ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

Contemporary patterns of prescribed fire and its risks and benefits to water quantity and water quality over the conterminous United States

To cite this article: Yulong Zhang *et al* 2025 *Environ. Res. Lett.* **20** 123002

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

Check for updates

OPEN ACCESS

RECEIVED
10 September 2025

REVISED
11 November 2025

ACCEPTED FOR PUBLICATION
18 November 2025

PUBLISHED
28 November 2025

TOPICAL REVIEW

Contemporary patterns of prescribed fire and its risks and benefits to water quantity and water quality over the conterminous United States

Yulong Zhang[1,2,*], **Wenhong Li**[1], **Peter Caldwell**[3], **Stephen D Sebestyen**[4], **Chunling Tang**[5], **Ryan Toot**[6], **Christopher Mihiar**[7], **Zack Mondry**[8], **Yiyun Song**[1], **Danika Mosher**[2] and **Ge Sun**[2,*]

[1] Division of Earth and Climate Sciences, Nicholas School of the Environment, Duke University, Durham, NC, United States of America
[2] Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Research Triangle Park, Raleigh, NC, United States of America
[3] Center for Integrated Forest Science, Southern Research Station, USDA Forest Service, Otto, NC, United States of America
[4] Forestry Sciences Laboratory, Northern Research Station, USDA Forest Service, Grand Rapids, MN, United States of America
[5] U.S. Environmental Protection Agency, Research Triangle Park, NC, United States of America
[6] Minnesota Department of Natural Resources, Saint Paul, MN, United States of America
[7] Center for Economics and Social Science, Southern Research Station, Research Triangle Park, NC, United States of America
[8] Forest Service George Washington and Jefferson National Forests, USDA Forest Service, Roanoke, VA, United States of America
[*] Authors to whom any correspondence should be addressed.

E-mail: yulong.zhang@duke.edu and ge.sun@usda.gov

Keywords: prescribed fire, evapotranspiration, runoff, soil erosion, water quality, CONUS

Supplementary material for this article is available online

Abstract

Prescribed fire has emerged as an essential ecosystem management practice for maintaining forest health and mitigating wildfire risks. However, its spatio-temporal patterns and potential impacts on water quantity and quality remain poorly understood compared to those of wildfires. By analyzing the Monitoring Trends in Burn Severity database (1984–2022), we characterized distinct regional, seasonal and interannual dynamics of large prescribed fires relative to wildfires across the conterminous United States. We found the Southeast dominated the national prescribed fire regime, accounting for 78.6% of total prescribed fire occurrences and 70.7% of total burned area. Seasonally, prescribed fires primarily occurred in the spring, contrasting with wildfires that peak in autumn, particularly in the West and Southwest. Prescribed fires in the Southeast increased significantly from the early 2000s, peaking around 2010, then temporarily declined, whereas wildfires in the West exhibited an overall upward trend with substantial interannual variability. Our synthesis of studies from 1969 to 2024 showed that prescribed fire could potentially reduce evapotranspiration, but increase surface runoff through alterations of vegetation structure, rainfall partitioning, soil properties, and flow generation processes. Additionally, prescribed fire may influence water quality by modifying soil nitrogen dynamics, dissolved carbon, erosion, and sediment transport. However, these impacts are typically short-lived and can be effectively mitgated through site-specific strategies, supporting the use of prescribed fires as as a safe and practical management tool. To this end, we developed an adaptive framework that guides prescribed burning by balancing its ecological and hydrological benefits against potenital risks, thereby promoting sustainable forest management, reducing wildfire risk, and protecting water resources.

1. Introduction

Prescribed fire, also known as controlled burning, is the intentional and carefully managed application of fire onto a designated landscape to achieve ecological and land management objectives (Yoder *et al* 2004, Hiers *et al* 2020, Schweitzer and Dey 2023). Unlike wildfires, which often ignite under extreme weather conditions and can spread uncontrollably with high severity across large areas, prescribed fires are conducted under controlled conditions following strict operational protocols (Ryan *et al* 2013, Han *et al* 2020). They are commonly used to reduce hazardous fuel accumulations of dead wood and leaf litter (McCaw 2013), restore fire-adapted ecosystems (Costanza and Moody 2011, Schweitzer and Dey 2023), promote nutrient cycling (Zhou *et al* 2022), and enhance wildlife habitats (Knapp *et al* 2009). In contrast, wildfires typically occur under extreme weather conditions (e.g. dry and windy), posing immediate public threats and causing severe socioeconomic damage (Balch *et al* 2024). Large wildfires are becoming more frequent and intense in both the western and humid eastern US (Donovan *et al* 2023, Zhang *et al* 2023). The high intensity and severity burns from wildfires can dramatically eliminate vegetation, alter soil structure, and trigger long-term adverse effects on eco-hydrological processes (Bowman *et al* 2020, Zhang *et al* 2021, Lopez *et al* 2024, McGuire *et al* 2024). In contrast, when carefully planned and executed, prescribed burns can effectively reduce the likelihood of such extreme wildfires (Hunter and Robles 2020), thus fostering ecosystem resilience, avoiding hydrological risks and protecting human communities (Kalies and Yocom Kent 2016, Coates *et al* 2017).

Fire has historically been an integral component of land management practices (Bowman *et al* 2020). Indigenous peoples used intentional burning as a tool to enhance forage, manage landscapes, and facilitate hunting worldwide (Kelly *et al* 2023). With European colonization, however, widespread fire suppression policies emerged in response to devastating wildfires in North America in the early 20th century (Baron *et al* 2022, Knight *et al* 2022). In recent decades, an increasing understanding of cultural and ecological roles of fire have spurred a reintroduction of controlled burning practices (Hiers *et al* 2020, McLauchlan *et al* 2020) particularly in the southeastern and western United States. There, prescribed burning is supported by 'right-to-burn' policies and more widespread cultural acceptance of fire as an ecological process (Ryan *et al* 2013, Wonkka *et al* 2015, Weir *et al* 2016). While the spatial and temporal patterns of wildfires have been extensively studied (Bowman *et al* 2020, Kelly *et al* 2023, Zhang *et al* 2023), our understanding of the contemporary patterns and dynamics of prescribed fires remains limited. The extent, frequency, and intensity of prescribed burns vary across different regions and time periods (Hiers *et al* 2020, Mason and Lashley 2021), yet these characteristics have not been as well documented as those of wildfires (Donovan *et al* 2023, Solander *et al* 2023, Balch *et al* 2024).

Despite its recognized ecological benefits (Elliott and Vose 2010, Klimas *et al* 2020b, Sample *et al* 2022), the use of prescribed fire remains a subject of debate (McCullough *et al* 2019, Beyene *et al* 2023). Public concerns, ranging from smoke and air quality issues to liability fears and the possibility of escape, can constrain its application (Navarro *et al* 2018, Frey 2024, Yoder *et al* 2004). Moreover, while the ecological role of prescribed fire is well understood, its hydrological impacts have received comparatively less attention. Current literature on the relationship between forest fires and water largely stems from studies focused on large-scale, high-intensity wildfires (Smith *et al* 2011, Abraham *et al* 2017a, Hampton *et al* 2022). However, a growing body of evidence suggests that even low-intensity burns have the capacity to modify vegetation cover, alter soil properties, and change watershed hydrological dynamics, which in turn can affect both water quantity and water quality at the local scales (Flerchinger *et al* 2016, Alcañiz *et al* 2018, Hahn *et al* 2019, Uzun *et al* 2020).

Regardless of the burn type (prescribed vs wildfire), forest fires can influence water quantity and quality through a range of interconnected ecohydrological processes (Klimas *et al* 2020b, Ebel *et al* 2023, Moazeni and Cerdà 2024). The loss of overstory and understory vegetation reduces canopy interception and transpiration, potentially lowering overall evapotranspiration (ET) and temporarily increasing soil moisture and streamflow (Flerchinger *et al* 2016, Hallema *et al* 2017, 2018). Soil heating can enhance hydrophobicity (Alcañiz *et al* 2018, Agbeshie *et al* 2022), reducing infiltration rates and directly increasing surface runoff and downstream flow (Cawson *et al* 2012, Zema *et al* 2024). In cases of severe vegetation and soil damage, fires have been shown to increase runoff volume and peak flows by up to threefold (Neary and Leonard 2015).

Without the protective cover of vegetation, soil erosion can be significantly amplified during subsequent precipitation events (James and Krumland 2018, Karban *et al* 2022, Zema *et al* 2024). Increased overland flow, coupled with the mobilization of nutrients and heavy metals (Abraham *et al* 2017b, Lopez *et al* 2024), enhances sediment transport and can directly degrade downstream water quality (Caldwell *et al* 2020, Clow *et al* 2024). Elevated concentrations of solutes such as phosphorus, nitrate, and other pollutants pose serious risks to aquatic ecosystems, drinking water supplies, and human health (Belongia *et al* 2023, Moazeni and Cerdà 2024). Additionally, forest fires accelerate the mineralization of organic matter, disrupt root uptake, and eliminate canopy shading over streams, which collectively influence stream temperature and nutrient concentrations (Ice *et al* 2004, Li *et al* 2024). The magnitude and duration of these impacts depend on multiple factors, including burn intensity, vegetation and soil types, topography, local climate, and the rate of post-fire vegetation recovery (Elliott *et al* 2024).

While the hydrologic and biogeochemical effects of wildfires are increasingly documented (Agbeshie *et al* 2022, McGuire *et al* 2024, Zhou *et al* 2025), the influence of prescribed fire on these processes remains less understood. Given prescribed burns generally occur at lower intensities with controlled fuel consumption, their effects on water quantity and quality are expected to be less severe (Mullen *et al* 2006, Hatten *et al* 2008, Alcañiz *et al* 2018, Karban *et al* 2022). However, a comprehensive assessment of the potential risks and benefits of prescribed fire to water resources is needed for effective burn planning and implementation (Richter *et al* 1982, Zema and Lucas-Borja 2023, Hashida *et al* 2025).

In this study, we first examined prescribed fire patterns over the conterminous United States (CONUS) from 1984 to 2022 and then synthesized existing literature on the impacts of prescribed burning on eco-hydrological processes and water quality. Our specific objectives were to: (1) characterize the spatial and temporal patterns of prescribed fire using the Monitoring Trends in Burn Severity (MTBS) dataset to delineate its distribution and frequency changes across CONUS; (2) assess water quantity impacts of prescribed fire on hydrological processes, including ET, soil water infiltration, and streamflow; (3) evaluate water quality effects of prescribed fires on changes in soil chemical properties, nutrient mobilization, sediment transport, and both on-site and downstream water chemistry; and (4) propose a conceptual framework for sustainable and adaptive prescribed burning that integrates its impacts on water quantity and quality, aiming to guide practices that minimize water-related risks while maximizing ecological and forest management benefits.

2. Materials and methods

2.1. Fire data and pattern analysis

To analyze spatial and temporal patterns of prescribed fire events, we used the MTBS dataset (www.mtbs.gov), which offers daily fire records from 1984 to 2022 at a 30 m resolution. The MTBS program is a collaborative effort between the US Geological Survey and the US Department of Agriculture Forest Service to consistently map and monitor fire activity across the United States (Eidenshink *et al* 2007). MTBS primarily uses satellite imagery from the Landsat TM sensor (Landsat 4 and 5), Landsat ETM+ (Landsat 7), and Landsat OLI (Landsat 8 and 9), ensuring continuity in modern multispectral data collection. Additionally, MTBS includes more recent satellite data from Sentinel-2 to supplement fire mapping efforts.

Wildfires and prescribed fires are differentiated in MTBS using multiple data sources, including official incident reports, land management and satellite imagery records. Wildfires often result from lightning strikes or human-caused ignition, whereas prescribed fires are intentionally set by land managers under controlled conditions. In this study, we conducted a regime analysis of prescribed fires in comparison to wildfires by calculating three key fire metrics: fire count, total burned area, and average fire size. These metrics were evaluated across five regions in the CONUS, including Southeast, Northeast, Midwest, Southwest, and West (figure 1).

We categorized fire occurrences into four seasons: spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). Seasonal fire metrics were aggregated to the annual scale, followed by an interannual variability and trend analysis spanning from 1984 to 2022. Note that, for the annual analysis, the preceding winter season was included in the current year assessment to ensure temporal consistency.

Note that MTBS include all fires larger than 1000 acres (>404 hectares) in the western US and 500 acres (>202 hectares) in the eastern US (the East-West dividing line seen in figure 1(a)), ensuring comprehensive spatial coverage of larger fire events. We acknowledge that smaller fires below these thresholds, particularly prescribed burns, are underrepresented in the dataset. However, we adopted MTBS for our study because it is the only high-resolution database providing consistent mapping of both wildfires and prescribed fires across CONUS, and larger fires—our analytical focus—are more likely to produce observable hydrological effects.

To assess this limitation, we compared MTBS against two additional databases, NFPORS (Kelp *et al* 2025) and GlobRx (Hsu *et al* 2025), and analyzed fire trends and seasonality (figure S2) across size classes using California as a test case. Overall, large fires among three datasets showed highly consistent in the long-term trend, interannual variability (figure S1), and seasonal patterns (figure S2) in California. However, small prescribed fires showed a slightly increased trend, though with some discrepancies between NFPORS and GlobRx, while large prescribed fires continue to dominate annual variability in burned area.

2.2. Fire literature review and impact analysis

We reviewed the literature on prescribed fires impacts on water quantity and water quality, covering studies published between 1969 and 2024. Primary sources were identified through databases such as Google Scholar and Web of Science using a systematic search strategy with key terms related to fire, hydrology, and geography:

- Fire-related: ‘prescribed fire’, ‘prescribed burning’, ‘controlled fire’, ‘controlled burning’
- Hydrology and water quality: ‘water,’ ‘stream,’ ‘river,’ ‘aquatic’, ‘evaporation’, ‘transpiration’, ‘canopy interception’, ‘ET,’ ‘water yield,’ ‘runoff,’

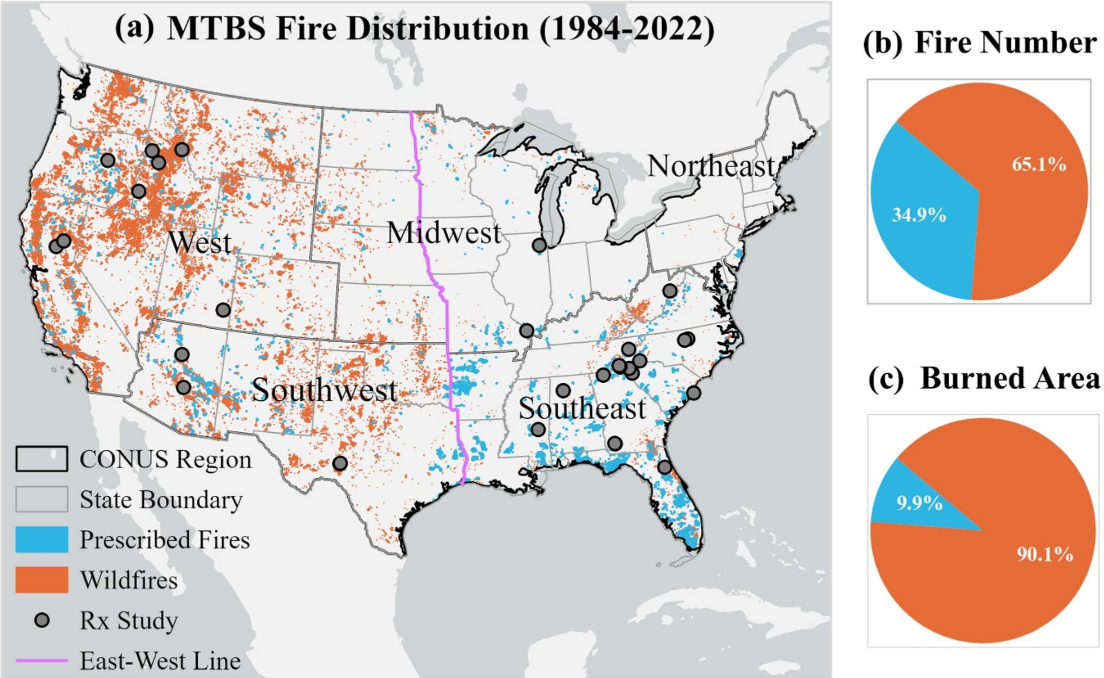

Figure 1. Spatial distribution and fire type composition of prescribed fires and wildfires derived across the conterminous United States (CONUS). (a) Spatial distribution of total prescribed fires and wildfires derived from the MTBS database during 1984–2022. (b) Proportion of prescribed fires versus wildfires by fire occurrence count and (c) their respective contributions to total burned area over the CONUS. In (a), gray circles illustrate the case studies of prescribed fire (Rx) included in our water impact review; the purple line marks the eastern-western divide.

'discharge,' 'soil property', 'soil erosion,' 'sediment', 'water quality,' 'nutrient export,' 'water chemistry.'

- Geography: 'CONUS,' 'United States,' 'US', 'South', 'Southeast,' 'Southern', 'West', 'Western', 'Midwest', 'East', 'Eastern'

In total, we identified 35 relevant prescribed fire studies over CONUS, of which 21 were in the eastern US and 14 in the western US (table S1), with regional boundaries following the MTBS delineation (figure 1(a)). Case studies were classified as eastern or western based on the dividing line used in the MTBS database (figure 1(a)). To evaluate the effects of prescribed fire on water quantity, we synthesized findings on key hydrological fluxes, including soil evaporation, canopy interception, ecosystem ET, runoff, and streamflow. For water quality, we examined how prescribed fires influence soil properties, nutrient dynamics, erosion rates, and metal mobilization, along with their secondary effects on aquatic ecosystems. Note that each case study represents one published research paper, which may include multiple sites or experimental treatments within a single study.

A structured pairwise analysis of pre-fire and post-fire conditions was conducted to classify impacts into three categories: increase, decrease, and no change. The statistical significance of these impacts were determined directly from each individual study, based on its specific paired design. Given distinct fire regime controls between eastern and western United States (related to climate, topography, vegetation, and fire intensity), we compared prescribed fire impacts across both regions to identify potential differences in their hydrological and water quality responses. While this study primarily focused on forest prescribed fires, we also included five non-forest studies (two shrub-dominated, two grassland, and one wetland; seen in table S1) due to limited forest case availability. These non-forest studies did not exhibit distinctly different hydrological responses compared to forest studies (table S1). Given their limited number, we included them in the aggregate analysis rather than analyzing them separately to avoid drawing conclusions from insufficient data.

2.3. Adaptive prescribed fire framework development

Based on our spatial and temporal analysis of prescribed fire patterns across diverse US regions, along with an extensive review of their hydrological and water quality impacts, we developed an integrated framework to support sustainable and adaptive prescribed fire implementation. This framework aimed to balance the benefits of fuel reduction and ecosystem restoration with the potential eco-hydrological risks posed by fire. It integrates key components within three chronological stages—pre-burn planning and risk assessment, post-burn monitoring and response, and adaptive strategies for future burns—including watershed-specific risk assessments, vegetation- and season-specific burn schedules, systematic hydrological monitoring, and real-time water quality alert systems to enhance transparency and preparedness.

3. Results and discussions

3.1. Contemporary pattern of prescribed fire over CONUS

We analyzed the contemporary patterns and dynamics of prescribed fire across CONUS based on the MTBS dataset since 1984. The analysis in this section highlighted the national overview, regional variations, seasonal patterns, and interannual variability, with a focus on the comparison between prescribed fires and wildfires.

3.1.1. National overview and regional comparison

Our analysis based on the MTBS data indicates that wildfires are overwhelmingly larger than prescribed fires both in number and total burned area, and that their distributions exhibit distinct regional patterns across the United States (figure 1). The Southeast consistently emerges as the leading region for prescribed fire application (figure 2). This region, which includes fire-adapted ecosystems (e.g. longleaf pine savannas and pine flatwoods) (Knapp *et al* 2018), not only exhibits the highest number of prescribed fire events (78.6% of CONUS; figure 2(a)) but also accounts for the largest cumulative prescribed burned area (70.5% of CONUS; figure 2(b)). Longstanding cultural practices, combined with supportive 'right-to-burn' policies and favorable climatic conditions, have entrenched the role of prescribed fire in this region (Ryan *et al* 2013, Han *et al* 2020).

In contrast, the West is dominated by wildfires, which account for 54.0% of total wildfire numbers and 70.5% of the total burned areas in CONUS, while prescribed burns play a minor role (figures 1 and 2). Although prescribed fire is mainly employed in western states (figure 1) for fuel reduction, its frequency and scale remain much lower, accounting for only 5.4% of total prescribed fires numbers and 8.8% of total burned areas in CONUS (figures 2(a) and (b)). This regional contrast reflects underlying differences in vegetation types, landscape diversity, climate conditions, and historical land management practices (Ryan *et al* 2013, Sample *et al* 2022).

As expected, prescribed fires had a much smaller average fire size (765 ha per fire) compared to wildfires (3754 ha per fire) (figure 2(c)). However, both fire types exhibited the largest average sizes in the West, followed by the Southwest, Midwest, Southeast, and Northeast. Notably, prescribed fires in the West and Southwest averaged over 1100 ha per fire, suggesting a potentially greater eco-hydrological and social impacts in these regions.

3.1.2. Seasonal variability

Prescribed fires and wildfires show distinct seasonality at the regional and national scales (figure 3), reflecting differences in fire management strategies, climatic conditions and wildfire regimes (Knapp *et al* 2009, Baijnath-Rodino *et al* 2022, Swain *et al* 2023). Prescribed fires occur predominantly in spring (51.7%) and winter (31.6%) based on annual totals across CONUS (figure 3), with spring emerging as the peak season in most regions—especially in the Southeast (51.7%), Midwest (81.0%), and Northeast (77.5%). This pattern aligns with controlled burning strategies, as fuel accumulation from the prior growing season provides sufficient fuels, while cooler temperatures and higher soil moisture create safer burning windows. In contrast, wildfires primarily occur in autumn (56.2% of annual totals over CONUS) and spring (22.0%), with autumn showing the highest wildfire occurrence, especially in the West (79.9%) and Southwest (42.2%), where favorable fire weather conditions and abundant dry fuels mainly contribute to increased fire activity.

The West exhibits a distinct fire seasonality, with wildfires concentrated in autumn and prescribed fires more evenly distributed throughout the year. Meanwhile, the Southeast stands out as the only region where prescribed fires significantly outnumber wildfires across multiple seasons, highlighting the regional fire management strategies. The Midwest and Northeast show the least wildfire occurrence, with prescribed fires dominating their seasonal fire regimes. At the national scale, prescribed fires are concentrated in spring (51.7%) and winter (31.6%), while most wildfires peak in autumn (56.2%), demonstrating a clear seasonal divergence between managed burns and wildfire occurrences. This seasonality contrast underscores the critical role of prescribed fires in reducing fuel loads to reduce wildfire risk outside peak wildfire seasons, particularly in fire-prone regions (Kolden 2019).

However, prescribed fire seasonality exhibits considerable spatial heterogeneity within regions. To illustrate this variability, we compared MTBS data with two additional prescribed fire datasets (NFPORS and GlobRx) for California. All three datasets indicate that autumn accounts for the majority of prescribed fires by frequency (figure S2), contrasting with the West's summer (figure 3(b)) and national spring (figure 3(f)) patterns. This finding is consistent with Baijnath-Rodino *et al* (2022), who reported that fall burns are most frequently implemented in California. These seasonal preferences likely reflect trade-offs among fire weather windows, fuel moisture conditions, burn effectiveness, and operational feasibility, though they entail elevated fire escape risks (Baijnath-Rodino *et al* 2022, Swain *et al* 2023).

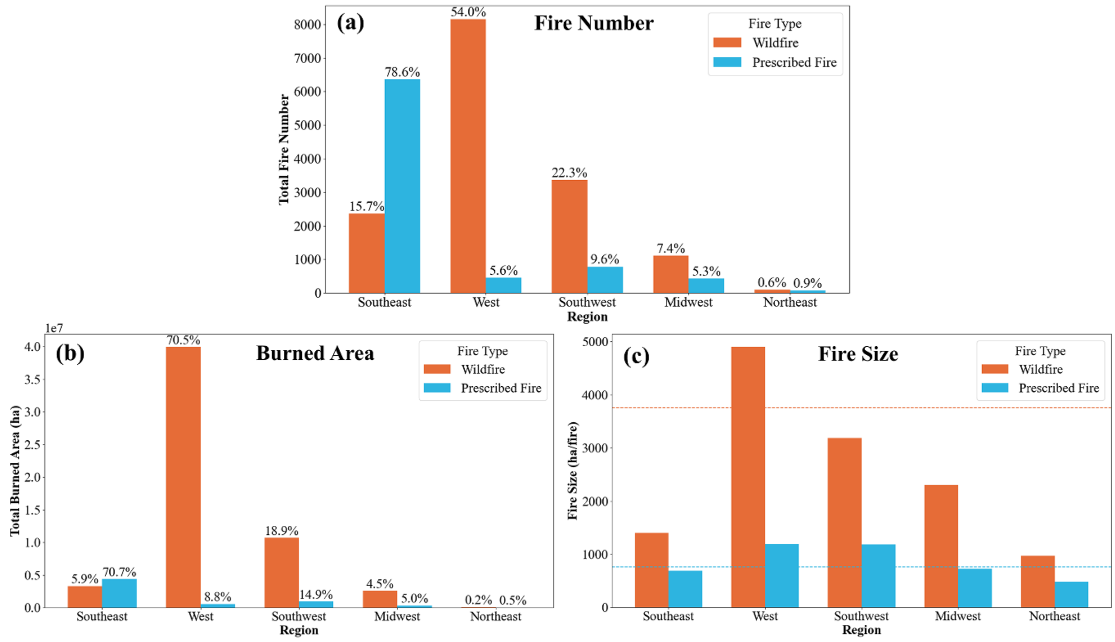

Figure 2. Regional variation in prescribed fire and wildfire characteristics across CONUS. (a) Fire occurrence, (b) total burned area and (c) average fire size for five regions based on MTBS database from 1984 to 2022. The boundaries for five regions are seen in figure 1. Percentages in (a) and (b) represent the proportion of each fire type's total CONUS value. Dashed lines in (c) indicate CONUS-wide averages.

3.1.3. Inter-annual variability

Given that the Southeast and West represent two major fire regimes for prescribed fires and wildfires, respectively, we further examined their long-term annual trends and variability from 1984 to 2022 (figure 4) to understand the evolving fire dynamics driven by land management, climate, and policy shifts. In the Southeast, prescribed fire usage has substantially increased since the early 2000s, reflecting policy shifts that recognize its role in fuel reduction, wildfire mitigation, and ecosystem maintenance (Wonkka *et al* 2015, Hashida *et al* 2025). A notable turning point occurred in 2003, when prescribed fires began to exceed wildfires in both fire numbers and total burned area. Before 2003, prescribed fire sizes were generally larger and more variable, but after this point, they became smaller and more stable likely due to refined fire management practices, stricter regulations, and improved burn prescriptions. A peak in prescribed fire activity around 2010 suggests enhanced interagency collaboration, increased funding, and improved burn management, followed by a temporary decline between 2010 and 2012, likely due to budget saturations, liability concerns and more stringent prescribed fire regulations (Wonkka *et al* 2015, Frey 2024). For example, North Carolina, South Carolina, and Alabama passed prescribed fire laws between 2011 and 2012 that required both written prescriptions and the presence of certified prescribed burn managers (Wonkka *et al* 2015). However, prescribed fire activity has gradually rebounded since 2012, reinforcing its importance in maintaining fire-adapted landscapes and reducing wildfire risk (Coppoletta *et al* 2016, Kalies and Yocom Kent 2016). In contrast, the total burned area in the West has substantially increased, driven primarily by larger wildfire sizes rather than an increase in fire frequency. While the number of wildfires has remained relatively stable, the expansion of individual fire sizes, likely fueled by rising temperatures, prolonged droughts, and excessive fuel accumulation from historical fire suppression (Alizadeh *et al* 2021, Iglesias *et al* 2022, Kreider *et al* 2024), has led to larger fires with potentially more severe and widespread wildfire impacts.

Unlike the Southeast, where prescribed fire is widely applied, its application in the West remains limited and relatively stable, likely constrained by regulatory restrictions, air quality concerns, and logistical challenges (Alizadeh *et al* 2021, Swain *et al* 2023, Davis *et al* 2024). These contrasting trends highlight the need for region-specific fire management strategies that account for local ecological, climatic, and socio-political factors (Hashida *et al* 2025). Expanding prescribed fire use in the West could be a crucial tool in mitigating escalating wildfire risks and restoring fire-adapted ecosystem resilience (Kolden 2019, North *et al* 2024). However, it is important to note that MTBS employs minimum fire size thresholds (500 acres in the Western US and 1000 acres in the Eastern US), meaning small prescribed fires are excluded from our analysis. Data from NFPORS and GlobRx indicate that the use of small prescribed fires in California has increased in recent

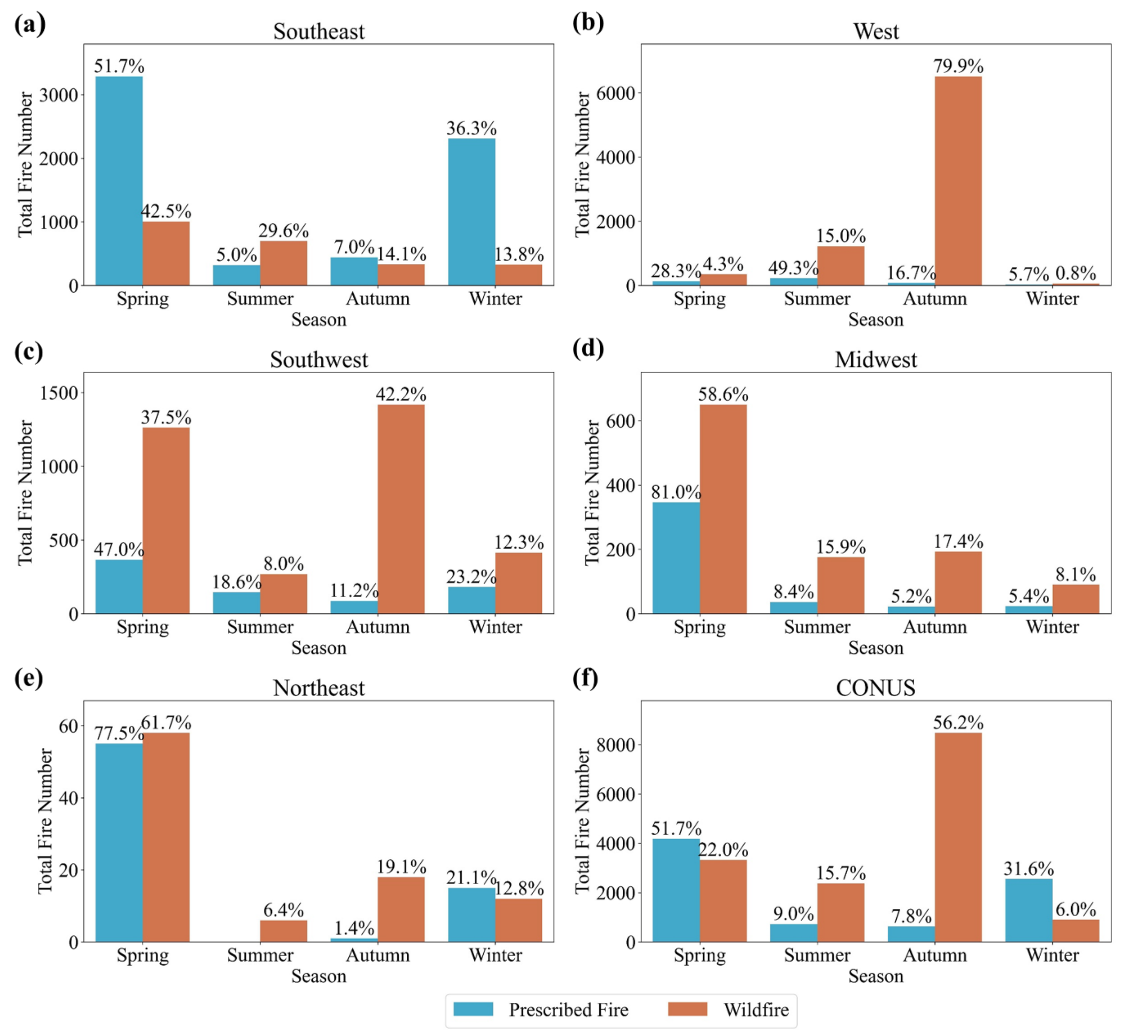

Figure 3. Seasonal distribution of prescribed fires and wildfires across five regions and CONUS. (a) Southeast, (b) West, (c) Southwest, (d) Midwest, (e) Northeast, and (f) CONUS. Seasonal fire occurrence totals derived from MTBS data (1984–2022). Percentages in (a)–(f) represent each season's contribution to the annual total by fire type.

years, though large prescribed fires continue to dominate both interannual variability and cumulative area burned annually (figure S1). Given their increasing prevalence, the patterns and impacts of small prescribed fires require further research attention.

Despite advances in remote sensing (RS), substantial challenges remain in accurately characterizing and distinguishing between prescribed fires and wildfires (Hsu *et al* 2025, Vanderhoof *et al* 2025). Multi-source satellite data have improved fire mapping, but detection reliability is still affected by spatial and temporal inconsistencies across sensor platforms, atmospheric interference from clouds and smoke, deficiencies in fire mapping algorithms etc (Gould *et al* 2023, Zhang *et al* 2023). These limitations are more pronounced for prescribed fires, which often lack consistent labeling, comprehensive reporting, and standardized identification across jurisdictions. Given prescribed burns are typically smaller, shorter in duration, and less systematically monitored than wildfires, they remain underrepresented in RS products. Continued progress will require integrating and cross-validating multiple data sources—such as satellite observations, ground reports, permit databases, and agency records—together with standardized reporting protocols and machine learning methods (Hsu *et al* 2025, Vanderhoof *et al* 2025). Such improvements will enhance the accuracy and comparability of prescribed fire datasets and support more evidence-based fire management and policy decisions.

3.2. Impacts of prescribed fire on water quantity

Prescribed fire, as a controlled disturbance in forest ecosystems, can influence water quantity by altering ET and runoff processes through changes in vegetation structure (e.g. leaf area index, species composition) and soil properties (e.g. infiltration capacity, moisture; figure 5). These changes affect precipitation partitioning and overland flow generation via infiltration-excess or saturation-excess mechanisms, with impacts occurring both immediately and over extended periods (figure 5).

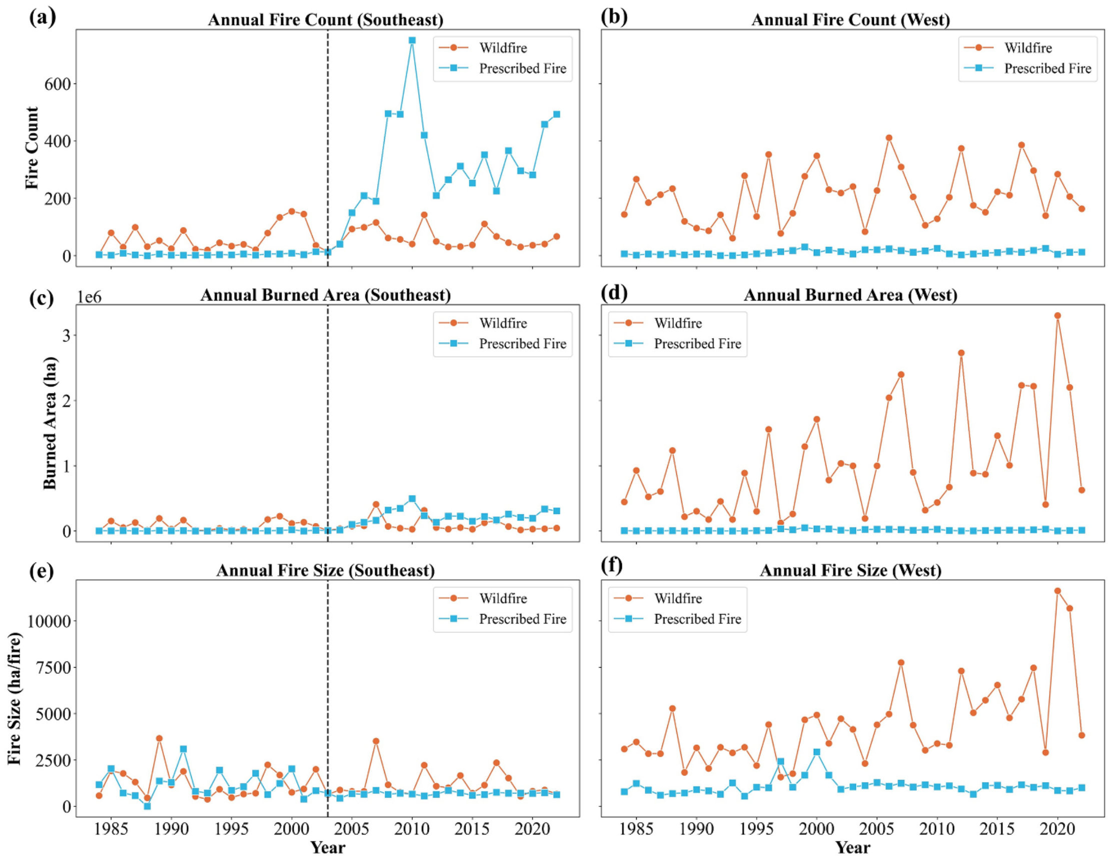

Figure 4. Inter-annual variability in prescribed fire and wildfire characteristics across the Southeast and the West from 1984 to 2022. Fire metrics include total fire numbers (a), (b), burned area (c), (d) and average fire sizes (e), (f) between the Southeast (a), (c) and (e) and West (b), (d) and (f) based on MTBS data from 1984–2022. Vertical dashed lines in Southeast panels (a), (c) and (e) mark a turning point year of 2003, when prescribed fires first exceeded wildfires in both frequency and total burned area, accompanied by smaller and more stable fire sizes thereafter.

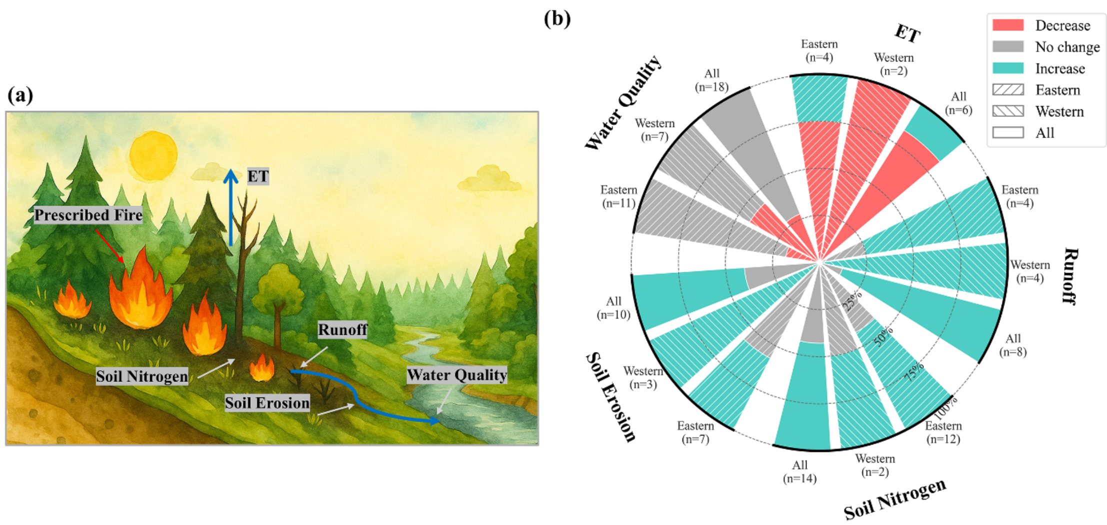

Figure 5. Conceptual framework and observed impacts of prescribed fire on watershed hydrology and water quality. (a) Conceptual diagram illustrating key hydrological processes affected by prescribed fire. (b) Synthesis of reported effects on water quantity and quality across CONUS based on literature review. In (a) and (b), water quantity metrics include ET and runoff; water quality metrics include soil nitrogen, soil erosion, and stream chemistry. Hydrological effects are classified as increase, decrease, or no change, and stratified by region: eastern US, western US, and CONUS-wide (All). Numbers in parentheses indicate the number of review case studies per region. Complete study references are seen in table S1. Background cartoon in (a) created with assistance from ChatGPT (OpenAI).

3.2.1. ET

ET represents the total amount of precipitation returned to the atmosphere through canopy interception, plant transpiration from overstory and understory layers, and evaporation from the soil and forest floor (Sun *et al* 2008, Yang *et al* 2023). As the primary driver of local hydrological cycling, any small changes in total ET due to forest disturbances can directly affect runoff at varying scales (Zhou *et al* 2015, Hallema *et al* 2018). Each component of ET is influenced by multiple biophysical factors, with compensatory responses being common. For example, a decrease in forest transpiration may be offset by an increase in forest floor evaporation. Here, we identified four studies in the eastern US and two in the western US that reported ET impacts from prescribed fires. Three of the four eastern studies and both two western studies observed reduced ET following prescribed fires (figure 5(b)).

A recent study on fire exclusion in longleaf pine woodlands in southern Georgia (Brantley *et al* 2024) suggests that the effects of prescribed fires on total ET and water balances were highly variable and dependent on site moisture status. For example, at the dry (xeric) site, frequent burns reduced overall ET by 15.3%, primarily by removing midstory vegetation. This reduction in canopy interception and transpiration from the midstory outweighed any increases in ET from remaining overstory, understory, groundcover, or enhanced soil evaporation. In wetter (mesic) areas, however, ET increased by 18.2% as fire opens the canopy, allowing sunlight and water to fuel groundcover regrowth that compensates for midstory losses (Brantley *et al* 2024). In another study at the Bankhead National Forest in northern Alabama, Siegert *et al* (2023) found that repeated prescribed burning modified physical properties of tree barks from loblolly pine and chestnut oak by reducing bulk density, increasing porosity, and enhancing water storage capacity, which accelerated drying rates and elevated evaporation from bark surfaces. A modeling study using empirical ET models (McLaughlin *et al* 2013) suggests that slash pine stands in Florida managed at lower basal areas can generate up to 64% more cumulative water yield over a 25 year rotation compared to high-density timber stands, with even greater yields possible when recurrent understory fires are used to further reduce ET.

In the western US, studies showed that prescribed fires tended to increase ET due to canopy thinning and changes in soil moisture dynamics. Flerchinger *et al* (2016) studied post-fire hydrological responses in a sagebrush-dominated rangeland and observed that ET initially declined following prescribed fires due to vegetation loss but rebounded within 2–4 years, depending on root depth and plant regrowth. During this period, canopy loss from prescribed burns led to higher soil evaporation, particularly in arid and semi-arid landscapes, where increased radiation exposure enhanced water loss from bare soils (Flerchinger *et al* 2016). Despite the insights provided by existing research, the scarcity of comprehensive ET studies related to prescribed fires highlights the need for further investigation to robustly characterize ET responses to such controlled burns.

3.2.2. Runoff

Prescribed fire can affect runoff generation through changes in soil infiltration capacity, surface water storage, and ecosystem ET. Among the reviewed studies, three out of four in the eastern US and all four in the western US reported increased runoff following prescribed fires (figure 5(b)). However, the magnitude of runoff impacts vary with fire intensity, severity and post-fire rainfall intensity (Douglass and Lear 1983, Robichaud 2000, Flerchinger *et al* 2016). Early paired watershed experiments in grass-covered abandoned fields (Ursic 1969) and hardwood forests (Ursic 1970) in northern Mississippi documented that prescribed burning led to a 22%–48% increase in stormflow within three years post-burn. Robichaud (2000) further found that prescribed fires in Northern Rocky Mountain forests resulted in a mosaic of burn severities, where high-severity burns led to hydrophobic soil conditions, reducing infiltration rates by 10%–40% and increasing overland flow. Conversely, low-severity burns had little effect on infiltration, allowing soils to maintain permeability. Douglass and Lear (1983) studied ephemeral streams in South Carolina and found that prescribed burns did not significantly alter storm runoff likely due to the lower fire severity. However, in semi-arid landscapes, prescribed burning can enhance runoff by reducing ET losses from vegetation. Flerchinger *et al* (2016) reported a 20% increase in streamflow in burned rangelands, primarily due to the transient lower ET demand and increased soil water percolation.

While prescribed fires could temporarily enhance streamflow, long-term impacts are highly dependent on site-specific vegetation recovery (Wright *et al* 1976, 1982, Flerchinger *et al* 2016). In a post-fire study in Idaho, Wright *et al* (1976) observed that the streamflow initially increased but gradually declined to pre-burn levels as vegetation cover recovered. Similarly, Wright *et al* (1982) demonstrated that prescribed burns on steep watersheds in Texas increased overland flow in the first year, but post-fire seeding and vegetation recovery helped stabilize runoff within one to two years. A more recent study from Flerchinger *et al* (2016) confirmed that prescribed fires initially increased surface water runoff in rangeland catchments but that this effect was transient, with hydrological conditions recovering within two to four years as vegetation reestablished. However, due to the typically limited extent of prescribed burns, their hydrological effects at the large watershed scale are often minimal. For example, the impacts of forest thinning on watershed hydrology are generally undetectable when basal area removal is less than 50% or when the burned area covers less than 20% of the watershed (Hallema *et al* 2018, Del Campo *et al* 2022).

3.3. Impacts of prescribed fire on water quality

Prescribed fire impacts water quality by modifying soil properties and nitrogen dynamics, driving soil erosion and sediment transport, and consequently altering stream water chemistry (figure 5). A thorough understanding of these hydrological processes is essential for balancing prescribed fire management goals with the protection of water resources (Klimas *et al* 2020b, Paul *et al* 2022).

3.3.1. Soil nitrogen

Prescribed fire alters soil nitrogen dynamics by combusting ground litterfall (Dukes *et al* 2020, Agbeshie *et al* 2022), directly impacting downstream water quality through nutrient release and indirectly influencing it by affecting post-fire vegetation recovery (Vose and Swank 1993), which subsequently modulates water quality restoration (Klimas *et al* 2020a, Hampton *et al* 2022). Among the reviewed studies, seven out of twelve in the eastern US and one out of two in the western US reported increased soil nitrogen caused by prescribed fires (figure 5(b)).

In the short term, prescribed burns typically increase soil nitrogen availability by accelerating organic matter decomposition and nitrogen mineralization through ash deposition, leading to transient pulses in nutrients, such as, ammonium (NH_4^+) and/or nitrate (NO_3^-) concentrations (Knoepp and Swank 1993, Carter and Darwin Foster 2004, Stephan *et al* 2012, Klimas *et al* 2020a). A long-term study in Midwestern oak forests further confirms that repeated prescribed burns can enhance total nitrogen levels and mineralization rates, with peaks occurring 12–24 months following the most recent fire (Scharenbroch *et al* 2012). This finding aligns with an earlier study conducted at a mature loblolly pine stand in North Carolina (Schoch and Binkley 1986), where prescribed fire nearly doubled the decomposition rate of forest floor, releasing up to 60 kg N ha^{-1} during the first growing season post-burn. Nevertheless, there are still 45% of the total studies in the Eastern US and one-third of those in the Western US reporting minimal changes in soil nitrogen levels (figure 5), primarily attributed to the lower intensity and severity of the prescribed fires (Richter *et al* 1982, Davis 1989, Hahn *et al* 2019, Thompson *et al* 2019).

3.3.2. Soil erosion

The removal of protective vegetation and litter during a prescribed burn can leave soils vulnerable to erosion, particularly on steep slopes, where enhanced surface runoff increases sediment transport (Ursic 1969, 1970, Wright *et al* 1976, Karban *et al* 2022). This process can thus lead to elevated sediment loads and other pollutants such as nutrients and metals into streams, reducing water clarity, and degrading stream water quality (Cawson *et al* 2012, Elliott *et al* 2024). Among the reviewed studies, three out of seven in the eastern US and all three in the western US reported increased soil erosion following prescribed fires (figure 5(b)). For example, Wright *et al* (1976) found that prescribed burns on Texas juniper lands caused minimal soil loss on level terrain, but large increases in erosion occurred on steeper slopes, lasting 9–30 months post-fire depending on vegetation recovery. Similarly, Karban *et al* (2022) observed that prescribed burns in piñon-juniper woodlands of Utah increased wind and water erosion by up to 17-fold, particularly after broadcast burns, which significantly remove vegetation and biological soil crusts.

Post-fire vegetation recovery is a critical factor in stabilizing soils and mitigating erosion. Wright *et al* (1982) found that erosion rates returned to pre-burn levels once vegetation and litter cover exceeded 64%–72% in wet years and 53%–60% in dry years. Additionally, post-fire seeding was shown to reduce erosion by 78%–93% and accelerate soil stabilization within six months to a year. Karban *et al* (2022) further demonstrated that pile burning, compared to broadcast burning, resulted in less soil disturbance and lower erosion rates, suggesting that more localized fuel reduction strategies may better preserve soil stability. While pile burning can enhance soil water repellency and reduce infiltration at burn pile sites similar to high-severity fires (Fowler *et al* 2024), the limited spatial footprint and intact litter and plant cover surrounding the piles could effectively capture and filter sediment and nutrients moving downslope, resulting in less watershed-scale soil disturbance than the more extensive impacts of broadcast burning (Hubbert *et al* 2015). Notably, several studies (4 out of 7 in eastern regions) showed negligible effects of prescribed fires on soil erosion (figure 5(b)), likely due to their low severity, retention of soil structure, and rapid post-fire vegetative recovery (Douglass and Lear 1983, Swift and Elliott 1993, Elliott and Vose 2005, Singh *et al* 2017, Thompson *et al* 2019).

3.3.3. Stream water quality

Prescribed fires influence stream water quality by increasing sediment and nutrient loads and thus altering water turbidity and chemical composition (Hahn *et al* 2019, Klimas *et al* 2020b), with the extent and persistence of these effects varying based on fire severity, slope steepness, precipitation patterns, and the rate of vegetation regrowth (Wright *et al* 1976, 1982, Battle and Golladay 2003, Bêche *et al* 2005, Beyene *et al* 2023). Among the reviewed studies, two out of eleven in the eastern US and three out of seven in the western US reported degraded downstream water quality following prescribed fires (figure 5(b)).

In Central Texas, controlled burning juniper woodlands increased stream turbidity (up to 132 Jackson Units) and total hardness (up to 95 mg l^{-1}) on watersheds with steep slopes for 1.5–2.5 years, though post-fire seeding reduced sediment loads by 78%–93%, and rapidly restored water quality in six months (Wright *et al* 1976, 1982). In Southwestern Georgia, prescribed fires in wetlands briefly elevated water ammonium (NH_4^+), phosphorus (P), dissolved organic carbon, pH, and alkalinity due to upstream soil scorching, with effects varying by year based on drought or rain (Battle and Golladay 2003). In the Sierra Nevada, a low-severity prescribed fire affecting 14% of a watershed caused short-lived spikes in stream nitrogen, phosphorus, sulfate, and cations, recovering within weeks to a year due to gentle slopes and low post-fire rain (Bêche *et al* 2005).

It is worth noting that most studies (80% in the eastern and 57% in the western regions; figure 5(b)) showed neutral effects on water quality from prescribed fires when compared to higher-severity wildfires (Vose *et al* 1999, Clinton *et al* 2003, Abraham *et al* 2017a, Hahn *et al* 2019, Beyene *et al* 2023). Hahn *et al* (2019) attributed this to low fire intensity and severity in moist-temperate eastern North America, where prescribed fires consume little soil organic matter, preserve overstory vegetation, and maintain intact riparian buffers, limiting erosion and minimizing sediment and nutrient runoff into streams—typically stabilizing within 1–3 years. In contrast, wildfires in the southern Appalachians (Caldwell *et al* 2020) and Colorado Rocky Mountains (Clow *et al* 2024), characterized by greater severity and larger burned areas, were shown to degrade water quality, with severe burns causing increases in nitrate, turbidity, and sediment during post-fire storms, alongside variable dissolved organic carbon responses and elevated water yield, posing risks to downstream water supplies. Abraham *et al* (2017a, 2017b) further indicated that wildfires incinerate organic horizons and vegetation, mobilizing toxic metals (e.g. chromium, cadmium, lead, arsenic) that are then transported by intensified post-fire erosion from rainfall and wind, leading to prolonged water quality degradation and risks to aquatic ecosystem. Similarly, Beyene *et al* (2023) found that in the western US, small, low-severity prescribed burns rarely elevated stream trace element concentrations (e.g. arsenic, selenium, and cadmium), whereas large, high-severity wildfires significantly increased these levels. These effects persisted over time due to the greater burn extent and associated increased runoff, underscoring the influence of fire severity and intensity.

Overall, based on the limited observed adverse effects, prescribed fires may temporarily degrade stream water quality. However, these impacts are typically short-lived and may be effectively mitigated through site-specific strategies, such as patchy burning, avoiding steep terrain, conducting post-burn seeding, and steering clear of sensitive riparian zones. These practices can reduce soil erosion and enhance soil stability, thereby limiting the mobilization of nutrients and metals and ultimately protecting downstream water quality. The controlled nature of prescribed fires, carefully timed and conducted specifically before the fire season, may largely reduce the risk of uncontrolled, high-severity wildfires (Kelp *et al* 2025) and help avoid more severe impacts on water quality (Arkle and Pilliod 2010, Uzun *et al* 2020), particularly in the western U.S (Beyene *et al* 2023). Although our review focuses primarily on forest ecosystems due to limited non-forest literature, the hydrological effects of prescribed fire in shrublands, grasslands, and wetlands require more comprehensive investigation as the literature base expands, given that these ecosystems have distinct vegetation structure, fuel characteristics, and management objectives that may result in varied hydrological impacts.

3.4. Adaptive framework for prescribed fire management

Given the multifaceted impacts of prescribed fire on both ecosystems and water resources (figure 5), a comprehensive, adaptive framework is essential for guiding its implementation. Here, we proposed such a framework by integrating six critical components within three chronological stages: pre-burn planning and risk assessment, post-burn monitoring and response, and adaptive strategies for future burns (figure 6). This approach incorporates best management practices to harmonize both immediate and long-term ecological and hydrological impacts from prescribed fires.

3.4.1. Pre-burn risk assessment and planning

Effective prescribed fire management requires a dynamic framework adapted to specific objectives—such as reducing hazardous fuel loads and mitigating wildfire risk, which are common priorities in the western US, and enhancing soil nutrient cycling, promoting forest regeneration, and maintaining long-term forest health, which are often emphasized in the eastern US (Step 1 in figure 6(a)). Pre-burn evaluations using RS and GIS include assessments of vegetation structure and composition, distributions of wet and dry fuel loads, soil texture, and hydrological mapping of vulnerable zones—such as steep slopes prone to erosion and riparian areas sensitive to sedimentation (Step 2 in figure 6(a)).

Based on the specific fire objectives and risk assessment, a detailed burn plan can be developed (Step 3 in figure 6(a)). Key components include identifying the localized burn window by balancing fire weather conditions, burn effectiveness, and fire

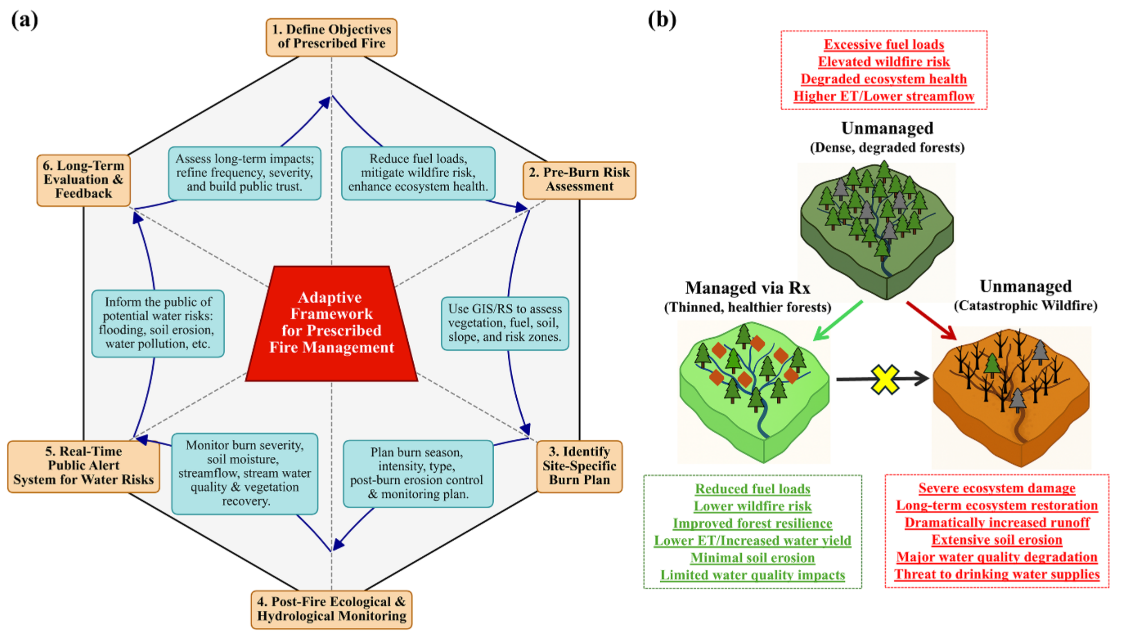

Figure 6. Proposed adaptive framework for prescribed fire management focused on water risk mitigation. (a) Iterative management cycle for prescribed fire planning and implementation with six steps clockwise (detailed in section 3.4). (b) Comparative hydrological outcomes across management scenarios. Unmanaged watersheds with dense, degraded forests exhibit elevated ET and reduced streamflow while carrying high wildfire risk. Strategic prescribed fire application (e.g. patchy burning, orange areas) could reduce ET, increase streamflow, and reduce wildfire risk, though with potential short-term water quality trade-offs. This proactive management helps prevent catastrophic wildfires that severely threaten both ecosystem health and public drinking water supplies. In (a), RS and GIS refer to remote sensing and geographic information systems, respectively. Background cartoons in (b) created with assistance from ChatGPT (OpenAI).

escaping risk; determining the appropriate burn area and intensity based on fire objectives, regional conditions, fire weather, fuel characteristics, and policy constraints; selecting the burn type (e.g. mosaic or patch burning) while minimize soil erosion and water quality risks (e.g. avoiding steep erosive slopes and off sensitive riparian regions); and establishing both post-fire erosion control strategies (e.g. mulching, reseeding, contour-felled log barriers, tackifier-only hydromulch etc) and post-fire monitoring plans (Robichaud *et al* 2013, Bontrager *et al* 2019).

3.4.2. Post-burn monitoring and response

Once prescribed fire is executed, post-fire monitoring is essential for evaluating whether the burn plan was successfully implemented and for informing adaptive management decisions (Step 4 in figure 6(a)). This process begins with immediate field-based assessments and RS–based evaluations of fire severity within days to weeks after the burn. Pre-deployed site-level sensor networks can be used to monitor key hydrological variables such as soil moisture, streamflow, and downstream water quantity. In the rainy seasons that follow, it is important to assess potential soil erosion and stream pollution. Over longer timescales, RS and GIS tools can be used to track vegetation recovery and evaluate its influence on hydrological processes.

It is worth noting that vegetation regrowth plays a critical role in shaping post-fire hydrological outcomes. The rate and pattern of recovery affect soil stabilization, erosion risk, and overall watershed response, with significant variation across regions and vegetation types. For example, in the southeastern US, rapid regrowth can stabilize soils quickly and shorten the erosion-prone period. In contrast, slower recovery in arid western regions extends post-fire vulnerability and may require longer recovery after burns. To minimize hydrological disruption, adaptive practices such as mulching and reseeding can be implemented before the onset of or during the rainy season. By aligning fire regimes with site-specific recovery dynamics and incorporating comprehensive post-fire monitoring, land managers can improve ecological outcomes—such as maintaining open forest structures to reduce wildfire severity—while mitigating adverse impacts on water resources across diverse landscapes.

Given public concerns about prescribed fire as a form of disturbance, it is necessary to develop warning systems that clearly communicate potential eco-hydrological risks to downstream communities with transparency and accountability (Step 5 in figure 6(a)). Collaboration among land managers, local communities, water utilities, and conservation groups is critical for recognizing and responding to both short-term concerns—such as smoke exposure and liability—and medium- to long-term impacts on water resources. A well-designed, real-time alert system can provide timely information on post-fire runoff hazards, particularly during extreme rainfall events that intensify erosion and the transport of sediment, ash, and contaminants into waterways. By integrating scientific data, proactive communication, and cross-sector coordination, such systems not only help protect public health and water quality but also foster trust in the responsible and adaptive use of prescribed fire as a land management tool.

3.4.3. Adaptive strategies for future burns

Strategic monitoring and research provide the scientific foundation needed for sustainable implementation of prescribed fire (Step 6 in figure 6(a)). Advanced monitoring tools including real-time sensor networks, RS, GIS-based mapping, and fire-behavior simulations enable tracking changes in key hydrological variables, such as soil moisture, streamflow, sediment transport, and nutrient loading. These data are essential not only for assessing immediate ecological responses, but also for guiding and refining adaptive fire prescriptions on the timing, location, and intensity of burns to minimize hydrologic impacts. In particular, understanding how fire interacts with seasonal fire weather, fuel moisture conditions, and ecosystem development stages (Zhang *et al* 2023, 2025) can help land managers optimize burn windows to ensure burn effectiveness while reducing post-fire erosion and water contamination risks (Emelko *et al* 2011, Nyman *et al* 2015, Li *et al* 2024). While long-term studies remain limited, they are crucial for evaluating cumulative effects on watershed stability, aquatic ecosystems, and water quality over extended periods. Establishing permanent monitoring sites and experimental watersheds will support the development of region-specific fire thresholds and hydrologic resilience metrics. Integrated monitoring of both upland forest conditions and downstream aquatic responses will further help optimize burn severity and frequency to achieve local ecological goals. Collectively, these monitoring and research efforts ensure prescribed fire continues to evolve as a data-informed, climate-resilient management tool (figure 6(b)) that supports ecosystem health and protects water resources and mitigate the growing risks of frequent and severe wildfires intensified by climate change (Jones *et al* 2022, Zhang *et al* 2023).

4. Conclusions

Prescribed fire, a controlled surface burning, has emerged as an indispensable tool in modern forest management. Our analysis of long-term national fire database (MTBS; 1984–2022) reveals marked regional, seasonal, and temporal differences in contemporary patterns of prescribed fires when compared to wildfires. The Southeast shaped the national prescribed fire regime by contributing the largest fire numbers (78.6%) and total burned area (70.5%) in CONUS. Prescribed fires exhibited a distinct seasonal pattern—primarily occurring in spring—contrasting sharply with wildfires, which peaked in autumn, particularly in the West and Southwest. Over time, policy shifted and refined management practices have driven a significant increase in prescribed fire usage in the Southeast since the early 2000s, with a notable peak around 2010 despite a temporary decline thereafter. Conversely, a rise in wildfire burned areas in the West was driven by climatic extremes and historical fire suppression, while prescribed fire use remained limited likely due to regulatory constraints, air quality concerns, liability risks, public opposition, and insufficient understanding of potential environmental trade-offs.

Our synthesis of studies conducted between 1969 and 2024 indicates that prescribed fire exerts both immediate and longer-term effects on water quantity—altering ET and runoff by modifying vegetation structure, soil properties, and hydrological processes—and water quality through changes in soil nitrogen dynamics, erosion, and sediment transport that impact stream chemistry. These effects are complex and vary across regions but are generally less severe than those associated with high-severity wildfires. Thus, when properly implemented, prescribed fire could benefit water resources through mitigating catastrophic wildfires that severely degrade water quality (particularly important in the western US), and maintaining healthy, fire-adapted ecosystems that sustain watershed function and water quality (especially critical in the eastern US). Finally, we proposed an adaptive framework by balancing ecological benefits against hydrological risks from prescribed fires, offering science-based guidelines to support sustainable forest management, mitigate wildfire risks, and safeguard water resources.

Data availability statement

All data that support the findings of this study are included within the article and the supplementary data.

Acknowledgments

We gratefully acknowledge the U.S. Geological Survey and the U.S. Forest Service for their ongoing support of the Monitoring Trends in Burn Severity (MTBS) project, which provides essential fire data for this research. We also extend our thanks to numerous researchers, land managers, and local stakeholders whose work and insights (shown in table S1) have significantly advanced our understanding of prescribed fire's eco-hydrological impacts. Funding support was from USDA Forest Service and U.S. Environmental Protection Agency through Joint

Venture Agreements (23-JV-11330180-119; 23-JV-11330180-054) with Duke University. The USDA also funded the contributions of Forest Service employees to this effort. The views expressed in this review are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency and the U.S. Department of Agriculture Forest Service. Portions of this manuscript were prepared with assistance from artificial intelligence tools, specifically OpenAI's ChatGPT, which was used to help refine grammar, improve clarity, and generate illustrative figures 5(a) and 6(b) under the supervision and full control of the authors. All intellectual content, analysis, and interpretations are the original work of the authors.

ORCID iDs

Yulong Zhang 0000-0001-6967-0051
Wenhong Li 0000-0002-5990-2004
Christopher Mihiar 0000-0002-9832-5262
Yiyun Song 0009-0007-8032-1750
Ge Sun 0000-0002-0159-1370

References

Abraham J, Dowling K and Florentine S 2017a Risk of post-fire metal mobilization into surface water resources: a review *Sci. Total Environ.* **599–600** 1740–55
Abraham J, Dowling K and Florentine S 2017b The unquantified risk of post-fire metal concentration in soil: a review *Water Air Soil Pollut.* **228** 175
Agbeshie A A, Abugre S, Atta-Darkwa T and Awuah R 2022 A review of the effects of forest fire on soil properties *J. For. Res.* **33** 1419–41
Alcañiz M, Outeiro L, Francos M and Úbeda X 2018 Effects of prescribed fires on soil properties: a review *Sci. Total Environ.* **613–614** 944–57
Alizadeh M R, Abatzoglou J T, Luce C H, Adamowski J F, Farid A and Sadegh M 2021 Warming enabled upslope advance in western US forest fires *Proc. Natl Acad. Sci.* **118** e2009717118
Arkle R S and Pilliod D S 2010 Prescribed fires as ecological surrogates for wildfires: a stream and riparian perspective *For. Ecol. Manage.* **259** 893–903
Baijnath-Rodino J A, Li S, Martinez A, Kumar M, Quinn-Davidson L N, York R A and Banerjee T 2022 Historical seasonal changes in prescribed burn windows in California *Sci. Total Environ.* **836** 155723
Balch J K *et al* 2024 The fastest-growing and most destructive fires in the US (2001–2020) *Science* **386** 425–31
Baron J N, Gergel S E, Hessburg P F and Daniels L D 2022 A century of transformation: fire regime transitions from 1919 to 2019 in southeastern British Columbia, Canada *Landscape Ecol.* **37** 2707–27
Battle J and Golladay S W 2003 Prescribed fire's impact on water quality of depressional wetlands in southwestern Georgia *Am. Midland Nat.* **150** 15–25
Bêche L A, Stephens S L and Resh V H 2005 Effects of prescribed fire on a Sierra Nevada (California, USA) stream and its riparian zone *For. Ecol. Manage.* **218** 37–59
Belongia M F, Hammond Wagner C, Seipp K Q and Ajami N K 2023 Building water resilience in the face of cascading wildfire risks *Sci. Adv.* **9** eadf9534
Beyene M T, Leibowitz S G, Dunn C J and Bladon K D 2023 To burn or not to burn: an empirical assessment of the impacts of wildfires and prescribed fires on trace element concentrations in Western US streams *Sci. Total Environ.* **863** 160731
Bontrager J D, Morgan P, Hudak A T and Robichaud P R 2019 Long-term vegetation response following post-fire straw mulching *Fire Ecol.* **15** 22
Bowman D M J S, Kolden C A, Abatzoglou J T, Johnston F H, Van Der Werf G R and Flannigan M 2020 Vegetation fires in the Anthropocene *Nat. Rev. Earth Environ.* **1** 500–15
Brantley S T, Stuber O S, Holder D L and Taylor R S 2024 Fire exclusion alters forest evapotranspiration: a comprehensive water budget analysis in longleaf pine woodlands *Ecol. Monogr.* **94** e1623
Caldwell P V, Elliott K J, Liu N, Vose J M, Zietlow D R and Knoepp J D 2020 Watershed-scale vegetation, water quantity, and water quality responses to wildfire in the southern Appalachian mountain region, United States *Hydrol. Process.* **34** 5188–209
Carter M C and Darwin Foster C 2004 Prescribed burning and productivity in southern pine forests: a review *For. Ecol. Manage.* **191** 93–109
Cawson J G, Sheridan G J, Smith H G and Lane P N J 2012 Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: a review *Int. J. Wildland Fire* **21** 857
Clinton B D, Vose J M, Knoepp J K and Elliott K J 2003 Stream nitrate response to different burning treatments in Southern Appalachian forests *Proc. Fire Conf. 2000: The First National Congress on Fire Ecology, Prevention, and Management*
Clow D W, Akie G A, Murphy S F and Gohring E J 2024 Dynamic water-quality responses to wildfire in Colorado *Hydrol. Process.* **38** e15291
Coates T A, Chow A T, Hagan D L, Wang G G, Bridges W C and Dozier J H 2017 Frequent prescribed burning as a long-term practice in longleaf pine forests does not affect detrital chemical composition *J. Environ. Qual.* **46** 1020–7
Coppoletta M, Merriam K E and Collins B M 2016 Post-fire vegetation and fuel development influences fire severity patterns in reburns *Ecol. Appl.* **26** 686–99
Costanza J K and Moody A 2011 Deciding where to burn: stakeholder priorities for prescribed burning of a fire-dependent ecosystem *Ecol. Soc.* **16** 27
Davis E A 1989 Prescribed fire in Arizona chaparral: effects on stream water quality *For. Ecol. Manage.* **26** 189–206
Davis K T, Peeler J, Fargione J, Haugo R D, Metlen K L, Robles M D and Woolley T 2024 Tamm review: a meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US *For. Ecol. Manage.* **561** 121885
Del Campo A D, Otsuki K, Serengil Y, Blanco J A, Yousefpour R and Wei X 2022 A global synthesis on the effects of thinning on hydrological processes: implications for forest management *For. Ecol. Manage.* **519** 120324
Donovan V M, Crandall R, Fill J and Wonkka C L 2023 Increasing large wildfire in the eastern United States *Geophys. Res. Lett.* **50** e2023GL107051
Douglass J E and Lear D H V 1983 Prescribed burning and water quality of ephemeral streams in the piedmont of South Carolina *For. Sci.* **29** 181–9
Dukes C J, Coates T A, Hagan D L, Aust W M, Waldrop T A and Simon D M 2020 Long-term effects of repeated prescribed fire and fire surrogate treatments on forest soil chemistry in the southern Appalachian Mountains (USA) *Fire* **3** 20
Ebel B A, Shephard Z M, Walvoord M A, Murphy S F, Partridge T F and Perkins K S 2023 Modeling post-wildfire hydrologic response: review and future directions for applications of physically based distributed simulation *Earth's Future* **11** e2022EF003038
Eidenshink J, Schwind B, Brewer K, Zhu Z-L, Quayle B and Howard S 2007 A project for monitoring trends in burn severity *Fire Ecol.* **3** 1

Elliott K J and Vose J M 2005 Initial effects of prescribed fire on quality of soil solution and streamwater in the southern Appalachian Mountains *South. J. Appl. For.* **29** 5–15

Elliott K J and Vose J M 2010 Short-term effects of prescribed fire on mixed oak forests in the southern Appalachians: vegetation response[1] *J. Torrey Bot. Soc.* **137** 49–66

Elliott S M, Hornberger M I, Rosenberry D O, Frus R J and Webb R M 2024 A conceptual framework to assess post-wildfire water quality: state of the science and knowledge gaps *Water Resour. Res.* **60** e2023WR036260

Emelko M B, Silins U, Bladon K D and Stone M 2011 Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for "source water supply and protection" strategies *Water Res.* **45** 461–72

Flerchinger G N, Seyfried M S and Hardegree S P 2016 Hydrologic response and recovery to prescribed fire and vegetation removal in a small rangeland catchment *Ecohydrology* **9** 1604–19

Fowler J A, Nelson A R, Bechtold E K, Paul R, Wettengel A M, McNorvell M A, Stevens-Rumann C S, Fegel T S, Anderson E and Rhoades C C 2024 Pile burns as a proxy for high severity wildfire impacts on soil microbiomes *Geoderma* **448** 116982

Frey G E 2024 Managed burning of forests: balancing economic incentives, risks, and liability *Environ. Law Rev.* **26** 259–77

Gould N P, Pomara L Y, Nepal S, Goodrick S L and Lee D C 2023 Mapping firescapes for wild and prescribed fire management: a landscape classification approach *Land* **12** 2180

Hahn G E, Coates T A, Latham R E and Majidzadeh H 2019 Prescribed fire effects on water quality and freshwater ecosystems in moist-temperate eastern North America *Nat. Areas J.* **39** 46

Hallema D W, Sun G, Bladon K D, Norman S P, Caldwell P V, Liu Y and McNulty S G 2017 Regional patterns of postwildfire streamflow response in the Western United States: the importance of scale-specific connectivity *Hydrol. Process.* **31** 2582–98

Hallema D W, Sun G, Caldwell P V, Norman S P, Cohen E C, Liu Y, Bladon K D and McNulty S G 2018 Burned forests impact water supplies *Nat. Commun.* **9** 1307

Hampton T B, Lin S and Basu N B 2022 Forest fire effects on stream water quality at continental scales: a meta-analysis *Environ. Res. Lett.* **17** 064003

Han X, Frey G E and Sun C 2020 Regulation and practice of forest-management fires on private lands in the southeast United States: legal open burns versus certified prescribed burns *J. For.* **118** 385–402

Hashida Y, Lewis D J and Cummins K 2025 Prescribed fires as a climate change adaptation tool *J. Environ. Econ. Manage.* **130** 103081

Hatten J A, Zabowski D, Ogden A and Thies W 2008 Soil organic matter in a ponderosa pine forest with varying seasons and intervals of prescribed burn *For. Ecol. Manage.* **255** 2555–65

Hiers J K *et al* 2020 Prescribed fire science: the case for a refined research agenda *Fire Ecol.* **16** 11

Hsu A, Jones M W, Thurgood J R, Smith A J, Carmenta R, Abatzoglou J T, Anderson L O, Clarke H, Doerr S H and Fernandes P M 2025 A global assemblage of regional prescribed burn records—GlobalRx *Sci. Data* **12** 1083

Hubbert K R, Busse M, Overby S, Shestak C and Gerrard R 2015 Pile burning effects on soil water repellency, infiltration, and downslope water chemistry in the lake Tahoe basin, USA *Fire Ecol.* **11** 100–18

Hunter M E and Robles M D 2020 Tamm review: the effects of prescribed fire on wildfire regimes and impacts: a framework for comparison *For. Ecol. Manage.* **475** 118435

Ice G G, Neary D G and Adams P W 2004 Effects of wildfire on soils and watershed processes *J. For.* **102** 16–20

Iglesias V, Balch J K and Travis W R 2022 US fires became larger, more frequent, and more widespread in the 2000s *Sci. Adv.* **8** eabc0020

James C E and Krumland B 2018 Immediate post–forest fire salvage logging, soil erosion, and sediment delivery *For. Sci.* **64** 246–67

Jones M W *et al* 2022 Global and regional trends and drivers of fire under climate change *Rev. Geophys.* **60** e2020RG000726

Kalies E L and Yocom Kent L L 2016 Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review *For. Ecol. Manage.* **375** 84–95

Karban C C, Miller M E, Herrick J E and Barger N N 2022 Consequences of piñon-juniper woodland fuel reduction: prescribed fire increases soil erosion while mastication does not *Ecosystems* **25** 122–35

Kelly L T, Fletcher M-S, Oliveras Menor I, Pellegrini A F A, Plumanns-Pouton E S, Pons P, Williamson G J and Bowman D M J S 2023 Understanding fire regimes for a better Anthropocene *Annu. Rev. Environ. Resour.* **48** 207–35

Kelp M, Burke M, Qiu M, Higuera-Mendieta I, Liu T and Diffenbaugh N S 2025 Effect of recent prescribed burning and land management on wildfire burn severity and smoke emissions in the western United States *AGU Adv.* **6** e2025AV001682

Klimas K, Hiesl P, Hagan D and Park D 2020a Immediate effects of prescribed fire on sub-surface water quality in a managed yellow pine forest *Fire* **3** 14

Klimas K, Hiesl P, Hagan D and Park D 2020b Prescribed fire effects on sediment and nutrient exports in forested environments: a review *J. Environ. Qual.* **49** 793–811

Knapp B O, Pile L S, Walker J L and Geoff Wang G 2018 Fire effects on a fire-adapted species: response of grass stage longleaf pine seedlings to experimental burning *Fire Ecol.* **14** 2

Knapp E E, Estes B L and Skinner C N 2009 Ecological effects of prescribed fire season: a literature review and synthesis for managers *No. PSW-GTR-224* (U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station) (https://doi.org/10.2737/PSW-GTR-224)

Knight C A *et al* 2022 Land management explains major trends in forest structure and composition over the last millennium in California's Klamath Mountains *Proc. Natl Acad. Sci.* **119** e2116264119

Knoepp J D and Swank W T 1993 Site preparation burning to improve southern Appalachian pine-hardwood stands: nitrogen responses in soil, soil water, and streams *Can. J. For. Res.* **23** 2263–70

Kolden C 2019 We're not doing enough prescribed fire in the western United States to mitigate wildfire risk *Fire* **2** 30

Kreider M R, Higuera P E, Parks S A, Rice W L, White N and Larson A J 2024 Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation *Nat. Commun.* **15** 2412

Li L, Knapp J L A, Lintern A, Ng G-H C, Perdrial J, Sullivan P L and Zhi W 2024 River water quality shaped by land–river connectivity in a changing climate *Nat. Clim. Change* **14** 225–37

Lopez A M, Avila C C E, VanderRoest J P, Roth H K, Fendorf S and Borch T 2024 Molecular insights and impacts of wildfire-induced soil chemical changes *Nat. Rev. Earth Environ.* **5** 431–46

Mason D S and Lashley M A 2021 Spatial scale in prescribed fire regimes: an understudied aspect in conservation with examples from the southeastern United States *Fire Ecol.* **17** 3

McCaw W L 2013 Managing forest fuels using prescribed fire—A perspective from southern Australia *For. Ecol. Manage.* **294** 217–24

McCullough I M, Cheruvelil K S, Lapierre J, Lottig N R, Moritz M A, Stachelek J and Soranno P A 2019 Do lakes feel the burn? Ecological consequences of increasing exposure of lakes to fire in the continental United States *Glob. Change Biol.* **25** 2841–54

McGuire L A, Ebel B A, Rengers F K, Vieira D C S and Nyman P 2024 Fire effects on geomorphic processes *Nat. Rev. Earth Environ.* **5** 486–503

McLauchlan K K *et al* 2020 Fire as a fundamental ecological process: research advances and frontiers *J. Ecol.* **108** 2047–69
McLaughlin D L, Kaplan D A and Cohen M J 2013 Managing forests for increased regional water yield in the southeastern U.S. Coastal Plain *JAWRA J. Am. Water Resour. Assoc.* **49** 953–65
Moazeni S and Cerdà A 2024 The impacts of forest fires on watershed hydrological response. A review *Trees Forests People* **18** 100707
Mullen R M, Springer A E and Kolb T E 2006 Complex effects of prescribed fire on restoring the soil water content in a high-elevation riparian meadow, Arizona *Restorat. Ecol.* **14** 242–50
Navarro K M, Schweizer D, Balmes J R and Cisneros R 2018 A review of community smoke exposure from wildfire compared to prescribed fire in the United States *Atmosphere* **9** 185
Neary D G and Leonard J 2015 *Wildland Fire: Impacts on Forest, Woodland, and Grassland Ecological Processes* (Nova Science Publishers)
North M P, Bisbing S M, Hankins D L, Hessburg P F, Hurteau M D, Kobziar L N, Meyer M D, Rhea A E, Stephens S L and Stevens-Rumann C S 2024 Strategic fire zones are essential to wildfire risk reduction in the Western United States *Fire Ecol.* **20** 50
Nyman P, Smith H G, Sherwin C B, Langhans C, Lane P N J and Sheridan G J 2015 Predicting sediment delivery from debris flows after wildfire *Geomorphology* **250** 173–86
Paul M J, LeDuc S D, Lassiter M G, Moorhead L C, Noyes P D and Leibowitz S G 2022 Wildfire induces changes in receiving waters: a review with considerations for water quality management *Water Resour. Res.* **58** e2021WR030699
Richter D D, Ralston C W and Harms W R 1982 Prescribed fire: effects on water quality and forest nutrient cycling *Science* **215** 661–3
Robichaud P R 2000 Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA *J. Hydrol.* **231–232** 220–9
Robichaud P R, Lewis S A, Wagenbrenner J W, Ashmun L E and Brown R E 2013 Post-fire mulching for runoff and erosion mitigation: part I: effectiveness at reducing hillslope erosion rates *Catena* **105** 75–92
Ryan K C, Knapp E E and Varner J M 2013 Prescribed fire in North American forests and woodlands: history, current practice, and challenges *Front. Ecol. Environ.* **11** e15–e24
Sample M *et al* 2022 Adaptation strategies and approaches for managing fire in a changing climate *Climate* **10** 58
Scharenbroch B C, Nix B, Jacobs K A and Bowles M L 2012 Two decades of low-severity prescribed fire increases soil nutrient availability in a Midwestern, USA oak (Quercus) forest *Geoderma* **183–184** 80–91
Schoch P and Binkley D 1986 Prescribed burning increased nitrogen availability in a mature loblolly pine stand *For. Ecol. Manage.* **14** 13–22
Schweitzer C J and Dey D C 2023 Prescribed fire for upland oaks *Upland Oak and White Oak Silviculture Practices Series* ed J Stringer (Cooperative Extension Service, University of Kentucky, Department of Forestry and Natural Resources) p 13
Siegert C, Ilek A, Wade A and Schweitzer C 2023 Changes in bark properties and hydrology following prescribed fire in Pinus taeda and Quercus montana *Hydrol. Process.* **37** e14799
Singh G, Schoonover J, Monroe K, Williard K and Ruffner C 2017 Prescribed burning and erosion potential in mixed hardwood forests of southern Illinois *Forests* **8** 112
Smith H G, Sheridan G J, Lane P N J, Nyman P and Haydon S 2011 Wildfire effects on water quality in forest catchments: a review with implications for water supply *J. Hydrol.* **396** 170–92
Solander K C, Talsma C J and Vesselinov V V 2023 The drivers and predictability of wildfire re-burns in the western United States (US) *Environ. Res. Clim.* **2** 015001
Stephan K, Kavanagh K L and Koyama A 2012 Effects of spring prescribed burning and wildfires on watershed nitrogen dynamics of central Idaho headwater areas *For. Ecol. Manage.* **263** 240–52
Sun G, McNulty S G, Moore Myers J A and Cohen E C 2008 Impacts of multiple stresses on water demand and supply across the southeastern United States *JAWRA J. Am. Water Resour. Assoc.* **44** 1441–57
Swain D L, Abatzoglou J T, Kolden C, Shive K, Kalashnikov D A, Singh D and Smith E 2023 Climate change is narrowing and shifting prescribed fire windows in western United States *Commun. Earth Environ.* **4** 340
Swift L W and Elliott K J 1993 Site preparation burning to improve southern Appalachian pine–hardwood stands: fire characteristics and soil erosion, moisture, and temperature *Can. J. For. Res.* **23** 2242–54
Thompson E G, Coates T A, Aust W M and Thomas-Van Gundy M A 2019 Wildfire and prescribed fire effects on forest floor properties and erosion potential in the Central Appalachian Region, USA *Forests* **10** 493
Ursic S J 1969 *Hydrologic Effects of Prescribed Burning on Abandoned Fields in Northern Mississippi* vol 46 (Southern Forest Experiment Station)
Ursic S J 1970 *Hydrologic Effects of Prescribed Burning and Deadening Upland Hardwoods in Northern Mississippi* vol 54 (Southern Forest Experiment Station, Forest Service, US Department of Agriculture)
Uzun H, Zhang W, Olivares C I, Erdem C U, Coates T A, Karanfil T and Chow A T 2020 Effect of prescribed fires on the export of dissolved organic matter, precursors of disinfection by-products, and water treatability *Water Res.* **187** 116385
Vanderhoof M K, Menick C E, Picotte J J, Robertson K M, Nowell H K, Matechik C and Hawbaker T J 2025 Modelling and mapping burn severity of prescribed and wildfires across the southeastern United States (2000–2022) *Int. J. Wildland Fire* **34** 1–18
Vose J M and Swank W T 1993 Site preparation burning to improve southern Appalachian pine–hardwood stands: aboveground biomass, forest floor mass, and nitrogen and carbon pools *Can. J. For. Res.* **23** 2255–62
Vose J M, Swank W T, Clinton B D, Knoepp J D and Swift L W 1999 Using stand replacement fires to restore southern Appalachian pine-hardwood ecosystems: effects on mass, carbon, and nutrient pools *For. Ecol. Manage.* **114** 215–26
Weir J R, Twidwell D and Wonkka C L 2016 From grassroots to national alliance: the emerging trajectory for landowner prescribed burn associations *Rangelands* **38** 113–9
Wonkka C L, Rogers W E and Kreuter U P 2015 Legal barriers to effective ecosystem management: exploring linkages between liability, regulations, and prescribed fire *Ecol. Appl.* **25** 2382–93
Wright H A, Churchill F M and Stevens C 1976 Effect of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas *J. Range Manage.* **29** 294
Wright H A, Churchill F M and Stevens W C 1982 Soil loss, runoff, and water quality of seeded and unseeded steep watersheds following prescribed burning *J. Range Manage.* **35** 382
Yang Y *et al* 2023 Evapotranspiration on a greening Earth *Nat. Rev. Earth Environ.* **4** 626–41
Yoder J, Engle D and Fuhlendorf S 2004 Liability, incentives, and prescribed fire for ecosystem management *Front. Ecol. Environ.* **2** 361–6
Zema D A and Lucas-Borja M E 2023 Effects of prescribed fire on the post-fire hydrological processes in agro-forest ecosystems: a systematic review and a meta-analysis *Hydrol. Process.* **37** e14957
Zema D A, Parhizkar M, Plaza-Alvarez P A, Xu X and Lucas-Borja M E 2024 Using random forest and multiple-regression models to predict changes in surface runoff and soil erosion after prescribed fire *Model. Earth Syst. Environ.* **10** 1215–28

Zhang Y, Mao J, Ricciuto D M, Jin M, Yu Y, Shi X, Wullschleger S, Tang R and Liu J 2023 Global fire modelling and control attributions based on the ensemble machine learning and satellite observations *Sci. Remote Sens.* **7** 100088

Zhang Y, Mao J, Sun G, Guo Q, Atkins J, Li W, Jin M, Song C, Xiao J and Hwang T 2025 Earth's record-high greenness and its attributions in 2020 *Remote Sens. Environ.* **316** 114494

Zhang Y, Song C, Hwang T, Novick K, Coulston J W, Vose J, Dannenberg M P, Hakkenberg C R, Mao J and Woodcock C E 2021 Land cover change-induced decline in terrestrial gross primary production over the conterminous United States from 2001 to 2016 *Agric. For. Meteorol.* **308** 108609

Zhou G *et al* 2015 Global pattern for the effect of climate and land cover on water yield *Nat. Commun.* **6** 5918

Zhou G *et al* 2025 Fire-driven disruptions of global soil biochemical relationships *Nat. Commun.* **16** 1190

Zhou Y, Biro A, Wong M Y, Batterman S A and Staver A C 2022 Fire decreases soil enzyme activities and reorganizes microbially mediated nutrient cycles: a meta-analysis *Ecology* **103** e3807