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Analyzing the impact of climate change on multi-depth soil temperature dynamics and surface environments using field data and satellite imagery in Wasit Province, Iraq

Ali Jawad Kadhim Al-Sarraji[1*], Albw Jbianah Mohanad Ismael Khalbas and Afrah Mahdi Saleh Al-Obaidi
Department of Soil Science and Water Resources, College of Agriculture, Wasit University, Wasit, Iraq
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Abstract

Climate change is a major driver of environmental change in semi-arid regions, as ecosystems are highly vulnerable to shifts in temperature and rainfall. The present study examines the long-term dynamics of soil temperature at multiple depths in Wasit Province, Iraq, for the period 2000–2024, and integrates soil-surface-related environmental changes derived from field observations. To assess temporal trends and subsurface thermal variations, the soil temperature was recorded at a number of monitoring locations at various depths. Remote sensing datasets derived from Landsat imagery were also employed to analyze land surface temperature (LST) and vegetation change using the normalized difference vegetation index (NDVI). Climate trends were examined using maximum air temperature, precipitation, and the Standardized Precipitation Index (SPI). Mann–Kendall and Sen's slope tests were used to evaluate trends in soil temperature, whereas Pearson correlation and linear regression were used to assess relationships between variables. Using Landsat data, NDVI and LST were obtained using Spatial analysis. The findings show a considerable warming of soil (around +1.5°C) in the surface layer (0–7 cm), as well as an increase in maximum air temperature by +0.8°C; NDVI did not exhibit significant temporal trends despite localized vegetation decline, while spatial increases of LST may have been observed between 8 and 10 °C in some regions located within areas experiencing drought years. Thus, soil temperature was highly correlated with air temperature but poorly correlated with NDVI and LST. This research helped address the scarcity of data on the long-term, multi-depth characteristics of soil temperature change in dry regions and provided insights into climate adaptation, land-use planning, and environmental monitoring in Iraq's arid climate.

Keywords: Climate change; Soil temperature; Multi-depth soil; NDVI; Land Surface Temperature (LST); Remote sensing; Semi-arid regions

Introduction

Climate change has emerged as a key driver of environmental change, fundamentally altering global temperature regimes, precipitation patterns and soil–atmosphere interactions (Shen *et al.,* 2026). These changes are particularly detrimental for semi-arid and arid regions, where climate variability affects soil health, crop productivity, water availability, and biodiversity loss (IPCC, 2021; Almazroui *et al.*, 2023). Having a fragile ecological and hydrological balance, these regions are very responsive to long-term warming trends and recurrent drought events. Climate variability and change are reshaping landscapes, and the need to understand and monitor environmental responses to climate variability has become critical for sustainable land management and climate adaptation strategies (Akol *et al.,* 2024).

Soil temperature is arguably one of the most important yet under examined indicators of climate change, particularly in semi-arid settings (Al-Salihi *et al.,* 2026). It is also an important controlling factor of evapotranspiration, microbial activity, nutrient cycling, root progression, and energy exchange between the land surface and atmosphere (Liu *et al.*, 2021; Jin *et al.*, 2022). Soil temperature differs from air temperature because it incorporates long-term effects of the surface energy balance and changes in land cover (Zhou *et al.*, 2023), whereas air temperature reflects short-term atmospheric conditions (Raza *et al.,* 2025). This helps strengthen understanding of subsurface climate through the vertical propagation of thermal signals, which

***Email:** akjwad@uowasit.edu.iq
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can be measured from multi-depth soil temperature profiles (Akram *et al.,* 2025; Arshad *et al.,* 2025a).

Remote sensing has become an effective tool for examining environmental changes across broad spatial scales. Satellite data allow us to extract indices such as the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST), which are effective for monitoring cross-vegetation dynamics and surface thermal status (Karnieli *et al.*, 2010; Liu *et al.*, 2020; Tahir *et al.,* 2025). These datasets, when used in conjunction with field-based measurements, enable detailed analysis of climate–land interactions. Moreover, statistical techniques such as the Mann–Kendall test and Sen's slope estimator are commonly applied to identify long-term trends in environmental time-series data (Hamed, 2009; Yue *et al.*, 2002; Arshad *et al.,* 2025b).

Climate change is palpable in Iraq, specifically Wasit Province. It has a semi-arid climate, characterized by hot, dry weather and rain throughout specific winter seasons. The symptoms of climate change are already visible; there has been a mean annual temperature rise of more than 0.8°C over the last 20 years, and the frequency of droughts and heatwaves has also increased (Ministry of Environment - Iraq, 2023). These have had strong effects on soil moisture regimes, vegetation cover, and land surface conditions internationally, particularly in rain-fed and marginal agricultural regions.

However, the interactive effects of soil temperature dynamics with climate variables remain poorly studied in Iraq. Until now, most studies have focused on surface proxies such as NDVI and air temperature independently, and very little effort has been devoted to studying subsurface thermal dynamics and their relationships with satellite data. Now, this is a research gap in understanding how climate change particularly impacts soil systems at various depths in semi-arid ecosystems.

This study aimed to investigate the long-term temporal variability and trends of multi-depth soil temperature in Wasit Province, Iraq, under the influence of climatic variability and change between 2000 and 2024. Another objective of the study was to assess the correlation between the dynamics of soil temperature, drought variability,

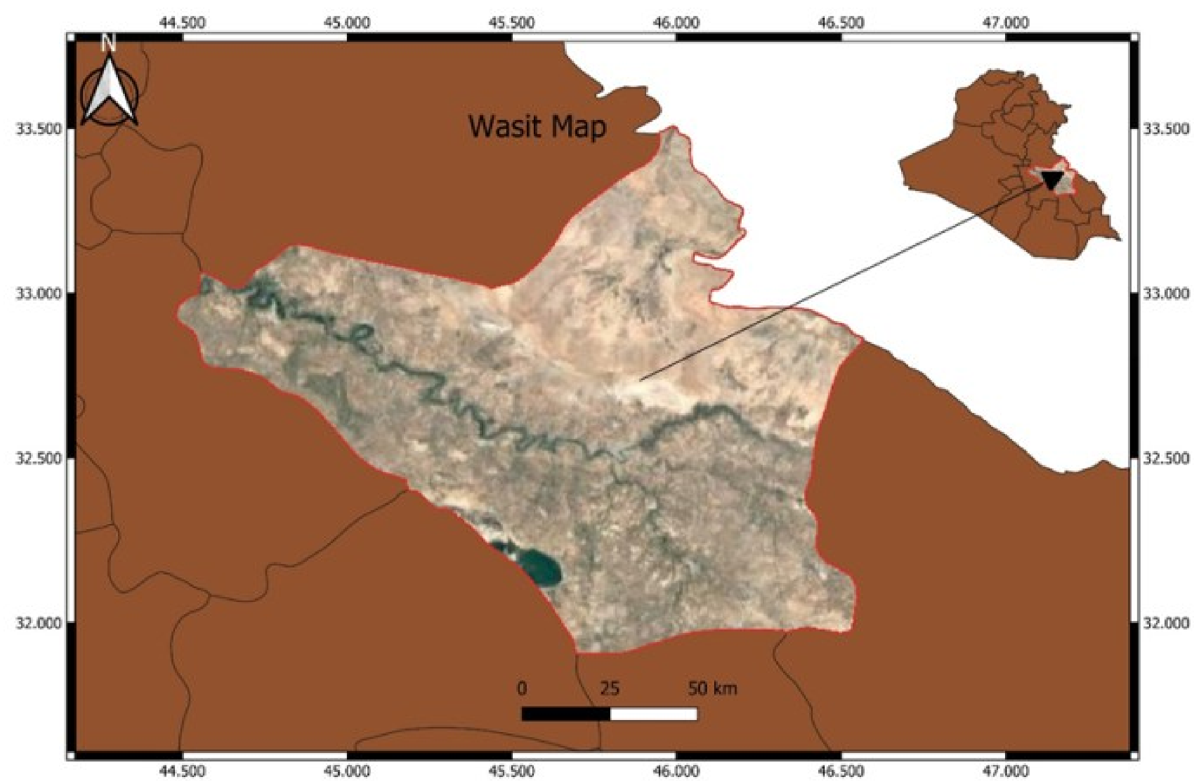

Figure 1: Map of area studied

vegetation cover (NDVI), and land surface temperature (LST) in the field based on integrated observations and satellite remote sensing data. It also aimed to explore spatial and environmental variations of surface thermal regime and soil thermal regime under subsurface conditions across an arid to semi-arid environment to enhance the understanding of the land–climate interactions in the study area. This study provides a novel contribution by integrating long-term multi-depth soil temperature measurements with remote sensing data in a semi-arid region. Unlike previous studies based primarily on surface observations or short-term analyses, this research focuses on subsurface thermal dynamics over a long time span.

Materials and Methods

Study area description

The study area is located in Wasit Province, southeastern Iraq (31° to 33° N and 45° to 47 °E) which has semi-arid climate characterized with low annual precipitation (<150 mm/ year) mainly concentrated during the winter season. Summers are prolonged, dry and hot, with significant evaporation (Figure 1). Climate variability is high with extensive temperature differences and other changes in surface environmental conditions in Wasit Province that increase its climate change vulnerability to thermal effects on the soil. The study area has a mix of agricultural and bare soil surfaces, and is urban populated and confined with barriers of suitable low vegetation cover; allowing for the assessment of long-term changes in soil temperature and land surface characteristics. Due to soil temperature dynamics and vegetation responses, Wasit Province is obviously much more sensitive than other provinces regarding climate variability.

Data Sources

Three primary types of data were utilized in this study, namely: climatic variables, soil temperature measurements and remote sensing from satellites.

Climatic data and drought assessment

Meteorological data such as air temperature and precipitation were extracted from climate datasets that were available and regionally climate records from the year 2000 to 2024. The Standardized Precipitation Index (SPI) was obtained through monthly precipitation data and used to assess the drought variability and climatic stress conditions. Soil moisture variability and cropland stress were considered, and the SPI-12 timescale was chosen to reflect the idea of long-term hydrological drought data. The SPI values were computed using the method suggested by McKee *et al.* (1993) where the precipitation data were approximated by a gamma distribution and transformed to standardized SPI values with a standardized mean of zero and a standard deviation of one. Positive SPI values are a sign of wet conditions, while negative SPI values represent a sign of drought conditions. Using the SPI analysis normal and stress years were determined and the relationship between drought variability and the soil temperature dynamics were assessed.

The Gamma distribution has the following probability density function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}$$

Where x is precipitation, α is the shape parameter, β is scale parameter and Γ(α) is gamma function.

After estimating the cumulative probability, it is transformed into the standard normal distribution using the following relation:

$$SPI = (X - \mu)/(\sigma)$$

Field soil data

Field soil temperature data were collected from multiple monitoring stations distributed across Wasit Province, Iraq, during the period 2000–2024. The monitoring stations were selected to represent different surface and environmental conditions within the study area, and the geographic coordinates and elevations of each station were recorded using a Global Positioning System (GPS). Soil temperature measurements were obtained at multiple depths, including 0–7 cm, 7–28 cm, 28–100 cm, and 100–289 cm below the soil surface, using calibrated digital soil temperature sensors installed according to standard meteorological and soil monitoring procedures. Data were recorded at regular intervals (hourly/daily) and subsequently aggregated into monthly and annual averages for trend analysis. Quality-control procedures included sensor calibration, removal of abnormal values and outliers, consistency checks, and interpolation of limited missing observations using temporal averaging methods. The collected field observations represented point-based measurements that were further integrated to develop averaged multi-depth soil temperature profiles for regional analysis and comparison with satellite-derived environmental variables. The exact locations and coordinates of all monitoring stations in Wasit Province, Iraq; soil temperature recording depths and sensor types; hourly/daily/monthly measurement intervals; source institutions responsible for data collection; procedures used for removing outliers and filling missing observations; calibration and quality assurance methods; and clarification that the analyzed values represent averaged multi-depth soil temperature profiles derived from station-based point measurements.

Remote sensing data

Satellite data were acquired using USGS Earth Explorer platform for different Landsat missions (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI). To ensure atmospheric correction, level-2 surface reflectance products were used. Images were chosen on low (:10%) cloud cover Pre-processing steps included cloud masking, radiometric calibration and spatial alignment. Standard remote sensing techniques were used to compute NDVI and Land Surface Temperature (LST) utilizing the processed images. The long-term spatial variation of vegetation cover and the surface temperature were analyzed with representative years (2000 to 2023) of satellite images.

Data processing and NDVI calculation

All satellite images were in the process of preprocessing in order to further enhance the image quality and to guarantee the uniformity of data sets. The pre-processing steps consisted of radiometric calibration, atmospheric correction, cloud masking, geometric correction and image resampling. Quality assessment bands and cloud masking algorithms at an initial stage were used to remove cloud contaminated pixels. Thermal and optical bands have been mapped to

Table 1: Linear trend analysis of climatic and environmental variables (2000–2024)

Variable	Trend Slope	Intercept	R²	P-Value
Soil_Temperature__0__7cm	0.037	226.210	0.17	0.040
Soil_Temperature_7_28cm	0.036	228.220	0.15	0.056
Soil_Temperature_28_100cm	0.033	233.841	0.127	0.08
Soil_Temperature_100_289cm	0.031	238.778	0.108	0.109
NDVI	0.001	-1.778	0.066	0.214
LST	-0.172	382.587	0.168	0.042
Precipitation	2.293	-4447.211	0.168	0.042
Max Temperature	0.035	235.497	0.133	0.073
SPI	0.057	-115.324	0.168	0.042

Table 2: Correlation between soil temperature and climatic variables

Soil Temperature Depth	Climatic Variable	Pearson r	P-Value
0-7	NDVI	-0.081	0.699
0-7	LST	0.022	0.916
0-7	precipitation	-0.141	0.50
0-7	SPI	-0.141	0.50
0-7	temperature_2m_max	0.973	0.0
7-28	NDVI	-0.122	0.560
7-28	LST	0.008	0.970
7-28	precipitation	-0.175	0.404
7-28	SPI	-0.175	0.404
7-28	temperature_2m_max	0.966	0.0
28-100	NDVI	-0.196	0.347
28-100	LST	-0.027	0.899
28-100	precipitation	-0.156	0.455
28-100	SPI	-0.156	0.455
28-100	temperature_2m_max	0.907	0.0
100-289	NDVI	-0.308	0.134
100-289	LST	-0.107	0.61
100-289	precipitation	-0.054	0.798
100-289	SPI	-0.054	0.798
100-289	temperature_2m_max	0.706	8e-05

correct and remove atmosphere and sensor distortion. The satellite data were projected into a common coordinate system for consistency of spatial aspects in conducting analysis. Google Earth Engine (GEE), ArcGIS, QGIS, and additional R/Python based analytical processes were utilized for image processing and spatial analysis.

Vegetation cover and land surface temperature were analyzed through spatial analysis using QGIS software (version 3.28) on two classes of data set in the Wasit Province. Cloud masking, land surface radiometric correction and spatial alignment were performed on two processed Landsat images. NDVI was derived using the standard / traditional formula (Hu *et al.,* 2024):

$$NDVI = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

Land surface temperature (LST) retrieval

Thermal Infrared (TI) data from Landsat were used in conjunction with typical radiative transfer and emissivity correction algorithms to estimate Land Surface Temperature (LST). The Digital Numbers from the thermal band were converted to spectral radiance and brightness temperature before LST was retrieved. NDVI based emissivity method was used to estimate the surface emissivity. The LST calculation method was based on the typical remote-sensing procedures and involved atmospheric correction and emissivity adjustment to enhance the accuracy of temperature estimations. The maps obtained were the LST maps, which were analyzed to assess spatial variation in LST and the relationship between vegetation coverage and LST changes.

Statistical analysis

Two approaches of parametric and non-parametric statistical techniques were used to measure temporal trends of soil temperature and climate variables. Linear regression analysis was used to calculate the slope, intercept, coefficient of determination (R^2) and statistical significance level (p-values). Moreover, long-term climatic and soil temperature data were processed by the Mann–Kendall trend test and Sen's slope estimator for trend estimation of climate and soil temperature (Alaei *et al.,* 2025). Relationships between soil temperature, NDVI and LST with drought were evaluated using correlation and regression analysis. Data was analyzed using R software, analytical packages based on Python programming, and Microsoft Excel, and displayed as graphics. The p-value was considered significant at $p < 0.05$.

Results

Temporal analysis of climatic variables and soil temperature (2000–2024)

Long-term trends in climatic and environmental variables were analyzed using linear regression based on annual time-series data from 2000 to 2024. Statistical significance was evaluated using p-values, while the strength of relationships was assessed using the coefficient of determination (R^2). Soil temperature increased with depth for all measurements, as shown in Table 1. Similarly, in the 7–28 cm layer, we derived (0.036K/year), but with marginal significance ($p = 0.056$). Increasing trends among deeper soil depths (28–100 cm and 100–289 cm) were also detected, but these differences did not achieve statistical significance ($p = 0.080$ and $p = 0.109$, respectively). This suggests that surface soil layers may be more sensitive to climatic warming, potentially due to direct exposure to atmospheric warming and land-surface processes.

Only a weak positive trend in NDVI was detected at the annual scale (+0.00096 units/year); it was not statistically significant ($p = 0.214$). There is no overall change in vegetation cover at an annual level. Yet localized or seasonal variability is not excluded from this analysis, nor is it characterized better through a spatio-temporal lens. These results reveal an overall trend towards increasing soil temperature, particularly at the surface layer, which corresponds with higher air temperature and heat waves in that area. A noted increase in atmospheric temperature has been observed since the early 1990s, while a strong temporal trend of NDVI over the last period was not detected. However, such warming may exert environmental stress on agricultural and natural ecosystems.

Correlation between soil temperature and climatic variables

Pearson correlation analysis was conducted to evaluate the relationships between soil temperature at different depths (0–7 cm, 7–28 cm, 28–100 cm, and 100–289 cm) and selected climatic and environmental variables, including NDVI, LST, precipitation, SPI, and maximum air temperature (Table 2). The results show that the strongest and most statistically significant relationship was observed between soil temperature and maximum air temperature. At the 0–7 cm depth, the Pearson correlation coefficient reached approximately 0.97 ($p < 0.001$), indicating a very strong positive relationship. This strong correlation persisted across all soil depths, though it decreased slightly with increasing depth. The strong correlation might be attributed to the predominantly atmospheric forcing of soil thermal regimes in semi-arid regions. In flat areas, such as Wasit Province, with low vegetation and high solar radiation, soil temperature is strongly influenced by near-surface air temperature through direct heat transfer (Figure 2).

Also, the applied annual-averaged data might increase correlations by nonsensically removing short-term variability. Still, these results point to a strong correlation between soil and air temperatures that needs to be understood in the context of temporal aggregation. In contrast, NDVI, LST, precipitation, and SPI showed weak, non-significant relationships with soil temperature (r = ±0.1–±0.2; $p > 0.1$). This indicates that the influence of these variables is likely much more localized, or covers a small seasonal span (not fully captured in an annual analysis). These results suggest that soil temperature dynamics in the study area are more influenced by atmospheric heating than by variations in vegetation cover or moisture, particularly during semi-arid conditions.

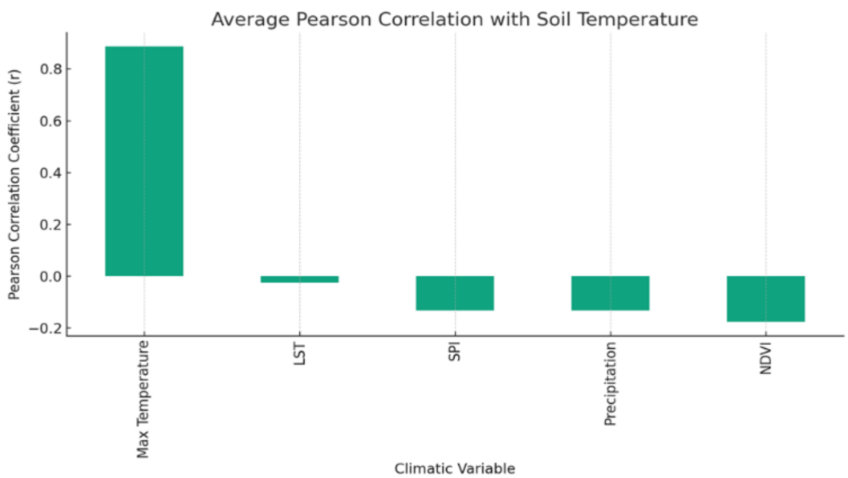

Figure 2: Average pearson correlation with soil temperature

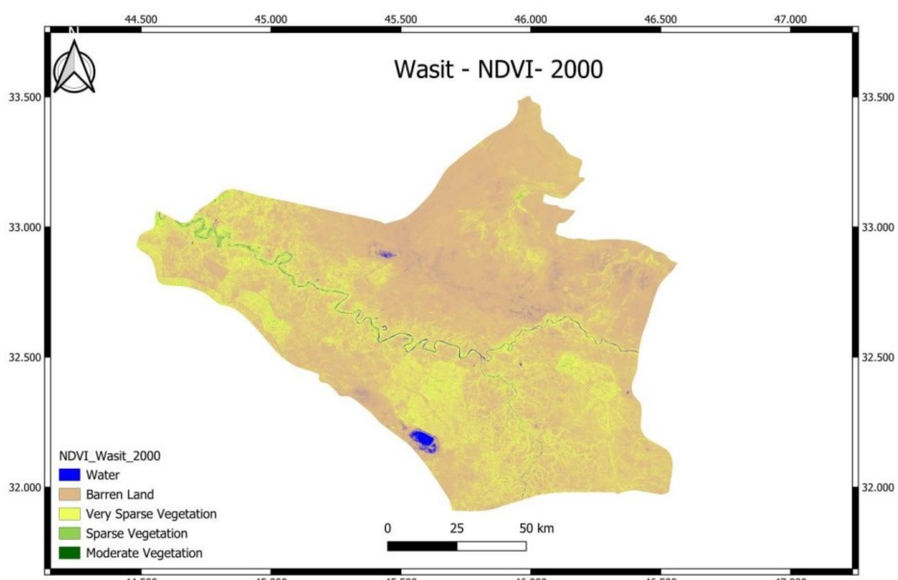

Figure 3: (A) Spatial distribution of NDVI in Wasit Province in 2000, representing baseline vegetation conditions prior to major climate variability impacts

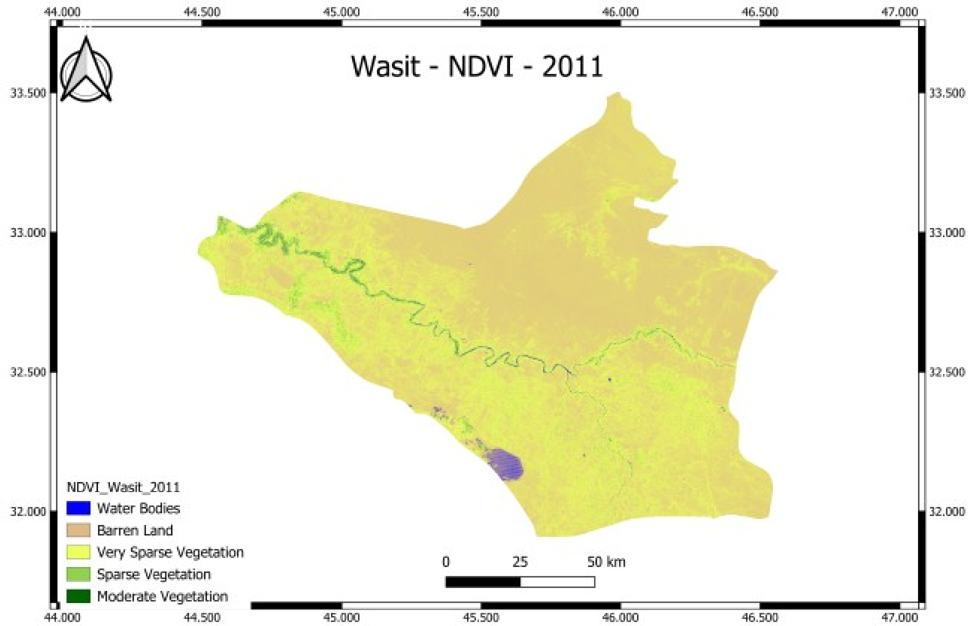

Figure 3: (B) Spatial distribution of NDVI in Wasit Province in 2011, showing changes in vegetation cover under prolonged climate stress and increasing drought frequency

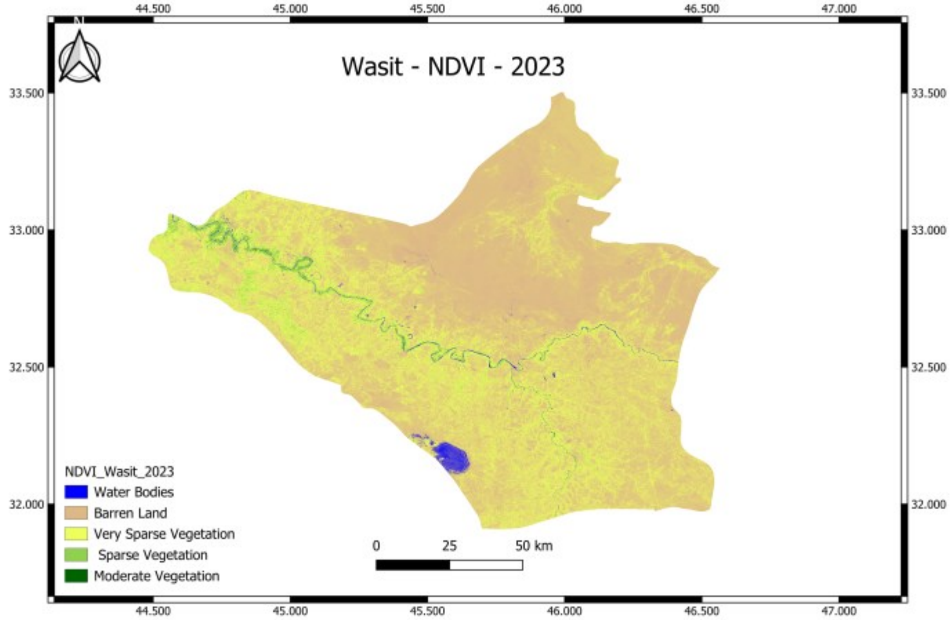

Figure 3: (C) NDVI map in 2023, highlighting areas of vegetation loss (negative values) and vegetation gain (positive values) across the study area

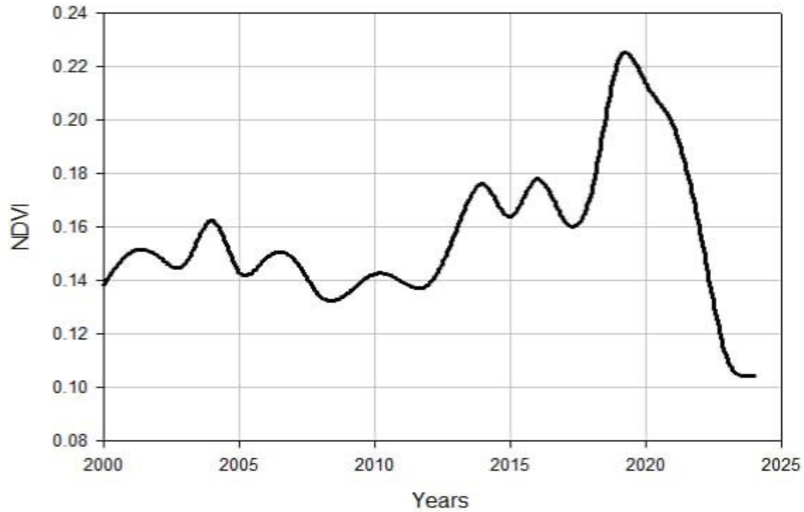

Figure 3: (B) Spatial distribution of NDVI in Wasit Province in 2011, showing changes in vegetation cover under prolonged climate stress and increasing drought frequency

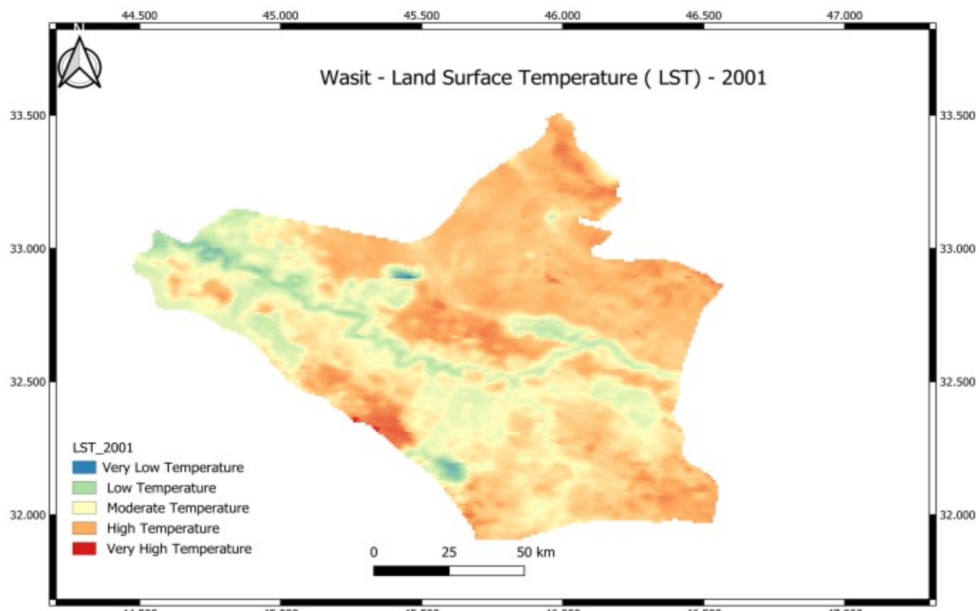

Figure 4: (A) Spatial distribution of Land Surface Temperature (LST) in Wasit Province in 2001, representing baseline surface thermal conditions

Correlation between soil temperature and climatic variable

Satellite data analysis of NDVI & LST

The NDVI satellite data for 2000 and 2023 were derived from Landsat 5 and Landsat-8, respectively, and land surface temperature (LST) data for different zones covering 2001 and 2022. Identifying zones of vegetative change and surface thermal difference in Wasit Province using raster difference methods. Similarly, the NDVI analysis indicated a significant drop in vegetation cover across multiple rain-fed and marginal regions. NDVI values dropped from approximately 0.078 in 2000 to as low as

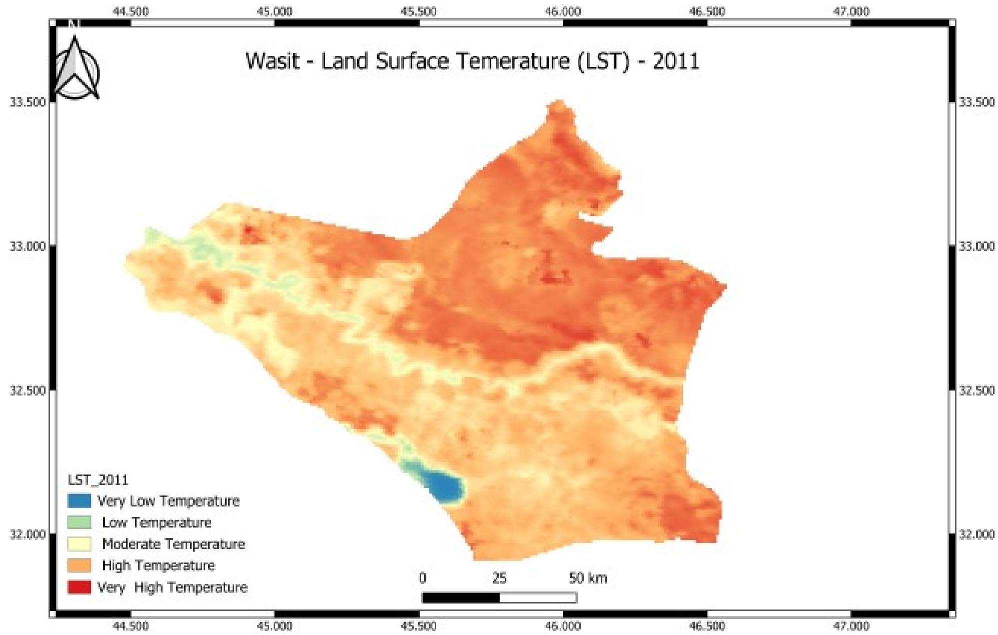

Figure 4: (B) Spatial distribution of Land Surface Temperature (LST) in Wasit Province in 2011, showing increased surface heating under prolonged climate stress.

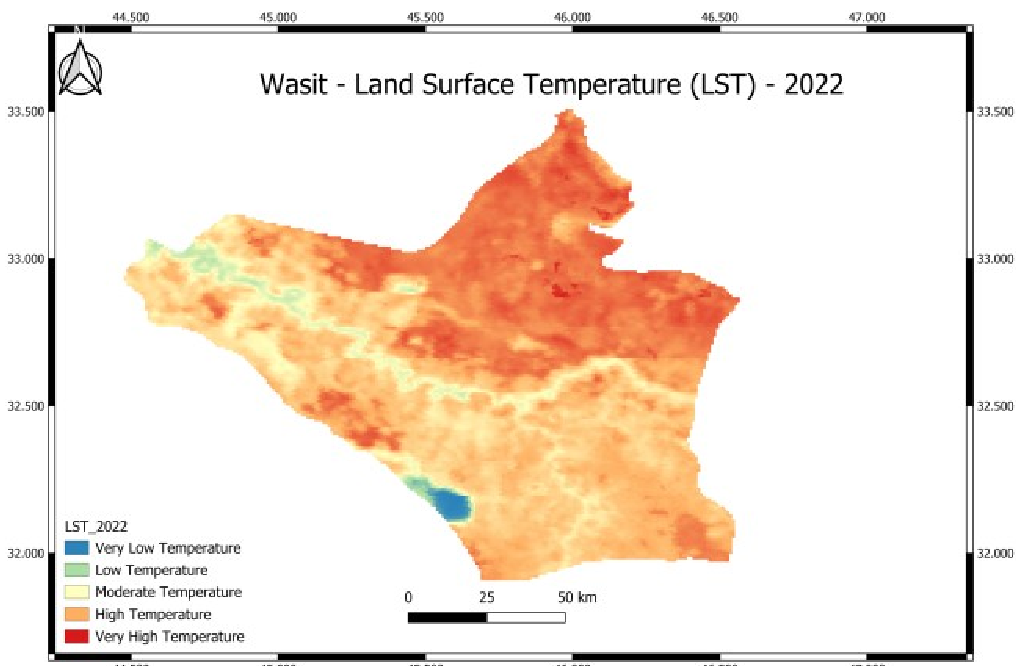

Figure 4: (C) Spatial distribution of Land Surface Temperature (LST) in Wasit Province in 2022), highlighting areas of surface temperature increase (positive values) and localized cooling (negative values)

0.052 during dry periods characterized by extensive bare-soil expansion and degradation (Figure 3 A, B, C and D). These spatial patterns are indicative of localized environmental degradation, and although the temporal trend analysis did not show any statistically meaningful change in NDVI on an annual level, due to a decrease in plant coverage, there is lower evapotranspiration, which might lead to low latent heat flux and high sensible heat at the land surfaces to a higher conversion of incoming solar radiation into surface heating and, consequently, a higher land surface temperature (LST).

Supporting this mechanism, there has been an increase in high-temperature zones with surface temperatures > 40°C (42.0°C over some years) promoted by LST maps (Figure 4 A, B, C). The areas recording the most damage in terms of vegetation loss also correspond to the hottest zones in terms of surface temperature, pointing to a significant negative correlation between vegetation cover and near-surface heating. But they differ for spatial observations and temporal trends. While the spatial analysis indicates localized increases in LST, regression detection results indicate low levels or an inconsistent long-term temporal trend. Such differences may arise from spatial heterogeneity and temporal aggregation. Analysis of integrated NDVI and LST results reveals that vegetation loss reduces the natural cooling benefits of evapotranspiration, enhances surface heat absorption, and promotes better conduction into deeper soil layers. In semi-arid environments, this process compounds dynamic soil temperatures and environmental stresses.

On the other hand, the spatial analysis of LST shows that high-temperature areas are increasing and are scattered throughout Wasit Province. In the early 2000s, the land surface average temperature reached nearly 40.17°C, but went over 42°C in recent years. This increase is consistent with the observed decline in vegetation cover and soil moisture. Since NDVI has a negative relationship with surface temperature, regions that experienced the sharpest NDVI decrease correspond to areas with high spatial LST. Reducing vegetation diversity reduced evapotranspiration and latent heat flux, and increased sensible heat and surface warming. By increasing surface temperature, heat can be transferred to deeper soil by thermal conduction, which explains their contribution to elevated temperatures at all soil depths. Moreover, increasing air temperatures are

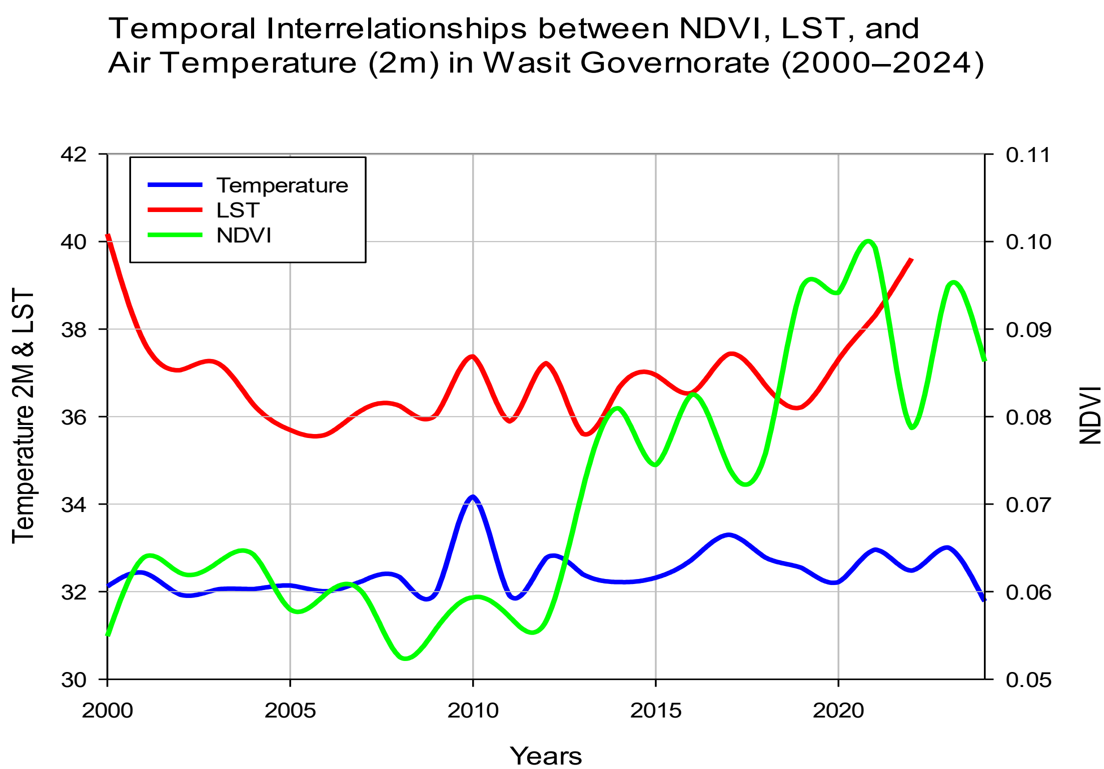

Figure 5: Temporal interrelationships between NDVI, LST, and air temperature (2m) in Wasit Governorate (2000–2024)

consistent with land surface temperature (LST) warming, implying a coupled surface–atmosphere warming process. All together, these findings indicate an amplification of surface heating and a decrease in thermal buffering capacity in the study area, resulting from vegetation loss and climatic stress under semi-arid conditions. Figure 5 showed the conceptual model illustrating the interactions between climate change, vegetation dynamics (NDVI), land surface temperature (LST), and multi-depth soil temperature in Wasit Province (2000–2024). The model shows how atmospheric warming and vegetation loss enhance surface heating and promote heat transfer into deeper soil layers.

Based on these findings, it can be concluded that integrating in-situ measurements with satellite observations offers a powerful approach to understanding soil-surface dynamics and the temporal influence of climate. Such integration enhances researchers' and decision-makers' ability to develop data-driven environmental management strategies, especially in climate-vulnerable regions like Wasit Province.

Impact of heatwaves and drought on environmental indicators

Figure 6 Comparison of environmental indicators (NDVI, LST, soil temperature, and SPI) between normal and stress years in Wasit Province, highlight the impact of drought and heatwaves on surface and subsurface thermal dynamics.

These results indicate that heat waves and droughts have a clear impact on soil and surface temperatures, potentially exacerbating environmental degradation-especially under conditions of weak vegetation. This underscores the importance of integrated climatic and environmental monitoring systems to track changes and predict long-term ecological consequences.

Discussion

This work aimed to understand how the multi-depth soil temperature evolved in the long period and how it correlated with the climate variability and the surface environmental conditions at Wasit Province, Iraq, by field observations and integrated satellites analyzing. These findings showed that there was significant temporal variation in soil temperature from one depth to the other in the period under review (2000–2024), attributed to the strong impact of the regional climatic conditions in arid and semi-arid regions. The observed differences are in line with the findings of other studies showing that the subsoil thermal regime, especially in water-restricted areas, is very sensitive to changes in temperature and precipitation amount, and to the duration of dry conditions.

A strong positive rheological warming trend was also observed in one or both soil classes, with more than +1.5°C at the surface layer (0–7 cm) and at other major depths in most of the soils used (data not shown). According to the trend in maximum air temperature (+0.8°C), this suggests a

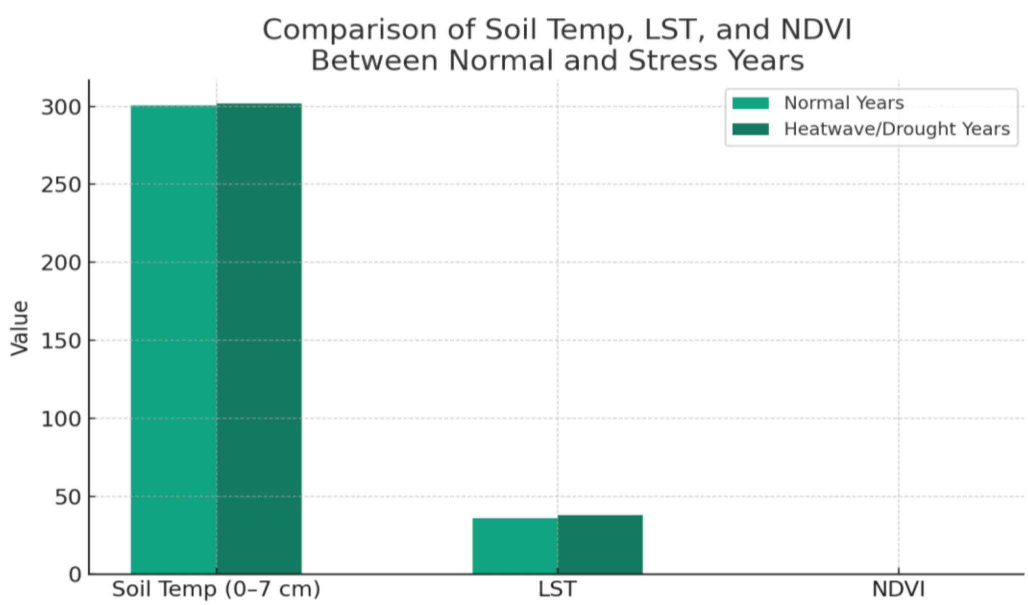

Figure 6: Comparison of environmental indicators between normal and stress Years

strong connection between the strength of coupling between atmospheric heating and the soil's thermal response. This high correlation coefficient ($r>0.95$) implies that atmospheric forcing is the dominant driver of semi-arid soil thermal dynamics. In dry regions with low vegetation cover and high solar radiation (e.g., Wasit), the increase in direct heat exchange makes soil temperature more sensitive to air temperature.

Soil temperature explains about half the variability of NDVI or LST (in independent cross-spectral relationships) in space and time when analyzed at the annual scale, suggesting that vegetation and surface thermal conditions can be expected to have a more localized (in space) or short-term (in time) effect. This is important because such trends need to be disentangled from spatial variability in environmental data from semi-arid regions. This trend was also corroborated by spatial analysis, indicating a substantial loss of vegetation cover in the study regions, particularly in rain-fed and marginal areas across the northwest and west-central regions. The degradation was correlated with constant LST hotspots, with an average increase of 8–10°C between 2001 and 2022. The findings reveal a too interlinked way in which vegetation loss and surface heating compound the environment’s stress.

The majority of these changes were driven by perturbations from climatic extremes (e.g., droughts in 2008 and heatwaves in 2010, 2017, and 2021). In parallel, the vegetation decline and surface warming feedback reinforced the region's sensitivity to climate variability. The analysis of long-term data from Wasit Province (2000–2024) indicates that the surface thermal regime is structural, primarily governed by land-cover changes. This changing NDVI, characterized by a substantial loss of greenness (its cooling capacity), was represented by a trend decline, with a general drop from 0.078 in 2000 to around 0.052 under drought conditions. Physically, that loss of plants leads to lower evapotranspiration — the primary way in which free solar energy is released as latent heat. Consequently, more incident solar radiation is converted to sensible heat, thereby increasing the LST. The spatial correlations of NDVI-LST maps have characterized this change in thermal landscape. Region with the largest loss of vegetation and surface temperature rise (~40.17 °C), despite above-normal to normal precipitation, e.g., 2011 & 2022 in post-drought years. To a certain degree, soil surfaces are exposed to sunlight, which determines heat absorption, and then heat continues to be conducted deep into the layers.

This vertical heat transfer modifies soil thermal dynamics by reducing its inherent buffering (its ability to stabilize temperature) and allowing heat to penetrate deeper layers, which can retain this energy for longer periods. In addition, the simultaneous increase in air temperature enhances this mechanism, establishing a coupled warming of the land–atmosphere system. Thus, the NDVI-LST-air temperature interaction explained empirically that surface degradation is likely to be a determinant of soil thermal behavior dynamics. In semi-arid areas, reductions in vegetation cover enable deeper vertical penetration of heat into the soil profile and increase thermally induced stress on soil physical and biological properties.

The schematic pathway (Figure 5) illustrated how climatic drivers affect subsurface soil layers in Wasit province through allotransformation and autotransformation, including their effects on atmospheric, surface, and subsurface processes. Climate change serves as a key driver via the following pathways: (1) air temperature increase and (2) vegetation cover decrease (NDVI) (Mohammed Suliman,2023; Al-Juthery *et al.*, 2025; Arshad *et al,*2025a; Abd *et al.*, 2025; Hassan *et al.,* 2023). A decrease in NDVI to critically low levels (as low as 0.052 during drought periods) leads the model to lower evapotranspiration and, consequently, to reduced latent heat flux. This alteration of the energy balance at the surface causes elevated land surface temperatures (LSTs) above 40.17°C, leading to a shift from vegetative cooling to direct heating in the topsoil. The vertical thermal transfer from air temperature and LST is summed, forming a profile temperature gradient to promote conduction cooling into deeper soil layers, as shown in the lower part of this model. This mechanism explains the increase in soil temperature observed from 2011 to 2024 (at various depths) compared with previous measurement periods. All things considered, it is the conceptual model accounting for atmospheric heating, vegetation decomposition, and ground thermal conditions together show that decreases in vegetation cover would reduce soil thermal buffering capacity, allowing heat to penetrate deeper into the soil and leading to stronger soil thermal stress in semi-arid regions.

The temporal variations in the Wasit Province dataset (2000–2024) established a relationship between the incidence of drought events, soil thermal regime disruption, and vegetation degradation. SPI: long-term drought (e.g., SPI ≈ 0.79) was characterized by a marked decline in NDVI, with values reaching down to 0.052. Weakening of transpiration not only reduces evapotranspiration but also increases LST (land surface temperature), as it is the sole cooling mechanism at the surface. Surface temperature has also increased, rising from more than 40.17 ºC in the early 2000s to more than 42 ºC in recent years, indicating more efficient surface warming under drought conditions. Thermal expansion causes the surface to warm, and the heat propagates into the subsurface by thermal conduction. At the maximum air temperature (Tmax ≈ 32.1°C), heat is transferred to deeper soil layers. Soil temperatures at greater depths (100–289 cm) were around 27.6°C, indicating that heat penetrates the entire soil profile. This indicates that a feedback mechanism is incorporated into SPI, NDVI, and LST, working together to stimulate the reflected variations of subsurface thermal processes. Scorched soil surfaces largely dominate, reducing thermal buffering capacity and allowing heat to be stored in deeper layers.

The findings of this study confirm previous results from regional and global-scale studies of soil thermal flux mechanisms in arid and semi-arid lands. The significant link between soil and air temperature ($r > 0.95$) reported here is consistent with a recent study in Iraq, which indicated that atmospheric warming mainly drives fluctuations in soil temperature rather than dynamic variations in mechanization (Arif *et al.*, 2024). Similarly, previous research in West and Central Asia dryland regions applying Mann–Kendall and Sen's slope analysis has found significant warming trends for soil or air temperature (Assiri *et al.*, 2025), which also provides evidence for the proportionate increase of detected surface soil temperature in this study. Similar to NDVI decline, remote sensing studies also reported concurrent increases in LST under arid environments (Mortier *et al.*, 2024; Lu *et al.*, 2024). This correlation is consistent with the spatial distribution in Wasit Province, where vegetation loss raised surface temperatures. Additionally, prior studies using indices such as the Vegetation Health Index (VHI) and the Temperature Vegetation Dryness Index (TVDI) provided strong evidence that the drought state actively participates in regulating vegetation cover and surface temperature (Karnieli *et al.*, 2010). Similar patterns in this study were also observed for drought and heatwaves, including across years. In summary, the findings verify the presence of interactions among vegetation dynamics, surface temperature, and climatic variables in Wasit Province, consistent with those at broader regional or global scales but offering novel observations specific to this region on subsurface soil temperature responses.

Key contribution of this research is the use of long-term multi-depth soil temperature records together with remotely-sensed environmental measures in a climatically sensitive area where these records are sparse. An integrated approach to understand the impacts of climate change on soil thermal regime and could influence future studies of land degradation, sustainability in dryland agriculture and climate change adaptation. Several shortcomings need to be recognized, however, in the work of this type. Selected representative years were used instead of continuous annual imagery for the satellite analysis, making it difficult to undertake long-term spatiotemporal analysis. Furthermore, energy balance on the land surfaces, evapotranspiration and latent and sensible heat flux were no direct quantifications. Continued research should incorporate long time series of remote sensed data, more sophisticated energy balance models, and finer resolutions of climatic measurements to better understand the soil thermal processes in an arid environment in response to climatic variations.

Conclusion

In this study, the effects of climate variability on multi-depth soil temperatures and surface environmental conditions in Wasit Province, Iraq, are assessed (2000-2024) using integrated field and satellite observations. The operating results revealed a high intertemporal variability in soil temperatures across different soil depths, with larger variations in shallow soil layers than in deeper ones, where surface heat exchange and its influence on the soil layer are greater. The long-term analysis additionally showed that climate variability and drought conditions affected both the subsurface thermal response and surface environmental parameters in the study area. The results confirm that atmospheric warming is the main driver of soil temperature variability in semi-arid systems, and its effects are partially countered by vegetation dynamics and by spatial differences that appear to be quantitatively less important but locally significant. Despite the lack of a notable long-term temporal trend in NDVI, both spatial (localized vegetation degradation) and internal mechanisms (LST increases driven by surface heating) were confirmed to explain this phenomenon. A coupled land–atmosphere system was revealed, with significant coupling, integrating NDVI, LST, and air temperature from field and remote sensing data. This interaction facilitates vertical heat transfer into deeper soil layers, thereby decreasing the soil's thermal buffering capacity and aggravating subsurface temperatures. An important contribution of this study is the integration of multi-depth field-based soil temperature measurements with remotely sensed environmental indicators, especially in arid and semi-arid regions where large-scale soil thermal investigations have not been conducted for long periods. The results contribute to knowledge of the climatic influence on the soil thermal regime and could be used for environmental monitoring, agricultural planning, and adaptation planning for future climate scenarios in the drylands of Iraq and perhaps other appropriate lands around the globe. Further studies with higher temporal resolution (e.g., monthly precipitation and temperature) and seasonal fluctuations in vegetation growth and soil are needed to match field-recorded biosphere dynamics while utilizing recent advanced Earth system models that account for vegetation–soil interactions and biogeochemical cycling.

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