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Soil Factors Influencing Wildfire Behavior and Severity: A Review

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Abstract This review synthesizes current knowledge on how soil-related factors influence wildfire behavior and burn severity. Key soil factors include soil moisture status, texture and structure, organic matter content (e.g., peat and duff layers), microbial activity, and properties like compaction, erosion, and water repellency. Soil moisture emerges as a critical control on fuel flammability and fire spread potential, with drought-prone soils and low soil water content strongly correlating with larger, more intense fires in many ecosystems. Soil texture and structure mediate infiltration and water retention, thereby affecting vegetation moisture and fuel continuity. Soils rich in organic matter (such as peatlands) can sustain smoldering combustion, and lead to extreme fire severity and carbon emissions when sufficiently dry. Repeated fires and intense burns can degrade soil structure, reduce nutrient availability, and induce hydrophobic (water-repellent) soil conditions that promote runoff and erosion, further influencing future fire regimes. We highlight global examples—from boreal peat fires and tropical rainforest burn scars to temperate forest and savanna soils—illustrating the multifaceted roles of soils in fire dynamics. Improving wildfire prediction and management under climate change requires integrating soil parameters (e.g., soil moisture monitoring, organic layer depth, post-fire soil assessments) into fire danger indices and ecosystem models. This review provides a comprehensive, up-to-date examination of soil–fire interactions and discusses implications for fire ecology, carbon cycling, and land management in fire-prone regions.

Keywords Wildfire Severity, Soil Moisture, Soil Texture, Soil Organic Matter, Hydrophobicity

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1. Introduction

Wildfires are natural disturbances in many ecosystems, but anthropogenic climate change and land-use practices have increased their frequency, intensity, and burned area. Extreme seasons such as Australia's 2019–2020 "Black Summer" and Canada's record 2023 fires highlight the urgency of understanding wildfire drivers. Classically, fire behavior is governed by weather, climate, fuel loads, and topography. Yet soils are now recognized as critical variables influencing ignition, spread, and severity [1,2]. They affect wildfires directly through moisture and heat transfer, and indirectly by shaping vegetation and productivity [3,4].

Soil moisture strongly controls flammability by regulating vegetation water status and fuel accumulation. It is a key predictor of wildfire hazard across biomes [2,5,6]. Drought-driven drying predisposes ecosystems to intense fires [7,8], while wet soils and high water tables can suppress spread and severity [9]. Fire danger indices like the Keetch–Byram Drought Index rely on soil water proxies, but actual soil moisture data improves predictive power [10].

Soil particle size and aggregation influence infiltration and water holding capacity, thereby controlling drying rates [11]. Coarse, well-drained soils dry quickly and foster intense fires, whereas fine-textured soils buffer drought

[12,13]. Fires themselves can degrade soil structure—breaking aggregates, compacting soils, and reducing porosity. These changes promote erosion and drying, reinforcing fire-prone conditions [14].

Organic layers such as litter, humus, and peat are critical fuels. They can sustain smoldering combustion, extending fire residence time [15,16]. In peatlands and boreal forests, organic soils often burn as ground fires, releasing vast carbon stores and driving deep heating [17,18]. Once dry, organic soils enable persistent underground fires, as seen in Indonesia and Siberia [8,17]. Yet low-severity fires that char litter can stabilize soil carbon by producing resistant charcoal.

Microbes regulate decomposition and fuel buildup. Rapid decomposition reduces litter and fire intensity [19], whereas slow decomposition allows thick fuel layers to accumulate [20]. Fires can sharply reduce microbial biomass, altering fertility and slowing litter breakdown, thereby feeding back into fire regimes [21]. Drought-induced microbial adaptations may also increase soil water repellency, hastening drying [22].

Heating of organic matter leaves behind waxy residues that repel water, lowering infiltration. This accelerates drying and extends fire-prone conditions [9,23]. Such repellency can persist for months to years, as shown in Mediterranean woodlands where severe fires created highly flammable post-fire surfaces. Even without fire, drought-driven microbial and chemical processes can produce hydrophobic soils [22].

High-severity fires remove vegetation and litter, exposing soils to erosion by wind and rain. Runoff, flooding, and topsoil loss are common [24]. This hinders vegetation recovery, sometimes converting forests into grasslands or shrublands [25]. Such transitions alter fire regimes, often favoring frequent, low-intensity grass fires [7,26]. Soil degradation from compaction, nutrient depletion, or erosion can thus reshape long-term fire dynamics. Mitigating erosion and maintaining soil health post-fire are essential for resilience [11].

Soil factors are integral to wildfire dynamics. Key variables include moisture, texture, organic matter, microbial activity, hydrophobicity, and erosion. Each influences ignition, spread, and severity, often through feedback loops that shape long-term fire regimes. Recent findings emphasize how soil–fire interactions vary globally yet share common mechanisms. Understanding these processes is critical for fire management and resilience in a warming climate. Drawing on many studies, this synthesis highlights soil management as a lever for predicting and mitigating wildfire severity.

2. Literature Review

2.1. Soil Moisture: The Bridge between Climate, Soil, and Fuel

Soil moisture is one of the most influential factors controlling wildfire behavior, linking climate variability with fuel flammability. When soils are moist, plants and surface fuels retain higher water content, reducing ignition and fire spread. Conversely, low soil moisture is strongly correlated with low fuel moisture and elevated fire activity across ecosystems. Satellite-based global analyses confirm this link: O et al. [5] showed that many of the world's largest wildfires followed anomalously dry soils, particularly in humid regions. In the western U.S., incorporating soil moisture improved predictions of large fire spread days compared to meteorological drought indices alone [2,6].

Dry soils reduce water availability to vegetation, lowering live fuel moisture [10]. Moisture-stressed plants drop leaves or desiccate, creating abundant fine fuels that ignite easily. Experiments in grasslands and forests show strong inverse relationships between soil moisture and ignition potential. In Mediterranean Europe, spring soil moisture deficits promoted earlier fuel drying and severe summer wildfires [27].

Soil moisture also influences spread. Wet soils maintain moist microclimates that act as naturalfirebreaks, while prolonged drought produces homogeneously dry fuels, enabling rapid, high-intensity fire [6,7]. In the Northern Rockies, soil moisture outperformed weather variables like wind or temperature in predicting daily forest fire spread, emphasizing its central role [6]. Globally, soil moisture moderates climate–fire interactions: even under hot, windy conditions, fire may not persist, if fuels remain moist, but under severe drought, moderate weather can drive large fires [28]. Boreal forests and Arctic tundra—normally too wet to burn—have experienced unprecedented fire spread during years of exceptional soil drying tied to permafrost thaw and heatwaves.

Soil moisture deficits extend the fire season by lengthening the window of flammable conditions. Fuel typically becomes combustible only after soils cross a drying threshold. Earlier spring drying or delayed re-greening prolongs this period. In Greece, negative spring anomalies preceded the largest fires of 2021–2023. Similarly, in the western U.S., low spring soil moisture led to earlier fire seasons and more high-danger days. Thus, soil moisture integrates off-season climate signals that govern season length [7].

Pre-fire soil moisture also affects burn severity. Moist soils yield patchier, lower-severity burns, while extremely dry soils permit combustion of surface organics, roots, and peat, producing high-severity outcomes [15]. In boreal forests, drier soils strongly predict deeper combustion of organic layers and higher carbon loss [29]. Remote sensing shows soil burn severity peaks when soil is driest. Maintaining higher water tables or irrigation can mitigate severity.

Soil moisture exerts first-order control on wildfire processes [2,5]. Accordingly, soil moisture is increasingly integrated into fire danger systems and models. Satellite-derived data (e.g., SMAP) are now used in global fire forecasting [30]. Case studies from North America, Europe, and Australia consistently show that soil moisture improves large-fire predictions [6,27]. As climate change intensifies droughts, monitoring soil moisture will be vital for preparedness.

However, the precise thresholds of soil moisture that trigger ignition or suppression vary widely among ecosystems and remain poorly quantified. While remote sensing provides regional trends, in-situ validation is limited. Disagreements also persist over whether soil moisture deficits drive fire severity independently or primarily through vegetation stress.

2.2. Soil Texture, Structure, and Infiltration Capacity

Beyond moisture content, inherent soil physical properties – texture (particle size), structure (aggregation), and porosity – strongly influence wildfire behavior and effects. These traits govern how water moves and is stored, shaping vegetation and fuel moisture [11]. They also affect soil heating during fire and susceptibility to post-fire erosion [14].

Fine-textured soils (silt, clay) hold more water than sandy soils. Such soils can sustain subsurface moisture into dry periods, supporting live fuel moisture and moderating fire intensity. By contrast, sandy soils drain quickly, drying fuels and raising ignition risk soon after rainfall. A Spanish study showed that sandier soils experienced quicker declines in live fuel moisture and earlier summer fire activity versus loams and clays. In African savannas, sandy soils support grassy vegetation that burns annually, whereas clayey soils favor woody plants and patchier fire regimes [12]. Thus, texture indirectly shapes flammability by influencing plant–soil water relations.

Shallow soils or those with hardpans hold little water, drying surfaces quickly. In Mediterranean shrublands, ridge-top thin soils burn more often than valley-bottom deep soils. Well-aggregated soils store water via infiltration, while crusted or poorly structured soils generate runoff. Fire can worsen structure: heat destroys aggregates and organic binders, raising bulk density and reducing porosity. This limits infiltration, increases runoff, and prolongs drying, hindering vegetation recovery and elevating erosion risk [11].

Compaction from machinery, livestock, or fire itself reduces macropores, lowering infiltration. Drier fuels then persist, compounding fire risk. While compaction might sometimes limit subsurface combustion, its dominant effect is negative. Wildfires can exacerbate compaction: rainfall after fire packs ash into pores. In pine forests, severely burned soils had 15% higher bulk density two years post-fire, nearly doubling runoff and erosion. Managers therefore view post-fire compaction as a major obstacle to watershed recovery. Remediation – subsoiling or planting deep-rooted species – restores porosity.

Soil traits also dictate heat penetration. Moist, fine-textured soils buffer temperature rise due to water's heat capacity. Dry, porous soils heat intensely near the surface, damaging seeds and roots, while deeper layers stay cool [14]. A controlled burn in Italy showed loamy, moist soils limited heat to <70 ℃ at a 2 cm depth despite surface ash at several hundred degrees. By contrast, dry peat smolders, sustaining subsurface heating for long durations. Thus, texture and moisture mediate vertical fire effects with consequences for seed survival and resprouting.

Soils with fine texture, good structure, and depth moderate wildfire by retaining moisture and reducing heating. Yet intense fires degrade these very properties through compaction and aggregate loss, creating feedback loops that heighten erosion, drying, and future fire risk. Protecting soil health via mulching, limiting machinery, and rehabilitation is vital. Ongoing research uses soil maps and experiments to predict refugia (moist soils) versus fire-prone zones (quick-drying soils) under climate change [13].

Although general relationships between texture and flammability are established, few studies quantify the combined effects of texture, aggregation, and post-fire compaction on long-term fire recurrence. Debate continues over whether soil compaction from low-severity burns is beneficial by retaining moisture or detrimental by reducing infiltration.

2.3. Soil Organic Matter and Combustible Soil Layers

The amount and nature of organic matter in soils strongly influence wildfire behavior and severity. Soil organic matter (SOM)—including litter, detritus, humus, and peat—acts as potential fuel when dry. In many ecosystems, the organic horizon can intensify fires by releasing energy and extending burning [23].

In forests, duff (partly decomposed litter) and surface layers are often first ignited. Thick duff sustains smoldering after flames pass, increasing flame residence time and soil heating. In North American coniferous forests, thicker forest floors correlate with higher soil burn severity, leading to tree root mortality and heating [31]. Moist duff smolders, but during drought it dries below 30% moisture and becomes highly flammable. The 2020 western U.S. fires showed how duff consumption killed large trees by destroying roots [26]. Managers sometimes use prescribed burns to reduce duff and litter, limiting future wildfire intensity [25].

In peatlands and wetlands, soil itself is the main fuel. Tropical peat swamps (Indonesia) and boreal peatlands (Canada, Russia) can store meters of peat. When dry, fires smolder through the profile, releasing vast carbon and haze [17]. Indonesia's 2015 and 2019 peat fires, linked to El Niño droughts, produced catastrophic emissions [17]. Peat fires burn downward and laterally, persisting underground even after rain. Boreal peat fires similarly release climate-significant emissions; one Siberian season can equal decades of surface fire carbon [18]. Normally, high water tables prevent ignition, but drainage and heat can dry peat to ~15–20% moisture, making it flammable.

The degree of SOM consumed measures burn severity. Fire severity indices often assess char depth or organic layer loss. Severe soil consumption affects fertility and hydrology. In boreal peatlands, bogs burned more deeply than fens due to moisture and vegetation, driving differing carbon losses [15]. In upland forests, full humus combustion volatilizes nutrients and induces water repellency. Globally, SOM contributes 5–20% of wildfire fuel but can exceed 50% in peatland or taiga fires [23].

Some SOM becomes charcoal (black carbon), resistant to decomposition and persistent for centuries [23]. Charcoal can alter soil color, structure, and nutrient adsorption. Low-severity fires often increase stable carbon without consuming deeper organic matter. In peatlands, low-severity burns increased aromatic compounds that slowed decomposition [16]. By contrast, high-severity fires leave ash and highly altered organics that erode, producing nutrient-poor soils.

Soil organic matter shapes wildfire dynamics. Deep organic soils (peat bogs, thick duff) support severe, persistent ground fires, while thin soils (deserts, grasslands) confine burning to aboveground fuels. Management strategies include prescribed burning, wetland rewetting, and fuel reduction to balance SOM’s ecological role with its fire risks [31]. Under climate change, drying trends increase vulnerabilities in organic-rich ecosystems [8]. Protecting soil conditions and managing SOM are essential for mitigating catastrophic wildfires.

Uncertainty remains about how repeated low-severity fires affect peat and duff carbon stability. Some evidence suggests that the formation of fire-resistant charcoal stabilizes carbon, while others show cumulative nutrient loss and hydrophobicity. Long-term trajectories of peatland recovery under recurring drought are still debated.

2.4. Soil Microbial Activity and Fuel Accumulation

Soil microbes – bacteria, fungi, and other microorganisms – mediate the relationship between soils and wildfire. By driving decomposition and nutrient cycling, microbes regulate whether organic matter is broken down or accumulates as fuel. Microbial communities also influence soil structure and moisture via effects on organic matter and porosity [24]. Wildfire can, in turn, shift soil microbial communities, feeding back into ecosystem flammability and recovery. Four key aspects are noteworthy.

Microbial decomposition removes dead biomass; when rapid, litter is minimized. Slow activity (from cold, acidity, or waterlogging) leads to fuel accumulation. In tropical rainforests, fungi and termites decompose litter quickly, helping explain rare wildfires. In boreal forests or peatlands, low temperatures and acidity foster thick organic layers that can burn intensely [18]. Climate change alters these dynamics: warming can accelerate decay and reduce fuel, while increased CO_2 can boost litter inputs that may outpace microbial consumption [20]. Fire suppression further emphasizes microbial decomposition as the main fuel removal pathway; if slowed, fuel loads rise. Prescribed burns often substitute for microbial activity by removing detritus [25].

Wildfires transform microbial habitats by consuming organic matter and heating soils. Fires typically reduce biomass, especially fungi in surface litter [24]. High-severity events can sterilize soil layers, eliminating mycorrhizal fungi, which are essential for plant recovery. In Colorado, severe wildfire sharply reduced ectomycorrhizal fungi, while spore-forming bacteria and pyrophilous fungi proliferated [24]. Pyronema fungi, for instance, immobilize nutrients on charred soil, affecting regrowth. Repeated fires can select for disturbance-tolerant microbes: Fox et al. [32] found pine savanna fungi became dominated by fire-tolerant species, reducing diversity and slowing decomposition. This paradoxically increases litter buildup [21]. Yet, low-intensity burns may temporarily stimulate processes like nitrogen mineralization [11].

Microbes drive soil C, N, and P cycling, influencing vegetation and fuels. Fires often add nutrients (P, Ca, Mg) via ash while volatilizing N and S. Such pulses favor fast-growing plants, while repeated burns deplete nitrogen, altering vegetation and fire behavior [3]. Slash-and-burn initially boosts fertility but eventually depletes soils, lowering biomass and fire intensity [11]. Nutrient-poor soils (pine barrens) support frequent, low-intensity fires, while nutrient-rich soils (volcanic) allow dense, occasionally severe burns. Repeated fires can decouple soil C-N-P cycles, depleting N and altering microbial genes [33], which slows decomposition and increases flammability.

Some microbes produce hydrophobic compounds that heighten soil water repellency. Under drought, bacteria increase cell-surface hydrophobicity, exacerbating post-fire runoff and dryness [22]. Fire and drought together may favor stress-tolerant microbes that intensify repellency, prolonging flammable conditions.

Soil microbes subtly but fundamentally link soils to wildfire regimes. Efficient decomposers reduce fuel buildup, while constrained or fire-altered communities increase it [21,32]. Severe fires can trigger long-lasting shifts in soil fertility and microbial diversity. Incorporating soil biology into fire models could improve predictions, while microbial restoration may enhance resilience. Recognizing living soil as part of the fire environment underscores the need to integrate soil health into fire management [20].

Microbial recovery rates and functional shifts after fire remain poorly characterized, especially in non-temperate regions. The direction of microbial feedbacks—whether they promote or suppress subsequent fires—remains unresolved. There is also limited consensus on how microbial traits translate into measurable fuel accumulation at landscape scales.

2.5. Soil Hydrophobicity and Post-Fire Hydrology

One of the most striking soil phenomena associated with wildfires is soil hydrophobicity – a condition where soils repel water. Although it can occur under prolonged dryness or due to vegetation such as eucalyptus or chaparral, it is most frequent and intense after fires [23]. Fire-induced hydrophobicity influences immediate fire behavior (via soil and fuel moisture) and post-fire response (runoff and erosion).

During combustion, organic compounds (waxes, oils, resins) volatilize, migrate downward, and condense on cooler particles, forming a hydrophobic layer a few centimeters below the surface. Its thickness depends on fire intensity, soil texture, and fuel. Coarse soils (sands) develop stronger layers since volatiles coat large particles effectively, while clay soils resist due to high surface area and moisture retention [23]. Hydrophobicity is strongest when soils are dry and disappears once moisture exceeds ~25% by volume [9]. Thus, repellency is most relevant during the early post-fire period with light rains; prolonged wetting overcomes it.

Hydrophobic soils drastically reduce infiltration, causing rain to bead and run off. After fire, this paradoxically leaves subsurface fuels drier, prolonging flammability. Runoff may also concentrate fuels downslope, spreading subsequent fires. However, hydrophobicity is temporary: rainfall and microbial decomposition restore infiltration over months to years [23]. Persistence depends on burn severity. High-severity fires generate thicker, longer-lasting layers, while low-severity fires may even increase wettability by burning off hydrophobic litter. Prescribed burns, for instance, can improve infiltration.

Hydrophobic soils generate rapid runoff, leading to flash floods and debris flows. With vegetation gone and water repelled, even modest storms mobilize soil. This strips nutrient-rich topsoil and threatens downstream communities. Emergency response teams map burn severity to anticipate hydrophobic zones. A strong hydrophobic layer creates lateral flow, triggering shallow landslides or debris flows. Following the 2018 Thomas Fire, rainfall on hydrophobic hillsides caused deadly debris flows in Montecito. Such erosion is most severe in the first one to two years, when repellency and vegetation loss peak [24]. Over time, permeability returns and vegetation regrows, restoring hydrologic function. Severe erosion can reduce fuels in the short term, lowering fire risk, but may promote colonization by flammable invasives like cheatgrass, raising long-term fire frequency.

Coarse soils show deeper repellency, while fine soils display patchiness. Maximum repellency forms at 200–300 ℃; higher temperatures (>400 ℃) completely combust organics, sometimes leaving a wettable ash. Thus, severely burned surfaces may be wettable and ash-covered, while water-repellent layers persist beneath. Post-fire assessments use water drop tests to locate hotspots. Mitigation strategies include mulching, sediment barriers, and seeding to break runoff cycles.

Soil hydrophobicity is a transient but critical post-fire factor. By inhibiting infiltration, it sustains drier conditions, prolongs flammability, and drives severe runoff and erosion. While its effects diminish with time, hydrophobicity strongly shapes short-term fire recovery and can influence long-term vegetation and fuel dynamics. Consequently, land managers prioritize treatments like mulching and drainage improvements in hydrophobic-prone areas to reduce risks.

There is still no agreement on how long hydrophobicity persists across soil types or how it interacts with rainfall patterns to influence re-ignition potential. Models diverge on whether repellency is a transient surface effect or a structural soil alteration lasting years.

2.6. Soil Erosion, Compaction, and Long-Term Site Changes

Severe wildfires often trigger significant soil erosion and compaction, leading to long-lasting changes in productivity and vegetation that feed back into fire regimes. While erosion and compaction are outcomes of fire, they also act as soil factors shaping future wildfire behavior and ecosystem vulnerability. Considering these factors temporally is crucial: a wildfire's soil legacy can alter subsequent fire risk and severity.

When vegetation and litter are consumed and soils develop hydrophobicity, erosion accelerates. Depending on terrain and climate, this ranges from sheet erosion to gullying and mass movements. Fire-driven erosion strips nutrient-rich upper layers, leaving coarser, drier, less fertile soil. Such losses hinder plant regrowth or shift species composition (favoring hardy colonizers). Reduced cover may temporarily lower fuel accumulation, decreasing fire risk. Yet invasive grasses like Bromus often colonize bare soil, forming flammable fine-fuel beds that heighten fire frequency. On steep slopes, erosion removes seed banks and mycorrhizae, delaying regeneration [26]. In the western U.S., severe fires plus erosion have caused forest failure and transition to persistent shrublands, which burn more frequently [25].

Fire and suppression activities can compact soils. Intense heating degrades aggregates, while raindrop impact and heavy equipment increase bulk density. Compaction reduces infiltration and root penetration. Over time, poor aeration and limited water availability suppress growth, altering fuel distribution. In Mediterranean pine forests, fire-induced compaction and erosion shifted stands toward open canopies with grassy understories, promoting faster surface fires rather than crown fires. Compaction may also trap moisture at the surface, prolonging smoldering in duff. However, its dominant effects are reduced infiltration, increased runoff, and heightened erosion. Managers often monitor bulk density post-fire and, if severe, scarify soils to restore infiltration and vegetation, preventing degraded, fire-prone conditions.

Repeated fires and erosion can degrade soils, reinforcing frequent burning. Sites stripped of nutrients may shift to low-productivity grassland or eroded shrubland, with enough fine fuel for frequent fire but insufficient resilience for recovery [20]. In the Mediterranean, overgrazing and repeated fire degraded soils into fire-prone scrub. In the tropics, soil degradation facilitates “savannization”: even if fires cease, degraded soils often cannot support forest regrowth. Severe fires may thus push soils and vegetation into alternative stable states maintained by fire. Conversely, low-severity or infrequent burns can have neutral or beneficial soil effects, releasing nutrients and reducing pathogens. This supports prescribed burning to recycle nutrients and avoid catastrophic erosion and compaction.

Climate change will amplify soil–fire feedbacks. In drying regions, erosion may reduce fuel continuity. Yet colonization by invasive grasses can drive fire frequency. In permafrost areas, thaw alters hydrology, producing drained soils prone to fire or wetlands that act as firebreaks but accumulate flammable peat [8]. Models increasingly integrate soil–vegetation feedbacks to predict regime shifts such as forest-to-nonforest transitions.

Soil erosion and compaction, though often framed as fire impacts, also predispose landscapes to future burning. Degraded soils foster sparse, flammable vegetation, flashier hydrology, and unstable fuel conditions. Maintaining soil integrity through erosion control, moderated burns, and restoration is essential for conservation and fire management. Healthy soils support resilient ecosystems less likely to spiral into fire-driven degradation [11].

Research gaps exist in quantifying thresholds of soil degradation beyond which ecosystems cannot recover to pre-fire states. The interplay among erosion, invasive colonization, and fire recurrence is still underexplored. Furthermore, long-term monitoring data on soil structure recovery post-fire are scarce.

3. Findings

Soil moisture is a key determinant of ignition, spread, and severity. Drier soil consistently correlates with increased wildfire activity worldwide. In North America and the Mediterranean, low antecedent soil moisture was linked to large fires [7,27]. Effects vary in grasslands, as wet years boost biomass for later fires, while in forests, dry soils directly lower fuel moisture. Incorporating soil moisture (satellite or in-situ data) into danger models improved large-fire prediction by 10–30% [2,6]. Climate-driven drying trends already intensify wildfire seasons in the western U.S., Australia, and Siberia [8]. A global satellite study found that wet anomalies followed by dry anomalies commonly preceding large fires, linking climate and fire through soil moisture.

Soil physical traits shape fire regimes through hydrology and vegetation. Coarse-textured soils (fast-draining sands) correspond to frequent, low-intensity fires [12]. Fine soils support dense vegetation that burns less often but more intensely under drought. Fires also alter soil properties: aggregate breakdown and increased bulk density reduce infiltration, raising aridity [14]. A meta-analysis of 67 sites found that fire raised bulk density by ~9% and cut infiltration by 30% in the first post-fire year, especially in sandy-loams under high-severity fire. Effects can persist in Portugal: soils five years post-fire remained compacted with low aggregate stability, slowing regrowth and favoring shrubs. This promotes reburning as shrub fuels mature on aridified soils.

Thick organic layers drive severe, long-lasting fires. The extreme events include Indonesia’s peat fires in 2019 and Siberia’s peat-permafrost megafires in 2020 [8,17]. When duff below ~20–30% of moisture, it sustains smoldering. In Alberta, peat fires burned deeper in bogs than fens [15]. Boreal peat droughts led to burn depths of 20–30 cm, versus <10 cm in moderate years, increasing emissions tenfold. Some low-intensity peat fires create stable soil carbon (charcoal), potentially slowing decomposition [16]. Yet severe burning causes long-term degradation: hydrophobic, eroding surfaces and carbon loss. Globally, peat fires contribute ~15% of wildfire carbon emissions despite peatlands’ limited area.

Fire alters soil microbes, shaping recovery and fuel cycles. High-severity fires sharply reduce microbial biomass, especially mycorrhizal fungi, which are critical for tree seedlings [21,24]. In California, high-severity burn areas had 70% lower fungal richness and proliferation of less-efficient decomposers, slowing litter decay and creating fuel buildup [32]. In savannas, annual fires simplified fungal communities and reduced nitrogen, reinforcing grass dominance and rapid fire return [21]. Conversely, long-unburned sites built thicker litter with fungi-dominated communities, raising risk of intense fires once ignited. Microbes thus both reduce and promote fire risk depending on context. Recolonization occurs over years via air- or animal-borne microbes [24]. Globally, dry tropical forests show microbial shifts toward fire-tolerant decomposers [33], influencing soil carbon persistence.

Wildfires often enhance soil water repellency, altering hydrology. Modeling in California showed that including hydrophobic thresholds improved runoff predictions [9]. Field studies in Portugal found up to 10-fold infiltration reductions in severely burned sandy soils, recovering in 2–3 years as vegetation returned. Hydrophobicity makes soils temporarily drier and more prone to erosion, though its direct role in reburning is short-lived. However, consecutive fires can exploit residual hydrophobicity. Research interest is growing [13], and treatments like soil wetting agents or hydrophilic polymers are under trial [11].

Severe fires can trigger ecosystem state shifts through erosion. In western North America, one-third of 1,500 post-2000 burn sites showed no tree regeneration after a decade, often where soils were shallow or eroded [26]. Such sites tend toward grass/shrub dominance and frequent, low-severity fire. In the Amazon, repeated understory fires degraded topsoil and shifted forests toward grassy woodland. Soil conservation helps prevent such transitions:

forests recovered better where erosion was mitigated. Modeling shows that topsoil loss lowers ecological thresholds, locking systems into high-fire states. Fire suppression activities also alter soils: bulldozer firelines compact soils, creating water flow paths and corridors for invasives that carry fire, as noted after California's 2020 fires.

Soils are active drivers of fire ecology: influencing ignition (moisture), spread (texture, moisture), severity (organic matter), and recovery (microbes, hydrophobicity, erosion) (refer to Table 1). Though ecosystem specifics vary (peat vs. chaparral vs. savanna), principles are universal. A central theme is resilience versus vulnerability: fire-adapted systems (savannas, dry forests) recover quickly, while non-adapted systems (peat swamps, alpine forests) risk long-term soil degradation and tipping points [20]. Under climate change, protecting vulnerable soils from burning is urgent.

Table 1. Influence of Key Soil Factors on Fire Ignition, Spread, Severity, and Post-Fire Recovery

Soil Factor	Influence on Ignition, Spread, Severity, Recovery	Representative references
Soil Moisture	• Low soil moisture increases fuel flammability and ignition probability; drought-stressed vegetation ignites easily. • Dry soils produce continuous, homogeneous fuels, facilitating rapid fire spread; moist soils act as natural firebreaks. • Drier soils enable deeper combustion and higher burn severity, especially in organic-rich soils. • High pre- and post-fire soil moisture supports vegetation regrowth and reduces severity.	[2,5–7,10,27,29,30]
Soil Texture & Structure	• Coarse, sandy soils dry rapidly, predisposing fuels to ignition. • Well-drained, coarse soils promote continuous flammable conditions; fine-textured soils retain moisture and slow spread. • Fine-textured, moist soils buffer heating; fires degrade aggregates and increase compaction, raising future severity. • Fire-induced compaction lowers infiltration and delays regrowth; well-structured soils recover faster.	[11–14]
Soil Organic Matter (Duff, Peat)	• Dry organic horizons (duff, peat) are highly flammable and sustain smoldering combustion. • Thick organic layers extend burn duration and lateral spread (ground fires). • Peat and duff fires produce high severity and carbon loss; low-severity burns can create stable charcoal. • Severe burns deplete nutrients and carbon, delaying recovery; rewetting peat reduces ignition risk.	[15–18,23,25,31]
Soil Microbial Activity	• Low microbial decomposition allows fuel accumulation, increasing ignition likelihood. • Reduced microbial activity slows litter turnover, maintaining continuous fuels. • Severe fires sterilize upper soil layers, depleting beneficial microbes and nutrient cycling. • Microbial recovery regulates nutrient availability and long-term vegetation succession.	[19–22,24,32,33]
Soil Hydrophobicity	• Hydrophobic layers reduce surface wetting, maintaining dry, flammable fuels. • Post-fire hydrophobic soils enhance runoff and limit infiltration, indirectly sustaining dry fuel beds. • Strong repellency after high-severity burns limits water absorption, increasing erosion and secondary ignition. • Over months–years, hydrophobicity declines as microbes recolonize; treatment (mulching, wetting agents) accelerates recovery.	[9,11,23,24]
Soil Erosion & Compaction	• Bare, compacted soils expose mineral layers that heat rapidly and dry quickly, increasing ignition potential. • Reduced infiltration and sparse vegetation create flashier fuels and runoff-driven fire spread. • Loss of topsoil and nutrients heightens long-term degradation and promotes the spread of flammable invasive grasses. • Erosion control, decompaction, and revegetation improve resilience and reduce reburning risk.	[11,20,25,26]

Despite growing recognition of soil–fire feedbacks, several knowledge gaps remain. Quantitative thresholds linking soil moisture to ignition are inconsistent across biomes. Soil microbial contributions to fire regimes are understudied outside temperate systems. Disagreements persist over the longevity and ecological significance of hydrophobicity. Moreover, few models integrate soil degradation, carbon loss, and vegetation shifts to predict long-term regime change. Addressing these uncertainties will enhance predictive fire models and inform adaptive management.

4. Discussion

4.1. Bridging Biophysical and Ecological Perspectives on Fire–Soil Interactions for Resilient Ecosystem Management

While consensus exists that soil moisture and structure strongly modulate fire behavior, the relative influence of biological versus physical factors remains debated. Some studies emphasize soil moisture as a dominant predictor, whereas others highlight organic matter or microbial composition. Resolving these discrepancies requires integrated field–model approaches.

The interplay between soils and wildfires has major implications for ecosystem management and fire prediction in a changing climate. Soil factors—moisture, texture, organic matter—can buffer ecosystems against fire or, when degraded, amplify risk. Recognizing this creates new opportunities for wildfire management and adaptation.

Fire danger indices (e.g., U.S. NFDRS, Canadian FWI) emphasize weather and fuels, with only indirect soil representation. Evidence shows that direct soil moisture improves prediction [7,10]. Agencies should invest in soil monitoring and remote sensing (e.g., SMAP, Sentinel) [27,30]. Australia already integrates soil anomalies into fire forecasts, linking prolonged drying to “megafire” risk. Defining fire season onset and end by soil thresholds could complement current indices, as Mediterranean fire seasons increasingly track earlier spring deficits and later autumn recharge [27].

Soil protection itself can reduce wildfire severity. Beyond fuel treatments, strategies include forest floor management, erosion control, and post-fire rehabilitation.

Effective fire management increasingly integrates soil-focused practices to enhance resilience and mitigate severe burns:

- Peatland Rewetting and Water Table Management: Restoring or maintaining high water tables in peat-rich landscapes (e.g., Indonesia, Canada, Siberia) prevents ignition and sustains soil moisture buffers. Indonesia’s national peat restoration agency has successfully used canal blocking and rewetting to suppress recurrent peat fires [17].
- Prescribed Burns to Manage Duff and Organic Layers: In conifer forests of North America, periodic low-intensity prescribed fires reduce excessive duff and litter accumulation that would otherwise sustain smoldering combustion. This approach stabilizes soil carbon by forming charcoal and limits root damage during future wildfires.
- Post-Fire Soil Rehabilitation and Erosion Control: Following severe burns, mulching, contour log barriers, and sediment traps reduce runoff and nutrient loss from hydrophobic soils. For example, hydrophobic slopes in California and Portugal recovered infiltration capacity within 2–3 years after such treatments.
- Soil Decompaction and Revegetation: Scarification or subsoiling of compacted soils improves infiltration and aeration, promoting vegetation regrowth and reducing flash-flood risk. Planting deep-rooted native species accelerates soil structural recovery.
- Microbial and Organic Amendments: Emerging practices include inoculating burned soils with microbial consortia or applying compost/char amendments to restore microbial diversity and soil fertility. These treatments enhance decomposition, stabilize nutrients, and reduce fuel accumulation in subsequent seasons.
- Soil Moisture Monitoring for Fire Prediction: Integrating soil moisture sensors or satellite-based soil water data (e.g., SMAP, Sentinel) into fire danger indices improves early warning and resource allocation. This has been operationalized in Australia’s fire forecasting systems.
- Soil-Adaptive Land Use Planning: Limiting heavy machinery, establishing green buffers, and protecting riparian soils can mitigate compaction and maintain natural moisture gradients. Agroforestry systems that conserve soil organic matter (e.g., silvopasture) provide long-term fire resistance.

Severe fires may already have shifted ecosystems (e.g., from forest to grassland via erosion). Managers must decide whether to restore soils and vegetation or accept new states. Passive recovery often fails where degradation is extreme. Active measures include soil amendments, erosion control, and planting nurse species. Climate unsuitability may limit reforestation, but soil triage can guide restoration priorities [25,26]. In California, agencies are considering converting erosion-prone slopes to oak savanna or fuel breaks rather than replanting dense conifers.

Long-term studies on repeated fires are scarce, particularly thresholds beyond which soils lose structure or nutrients. Microbial recovery, accessible through metagenomics, remains underexplored. Fire behavior models rarely explicitly include soil; coupling hydrology and fire spread could improve predictions, especially for ground fires. Remote sensing could better map soil burn severity, refining carbon emission estimates. Preventing soil carbon loss, especially in peatlands and boreal forests, is critical for climate mitigation [18].

Agencies should embed soil science in pre- and post-fire planning. Regulations must account for soil impacts of tactics (e.g., bulldozer lines). Agroforestry and silvopasture that preserve soil moisture may lower fire risk. In the wildland–urban interface, soil treatments (check dams, targeted wetting) could reduce post-fire debris flows. Indigenous burning practices preserved soil moisture and patchiness, offering models for cultural and ecological fire management.

Soils are both vulnerable and defensive. Protecting soil health sustains biodiversity and productivity while mitigating wildfire damage. Holistic fire-soil strategies are essential for resilience under climate change.

4.2. Conceptual Framework: Integrating Soil Properties into Wildfire Prediction

The conceptual framework (Figure 1) illustrates the integrative pathways through which soil properties influence wildfire prediction. Climate, topography, and land use determine baseline soil conditions—particularly moisture, texture, and organic matter content—that directly affect fuel moisture and vegetation composition. These soil characteristics, together with microbial activity and hydrophobicity, regulate ignition potential, fire spread rate, and burn severity. Following fire events, soil degradation processes such as erosion, compaction, and hydrophobic layer formation alter these properties, creating feedback loops that influence the likelihood and intensity of subsequent fires. This cyclical interaction underscores soil's dual role as both a driver and feedback component in wildfire dynamics, highlighting the necessity of incorporating soil variables into predictive fire models for more accurate and resilient fire risk assessment.

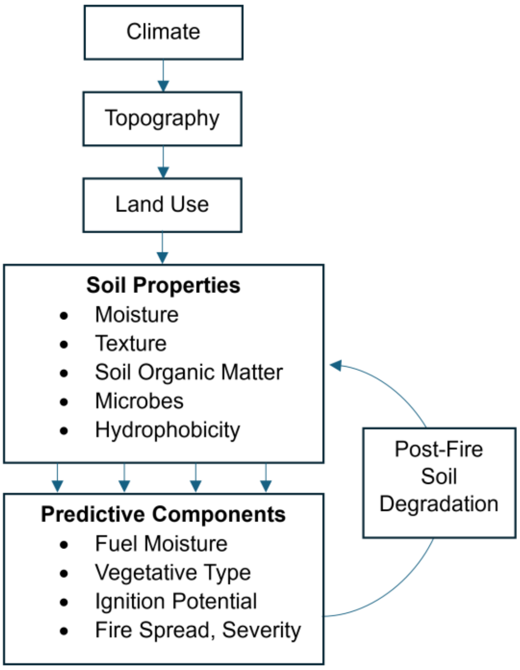

Figure 1. Conceptual model linking soil properties to wildfire prediction and feedback mechanisms

5. Conclusions

Soil actively shapes wildfire behavior and recovery, influencing ignition, fire intensity, and post-fire resilience through its moisture, structure, organic content, and biology. Key determinants include soil moisture (controlling fuel flammability), texture and structure (governing water retention), organic layers such as duff or peat (amplifying severity when dry), microbial communities (fuel decomposition and nutrient cycling), and fire-induced properties like hydrophobicity (affecting infiltration and erosion).

Recent literature highlights soil moisture as the dominant factor across biomes. Drying from drought or seasonality increases fire probability and severity, while moist soils buffer ecosystems. Monitoring and preserving soil moisture should thus be a management priority. Soil organic matter (SOM) is double-edged: it sustains ecosystems in wet conditions but becomes hazardous fuel in drought. Peatlands and thick duff exemplify this duality, experiencing extreme fires when SOM ignites.

Soil properties also shape fire regimes. Coarse soils favor fire-adapted grasses with frequent burns, while fine-textured soils support forests that may burn less often but more severely during drought. Post-fire degradation through erosion and compaction fosters flammable colonizers, hindering recovery. Feedback can be stabilizing — low-intensity fires recycling nutrients and limit fuel — or destabilizing, where severe fires deplete soils and perpetuate degradation.

Management can mitigate impacts: moderate litter/duff removal reduces soil heating, while mulching, cover crops, or decompaction accelerate recovery. Advances in remote sensing now integrate soil variables into fire forecasting. Policies such as peatland protection, prescribed burning, and soil-focused rehabilitation demonstrate success.

Ultimately, soil must be treated as central to fire systems. Climate change will intensify drying, SOM vulnerability, and post-fire erosion, underscoring the imperative: protecting soils is protecting ecosystem futures.

Future work should quantify soil moisture thresholds for ignition, evaluate cumulative effects of repeated burning on soil carbon and microbes, and develop coupled soil–fire–climate models. Understanding feedback among hydrophobicity, erosion, and vegetation succession remains essential for predicting long-term ecosystem resilience.

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