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Interdependencies Between Wildfire-Induced Alterations in Soil Properties, Near-Surface Processes, and Geohazards

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Key Points:

- Post-wildfire soil conditions control the persistence, severity, and timing of cascading geohazards in burned landscapes
- We synthesize the interplay between geohazards and wildfire-induced changes to soil properties, land cover, and near-surface processes
- Future directions are identified to advance knowledge on how wildfires affect surface processes and geohazards over time

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Interdependencies Between Wildfire-Induced Alterations in Soil Properties, Near-Surface Processes, and Geohazards

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Abstract The frequency, severity, and spatial extent of destructive wildfires have increased in several regions globally over the past decades. While direct impacts from wildfires are devastating, the hazardous legacy of wildfires affects nearby communities long after the flames have been extinguished. Post-wildfire soil conditions control the persistence, severity, and timing of cascading geohazards in burned landscapes. The interplay and feedback between geohazards and wildfire-induced changes to soil properties, land cover conditions, and near-surface and surface processes are still poorly understood. Here, we synthesize wildfire-induced processes that can affect the critical attributes of burned soils and their conditioning of subsequent geohazards. More specifically, we discuss the state of knowledge pertaining to changes in mineralogical, hydraulic, mechanical, and thermal properties of soil due to wildfire with a focus on advances in the past decade. We identify how these changes in soil properties alter evapotranspiration, interception, sediment transport, infiltration, and runoff. We then link these alterations to the evolution of different geohazards, including dry raveling, erosion, rockfalls, landslides, debris flows, and land subsidence. Finally, we identify research gaps and future directions to advance knowledge on how wildfires control the evolution of various earth surface processes and geohazards over time.

1. Introduction: Growing Risk of Wildfire and Associated Geohazards

Rising temperatures, increasingly hot and lengthy droughts, and land use changes have contributed to intensifying wildfire activity around the world (Abatzoglou & Williams, 2016; Donovan et al., 2023; Keeley, 2004; Littell et al., 2009; Madadgar et al., 2020; Miller et al., 2009; Turco et al., 2014; Westerling et al., 2006) with substantial repercussions on the natural and built environment (Moftakhari & AghaKouchak, 2019; Thompson et al., 2011) and human health (Bowman & Johnston, 2005). For instance, the average annual area burned in the United States in the 1990s was 3.3 million acres, which more than doubled between 2013 and 2022, reaching an annual average of 7.2 million acres (CRS, Congressional Research Services, 2022). In the western United States, the average annual area burned by large (> 400 ha) forest fires has increased ten-fold over the past 50 years (Abatzoglou et al., 2021; Westerling, 2016). Fires are also occurring at higher elevations at an unprecedented rate in modern history (AghaKouchak, et al., 2018; Alizadeh et al., 2020, 2023). With projected climatic changes, the increasing trend in burn severity and frequency is expected to continue (Abatzoglou et al., 2021; Jin et al., 2015) The devastating wildfires that occurred between 2019 and 2021, which destroyed thousands of structures and resulted in several hundred direct and indirect deaths, were a stark reminder of the destructive impact of climate change. These fires ravaged different parts of the world, including the United States, Australia, Amazonia, and northern Europe, and served as a warning of the potential future of wildfires in a warming world (Engström et al., 2022; Le Breton et al., 2022; Ohneiser et al., 2022).

The adverse impacts of wildfires on the natural and built environments and communities persist for years and potentially decades after the containment of the wildfire (Ebel, 2020; Raiesi & Pejman, 2021; Wagenbrenner et al., 2021; Yang et al., 2022). While wildfires can pose a significant risk to communities and the environment, the greatest danger arises when they are followed by other natural hazards and extreme events. In many regions

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worldwide, such multi-hazard conditions have been observed, leading to extensive research over the past decade to improve our understanding of the impact of wildfires under multi-hazard conditions and their interrelationships (AghaKouchak et al., 2018; McNamee et al., 2022; Peers et al., 2021; Vitolo et al., 2019). Geohazards (Table 1), such as shallow landslides, debris flows, and soil erosion, are some of the most notable and far-reaching post-fire processes that can trigger a catastrophic ripple effect. Coincident with worsening wildfires, longer fire seasons, expanding fire-prone terrain, and the growing wildland-urban interface, wildfire-induced geohazards and their associated mortality and morbidity risks are increasing in many regions globally (Abbate et al., 2019; De Graff, 2014; Fraser et al., 2022; He et al., 2021; Neary et al., 2019; Tang et al., 2019; Vitolo et al., 2019).

Wildfires can affect the mechanical, hydraulic, chemical, biological, and thermal properties of near-surface soils. Further, as shown in Figure 1, wildfires significantly impact land cover and near-surface processes, which may result in cascading hazards that persist for timeframe after a disturbance that is poorly constrained. These altered behaviors and processes include evapotranspiration and interception, vegetation cover and root vitality, sediment transport, erosion, infiltration, and runoff (Figure 2). The triggering and evolution of wildfire-related geohazards are primarily a result of wildfire-induced alterations in soil and land cover properties and the associated near-surface and surface processes. Figure 2 demonstrates the interconnectedness of these wildfire-induced

Table 1
Wildfire-Related Geohazards Along With Examples

Type	Linkage to wildfire	Examples
Dry Ravel	Destruction of vegetation, root structure, soil particle fracturing, and potential changes in soil properties result in increased dry ravel in wildfire-impacted areas. Dry ravel can then occur when the soil surface is dislodged and transported downslope by gravity, either as individual particles or larger clumps of soil and debris. This type of erosion can be exacerbated by steep slopes, intense rainfall, and the presence of channelized flow paths (Florsheim et al., 2016).	In California, several dry ravel incidents occurred in areas affected by the 2009 Station Fire (Lamb et al., 2011; Parise & Cannon, 2012), the 2013 Springs Fire (Florsheim et al., 2016), and the 2016 Fish Fire (Rengers et al., 2021). In the Mediterranean region, dry ravel has been observed in areas affected by wildfires, such as the 2017 wildfires in Portugal (Araújo Santos et al., 2020).
Rockfall	Wildfires can increase the risk of rockfalls by weakening the rock mass and removing vegetation cover (Sarro et al., 2021). The heat from the fire can cause thermal expansion and cracks in the rock, while the removal of vegetation can reduce slope stability and expose the rock to the elements. These factors can make the rock more susceptible to detachment and increase the likelihood of rockfalls during and after rainfall events.	Examples are many (De Graff & Gallegos, 2012; Guasti et al., 2013; Melzner et al., 2019; Sarro et al., 2021; Wondzell & King, 2003), including rockfall incidences in the eastern Alps of Austria following a 2018 wildfire (Melzner et al., 2019). Observation of wildfire-impacted areas in the United States found that seven of 16 wildfire areas observed experienced significant rockfalls within days of wildfire events (De Graff et al., 2015).
Erosion	Wildfires decrease rainfall interception and increase eroding the capacity of rainfall impact on the ground, increase overland flow velocity, and reduce soil's cohesion, all of which collectively increase erosion. Erosion contributes to the accumulation of downslope soil deposits, surface water redirection, and often redistribution of topographic conditions (Girona-García et al., 2023).	Erosion may come in the form of sheet flow, interrill, or rill erosion (Moody & Martin, 2001; Sheridan et al., 2007). In 2002, the Gondola Fire in the Lake Tahoe area resulted in approximately 28 metric tons of material accumulating downslope as a result of erosion (Abney et al., 2017). In some cases, post-wildfire conditions are estimated to result in up to a three-fold increase in erosion relative to pre-wildfire conditions (Delong et al., 2018).
Landslides	Wildfires can increase the likelihood of shallow landslides by weakening the roots, reducing evapotranspiration rates, changing vegetation coverage and canopy interception, and altering soil mechanical and hydraulic properties (Gehring et al., 2019; Lei et al., 2022; Masi et al., 2021; Shakesby & Doerr, 2006; Vergani et al., 2017).	In January 2019, an intense rainstorm triggered widespread landslides in a 70 km^2 area of the San Gabriel Mountains in Southern California, particularly in regions that had experienced wildfires between three to 10 years earlier, including the 2009 Morris Fire, 2014 Colby Fire, and 2016 San Gabriel Complex Fire (Fish Fire and Reservoir Fire). More than 90% of these landslides were located within the boundaries of the San Gabriel Complex Fire (Abdollahi et al., 2023; Rengers, 2020; Rengers et al., 2020).
Debris Flows	Excess runoff resulting from reduced ground cover, exposed disturbed soil, and accumulated debris combined with convergent topography and narrow, sediment-laden channels result in significant damage to downslope areas (Kean et al., 2019).	Post-wildfire debris flows in the Glenwood Canyon area of Colorado damaged and closed major highways and railroad lines in 2021 (Graber & Santi, 2023). The 2018 Montecito debris flow event near Santa Barbara killed 23 residents, injured at least 167 others, and damaged 408 homes (Kean et al., 2019).
Land Subsidence	Wildfires in permafrost areas can trigger land subsidence by altering the surface albedo, melting the permafrost layer through heat exposure, and removing vegetation cover (Yanagiya & Furuya, 2020).	Post-wildfire surface deformation in Alaska (Abbott et al., 2021; Brown et al., 2015; Holloway et al., 2020) and Siberia (Arcenegui et al., 2008; Badía-Villas et al., 2014; Moody & Ebel, 2014; Ngole-Jeme, 2019)) occurred from surface vegetation changes above permafrost.

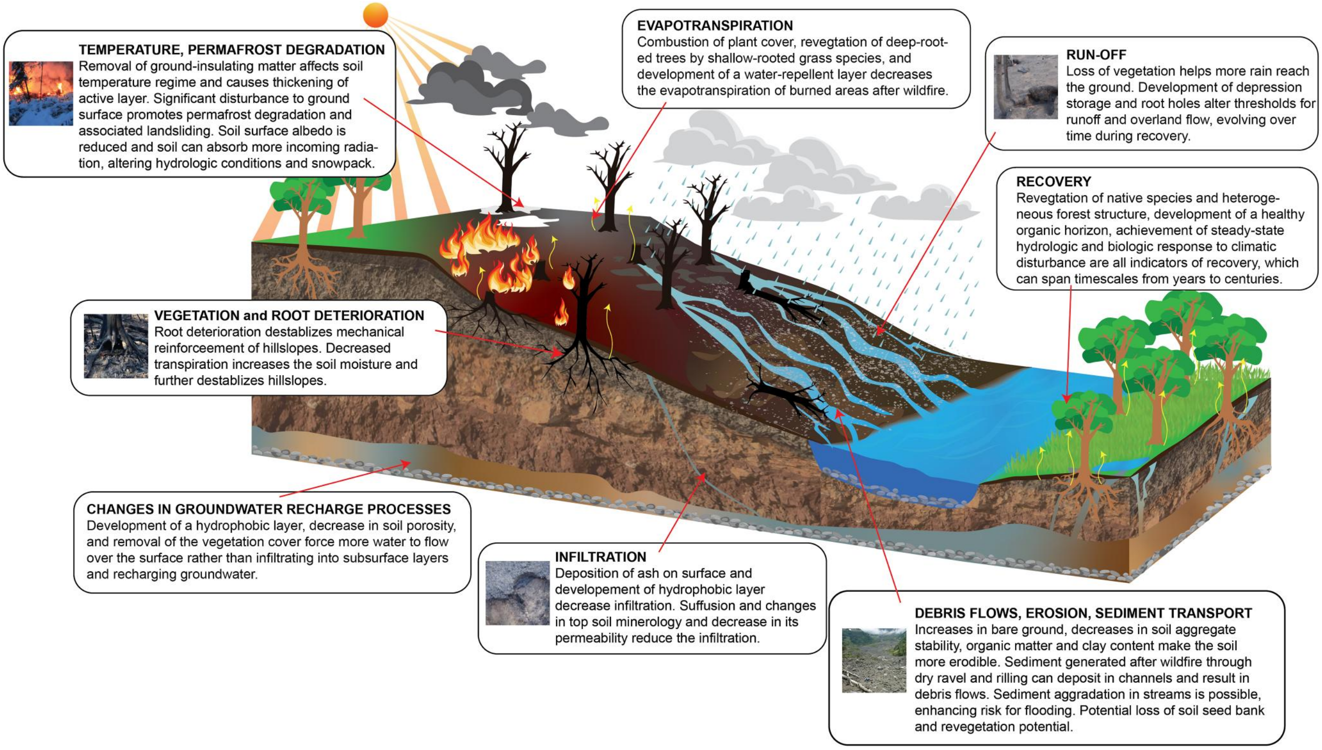

Figure 1. Evolution of wildfire-induced near-surface processes evapotranspiration and interception, vegetation cover and root deterioration, sediment and erosion, infiltration, and runoff. The burning of vegetation and organic litter (bottom left and top left insets) can alter a variety of properties and behaviors that manifest in evolving earth surface processes. Removal of vegetation may enhance infiltration through reduced canopy interception of rain and snow, while potentially reducing transpiration of stored groundwater. These hydrological alterations, in combination with the reduction of root mechanical strength, may yield eventual slope instability in the form of shallow landslides if landscape recovery is slow—the timescales of this recovery are poorly constrained. Conversely, these changes in vegetation may result in the deposition of hydrophobic ash and consequently, enhanced rain splash associated with amplified runoff and potential for flooding, along with increased sediment deposition in higher order channels, increasing the likelihood of debris flows (top right and bottom right insets). This sediment deposition may also stem from near-immediate dry ravel that occurs from loss of surface roughness and altered thermal properties in the near-surface. In the cryosphere, loss of vegetation offsets the sensitive thermal regime that enables growth or preservation of frozen ground, resulting in permafrost loss, an increase in active zone thickness, and consequently a propensity toward subsidence, and various landslide mechanisms, such as retrogressive thaw slumps and detachment slides. The immediate and long-term propensity toward post-fire hazards in landscapes varies as a function of burn severity, soil texture, climate, topography, and spatial heterogeneity. However, the timescales in which these hazards persist are poorly constrained as the interconnected evolution of properties, processes, and their controls is complex and stochastic.

alterations and processes and the need to consider their feedback mechanisms when assessing the risks of post-wildfire geohazards. Here we synthesize literature to unravel the interplay between wildfire-induced alterations in soil properties, near-surface processes, and geohazards. We critically discuss underlying physical processes, triggering factors, and connections to wildfires across time. To provide new insights into causes and triggering mechanisms, we critically review the recent literature on wildfire-induced changes in soil mineralogy and its hydraulic, mechanical, chemical, and thermal properties. Lastly, we identify future research directions and gaps that will contribute to mitigating the risks of wildfire-induced geohazards in various disciplines. The article primarily focuses on the most recent literature in the past decade when increased wildfire activities in many regions worldwide occurred. To the best of the authors' knowledge, none of the previous studies and review papers have investigated the interplay and feedback between geohazards and wildfire-induced changes to soil properties, land cover conditions, and near-surface and surface processes to the level discussed in this article. Although some of these wildfire-induced processes are discussed in the literature, there has been no such attempt to connect these elements and investigate interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards in the details that this article offers.

2. Recent Catastrophic Examples of Cascading Geohazards Associated With Wildfires

A tragic example is the fatal debris flow event in Montecito, California, in January 2018 that occurred following extreme rainfall over the burned scars of the December 2017 Thomas Fire (Cui et al., 2018; Oakley et al., 2018),

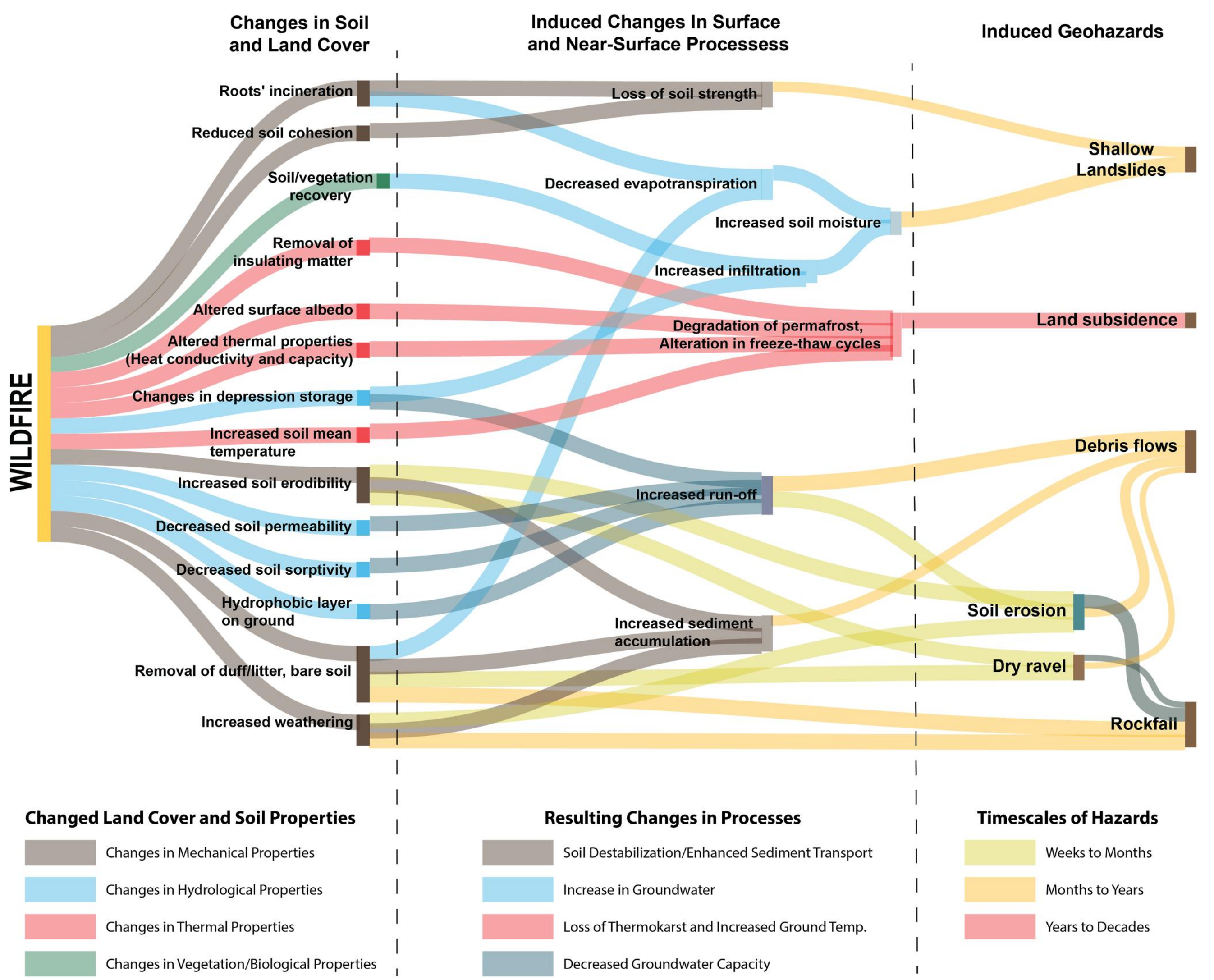

Figure 2. Evolution of wildfire-triggered changes in soil and land cover and the associated changes in surface and near-surface processes leading to geohazards versus time. Starting on the left-hand side of this Sankey diagram, wildfire results in a variety of altered soil properties and land cover behaviors. These changes are color-coded to reflect the nature of the alteration, whereas blue represents hydrological changes, brown represents mechanical changes, green represents biological changes, and orange represents thermodynamic changes. These changes in soil properties alter, at various timescales, the near-surface processes that predispose a landscape to a variety of geohazards. Shown in the middle portion of the display are the near-surface processes that are dependent on the aforementioned changes in soil and land cover. Some of these processes are contrasting, such as increased runoff (dark purple) and increased infiltration (pink), and may depend on burn severity, landcover type, climate, and/or other controls; however, these processes may evolve into one another with sufficient time (e.g., initially increased runoff until erosion of hydrophobic materials enables increased infiltration). Many of the fire-induced hydrological changes that decrease infiltration and alter mechanical properties also enhance erosional processes, including ravel and sediment transport; this preconditions landscapes toward hazards like debris flows (right side of the display). However, increased infiltration may also enhance erosion in the form of shallow landslides and debris flows, which both aggrade and scour higher-order channel networks. Altered thermal properties may increase rockfall, decrease infiltration, and drive ravel but have compounding effects of increasing the rate of permafrost loss in arctic regions owing to reduced protection against solar radiation and increased ground temperatures, which may result in land subsidence and potential landslides. The loss of vegetation has implications both on hydrological and mechanical processes (e.g., altered transpiration, loss of root strength, etc.) that predispose landscapes to a variety of landslide mechanisms.

which also is a lucid example of fire-induced geohazards in the multi-hazard context (Kappes et al., 2012) and is directly related to compounding and cascading hazards typology (Zscheischler et al., 2018, 2020). The Montecito debris flow mobilized about 680,000 m^3 of sediments, killed 23 people, and caused severe damage to over 400 homes (Kean et al., 2019) (Table 1).

A more recent example is the Pacific Coast Highway (Highway 1) embankment failure following the Dolan Fire in California, USA, in January 2021 (Figure 3) (Embankments, Dams, and Slopes Technical Committee, 2023)

Figure 3. Highway one Embankment Failure Following the Dolan Fire, CA. (a) Aerial photograph showing a V-shaped canyon created by the erosion of the Highway one embankment material, (b) Photograph showing the main breach area and secondary breach areas that likely occurred before the main breach based on observed scour and water retention, (c) Photograph showing one of the investigators standing at the entry point to the left secondary breach area and fallen tree trunks above for comparison purposes, and (d) View looking upslope within Rat Creek showing the eroded channel and residual burned tree trunks in and on the slopes of the creek.

that closed the road for over 1 year. On 28 January 2021, a portion of scenic Highway 1 was eroded at Mile Marker 30 just south of Esalen, California, and north of Lucia, California 37. This resulted in the complete closure of Highway 1 at that location and a detour of 255 km for residents. This erosion-induced failure occurred after about 300 mm of rainfall in an upstream catchment impacted by the 18 August 2020, Dolan Wildfire. The Dolan Fire burned for over 4 months and was not contained until 31 December 2020. Therefore, the embankment failure occurred less than 1 month after the fire was contained. The fire impacted an area of approximately 52,000 ha. The removal of vegetation by the Dolan Fire increased sediment accretion behind a pre-existing debris dam consisting of sediment and fallen trees, which facilitated the impoundment of significant precipitation and runoff until the debris dam failed. The Dolan Fire also facilitated the downslope movement of fallen redwood trees that contributed to the tree entrainment and constricted the creek channel at locations downstream of the dam, which caused significant bulking. When the debris dam breached about 650 m upstream of Highway 1, it released a large quantity of water and sediment at high velocity. This caused a scour depth of at least 2 m and the transport of a large amount of sediment and debris, for example, fallen redwood trees and boulders, down the creek channel. This large volume of debris damaged the riser for the buried culvert under the highway, so the creek flow and precipitation quickly filled the debris collection basin just upstream of Highway 1. After filling the collection basin, surface water flowed over Highway 1 and initiated erosion on the downslope side of the pavement. Water flowing over the earthen embankment started to quickly erode the embankment material so that erosion retrogressed upslope and eventually undermined the roadway to failure. Once erosion started, it progressed rapidly until the highway was breached, until a valley with a volume of about 382,000 cubic meters was cut through the highway embankment fill material. The debris flow-induced erosion washed both highway lanes and some of the surrounding embankment material into the Pacific Ocean about 122 m below. This erosion carved a near V-shaped valley in the embankment material.

These catastrophic examples of cascading geohazards associated with wildfires highlight the need to identify and manage these multi-hazard conditions to minimize their impacts on communities and the environment.

3. Immediately After Wildfire

After a wildfire, the properties of soil and land cover will be immediately affected (Figure 2). These changes, however, are mostly limited to surface and shallow depths (Badía-Villas et al., 2014). Because of the low thermal conductivity of soils, especially when dry, wildfire-induced heat is unlikely to alter soil conditions deeper than a few centimeters below the ground surface (Zavala et al., 2014). The severity and persistence of wildfire-induced changes in soils highly depend on fire characteristics (intensity, duration, and frequency), site characteristics (soil type, geology, slope inclination, area physiography, plant cover type, and regrowth rate), and climatic conditions (Prats et al., 2016; Vieira et al., 2015; Wagenbrenner et al., 2021; Wittenberg & Inbar, 2009).

Depending on wildfire behavior and severity, an immediate effect of wildfire is the combustion of the above-ground biomass and destruction of the near-surface soil organic material (Efthimiou et al., 2020; Granged et al., 2011; Moody et al., 2013). Loss of vegetation and litter cover reduces canopy interception, evapotranspiration, and storage of rainfall (Shakesby & Doerr, 2006; Stoof et al., 2012), altering the dynamics of surface and groundwater following disturbance (Figure 2) Soil water repellency, loss of soil structure, suffusion of ash particles into soil pores, creation of hydrophobic layers, and reduction in soil hydraulic conductivity are among other changes that can occur immediately after the fire, influencing the flashiness and potential for flooding (Chen et al., 2020; DeBano, 2000; Lei et al., 2022; Xue et al., 2014) (Figure 2) The extent of changes depends on the temperature reached during the fire and the soil type, among others. In soils with high clay contents, the magnitude of soil water repellency will manifest depending on the clay type. The development or enhancement of water-repellent layers in fire-affected soils results from the condensation of previously vapourized organic matter in fire-induced heat that potentially coats the soil particles and decreases their adhesion with water molecules (Neary, 2011; Stavi, 2019). Water repellency development is highly dependent on the heat generated during the fire, but there are some discrepancies in the literature about the effect of wildfire on soil hydraulic conductivity and sorptivity (Figure 2). Temperatures above 300℃, for example, can destroy the water-repellent layer on the ground surface and temporarily enhance the soil hydraulic conductivity (Doerr et al., 2006; Varela et al., 2015). However, most studies reported decreases—as high as 40%—in soil hydraulic conductivity and sorptivity due to fire-induced temperatures (Ebel & Moody, 2020; Woods & Balfour, 2010). Although hydrophobicity of the ash layer has been documented in some cases (Bodí et al., 2011), generally, the ash generated during a wildfire has a high infiltration rate and can store water, which can act as a buffering layer on top of the burned soil, delaying or preventing runoff generation (Balfour, 2015; Cerdà & Doerr, 2008; Ebel et al., 2012). However, the hydraulic effects of ash are only present for a relatively short period because ash can be easily removed by wind and water (Ebel et al., 2012).

Fire energy can affect near-surface soils and vegetation structure and cause large pores to collapse by decreasing soil aggregate stability, consequently increasing soil bulk density and reducing soil porosity and hydraulic conductivity while increasing erodibility (Ebel & Moody, 2020). A slight increase in aggregate stability is also observed when the soil is exposed to lower temperatures (< 200ºC) during a wildfire (Terefe et al., 2008). The observed change in temperatures below 200°C is commonly attributed to the development or increase of soil water repellency, while recrystallization is reported to occur at higher temperatures (Mataix-Solera et al., 2011). Decreased vegetation cover and soil aggregate stability elevate the risk of dry slope ravel and have been observed to increase post-fire sediment yields by up to three orders of magnitude (DeLong et al., 2018; Wagenbrenner & Robichaud, 2014) (Figure 2).

Immediately following a fire, damaged or incinerated vegetation roots decrease soil reinforcement and, thus, superficial strength and stability (Figure 1). Roots considerably enhance soil strength by providing mechanical reinforcement and maintaining matric suction through transpiration (Masi et al., 2021). The strengthening effects of roots may be diminished by fire during decay and tree mortality, a loss that could last for decades, depending on the biome (Gehring et al., 2019). The number of roots, the tensile strength of the roots, and the shear strength of the soil-root system can be reduced between 50% and 80% following a fire (Lei et al., 2022) (Figure 2). Further, wildfire degrades soil shear strength by decreasing soil cohesion (in fine-grained soils) and breaking particles (in coarse-grained soils) (Blake et al., 2007; Mataix-Solera et al., 2011; Wondzell & King, 2003).

Wildfires can also alter the thermal properties of the landscape (Figure 2). Fire generally increases surface temperature (Gibson et al., 2018; Holloway et al., 2020; Li et al., 2019; Walker et al., 2018). The rise in the mean annual ground surface temperature as high as 7°C has been observed in burned boreal forests and tundra in Alaska, Canada, Mongolia, Siberia and northeast China (Holloway et al., 2020). The majority of studies show a decrease in surface albedo post-fire that could be attributed to the darkening of the surface, the disposition of ash on the ground, and the impact of smoke on atmospheric conditions (Aubry-Wake et al., 2022; Rother & De Sales, 2021). An increase in post-fire surface albedo also has been observed and attributed to canopy removal and species composition change (Chen et al., 2018) (Figures 1 and 2).

4. When the Rains Begin

Following a wildfire, altered soil and vegetation conditions leave a landscape predisposed to various changes—and hazards—during and after the first few large precipitation events (Figure 1). Debris flows are the dominant hazard in channels proximal to steep slopes for the first months following a fire (Hoch et al., 2021; Nyman et al., 2011; Rengers et al., 2016). Entrainment of eroded material from surface runoff and shallow landslides are two primary causes of debris flows following a fire (Cannon et al., 2001). Debris flows during the first wet season or series of heavy precipitation events are frequently generated through sediment-laden overland flow concentrated in hollows and headwater channels and are often triggered by high-intensity, short-duration rainfall events with a return interval below two years (DeGraff et al., 2015; Moody et al., 2013; Staley et al., 2020) For example, within the months following the 2020 Dolan Wildfire, accretion of entrained debris and persistent debris flows resulted in the failure of Highway 1 in California, USA (Figure 3), a major lifeline critical to emergency access, local communities and commerce. The rainfall intensity threshold for runoff-driven debris flow triggering tends to be lowest immediately following the fire. In contrast, longer rainfall events with lower intensities may drive shallow landslide-controlled debris flows after three or more years of post-fire recovery, owing to long-term hydrological changes and loss of native vegetation (Thomas et al., 2021) (Figure 2). The loss of canopy (Williams et al., 2019; Niemeyer et al., 2020; Seibert et al., 2010), increase in soil water repellency, and removal of the organic horizon (Merino et al., 2018) result in direct exposure to rainfall and decreased infiltration capacity (DeBano, 2000; Hallema et al., 2018; Larsen et al., 2009; Letey, 2001), altering the short-term landscape response to rainfall (Williams et al., 2019; Niemeyer et al., 2020). Increased rain splash of loosened near-surface sediment, decreased grain sizes, weakened soil aggregate structure, potential hydrophobicity of burned organics, and thermal dilation (altered surficial porosity) of soil minerals result in higher runoff and erosion of material into downstream channels (Shakesby & Doerr, 2006; Shakesby et al., 1993; Zavala et al., 2009).

Sheet erosion, rilling, and dry ravel in hillslopes and channel incisions accelerate debris flow probability following a fire by loading channels with unstable sediment (Lamb et al., 2011; Meyer & Wells, 1997; Palucis et al., 2021) (Figure 1). Rain splash of loosened surficial sediment and entrainment of loosened surficial soils, ash, and debris within overland flows move sediment through convergent terrain associated with channel formation (Ice et al., 2004; Moody et al., 2013). In some instances, for example, where significant slope ravel and accretion of woody debris and sediment within drainage channels has occurred, debris flows may initiate from the failure of in-channel debris dams (May & Gresswell, 2004; McGuire et al., 2017), as happened in the Highway 1 embankment failure in California (Figure 3). Runoff often controls debris flow characteristics before it is confined by the boundaries of drainage channel (Nyman et al., 2011).

Removal of vegetation cover and decreased hydraulic roughness of channels are among the other factors amplifying debris flow occurrence following a wildfire (Canfield et al., 2005; Moody & Martin, 2001) (Figure 2). Such debris flows tend to occur from small debris dam failures, slumps, and bank collapses stemming from weakened channel root systems, the scour of high peak flows, and the entrainment of channel debris during flow (Alessio et al., 2021; Cannon et al., 2003; Shakesby & Doerr, 2006). These processes may result in debris flow bulking and the entrainment of added coarse materials (Cannon et al., 2003). Concentrated flows may occur with high peak flows and lower concentrations of typically fines-dominated debris (Florsheim et al., 2017), resulting in significant erosion and entrainment of channel sediment.

As the wet season progresses, either through liquid precipitation or snowmelt, the loss of interception from destroyed vegetation results in increased soil moisture and groundwater flows (Figure 2) (Cardenas &

Kanarek, 2014; Helvey, 1980; Jakob et al., 2005). Depending on the climate, the first several significant rain events may remove a substantial proportion of the burned organic and ash horizon, resulting in increased infiltration capacity throughout the remaining wet season (Bodí et al., 2014; Gabet & Sternberg, 2008). This behavior may be augmented by increased soil hydraulic conductivity stemming from macropores that remain from incinerated root systems in severely burned environments (Blount et al., 2020; Holden et al., 2014; Leslie et al., 2014). Further, wildfire is shown to diminish water retention capacity, resulting in enhanced, gravity-driven subsurface flow (Megahan, 1983). Increased soil moisture content, combined with altered soil properties and the diminished mechanical effects of pre-wildfire root networks, may result in a propensity for shallow landslides (Figure 1) (Gehring et al., 2019; Jackson & Roering, 2009; Schmidt et al., 2001). These shallow landslides may have enhanced mobility as a flow failure, particularly in the presence of long-duration rainfalls and contractive materials and where downslope channels are present (Iverson, 1997).

5. Long-Term Impacts

Various wildfire-induced geohazards, such as debris flows, can persist for years, or even decades after a wildfire, although triggering mechanisms and thresholds can shift (Bowd et al., 2019) (Figure 2). For example, after the 2016 San Gabriel Complex Fire in Southern California, the modes of ground instability transitioned from runoff-triggered debris flows in 2017 into infiltration-triggered shallow landslides in 2019 (Rengers et al., 2020) (Table 1). The soil type, burn severity, preconditioning of sediment in channels before the wildfire, and natural revegetation of a burned landscape are expected to influence the timeframe in which post-wildfire geohazards are likely to occur (Alcañiz et al., 2018; Bowd et al., 2019; Holloway et al., 2020; Thomas et al., 2021; Yang et al., 2021) (Table 1) Further, the persistence of geohazards depends on climatic controls that are complex and, to some extent, poorly constrained (Thomas et al., 2021) (Figure 1). While long-term effects are relatively understudied (DeLong et al., 2018), the literature concurs that as time since fire increases, the probability and magnitude of fire-induced geohazards generally decrease, and the activating thresholds for the processes that trigger those hazards increase (Thomas et al., 2021). It is noted that some of the aforementioned studies do not address the effect of the wildfires alone but consider wildfire recurrence, logging, and prescribed fires (Alcañiz et al., 2018). While both prescribed fires and wildfires can result in changes to the landscape, the effects of prescribed fires tend to be less severe and more short-lived. They often result in less damage to the underlying soil and vegetation than the more intense heat generated by a wildfire. The influence of forest management, such as stand and rotation age, forest density, and salvage logging as controls on post-fire geohazards are largely unconstrained. Further, the potential influence of reburning or burn frequency is poorly understood and may result in a protracted recovery of burned soils and land cover.

Longer-term (>5 years) impacts of fires include consequential sediment redistribution across the landscape (Ravi et al., 2009) (Figure 3), modification of surface stoniness with the erosion of finer particles (Rengers et al., 2020), and increased rockfall likelihood (Sarro et al., 2021) (Figure 2). Fires also enhance rock weathering rates as a fire-induced thermal shock causes rock surface exfoliation, clast formation, and potential hardness reduction (Shakesby & Doerr, 2006). The majority of flakes and spalls are eroded from the rock surface in a decade post-fire, exposing new rock surfaces to weathering (Shtober-Zisu & Wittenberg, 2021). Another long-term (>5–10 years) post-fire impact on soil characteristics with the potential for enhanced primary, secondary, and tertiary geohazards is nutrient depletion due to erosional processes, nutrient leaching, vegetation removal, and altered soil microbial community structure and activity (Alcañiz et al., 2018; Bowd et al., 2019; Certini, 2005; Francos et al., 2018). Nutrient depletion can induce changes in soil biological processes and composition, such as inhibiting vegetation recovery, especially in nutrient-limited biomes like tundra (Abbott et al., 2021). However, there is no consensus on long-term post-fire nutrient depletion. Some studies report the recovery of soil nutrients to pre-burn status in a few years, depending on burn severity and environmental conditions (Alcañiz et al., 2016). Furthermore, fires can prompt land cover changes. Shifts from forested land to shrubland and from shrubland to grassland are more common in fire-impacted landscapes, especially in lower-elevation dry sites (Alizadeh et al., 2021). Invasive species, such as cheatgrass, accelerate shifts in the vegetation cover in the aftermath of fires (Nagy et al., 2021).

Fires also promote landscape-altering processes and landform changes with significant long-term implications for hydrological, ecological, and geomorphological hazards (Garcia et al., 2021; Moreira et al., 2011) (Figure 1). Specifically, post-fire erosion drives surface and topographical changes, as shallow overland flows erode fire-impacted surfaces to form rills and channelize flows to form gullies (DeLong et al., 2018). Post-fire debris flow expands the drainage network, deepens gullies, and incises streams (Wilson et al., 2021), decreasing the residence time of water upstream and increasing the streamflow velocity at the watershed scale, collectively leading to higher flood probability (Shakesby & Doerr, 2006). These processes also disconnect streams from floodplains and reduce groundwater recharge, with drought resilience implications for socio-environmental systems (Maples et al., 2019). Not only do fires promote secondary impacts through landform changes, but also, they boost human interventions and activities, such as salvage logging and fuel management. These human interventions commonly involve potential heavy machinery encroachment on burned areas, trail development, soil compaction, disturbance, sediment production, and slash pile burning (Wagenbrenner et al., 2015). These changes can collectively increase erosion rates and have major ecological and functional implications extending to several decades post-fire (Bowd et al., 2019). Compounding impacts of successive fires and anthropogenic stressors further exacerbate and extend soil disturbance impacts (Bowd et al., 2019).

Finally, a recently discovered long-term (years to decades) impact of fires is permafrost degradation through thawing and thaw settlement (Brown et al., 2015; Minsley et al., 2016; Yanagiya & Furuya, 2020; Zhang et al., 2015) (Figure 2). While the degree of impact is modulated by burn severity, climate conditions, and soil type, fires generally remove insulating vegetation cover that protects the permafrost layer and increases soil heat flux (Kornei, 2020) (Table 1) This promotes permafrost thawing, active layer thickness increase, surface and ground temperature increase, surface subsidence, soil moisture enhancement, and talik and thermokarst formation and expansion (Holloway et al., 2020). These impacts not only change the hydrology and biogeochemistry of permafrost zone with regional to global implications—for example, the release of permafrost stored carbon and climate change acceleration—but also have direct implications on human infrastructure and security (Abbott et al., 2021; Hjort et al., 2022).

6. Gaps and Call for Action

The risk of wildfires and wildfire-triggered geohazards is on the rise in several regions. Fires can trigger unprecedented geohazards with immense socio-environmental repercussions, especially as climate change exacerbates the patterns of extreme events (Alizadeh et al., 2020; Swain et al., 2018). For example, previous studies (Kean & Staley, 2021) report that massive debris flows are roughly an order of magnitude more sensitive to rainfall intensity than burn severity and frequency. As more widespread and intense fires occur, compounded by increasingly intense and clustered precipitation events, wildfire-induced geohazards further threaten the natural and built environments and communities (Touma et al., 2022). Furthermore, some regions, such as areas rich in permafrost, are at an ever-increasing risk of passing tipping points in a warming climate and increasing fire activity. This trend has significant ecological and functional implications and may cause unknown consequences (Abbott et al., 2021). Finally, wildfire-induced geohazards can cascade to other systems and sectors (Reed et al., 2022), such as water quality, agriculture, and health. These alarming points indicate an urgent need to enhance the state-of-the-art and practice to better understand the linkage between the wildfire-induced alterations in soil and land cover properties, near-surface processes, and resulting geohazards in a changing climate.

Despite significant research in the past decade, there are still several knowledge gaps that require attention. The lack of comprehensive and long-term data and landscape recovery remains one of the most significant challenges in understanding the interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards. Although studies have examined specific aspects of this interplay, more comprehensive data sets are necessary to fully capture the interactions between these factors. Moreover, there is a critical need to better comprehend the temporospatial feedback mechanisms between soil properties, land cover, near-surface processes, and geohazard risks. Further, given climate change is expected to increase the frequency and severity of wildfires in many regions, it is critical to understand how these changes will impact the interdependencies between soil properties, near-surface processes, and geohazards.

The science, policy, and engineering communities need to work together to address the gaps in the literature regarding the fundamental behavior and response of burned soil when subjected to compounding—subsequent or concurrent—climatic and non-climatic stressors such as floods, heavy precipitation, earthquakes, and wildfires. Understanding the recovery timeline of different properties of soil and landscape post wildfires is very limited (Yang et al., 2022). More in-depth research and coordinated interdisciplinary studies are required to enhance current modeling capabilities to study the complex spatiotemporal factors governing the evolution of cascading geohazards linked to wildfire (e.g., drought-wildfire-debris flow, drought-wildfire-land subsidence). Finally, with a vision toward ensuring the safety and economic security of communities, there is a need for a multidimensional framework examining the spatiotemporal effects of wildfire-related cascading hazards by integrating physical and social sciences.

Data Availability Statement

No new data was used in this article.

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