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Key Points:
- Soil heat extremes show a significant 20% increase in land areas affected by flash droughts
- Humid regions are at a higher risk of experiencing soil heat extremes
- Soil heat extremes are becoming more frequent and longer-lasting following flash drought outbreaks, particularly in humid regions

Supporting Information:

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

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Increasing Trends in Soil Heat Extremes Following Flash Drought Outbreaks

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Abstract Flash droughts, characterized by rapid declines in soil moisture (SM), pose significant threats to ecosystems. Understanding the response of soil temperature (ST) to the rapid SM decline during flash droughts has critical implications for the root systems of terrestrial ecosystems. In this study, we identify soil heat extreme events that follow flash drought outbreaks. Our findings reveal that global land areas experience a significant increase in soil heat after the outbreak stage of flash droughts, with affected areas expanding by an average of 4.36%–9.74% per decade. Humid regions show a significantly higher percentage of affected land areas compared to arid regions. The proportion of soil heat extremes following flash drought outbreaks increases significantly by 16.53%–23.38%, with event days occurring twice as often, particularly in humid regions. This suggests that root systems will encounter exacerbated stress as soil heat intensifies during sudden abnormal soil drying.

Plain Language Summary Flash droughts, characterized by sudden and rapid reductions in soil moisture (SM) during the outbreak stage, pose threats to ecosystems worldwide. Understanding how soil temperature changes when soil dries out quickly during flash droughts is crucial, as it directly affects plant roots and ecosystem health. This study identifies extreme soil heat events following rapid soil drying during flash droughts. We demonstrate that as SM sharply declines during flash drought outbreaks, soil temperatures rise significantly, leading to more frequent and intense heat extremes. Our findings indicate that the land area at risk of soil overheating is increasing globally after flash drought outbreaks, particularly in wetter regions. Notably, these soil heat extremes now occur twice as often as they did decades ago and last longer, which can place additional stress on plant roots and disrupt natural processes. This combination of rapid drying and intense soil heat can stress plant roots, reduce soil fertility, and hinder ecosystem recovery. Understanding these intensified soil heat extremes is crucial for managing agricultural practices and protecting natural habitats.

1. Introduction

The increasing frequency and intensification of flash droughts can critically damage the health of ecosystems (Jing et al., 2025; Sungmin & Park, 2023, 2024; Xi & Yuan, 2023; Yao et al., 2022; M. Zhang & Yuan, 2020). These droughts are characterized by rapid soil moisture (SM) depletion (Mukherjee & Mishra, 2022; Otkin et al., 2018; Qing et al., 2022; Sehgal et al., 2021; Yuan et al., 2023). In addition to SM, soil temperature (ST) is an important component that can influence the ecosystem root growth and soil chemical properties, affecting the ecosystem carbon cycle by enhancing decomposition rates and increasing carbon dioxide release, which in turn alter carbon sequestration and emissions (Achury et al., 2022; Kang et al., 2000; Luo et al., 2020; Nievola et al., 2017; Onwuka & Mang, 2018; Pivonia et al., 2002; Soong et al., 2021). The soil thermal condition is also affected by SM content and heat transfer between soil and air (Niu et al., 2015; Ochsner et al., 2001; Roxy et al., 2014; Sugathan et al., 2014).

Droughts and heatwaves are likely to occur simultaneously since antecedent droughts can heat the land surface and raise the air temperature (Mukherjee & Mishra, 2021; Osman et al., 2022; Tripathy et al., 2023; Zeng et al., 2023; Zhang et al., 2022; Zhou et al., 2024; Zhou & Yuan, 2023). However, heat extreme events in soil that are likely to follow the decline in SM have been understudied, particularly in the context of flash droughts characterized by rapid SM depletion during their outbreak. Previous studies have indicated that heatwave events tend to exhibit higher intensities and longer durations during flash droughts, which could lead to disproportionate losses (Christian et al., 2020; K. Fu & Wang, 2023; K. Fu et al., 2024; Wang et al., 2023). Under drying conditions, heat can reduce root production, prolong the recovery time of ecosystems, and lead to a significant reduction in the terrestrial carbon sink (Haghighi et al., 2021; Li et al., 2021; Yao et al., 2024).

Under drought conditions, air temperature cannot fully capture the dynamics of soil heat (Fan et al., 2024). More importantly, extreme ST is increasing faster than air temperature (García-García et al., 2023; Wang et al., 2024), highlighting the need to identify the soil heat extremes following rapid soil drying. ST is negatively correlated with SM (Cortez, 1998; M. S. Jin & Mullens, 2014; Li et al., 2008, 2020; Zhang et al., 2020). The outbreak of flash droughts could thus lead to a high risk of subsequent soil heat extremes. SM significantly influences ecosystem productivity (Liu et al., 2020; Song et al., 2019; Stocker et al., 2019; Xu et al., 2019), highlighting the substantial threats posed by the increasing frequency of flash droughts characterized by rapid SM depletion in a warming climate. Additionally, ecological phenology is sensitive to ST changes, and extreme high ST may significantly weaken ecosystem root systems by inhibiting root growth and function, disrupting water and nutrient uptake. This weakening can lead to altered soil thermal, reducing the ecosystem ability to cope with environmental stress and potentially causing plant mortality due to insufficient water and nutrient supply (Huang et al., 2024; Majdi & Öhrvik, 2004; Wang et al., 2007; Zhang et al., 2020). For instance, a prior study examined the advanced spring phenology (SOS) of the forest in China and simulated the coupling temperature and SM effects on SOS, indicating that ST is the main driver of SOS variability, as widespread increases in ST promote earlier root growth and enhance soil microbial activity (Liu et al., 2024).

Elevated ST can also enhance root hydraulic conductivity, which may lead to increased water loss and reduced water use efficiency. These factors can lead to water stress and nutrient deficiencies, which are potentially detrimental to plant growth by stunting development, reducing biomass, and impairing physiological functions (Lipiec et al., 2013). A systematic understanding of interactions between potential soil heat extremes and flash drought events in addition to ST dynamics following rapid SM decline is thus crucial for developing early warning systems to mitigate impacts on various soil processes and terrestrial root systems. Previous studies have rarely addressed the interaction between extreme flash droughts (a rapid-onset, severe subset of droughts) and soil heat extremes beyond simple correlations between variables. Moreover, the mechanisms linking these extreme events remain unknown. Understanding these interactions is crucial, as the co-occurrence of such extremes may amplify ecosystem risks beyond what is suggested by changes in individual variables alone.

Flash droughts are more likely to occur in humid regions and could be more severe (L. Wang & Yuan, 2018; Zhu & Wang, 2021). Unfortunately, ecosystems in these regions have lower hydrological resilience and are vulnerable to rapid changes in drought frequency (Booth et al., 2012; Helman et al., 2017). The surface energy budget differs over dry and wet land surfaces with different physical properties (Bastiaanssen et al., 1998; Betts et al., 1996; Jiménez et al., 2011; Lei et al., 2018; Petrone et al., 2000), which can influence heat flux and thus affect the increase in ST differently in humid and arid regions (Sauer & Peng, 2020). Further analysis of soil heat extremes following flash drought outbreaks in regions with varying aridity and humidity is thus crucial.

In this study, we aim to fill the knowledge gaps by investigating soil heat extreme events following the outbreak of flash droughts on a global scale. The main objectives are: (a) to identify soil heat extreme events following the rapid SM decline during flash drought outbreaks, (b) to assess changes in soil heat characteristics, and (c) to explore the mechanisms linking flash drought events and subsequent soil heat extremes. Additionally, we explore the role of land surface heat fluxes in mediating soil heat dynamics after the outbreak stage of flash droughts. We test the overarching hypothesis that the rapid decline in SM critically affects extreme high ST, thus exacerbating the threat of soil heat extremes. By focusing on the interaction between two extremes from the perspective of soil dynamics rather than solely on variable correlations, our study provides new insights into the amplified risks posed to terrestrial root systems.

2. Data and Methods

2.1. Data

In this study, soil temperature (ST) was obtained from European Center for Medium-Range Weather Forecasts (ERA5) (0–7 cm) and two NASA GLDAS-2 (Global Land Data Assimilation System Version 2) models (Muñoz Sabater, 2019; Rodell et al., 2004), including Noah (Barlage et al., 2010; Wei et al., 2013) (0–10 cm) and the Variable Infiltration Capacity (VIC) model (Andreadis & Lettenmaier, 2006; Sheffield et al., 2004) (0–30 cm).

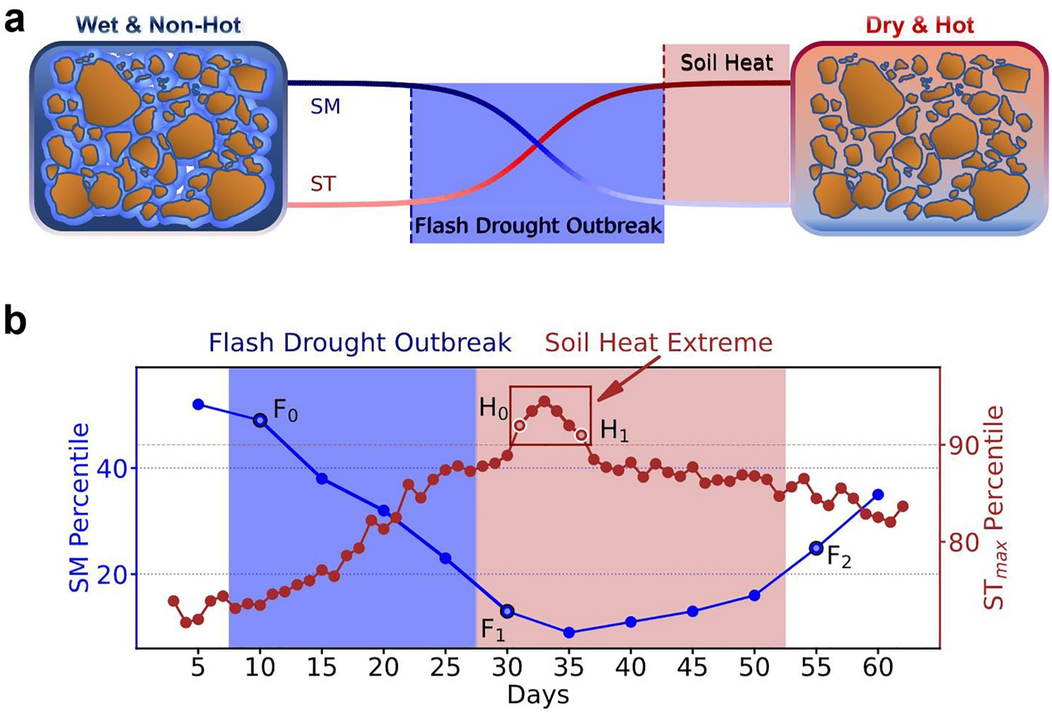

Figure 1. Schematic representation of soil heat extremes following a flash drought outbreak. (a) Trajectory of soil moisture (SM) and soil temperature during and after the flash drought outbreak. The blue and red vertical shaded areas indicate the outbreak stage of flash droughts and the following soil heat extremes, respectively. (b) Schematic diagram identifying soil heat extreme events following a flash drought outbreak. The blue vertical shading indicates the rapid decline period of SM. The red vertical shading indicates the period to identify soil heat extreme events. The red rectangle shows a soil heat extreme event.

Daily root-zone SM was obtained from the Global Land Evaporation Amsterdam Model (GLEAM) (Martens et al., 2017), Noah, and VIC data sets. Aridity index was calculated using precipitation and potential evaporation from the Climatic Research Unit (CRU) (Harris et al., 2014) (see details in Text S1 and Figure S1 in Supporting Information S1). We used the daily near-surface (2-m) temperature (T) data from the ERA5 data set. Bowen ratio, defined as the ratio between sensible heat and latent heat (Bowen, 1926), was calculated using the sensible and latent heat from Noah, VIC, and ERA5 data sets. All these data were aggregated to the same resolution at $1^\circ \times 1^\circ$. The daily ST, SM, sensible and latent heat data from in situ eddy covariance observation sites were obtained from the FLUXNET 2015, AmeriFlux, and ICOS Drought 2018 data sets (Chu et al., 2023; Pastorello et al., 2020; Team & Centre, 2020) (see details in Table S1 in Supporting Information S1). Daily evapotranspiration (ET) was obtained from GLEAM, Noah, and VIC data sets.

2.2. Identification of Soil Heat Extremes Following a Flash Drought Outbreak

To identify soil heat extremes following the flash drought outbreaks, we focused on the rising ST after the rapid SM decline during the flash drought outbreak stage (Figure 1a). Flash drought outbreaks and soil heat extreme events are identified separately when their respective indices exceed predefined thresholds. Soil heat extremes are identified by the maximum daily ST, while the outbreak of flash droughts is defined using the pentad-mean (5 days) root-zone SM percentile. We identified the flash drought outbreak phase when SM decreases rapidly from above the 40th percentile (F_0) to below the 20th percentile (F_1), with an average decline rate of no less than the 5th percentile for each pentad (5 days) within 5 pentads. The outbreak phase ends when SM remains below the 20th percentile (F_1) (Figure 1b). To further enrich the robustness of interaction between flash drought and soil heat, we also use the soil water deficit index (SWDI) as an instantaneous measure based on plant water stress in addition to our percentile-based metric to identify flash droughts. Detailed information on the identification of SWDI-based flash droughts is shown in Text S3–S4 in Supporting Information S1.

As shown in Figure 1b, a soil heat extreme event is identified when the daily maximum ST exceeds the 90th percentile of daily maximum ST (H_0) for at least three consecutive days (H_1). To account for both water stress and heat stress in soil, soil heat extreme events are identified during the period from the end point of flash drought outbreak (first pentad of SM less than the 20th pct (F_1)) to the shorter time scale between the end point of flash drought duration (first pentad of SM greater than the 20th pct (F_2)) and 6 pentads after the last pentad of the outbreak. More detailed information on the identification of soil heat extreme events following flash drought outbreak is shown in Text S2 in Supporting Information S1.

In this study, soil heat extreme events following flash drought outbreak are characterized by two metrics: (a) the proportion of flash droughts that are followed by soil heat extremes relative to all flash drought events; and (b) the heat days, defined as the mean number of soil heat extreme event days per flash drought event observed in a given year (the total days of soil heat extremes following the flash drought outbreak relative to all flash drought events).

3. Results

3.1. Global Land Areas Affected by Soil Heat Following Flash Drought Outbreaks

We first examined the temporal evolution of ST and anomalies in ST averaged across flash drought events. The temperature and anomalies in ST were found to increase significantly as the SM percentile declined rapidly during the outbreak of flash droughts, supporting the basic hypothesis on soil heat extreme events (Figures S2–S3 in Supporting Information S1). To assess the efficacy of the percentile-based flash drought identification for the following increasing temperature and anomalies in ST, we also examined the temporal evolution of ST and ST anomalies during the SWDI-based flash drought outbreaks in addition to our percentile-based metric. The averaged temporal evolutions of ST and ST anomalies show similar variation through SWDI-based flash drought outbreaks (Figures S4–S5 in Supporting Information S1).

We further investigated the global land area witnessing soil heat extremes after flash drought outbreaks. The percentage of land areas witnessing soil heat extremes after flash drought outbreaks, relative to those witnessing flash droughts, shows a statistically significant ($P \leq 0.05$) increase of about 20% in all data sets (Figure 2a). Roughly 40% of global land areas affected by flash droughts observed soil heat extremes following the flash drought outbreak in 2017 (37.88–54.55%).

To test whether the affected land area varies across aridity, we compared the affected land area between humid and arid regions. On average, soil heat extremes affect 30.82–35.04% of humid areas experiencing flash droughts, while a significantly lower percentage of 24.64–30.19% is observed in arid areas (Figure 2b), indicating a higher risk of soil heat extremes after flash drought outbreaks in humid regions. Additionally, increasing trends in this percentage are found in both humid and arid regions (Figure S6 in Supporting Information S1). We then quantified the spatial pattern in the proportion of flash droughts with soil heat extremes after the outbreak relative to all flash drought events. Our analysis revealed that for most grid cells, almost 40% of flash droughts are likely to be followed by soil heat extremes after a rapid outbreak, with especially higher proportions of more than 80% in flash drought hotspots such as Brazil, India, and China (Christian et al., 2021). The proportion of flash droughts with subsequent soil heat extremes relative to all flash drought events at each eddy tower is consistent with the grid cell co-located with the observation site (Figure 2c). Our analysis further revealed that the proportion for humid regions is significantly higher than for arid regions. Consistent spatial patterns in the proportion and the higher proportion in humid regions were also obtained from different data sets (Figure S7 in Supporting Information S1).

The trend and percentage of land area witnessing soil heat extremes after flash drought outbreaks derived from percentile-based and SWDI-based flash droughts are highly consistent and align well (Figure S8a in Supporting Information S1). The significantly higher proportion in humid regions and increasing trends also show similar patterns (Figures S8–S10 in Supporting Information S1). Despite using different flash drought inventories, the results consistently show an increasing risk of soil heat extremes following flash drought outbreaks, demonstrating robustness for the interaction between percentile-based flash drought and soil heat extremes. These results suggest that global land areas will be subject to an increasing risk of soil heat extremes, especially in humid regions. Thus, it is imperative to assess the characteristics of soil heat extremes to mitigate the impacts on soil processes and terrestrial root systems.

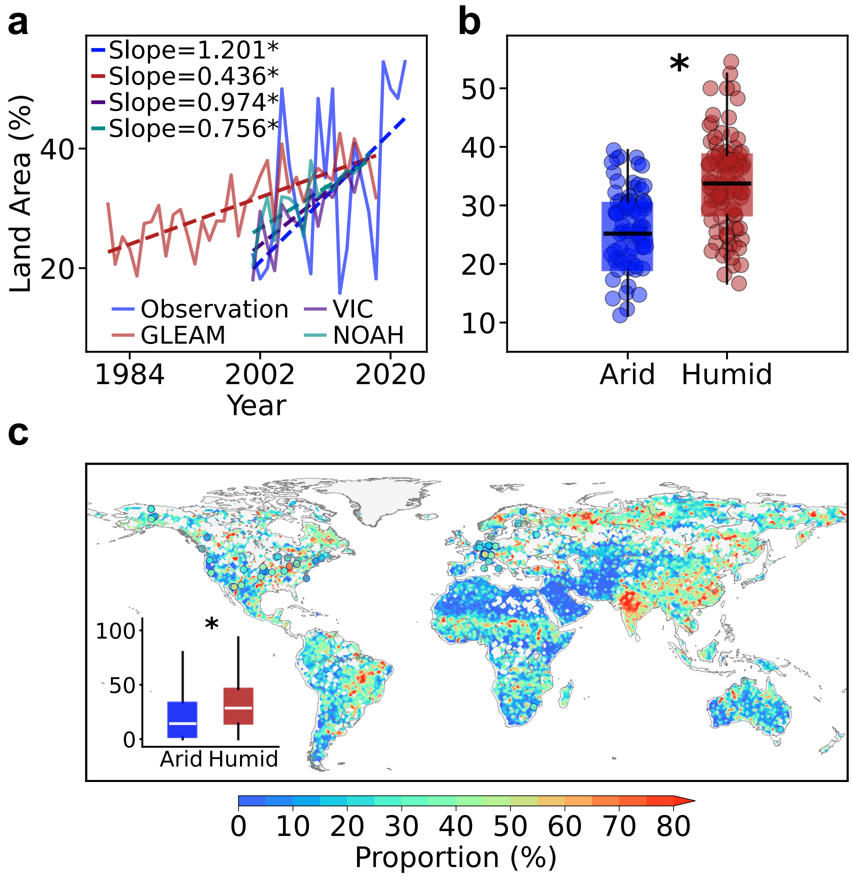

Figure 2. Spatiotemporal pattern of global risks of soil heat extremes following flash drought outbreaks. (a) Annual time series (solid lines) showing the percentage of global land areas experiencing soil heat extremes following flash drought outbreaks, relative to areas experiencing flash droughts. The linear annual trends (dashed lines) are estimated using Sen's slope estimator. An asterisk denotes statistically significant trends (*$P \leq 0.05$) based on the Mann–Kendall test (1981–2018 for GLEAM; 2001–2017 for Variable Infiltration Capacity and Noah; 2001–2022 for observation). The percentage for observation is defined as the number of sites experiencing soil heat extremes relative to sites experiencing flash droughts. (b) Box plots showing the percentage of affected areas in humid and arid regions across three data sets. The lines in the box plots represent the interquartile range and mean values. Asterisks indicate significant differences between humid and arid regions (Mann–Whitney U test, $P \leq 0.05$). (c) Spatial pattern of the ensemble mean proportion of flash droughts with subsequent soil heat extremes, relative to all flash drought events for each pixel. The inset in (c) shows the box plots of the proportion for humid regions (red) and arid regions (blue). The scatters in (c) show the proportion of flash droughts with subsequent soil heat extremes relative to all flash drought events for each in situ site.

3.2. Temporal Changes in Soil Heat Characteristics

We assessed changes in the proportion of soil heat extremes following flash drought outbreaks relative to all flash drought events and soil heat days (see Methods). The trends in soil heat characteristics were evaluated from 1981 to 2018 for GLEAM, from 2001 to 2022 for observation, and from 2001 to 2017 for VIC and Noah data sets at a global scale. The results demonstrate significantly increasing trends in both the proportion and the number of heat days across all four data sets (Figure S11 in Supporting Information S1). In 2017, over 40% of flash droughts experienced soil heat extremes after the outbreak (40.00–45.07%), with heat days doubling since the start of the study period. To further enrich the robustness of soil heat characteristics following flash drought outbreaks, we examined the proportion and heat days using SWDI-based flash drought inventory. Consistent increases in both the proportion and the number of heat days across four data sets were obtained (Figure S12 in Supporting Information S1). Specifically, we also investigated the soil heat events from two eddy covariance observations with relatively high proportions of soil heat extremes (Figure 2c) from humid and arid regions, respectively. The US-MMS and ZA-Kru are the two sites from the Northern and Southern Hemisphere, respectively (Figure S13 in Supporting Information S1). More than half of the flash droughts at ZA-Kru experienced soil heat extremes, with

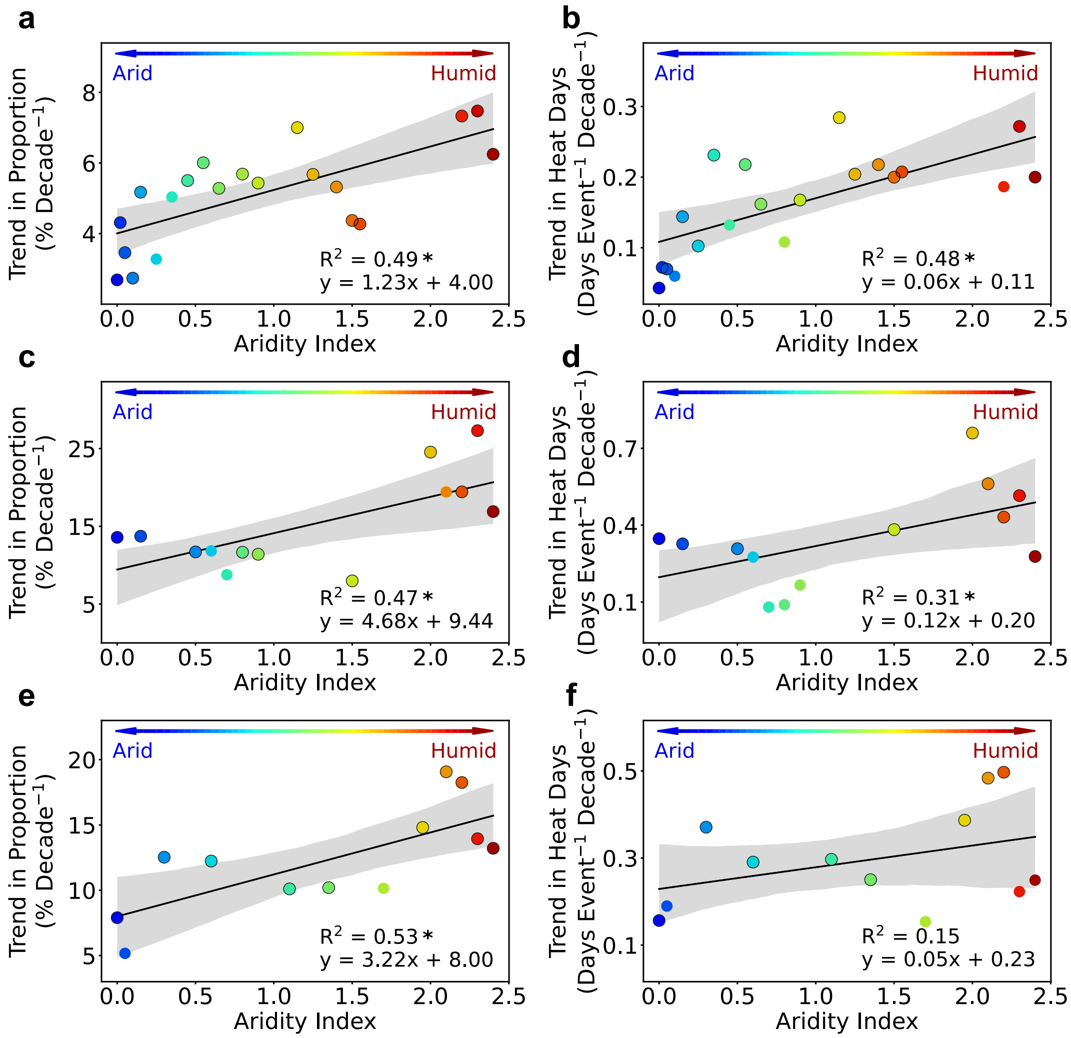

Figure 3. Trend of the proportion of flash droughts with soil heat extremes after outbreaks relative to all flash drought events (a, c, e) and the number of soil heat event days per flash drought event (b, d, f) along the aridity index. The ringed dots indicate statistically significant trends (*$P \leq 0.05$) based on the Mann–Kendall test. Black lines show linear regression between the trend and aridity index for (a, b) GLEAM during 1980–2020 (c, d) Variable Infiltration Capacity during 2001–2017, and (e, f) Noah during 2001–2017. The asterisk denotes a significant linear relationship (*$P \leq 0.05$). The gray ribbon represents the 95% prediction interval.

heat days tripling from three days in 2001 to nine days in 2008 (Figures S14–S15 in Supporting Information S1). At US-MMS, the 2012 flash drought experienced a total of 23 soil heat days during its duration, which is more than 2.5 times the number of heat days in 2001 (Figures S16 and S17h in Supporting Information S1). These suggest that more flash droughts are likely to witness soil heat extremes following rapid soil drying and experience longer durations of soil heat, indicating intensified soil heat activity after flash drought outbreaks.

To further explore the pattern of soil heat characteristics along the aridity index, we investigated the variations in trends in the proportion and heat days across the aridity gradient. Importantly, the proportion and heat days per event show a greater increase in more humid regions, as indicated by a higher aridity index (Figure 3). The proportions in more humid regions are increasing about twice as fast as in more arid regions, implying that soil heat extremes are likely to occur more frequently after flash drought outbreaks with an increasing aridity index along the gradient of aridity. The heat days also show a similar pattern, with the magnitude of the estimated slope increasing along the aridity index, suggesting that flash droughts could experience longer soil heat following rapid soil drying.

These suggest that contrary to the common perception that arid regions are more vulnerable to heat extremes, humid ecosystems may experience a disproportionately greater escalation in soil heat stress following the aridity gradient. The parallel increase in the number of heat days further underscores the potential for prolonged heat exposure following flash droughts in humid areas. These findings align with other studies (Böhnisch et al., 2025) that highlight the compounding effects of heat and water stress in humid regions, where vegetation and root systems are typically less adapted to withstand concurrent extremes. The observed patterns imply that humid regions, often considered less susceptible to heat extremes, may in fact face heightened risks.

Collectively, vulnerable ecosystems in humid regions will face higher heat stress alongside water stress, indicating more serious threats posed by soil heat extremes in these areas.

3.3. Mechanisms Underlying the Increased Risk of Soil Heat

It is widely accepted that differentiated soil thermal properties, land–atmosphere interactions, and the distribution of surface fluxes vary between drier and wetter climate regimes (Alrtimi et al., 2016; Entekhabi & Rodriguez-Iturbe, 1994; Hsu & Dirmeyer, 2023). Soil water content significantly affects soil thermal conductivity, playing an important role in surface–energy partitioning and temperature distribution (Y. Fu et al., 2024; Hsu & Dirmeyer, 2023; Usowicz et al., 2006). SM also strongly controls the partitioning of available energy between latent and sensible heating (Entekhabi & Rodriguez-Iturbe, 1994; Hsu & Dirmeyer, 2023). When the soil is wetter, latent heat is the dominant flux, while dry landscapes are characterized by a high flux of sensible heat (Benson & Dirmeyer, 2021; Hsu & Dirmeyer, 2023; Molnar, 2022). We thus investigated changes in the Bowen ratio (β) in humid and arid regions, which reflects energy balance and partitioning processes and is calculated as the ratio between sensible heat and latent heat (Bowen, 1926; Sun et al., 2024). We found that β shows consistent changes among the ERA5 and GLDAS data sets. Specifically, β increases with the rapid SM depletion of flash droughts. The value of β is lower for flash droughts experiencing soil heat compared to those without soil heat extremes, indicating more energy that could further support soil heat extremes (Figure S18 in Supporting Information S1).

The partitioning of available energy also strongly influences the difference between soil and air temperature (Wang et al., 2024). Contrasting spatial and temporal patterns of the relationship between soil and air temperature are observed, where higher maximum air temperatures occur more in humid regions (Figures S19–S20 in Supporting Information S1). The difference between soil and air temperature also changes in differentiated ways between humid and arid regions during flash droughts (Figures S19b and S21 in Supporting Information S1).

Interestingly, the ratio of β between flash droughts with and without soil heat extremes changes differently in humid and arid regions across all three data sets (Figure S22 in Supporting Information S1). This ratio tends to decrease as flash droughts evolve in humid regions, implying relatively higher latent heat, which manifests as the evaporation of liquid water. Soil pores are mainly filled with water when the soil is wet, enhancing heat transfer through water bridges and menisci. In contrast, dry soils in arid regions have air-filled pores, resulting in lower thermal conductivity due to limited contact points (Alrtimi et al., 2016; Hall & Allinson, 2009; Tarnawski et al., 2000). Additionally, wet soils in humid regions have lower albedo, increasing solar absorption and available energy (Small & Kurc, 2003). More importantly, the release of heat from the atmosphere into the soil may occur in humid regions with higher air temperatures due to increased contact points, potentially leading to a higher risk of soil heat extremes. In contrast, the ratio tends to increase in arid regions, indicating that more energy may be dissipated as sensible heat. Heat exchange may occur from the soil to the atmosphere because the soil is warmer than the air, which could further contribute to the intensification of heatwaves.

In humid regions, the onset of flash droughts is often accompanied by a reduction in precipitation and consequently cloud cover, leading to increased solar radiation. This increase in solar radiation initially enhances the following ET, as the ET regime remains energy-limited. Consequently, the Bowen ratio might transition to a decrease, reflecting a shift toward latent heat flux dominance. This phenomenon aligns with previous findings highlighting the initial increase in ET (Figure S23 in Supporting Information S1) due to energy availability in eco-hydrological responses to droughts in tropical South America (Jiang et al., 2022). As flash droughts persist, SM gradually depletes, transitioning the ET regime from energy-limited to water-limited. This shift results in a subsequent decrease in ET, which may not fully materialize by the end of a short-lived flash drought (Figure S23 in Supporting Information S1). These nuanced understandings of dynamics during flash droughts highlight the dominant role of SM feedback in shaping the relationship between drought and heat extremes (Jiang & Wang, 2024). Furthermore, we found that ET and ET anomalies for flash droughts with soil heat extremes are significantly higher than those without soil heat extremes (Figures S24–S26 in Supporting Information S1), highlighting the important role of ET in governing the sequence of flash drought outbreak and soil heat extremes.

We also investigated the changes in β using in situ data from ZA-Kru and US-MMS sites, located in arid and humid regions, respectively. We found that the changes in β and the ratio are consistent with the reanalysis results (Figure S27–S28 in Supporting Information S1).

4. Discussion

This study highlights the increasing occurrence of soil heat extreme events shortly after flash drought outbreaks while still under soil drying conditions. The risk of soil heat extremes following flash drought outbreaks is notably higher in humid regions. After rapid soil drying, more frequent soil heat extremes tend to affect larger areas and last longer. Our findings support the hypothesis that a rapid decline in SM can trigger extremely high ST and exacerbate the threat of soil heat extremes.

It should be noted that spatial patterns of flash drought distribution could be largely affected by the metric chosen to identify flash droughts. To enrich the robustness considering the uncertainties related to percentile-based flash drought definition, we compared the interaction between soil heat and flash droughts derived from different flash drought definitions. The percentile-based flash drought definition is widely applicable across various climatic regions and allows for a standardized approach by comparing SM conditions to historical norms (Osman et al., 2024). However, its reliance on percentiles may lead to the identification of flash droughts in humid regions or seasons where meteorologically dry episodes occur, even if SM remains high, these flash droughts may have minimal ecological impacts (Sungmin & Park, 2023). Thus, we also utilized the SWDI-based method to identify flash droughts that are more suited to regions prone to agriculture, rather than all instances of flash droughts, as the SWDI is an instantaneous metric reflecting plant water availability by integrating root-zone SM and hydraulic soil properties (Lovino et al., 2024; Mohammadi & Wang, 2025). We find that the increasing risks of soil heat extremes following flash drought outbreaks are similar under different flash drought inventories, but the spatial distribution varies greatly. The proportions of flash droughts with soil heat extremes after the outbreak relative to all flash drought events show very different patterns in the tropics (Figure 2c and Figure S8 in Supporting Information S1). The proportions for SWDI-based flash droughts are lower in the tropics than percentile-based flash droughts, since SM might remain high under the percentile-based definition. Although the nuances of the spatial distribution of interaction between soil heat and flash droughts from different definitions, our findings show that the significantly higher proportion for humid regions and the increasing trends are highly consistent (Figures S6–S10 in Supporting Information S1).

It should be noted that since we focus on the partitioning of available energy moderating the relation between soil and air temperatures, other factors such as vegetation cover and soil properties could also moderate their relationship. We found that deciduous forests experienced higher air temperature, while other types of vegetation faced higher ST. In addition, sandy soil could have higher ST than clayey soil (Figure S29 in Supporting Information S1).

To further ensure the robustness of our analysis, we used three data sets, which showed similar spatial patterns of ST (Figure S30 in Supporting Information S1). Additionally, we also used the eddy covariance observations to better verify our results. Specifically, for the large-scale 2012 flash drought in US-MMS with severe impacts (Jin et al., 2019), we found that soil heat extremes could occur more frequently and last for longer days during the whole drought duration (Figure S17 in Supporting Information S1). This indicates the exacerbated threats to ecosystems posed by soil heat extremes under soil drying conditions, particularly in the growing season. To further explore soil heat characteristics, we conducted a sensitivity analysis comparing soil heat extreme events following flash droughts and traditional droughts (see details in Text S4 in Supporting Information S1). We found that flash droughts exhibit significantly higher ST and ST anomalies than traditional droughts, with ST anomalies increasing faster (Figure S31 in Supporting Information S1). In addition, the proportion and heat days per event are also higher for flash droughts than traditional droughts, suggesting that flash droughts are more likely to experience prolonged soil heat extreme events compared to traditional droughts (Figure S32 in Supporting Information S1). Thus, flash droughts characterized by rapid water stress development could face higher heat stress than traditional droughts with longer onset time, indicating more serious threats to these extreme droughts posed by soil heat extremes.

We limited our analysis of soil heat extremes to within six pentads after the last pentad of a flash drought outbreak—or, for shorter flash droughts, within their duration—to consider a potential time lag between flash drought outbreaks and soil heat extremes (see Methods). It was found that 86.51–91.08% of flash droughts reach maximum ST within 10 pentads after the start (Figure S33 in Supporting Information S1), indicating a high likelihood of soil heat extremes shortly after rapid SM depletion. Thus, soil heat extremes remained confined within six pentads when flash drought duration is longer, representing concurrent and tightly linked water-stressed and heat-stressed conditions.

Our analysis underscored the crucial increase in ST related to rapid SM depletion. The increasing trends in soil heat extremes after rapid soil drying could impact plant and ecosystem carbon cycles. As a major flux in the global carbon cycle, the release of carbon dioxide from soil respiration can be accelerated by higher soil temperatures (Carey et al., 2016). More importantly, rising temperatures critically stimulate soil carbon net loss to the atmosphere, driving a positive land carbon-climate feedback that could further accelerate warming (Crowther et al., 2016). Long-term site experiment indicates that soil warming significantly alters phenological activities by inducing earlier leaf bud break, flowering, and leaf senescence, thereby causing limitations in carbon sequestration (Khorsand Rosa et al., 2015). The warm and dry soil could also potentially provide fuel for wildfires burning slowly below the surface and may facilitate the overwintering fires known as "zombie fires." Our findings also shed light on the global patterns and changes in soil heat characteristics along the aridity index.

Data Availability Statement

The two NASA GLDAS-2 data sets models (Rodell et al., 2004) are collected from https://doi.org/10.5067/E7TYRXPJKWOQ and https://doi.org/10.5067/ZOG6BCSE26HV. The ERA5 data set (Muñoz Sabater, 2019) can be obtained from https://cds.climate.copernicus.eu/datasets. The GLEAM data set (Martens et al., 2017) is available at https://www.gleam.eu/. The FLUXNET data (Pastorello et al., 2020) are available at https://fluxnet.org/. The AmeriFlux data (Chu et al., 2023) are available at http://public.ornl.gov/ameriflux. The ICOS Drought 2018 data (Team & Centre, 2020) are available at https://www.icos-cp.eu/data-products/YVR0-4898. The CRU data set (Harris et al., 2014) is available at https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.07/. Relevant processed data is stored at Y. Jing (2025).

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