine the spatiotemporal distribution of ST and soil moisture variables across five southern provinces of Iran regions characterized by diverse climatic conditions and land uses. The research highlights how climate change and human activities differently affect various land use types (such as barren lands, agricultural areas, forests, and rangelands).

By identifying distinct patterns of temperature and moisture changes for each land use, the results offer a valuable tool for planning and implementing sustainable land and water management strategies in arid and semi-arid regions, an approach that has rarely been addressed in previous studies from a land use-specific and regional perspective.

Ultimately, this research contributes to bridging a critical gap in the region by demonstrating how land use change, in the context of climate stress, manifests in measurable soil-climate interactions—an area previously underexplored in southern Iran.

LIMITATIONS AND AVENUES FOR FUTURE RESEARCH

Although this study has valuable achievements, it also has some limitations. One of the most important limitations is the absence of certain soil variables such as bulk density and deep soil moisture, which require field measurements or detailed regional data that were not available in this study. Additionally, socio-economic factors affecting land use changes, such as policy shifts, population growth, and local management practices, were not examined in this research and could provide useful supplementary information.

For future research, it is recommended to include these additional soil variables in the analysis to gain a better understanding of soil-climate interactions. Moreover, investigating seasonal and monthly patterns of climatic variables and their relationship with vegetation cover can better reveal the role of natural ecosystems in regulating soil conditions.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: The data used in this study are publicly available from the following sources: ERA5 climate reanalysis data were obtained from the Copernicus Climate Data Store. MODIS land cover product (MCD12Q1) was obtained from the NASA Earthdata portal. These datasets are hosted in open-access repositories and do not require an accession number.

AUTHOR CONTRIBUTIONS

OS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing – original draft, Funding acquisition. SeB: Conceptualization, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review and editing. SaB: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review and editing. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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