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Growing Risk of Soil Salinization Linked to Soil Droughts in a Changing Climate

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Key Points:

- 14.73% of global soils experienced a significant increase in salinity between 1980 and 2018
- Long-term droughts have contributed to the development of saline soils in 6.78% of global dry regions
- Vapor pressure deficit and potential evapotranspiration play distinct roles in promoting salt accumulation induced by soil drought across different climate regions

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Soil salinity and soil drought are primary global threats to cultivated land and crop productivity, yet their interrelationships and responses to a changing climate remain unclear. This study investigates the global distribution and long-term trends of soil salinity, as well as its relationships with soil droughts from 1980 to 2018. Our findings reveal that 14.73% of global soils have experienced a significant increase in salinity. The increasing trend of soil salinity is closely linked to changes in soil drought patterns, particularly the increased total number of drought days. Critically, long-term drought events (>6 months) play a key role in the transition from non-saline to saline soil, setting the stage for the formation of saline soils in 6.78% of the world's dry regions. This study highlights a growing risk of soil salinization and provides critical insights for assessing soil vulnerability to degradation in the face of persistent droughts.

Plain Language Summary Soil salinity and soil drought are recognized as major threats to global farmland and crop yields. This study explores their interaction under a changing climate. Our findings reveal that 14.73% of global soils experienced a significant increase in salinity from 1980 to 2018. These increases are closely linked to more severe soil drought, particularly an increase in the total number of drought days. We identify long-term droughts (>6 months) as a key driver of the transition from non-saline to saline soils, a process that has contributed to salinization in 6.78% of the world's dry regions. As salinization degrades soil structure and fertility, hindering crop growth and complicating restoration, it represents a critical form of soil degradation. Therefore, this study provides valuable insights for assessing soil vulnerability to degradation under long-term droughts.

1. Introduction

Soil salinization is one of the major threats to soil fertility, stability, and biodiversity (Hassani et al., 2020a; Lal, 2012), and has become a significant soil degradation issue affecting numerous countries worldwide (Lal, 2015). Salt accumulation in soil pores reduces matrix porosity and vapor diffusivity, influencing soil permeability and tillage ability (Nachshon, 2018). Additionally, salinity limits plant water uptake and damages transpiring leaves by reducing osmotic potential, directly impacting vegetation growth (Munns & Termaat, 1986; Parihar et al., 2015). For example, the Mekong Delta experienced an unprecedented salinity peak in 2020, impacting over half a million hectares of farmland and resulting in the destruction of approximately 30,000 hectares of rice and 20,000 hectares of vegetables (Park et al., 2022). Over the past few decades, soil salinity has exhibited a long-term increasing trend in specific regions (Abbas et al., 2013; Bhuyan et al., 2023; Chhabra, 2021; Hassani et al., 2020a), which may contribute to further soil salinization and land degradation. Saline soils, once formed, are extremely challenging to restore due to the severe damage to soil structure and fertility, and the high costs of improvement make them prohibitive for farmers, particularly in developing countries (Qadir et al., 2007). The sources of soil salts can be classified into two categories: primary and secondary. Primary soil salinity arises from the Earth's crust and natural processes (Abrol et al., 1988; Corwin, 2021), whereas secondary soil salinity is human-induced (Corwin, 2021; Singh, 2015; Utset & Borroto, 2001). The problems of soil salinity are most widespread in arid and semi-arid regions, but saline soils also occur extensively in dry sub-humid and humid regions (Abrol et al., 1988). Soil salinity exhibits spatially, vertically, and temporally dynamics (Mulder et al., 2011; Zaman et al., 2018), particularly in the topsoil layer (0–30 cm), which is significantly sensitive to changing climatic conditions (Hassani et al., 2020a). Climate change may worsen soil salinization through more frequent extreme drought events (Dasgupta et al., 2015; Kreibich et al., 2022).

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Salts accumulate in soil primarily due to the process of evaporation. Evaporation at the soil surface, combined with plant transpiration, drives water upward through capillary action, depositing salts as the water evaporates (Corwin, 2021). This process leads to salt accumulation at the soil surface and in the root zone. An increase in evaporation will increase the amount of salts drawn to the soil surface and root zone, exacerbating salinization (Schofield & Kirkby, 2003). Existing studies have demonstrated there is a well-established causal relationship between drought and salinity (Hassani et al., 2020a; Perri et al., 2020, 2022). One study has also concluded that climate change primarily influences farmland salinity by altering soil moisture (SM) levels (Corwin, 2021). However, there is limited quantitative assessment of the link between soil salinity and drought induced by SM deficiency on a global scale. Specifically, while soil salinity accumulation follows a gradual process over time, the mechanisms by which soil drought events influence salinity accumulation remain incompletely understood. Furthermore, the developmental processes and the thresholds at which soil drought triggers a transition from non-saline to saline soils during soil salt accumulation are still unclear.

In this study, we examine the global distribution of saline soils and identify regions that have experienced significant increases in salinity from 1980 to 2018. The primary aim is to explore the mechanisms and thresholds underlying salinity dynamics, thereby clarifying the quantitative relationship between salinity changes and soil drought. Additionally, we identify the dominant climatic factors driving salt accumulation induced by soil drought across different climate regions. Our findings highlight the growing risk of soil salinization under long-term droughts and offer valuable insights for assessing soil vulnerability to degradation.

2. Methods

2.1. Definition of Soil Salinity

In this study, we used the electrical conductivity of soil extract (EC_e) to quantify soil salinity levels (Corwin, 2021) and categorized soils into two categories (Abrol et al., 1988): saline soils and non-saline soils. Saline soils are characterized by the excessive accumulation of soluble salts both on the soil surface and within the root zone, with $EC_e \geq 2dS\ m^{-1}$. Here, “dS” stands for deci-Siemens; $1\ dS\ m^{-1}$ equals $0.1\ S\ m^{-1}$, which means one-tenth of a Siemens per meter. This threshold represents the upper salinity limit tolerable by sensitive crops (Maas & Grattan, 1999). In contrast, non-saline soils have a negligible effect on crop plants, with $0 < EC_e < 2dS\ m^{-1}$.

The annual surface salinity (EC_e) data used in this study were obtained from the University of Manchester (Hassani et al., 2020a). The data were developed using machine learning techniques that integrated multiple global and regional soil profile databases into a labeled training set. These data sources include the World Soil Information Service (WoSIS) Data set (Batjes et al., 2017), the National Cooperative Soil Survey Characterization Database (<https://ncsslabdatamart.sc.egov.usda.gov/>), the Africa Soil Profiles Database (Leenaars et al., 2014), and the ISIRC-WISE Harmonized Global Soil Profile Data set (Batjes, 2009). A detailed description of EC_e data can be seen in Text S1 in Supporting Information S1.

2.2. Definition of Dryness Conditions and Drought Events

We defined soil drought as occurring when SM values (percentiles) fall below a threshold value continuously in time over a contiguous area (Andreadis & Lettenmaier, 2006), which reflects the rarity and extremity of the event. In this study, a threshold value of the 20th percentile of SM quantile was used to distinguish drought from non-drought, as in previous drought identification work (Andreadis & Lettenmaier, 2006; A. Wang et al., 2008). This is also the threshold used in the U.S. Drought Monitor (available at <https://droughtmonitor.unl.edu/About/AbouttheData/DroughtClassification.aspx>).

To account for seasonal variability, we converted daily SM data (see a detailed description of SM data in Text S1 in Supporting Information S1) into weekly averages and computed percentile ranks based on weekly data from 1980 to 2018. Weekly SM values below the 20th percentile were classified as drought conditions, while values above this threshold were considered non-drought.

This study primarily focuses on drought events with a minimum duration of 4 weeks (i.e., monthly droughts). Adjacent drought events were not merged for this study. We selected the total number of days, frequency, and severity as key indicators of soil drought events. For brevity and clarity, the term “total number of days” is hereafter referred to as “total days.” Total days are defined as the cumulative duration of all drought events in the

region for a given year. Frequency is defined as the total number of drought events. Severity is defined as the cumulative difference between the SM value and the 20th percentile threshold during a drought event (20th percentile minus SM value). A detailed description and schematic diagram are provided in Text S2 and Figure S8 in Supporting Information S1.

2.3. Definition of Drylands

We distinguished climate regions through the classic aridity index (AI), defined as the ratio of long-term mean precipitation (P) to potential evapotranspiration (PET) (Zomer et al., 2022), which is a widely used indicator of regional moisture conditions. The aridity classifications are as follows: hyper-arid (<0.03), arid ($0.03\text{--}0.2$), semi-arid ($0.2\text{--}0.5$), dry sub-humid ($0.5\text{--}0.65$), and humid (>0.65) regions (Zomer et al., 2022).

This study uses the terms “dry regions” and “wet regions” for classification purposes. It is notable that “dry regions” are defined as broader dry areas with $AI \leq 0.65$, including hyper-arid, arid, semi-arid, and dry sub-humid regions (Hassani et al., 2021). In contrast, “wet regions” are defined as areas with $AI > 0.65$. A detailed description of Climatic data can be seen in Text S1 in Supporting Information S1.

2.4. Trend Detection

We used a time series analysis approach that integrated both the Theil-Sen slope estimator (TS) and the Mann-Kendall (MK) significance to examine spatiotemporal variations in soil salinity. We used the coefficient of variation to analyze the volatility of EC_e data, which is commonly used in vegetation research to reflect the discrete degree and annual or inter-annual volatility (Tucker et al., 1991). According to previous studies, the coefficient of variation (CV) is classified into three levels: strong volatility ($CV > 0.25$), moderate volatility ($0.1 < CV \leq 0.25$), and slight volatility ($CV \leq 0.1$) (Shi et al., 2002). A detailed description of methods can be seen in Texts S3 and S4 in Supporting Information S1.

3. Results

3.1. Spatiotemporal Patterns and Changes in Soil Salinity

Over the past four decades (1980–2018), the global spatial distribution of soil salinity has shown that saline soils are primarily located in Central Asia, the Middle East, Northern Africa, Western North America, Northern South America, and Central and Western Australia (Figure 1a). This observation is consistent with the conclusions from the World Soil Day Conference (available at <https://www.fao.org/world-soil-day/en/>). Among these regions, some exhibit high levels of salinization, as indicated by the red regions in Figure 1a. Globally, the percentage of saline soils in dry climate regions (hyper-arid and arid regions) is higher than that in wet climates (semi-arid, dry sub-humid, and humid regions), as shown in Figure 1c. Specifically, the percentage of saline soils in arid regions is much higher than that in other climate regions (Maas & Grattan, 1999; Szabolcs, 1990). Figure 1d also shows that the highest salinity levels are observed in the arid and hyper-arid regions. A comparison of the spatial distribution of saline soils (Figure S1a in Supporting Information S1) with the distribution of AI (Figure S1b in Supporting Information S1) clearly demonstrates that climate regions with low AI are associated with a high risk of salinization. This observation aligns with previous studies (Hassani et al., 2020a; Perri et al., 2018; Schofield & Kirkby, 2003), indicating that regions with AI lower than 0.5 often have saline soils (Osman, 2018). Specifically, salt in the soil migrates and accumulates with water, and the dryness or wetness of the climate determines the distribution of water, thereby affecting the type and rate of salinization (R.-M. R. Yang & Guo, 2019).

Additionally, to analyze the salinity data volatility using the coefficient of variation, assessments were carried out at three levels (see Section 2). The results indicate that the volatility of soil salinity varies across different spatial scales. Figure S1c in Supporting Information S1 illustrates that 34.77% of global regions exhibit significant variability in soil salinization, mainly distributed in Western Asia, the Middle East, Northern Africa, Southern Africa, Western North America, Northern South America, and Central and Western Australia. Meanwhile, 29.19% of regions show moderate variability, while 36.05% of regions present slight volatility. The regions with relatively stable soil salinity ($CV \leq 0.25$) are primarily distributed in Europe, Eastern, and Central North America, Eastern South America, Central Africa, and Eastern Asia. Previous studies have shown that the observed overall volatility in soil salinity may be related to complex multi-year climate patterns or extreme environmental events

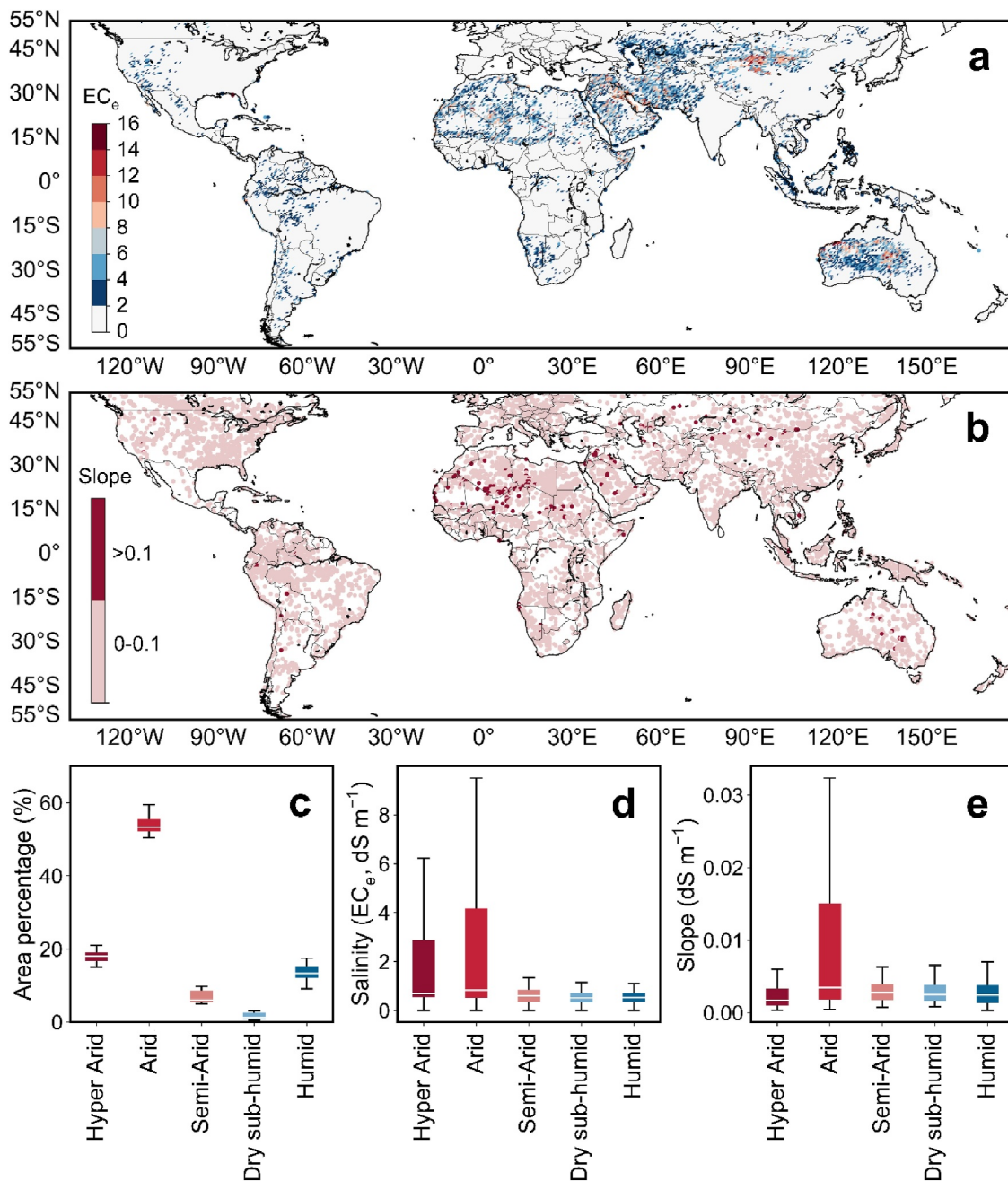


Figure 1. Global trends in soil salinity (1980–2018). (a), Mean soil salinity over the 39-year period. (b), Regions with a statistically significant increases ($P < 0.05$) in soil salinity. (c–e), Box plots illustrating, by climate region, the percentage of saline soil area (c), salinity distribution (d), and rate of change (slope) (e). In the box plots, the white lines indicate the median, and the bottom and top edges of the boxes represent the 25th and 75th percentiles, respectively. Outliers are not shown.

(Hassani et al., 2020a). For example, soil salinity in Australia fluctuated significantly from 1998 to 2015, possibly related to continent-wide hydrological variations between dry and wet periods as a result of the El Niño–Southern Oscillation Cycle (Hassani et al., 2020a; Van Dijk et al., 2013).

Furthermore, the Theil-Sen estimator (TS) was used to analyze the global trend of soil salinity from 1980 to 2018 and identified regions with significantly increased salinity, as shown in Figure 1b. It is evident that these increases in salinity are globally distributed, rather than being concentrated in specific regions. About 14.73% of global soils have experienced a significant increase in salinity. Figure 1b indicates that these significant increases occur in both dry and wet regions. This finding corresponds with existing studies, which have reported an aggravation of

soil salinization in arid and semi-arid regions due to climate change and overexploitation of water resources for agricultural irrigation, with the mean increased trend of soil salinization in wet regions being significant (Eswar et al., 2021). The regions where salinity has increased most rapidly are primarily distributed in Northern Africa and the Middle East.

It is worth noting that the slope of salinity change in arid regions shows a wide range (Figure 1e). A comparison of Figures 1a and 1b reveals that 15.53% of the areas with significant increases are found in saline soils, while 84.47% are located in non-saline soils. This phenomenon indicates that not only do saline soils need attention because they are at risk of further deterioration, but non-saline soils also deserve special attention because their salinity levels are increasing significantly, which is likely to directly affect plant growth and soil fertility in the future. Although there are regions around the world where salinity has been reduced or remained unchanged, existing research has shown that saline soil management is being taken seriously by various stakeholders, achieving positive outcomes (Singh, 2021). Since the phenomenon of salinity reduction and stability caused by management measures and other reasons is not within the scope of our study, these regions are not highlighted.

3.2. Salinization Trends Related to Changes in Soil Drought

Lack of SM is an important driver of soil salinity (Corwin, 2021). In this study, we focused on regions where salinity has significantly increased over the past 39 years and investigated the correlation between the increase in salinity and soil drought in these hotspot areas. To eliminate the spatiotemporal differences in soil water content, we compared the spatiotemporal patterns of soil dry and wet conditions on a global scale. We identified drought and non-drought conditions using the 20th percentile of SM as a threshold, focusing on soil drought events with a minimum duration of 4 weeks (see Section 2).

Using the total number of days as a key indicator of soil drought events, we mapped the global distribution of the 39-year average of soil drought events (Figure 2a and Figure S2 in Supporting Information S1). For brevity and clarity, the term “total number of days” is hereafter referred to as “total days.” It is evident that in hyper-arid regions, such as the Sahara Desert, there were fewer total days of soil drought events per year than expected. In contrast, arid regions exhibit a higher range of total days of soil drought events compared to other climate regions, while humid regions also show relatively high total days of soil drought events (Figure 2d). Figure 2b illustrates a significant increase in total days of soil drought events in both dry and wet regions, with the increase in dry regions being much greater than in wet regions. The frequency of drought events has also risen significantly, with the increase being slightly greater in wet regions compared to dry regions (Figure S3c in Supporting Information S1). However, the increase in the severity of soil drought events is not as pronounced (Figure S3d in Supporting Information S1). Meanwhile, Pearson correlation analysis reveals a significant positive correlation between the increased soil salinity and the increased total days of soil drought events (Figure 2c and Figure S4 in Supporting Information S1), as well as the increased frequency of soil drought events (Figure 2e), with total days showing a stronger correlation in dry regions. Pixel-based maps of the Pearson correlation coefficient between soil salinity and total days of soil drought events are shown in Figure S5 in Supporting Information S1.

The total days of soil drought events were further categorized into intervals of 4–8 weeks, 8–12 weeks, ..., and 48–52 weeks, to examine the effects of drought events with different total days of soil drought events on soil salinity. As shown in Figure 3a, in dry regions, soil salinity significantly increases as the total days of soil drought events increase. When the total days of soil drought events exceed 6 months (184 days), a critical threshold is observed, making the transition of soil property from non-saline to saline, with soil salinity increasing from $EC_e < 2dS\ m^{-1}$ to $EC_e \geq 2dS\ m^{-1}$. This critical change in soil salinity is referred to as “the transition of soil property” in this study. Previous research has also confirmed that long-term droughts have the potential to release large amounts of salts from the geological substrates with high salt concentrations (Hassani et al., 2021). Further analysis has revealed that over the past 39 years, 12.84% of dry regions within hotspot areas and 6.78% of global dry regions have experienced the transition of soil properties, which can be attributed to the increase in total days of soil drought events. Compared to non-saline soils, the salinity in saline soils increases more rapidly over time (Figures 3b and 3c). Additionally, the soil areas that have experienced long-term drought events (total days > 6 months) have shown a significant increasing trend in both non-saline and saline soils, which has contributed to further soil salinization (Figure S6 in Supporting Information S1). These findings indicate that the risk of soil property transition due to long-term drought events is likely to increase gradually.

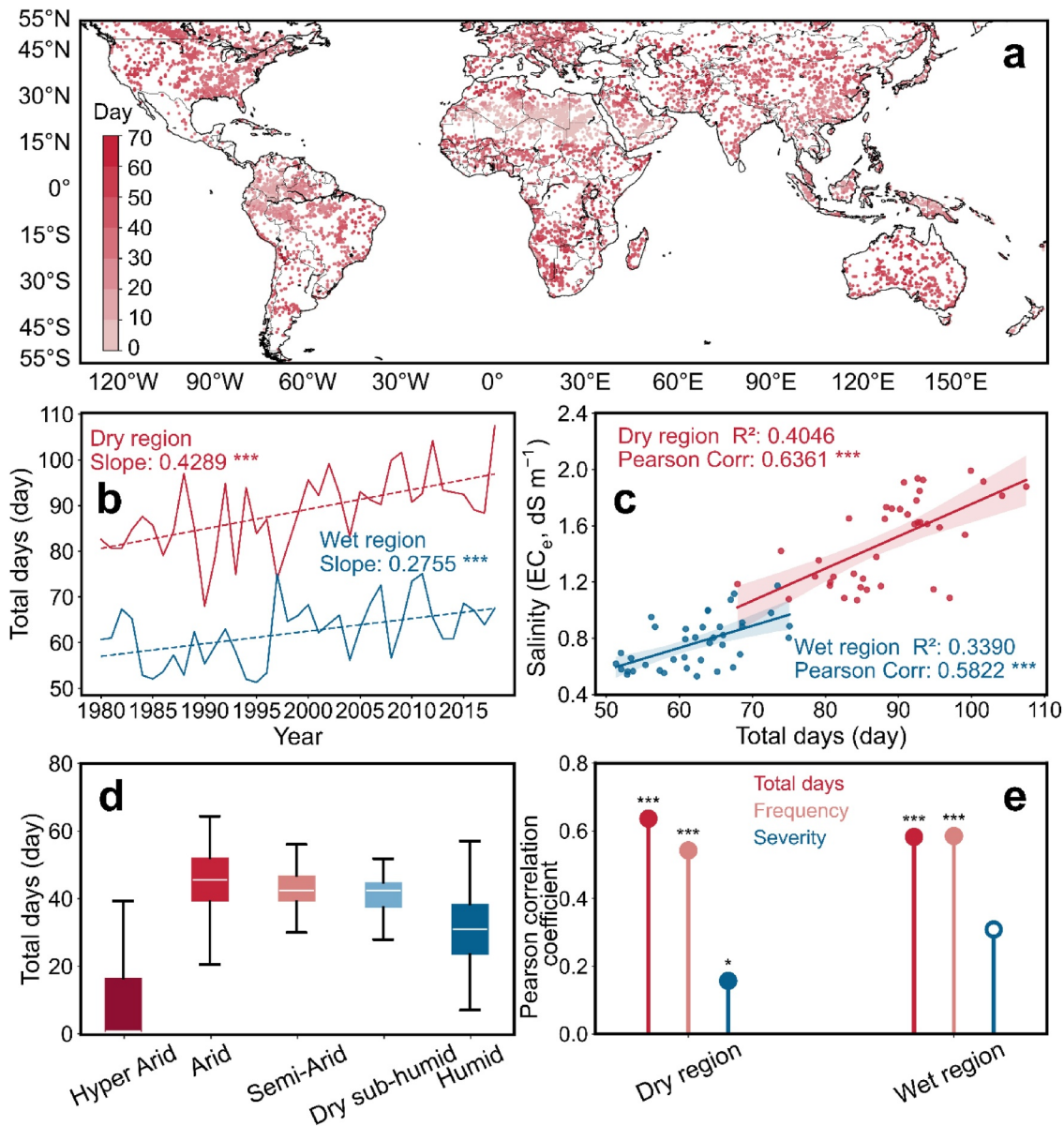


Figure 2. Global patterns of soil drought events. (a), Global distribution of soil drought events in hotspot areas. (b), Trends in the total days of soil drought events in dry and wet regions from 1980 to 2018. (c), Correlation between the total days of soil drought events and EC_e for dry and wet regions. Solid lines represent the best-fit lines based on the Pearson correlation coefficient (R^2 ; $P < 0.1^*$; $P < 0.05^{**}$; $P < 0.001^{***}$). The best-fit line indicates a linear relationship for all factors. The shaded area represents the 95% confidence interval. (d), Distribution of total drought days grouped by climate region. (e), Correlation coefficients between key soil drought indicators and EC_e in dry and wet regions. Solid circles represent statistically significant correlations, while hollow circles represent non-significant correlations. The vertical position of each circle indicates the correlation coefficient value.

It is important to note that when analyzing the transition of soil property from non-saline to saline, specific criteria were applied to avoid accounting for short-term or incidental increases in salinity in certain years. A region was classified as non-saline if more than 75% of the years before the transition were characterized by non-saline conditions (Hassani et al., 2020a). Similarly, a region was classified as saline if more than 75% of the years after the change exhibited saline conditions (Hassani et al., 2020a). Previous studies have indicated that as climate conditions become wetter, factors such as topography, groundwater, and soil texture have an increasing influence on salinity (Nosetto et al., 2013; Schofield & Kirkby, 2003). Meanwhile, in wet regions, there are fewer long-term drought events, resulting in limited data samples. Therefore, apart from the significant positive correlation

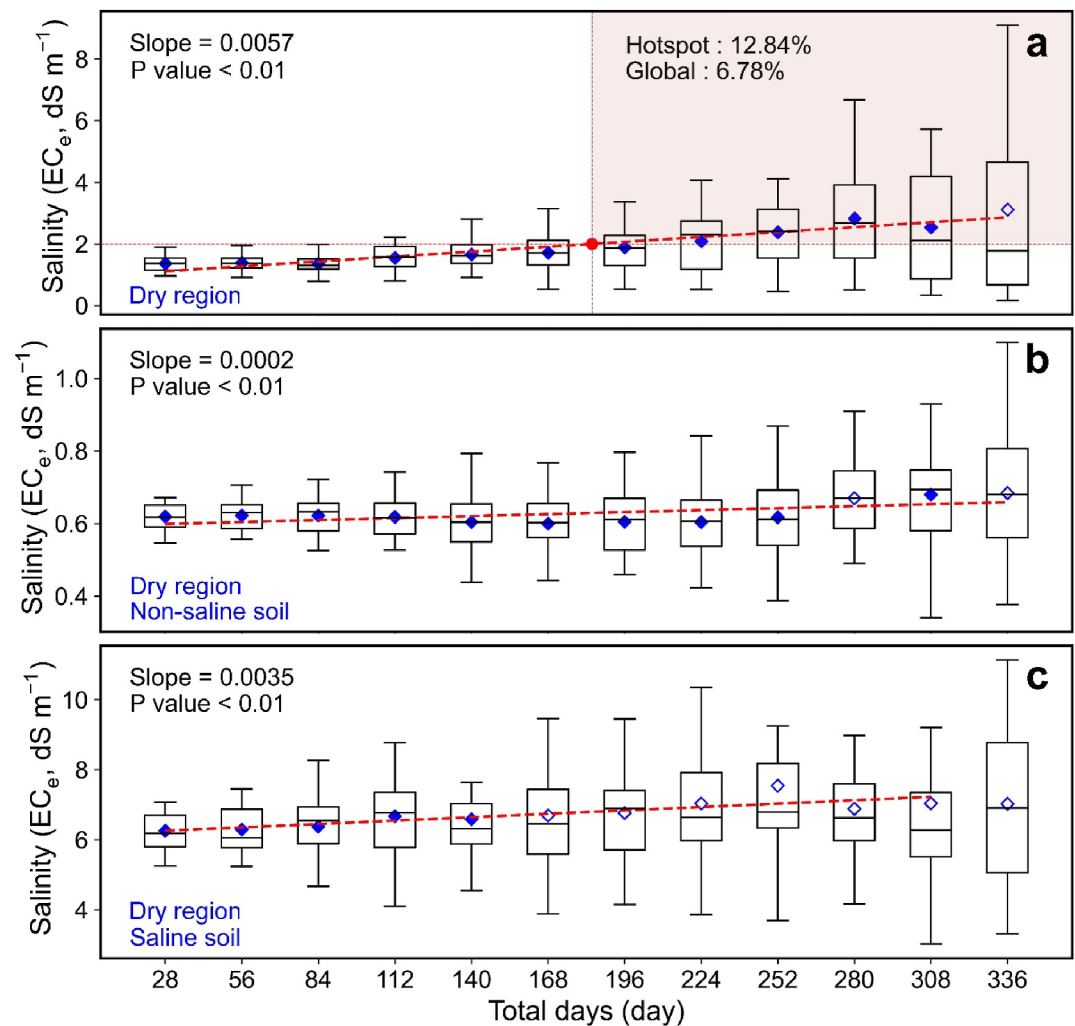


Figure 3. Salinity trends related to the total days of soil drought events. (a), Global dry regions within the hotspots. The red horizontal dotted line corresponds to the threshold ($EC_e = 2 \text{ dS m}^{-1}$) for the transition of from non-saline to saline soils. When the total days of soil drought events exceed 6 months (184 days), the soil transitions from non-saline to saline, with soil salinity increasing from $EC_e < 2 \text{ dS m}^{-1}$ to $EC_e \geq 2 \text{ dS m}^{-1}$. (b), Non-saline soils in dry regions of the hotspots. (c), Saline soils in dry regions of the hotspots. The black central marks indicate the median, while the blue diamond marks indicate the mean. The red dotted line represents the trend of the mean salinity. A solid blue diamond represents a complete 39-year record, while a hollow blue diamond represents an incomplete record, primarily due to the lack of drought events off the specified duration in those years. The threshold for missing data is set at 50%. If the proportion of valid data falls below this threshold, the corresponding data will be excluded from the trend line plot.

observed between soil salinity and drought events in wet regions (Figure 2d), no further analysis was conducted for these regions.

3.3. Physical Processes That Cause Soil Droughts

Changes in soil drought characteristics are associated with a range of climatic factors that can influence SM dynamics, including temperature (T), vapor pressure deficit (VPD), potential evapotranspiration (PET), and precipitation (P) (Mukherjee et al., 2023; Qing et al., 2023). To investigate the evolution of soil drought characteristics that directly impact soil salinity, we plotted the time series of annual mean total days, annual mean SM, annual mean PET, annual mean VPD, annual mean T, and annual mean P from 1980 to 2018 (Figure S7 in Supporting Information S1). PET represents the atmospheric evaporative demand, which combines soil surface evaporation and plant transpiration (Thornthwaite, 1948). VPD dictates the evaporative demand placed on plant leaves (Jensen et al., 2016). Both high PET and high VPD (Liu et al., 2020) exacerbate SM depletion. It can be

observed that SM has decreased over the past 39 years, while the total days of soil drought events have increased gradually. Correspondingly, T, VPD, and PET have shown an upward trend year by year, while P exhibits a more complex pattern (Blankenau et al., 2020; Jiang et al., 2019). The results further indicate that high T, high PET, and high VPD are often associated with low SM, contributing to the increased total days of soil drought events (Figure S7 in Supporting Information S1). It can be seen intuitively that, with the year 2000 as a boundary, SM was at a relatively high level during the 39 years before 2000, while VPD, PET, and T were all at a low level; after 2000, the opposite trend is evident. In contrast, P lacks obvious temporal and regular patterns. The lack of a clear relationship is likely because this study used annual mean P data, which fails to capture the effects of different rainfall event characteristics on soil salinity. Existing studies have shown that even in the driest environments, sporadic but intense rainfall events are sufficient to suppress soil salinity (Stocker et al., 2019; Van Der Zee et al., 2014). Conversely, relatively humid environments characterized by more frequent but low-intensity precipitation are prone to salinization due to the low incidence of leaching (Perri et al., 2022). Therefore, it is impossible to effectively identify the mechanisms of soil salt leaching or accumulation for different rainfall events through annual mean P data.

To further explore the contribution of climatic factors to soil droughts and identify the key drivers, we conducted a correlation analysis between climatic factors and total days of soil drought events across five climate regions. Pearson correlation analysis revealed significant positive correlations between PET, VPD, T, and total days (Figures 4a–4c). Moreover, PET and VPD showed diverse distribution patterns across different climate regions, while T exhibited a more uniform distribution. Additionally, the dominant factors influencing total days of soil drought events varied across different climate regions. As shown in Figure 4d, T plays a significant role in the hyper-arid regions, whereas PET is the dominant factor in arid regions. These findings align with previous studies (Taghizadeh-Mehrjardi et al., 2021; N. Wang et al., 2024). In drylands, SM levels are primarily controlled by strong evaporation (N. Wang et al., 2024). At the same time, soil salinity in drylands is mainly influenced by soil drought induced by low SM and high T (Taghizadeh-Mehrjardi et al., 2021), which helps explain why high T and high PET in drylands contribute to increased soil salinity. Meanwhile, VPD mainly contributes to the total days of soil drought events in regions with $AI \geq 0.2$ (semi-arid, dry sub-humid, and humid regions). It is believed that high VPD enhances the atmospheric evaporative demand, thereby intensifying SM depletion through land-atmosphere interactions (Zhou et al., 2019). The increasing VPD triggers a rapid decline in SM (Qing et al., 2022). This phenomenon can be used to explain the occurrence of soil drought events induced by low SM and an increase in total days of soil drought events within the regions with $AI \geq 0.2$.

4. Discussions and Conclusions

In this study, we examined the global distribution of saline soils and regions that have experienced significant increases in salinity from 1980 to 2018. As reported in previous studies (Hassani et al., 2020a; Mulder et al., 2011; Rozema & Flowers, 2008), Central Asia, the Middle East, Northern Africa, Western North America, Northern South America, and Central and Western Australia are the primary regions affected by salinity. Our analysis revealed that the increase in salinity distribution from 1980 to 2018 represents a global phenomenon rather than being concentrated in specific regions. Furthermore, we analyzed the trend of global soil drought events by examining the total days, frequency, and severity as key indicators. Our findings illustrate that the total days and frequency of soil drought events increased significantly in both dry and wet regions, with total days of soil drought events showing a steeper upward trend. However, the increase in drought severity was not statistically significant across these regions. This positive correlation between soil salinity and total days of soil drought events suggests that long-term soil drought events contribute to increasing soil salinity. Additionally, we observed an expanding area of soils experiencing long-term drought events (total day > 6 months). This finding is particularly concerning, as long-term soil drought events play an important role in the transition of soil property from non-saline to saline. Notably, this change has resulted in soil salinization in 12.84% of dry regions within hotspot areas and 6.78% of global dry regions over the past 39 years, mainly attributed to the increase in total days of soil drought events. Given the upward trend in soil areas affected by long-term droughts, the potential risks of further soil salinization should be taken seriously.

Considering that the EC_e data used in this study was derived from machine learning predictions and thus inherently uncertain, we conducted an error analysis of the results, as presented in Figures S9–S15 in Supporting Information S1. A detailed description can be seen in Text S5 in Supporting Information S1. In addition, to account for the uncertainty associated with ERA5 SM data set, we employed the Global Land Evaporation

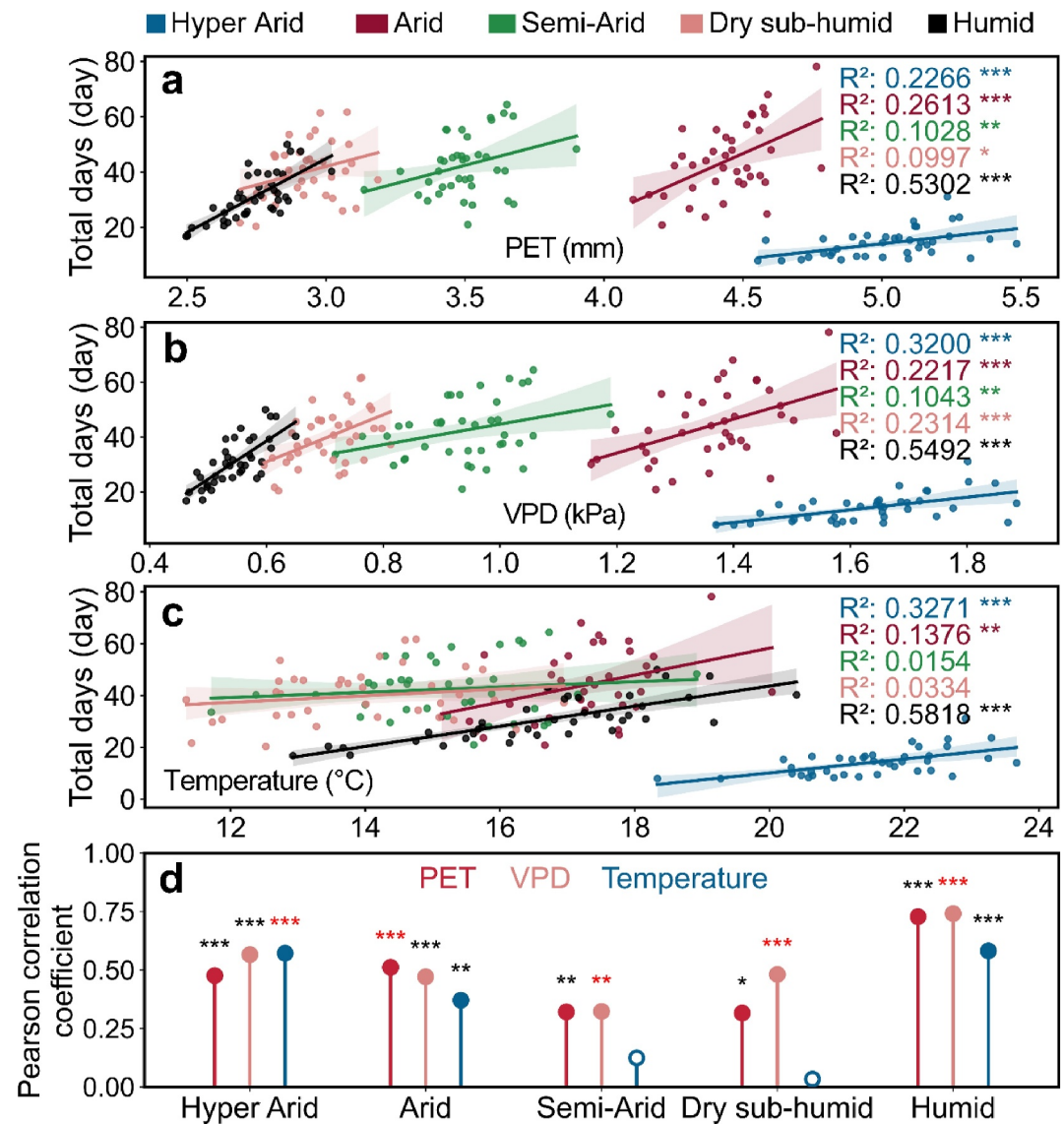


Figure 4. Correlation between the total days of soil drought events and climatic factors across different climate regions. (a), PET. (b), VPD. (c), T. (d), Statistics of dominant climatic factors across different climate regions. Solid and hollow circles denote significant and non-significant correlations, respectively. The vertical position of each circle indicates the R value. Red asterisk (*) represents the dominant factors with the highest Pearson correlation coefficient (R^2 ; $P < 0.1^*$; $P < 0.05^{**}$; $P < 0.001^{***}$).

Amsterdam Model (GLEAM) Data set (Miralles et al., 2025) (<https://doi.org/10.5281/zenodo.14724263>) to assess the robustness of the results (see Figures S16–S19 in Supporting Information S1). Figure S16 in Supporting Information S1 demonstrates that both the total number of drought days and drought frequency increased significantly in both dry and wet regions, with the total number of drought days exhibiting a steeper upward trend. The observed positive correlation between soil salinity and the total number of drought days indicates that long-term drought events contribute to increasing soil salinity (Figures S17–S19 in Supporting Information S1). Notably, when the total number of drought days reaches six months, soil salinity exceeds the threshold (Figure S17 in Supporting Information S1), which is consistent with our analysis.

The changes in soil drought characteristics are associated with various climatic factors. In this study, we investigated the evolution of soil drought characteristics that have a direct impact on soil salinity and conducted an attribution analysis by choosing five common climatic factors, including SM, T, PET, VPD, and P. We found that high T, high PET, and high VPD often coincide with low SM, which contributes to the high total days of soil

drought events. It is notable that the dominant factors influencing total days of soil drought events vary across different climate regions. T plays a significant role in affecting total days of soil drought events in hyper-arid regions, with PET as the dominant factor in arid regions. Meanwhile, VPD mainly contributes to the total days of soil drought events in regions with $AI \geq 0.2$ (semi-arid, dry sub-humid, and humid regions). This finding is also supported by previous studies, which illustrates that soil salinity in drylands is primarily controlled by drought and heat (Taghizadeh-Mehrjardi et al., 2021). Meanwhile, high VPD enhances the atmospheric evaporative demand, which leads to low SM that causes soil drought events. Therefore, high soil evapotranspiration leads to salt accumulating on the soil surface and in the root zone, with high T, high PET, and high VPD playing significant roles in promoting this effect. Although P plays a significant role in leaching soil salinity, the annual mean P cannot capture the variability and characteristics of individual rainfall events. Due to large intra-annual variations of P, the clear temporal and regular patterns between P and soil salinity cannot be identified when relying solely on annual averages.

Our study addresses part of the existing knowledge gap by quantifying the correlation between soil drought and salinity. It demonstrates that soil salinity has significantly increased with the rise in the total days and the frequency of soil drought events, while the correlation between severity of drought events and soil salinity remains insignificant. The observed weak correlation between drought severity and soil salinity is likely due to their distinct formation mechanisms and response scales of salinization. Soil salinity is primarily governed by the long-term balance of water and salt (Corwin, 2021). It develops through the gradual accumulation of salts resulting from persistent evaporation, a slow process with a lagged response (Shokri et al., 2024; T. Yang et al., 2023). Conversely, the frequency and duration of leaching events, such as rainfall or irrigation, further determine whether salts accumulate in the surface and root zones (T. Yang et al., 2023). Consequently, a short but severe drought has limited impact on salinization if followed by relatively wet conditions (Perri et al., 2022). For these reasons, the duration and frequency of drought events are often more influential on soil salinity than the severity of any single event. Consequently, if future studies analyze long-term scale-related issues of soil drought events affecting soil salinity, they should focus more on the total days of soil drought events and their frequency as key indicators. Additionally, long-term droughts contribute to increased soil salinity, posing a serious threat of further soil degradation. Current drought emergency plans primarily focus on optimizing distribution of water resources from the perspective of human livelihood and socio-economic factors, often neglecting the urgent protection and remediation of usable land, such as through effective water delivery for leaching of accumulated salts. Therefore, the drought threshold identified in this study, which triggers the transition of soil property, can broaden the insights for policymakers when formulating drought emergency plans and implementing emergency measures. Our findings enable managers to prioritize not only the protection of human livelihood and economic development but also to address the risk of hard-to-recover soil degradation exacerbated by drought, facilitating more effective and sustainable planning of water resources. We hope that our study contributes to policy debates by identifying regions at risk of salinization and highlighting the increased vulnerability of soils under climate change. By promoting proactive soil protection measures, we aim to reduce the reliance on costly remediation efforts for already salinized soils.

Despite the valuable insights gained, this study has several limitations. Firstly, the EC_e data used in this study are not direct observations but predictions derived from a machine learning model. Although the previous study provided an overall accuracy of 89.65% (95% CI: 88.33%–88.87%) for the EC_e data source based on 10-fold cross-validation (Hassani et al., 2020a), these data are inherently less reliable than actual observations. Secondly, the analysis relies on annually modeled EC_e data (generated by the machine learning model) and climatic factors, which may overlook extreme weather events that significantly drive the short-term fluctuations in soil salinity. Utilizing monthly or seasonal data of salinity could provide a more in-depth understanding of how droughts or rainfall influence salt accumulation and leaching in soils. However, global salinity data with high temporal resolution are currently unavailable. Thirdly, our analysis does not account for the effects of human activities, such as irrigation practices, land use changes, and agricultural management, which play crucial roles in soil salinity dynamics (Utset & Borroto, 2001). For instance, improper irrigation techniques can lead to salt accumulation, while deforestation and urbanization can alter water availability, thereby affecting salinity levels. Incorporating these factors in future studies would offer a more comprehensive perspective on the interplay between human activities and climatic influences in driving soil salinization. For instance, whether there is a relationship between increased salinity and reduced vegetation cover in the Amazon basin is an interesting question that remains to be explored. Finally, while this study highlights the connection between increased soil

drought and salinization, further research is needed to predict the future dynamics and extent of soil salinity, as well as to assess the potential impacts of climate change on this relationship. Under different future climate scenarios, rising temperatures and shifts in precipitation patterns are likely to alter the characteristics of drought events, potentially accelerating salinization processes in both dry and wet regions. Addressing these gaps will improve our understanding of soil salinization mechanisms and inform more effective mitigation strategies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All datasets used in this study are publicly available. The electrical conductivity of soil extract (EC_e) dataset is available at <https://doi.org/10.17632/v9mgbmtmf2.1> (Hassani et al., 2020b). Soil moisture (SM) dataset are provided by the European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5, <https://doi.org/10.24381/cds.e2161bac>) (Muñoz-Sabater, 2019) and the Global Land Evaporation Amsterdam Model (GLEAM, <https://doi.org/10.5281/zenodo.14724263>) (Miralles et al., 2025). Climatic datasets are provided by the gridded Climate Research Unit Time Series (CRU TS v.4.04, <https://catalogue.ceda.ac.uk/uuid/89e1e34ec3554d-c98594a5732622bce9>) (Harris et al., 2020). Relevant processed data of this study is stored at Zenodo (Li, 2025).

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