

Post-fire erosion and debris flows in the western Pacific Northwest, United States: recent science and opportunities

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ABSTRACT

Most research into post-fire geomorphology has been conducted in regions with frequent fire, such as in dry Mediterranean and temperate climates and less has been conducted in wet forests where wildfire is now expanding with climate change. Because climate, soils, topography, vegetation, management legacies and fire history influence post-fire geomorphic processes, research into post-fire erosion and debris flow hazards across a broader set of climatologies is needed. The western Pacific Northwest (wPNW) of the United States is susceptible to multiple types of post-fire debris flows (i.e. shallow landslide-initiated and runoff-generated) that can be initiated by longer-duration lower-intensity rainfall compared to other regions in the western US. Therefore, knowledge of how wildfire impacts geomorphic processes in drier, more frequently burned regions does not necessarily apply to the wetter wPNW climate. Significant gaps in data coverage remain a key limitation for predictive modeling and empirical studies in this region. This review synthesizes the current state of post-fire geomorphic knowledge and identifies gaps in data and understanding for the wPNW. These gaps and opportunities for future work can help expand knowledge and evaluate assumptions about post-fire geomorphology in other regions, such as those with similar pyro-climatology and others not yet well represented by current post-fire geomorphology research.

Keywords: Cascade Range, erosion, geologic hazards, landslides, Pacific Northwest, post-fire debris flows, sediment, wildfire.

Introduction

Wildfires impact soil properties, vegetation, hydrology and erosional processes, and can greatly influence landscape evolution (Fig. 1a). Post-fire geomorphic responses of hillslopes and channels can cause widespread impacts to critical natural resources and infrastructure, including forest ecosystems, aquatic habitat and water resources (Cannon and Gartner 2005; Bixby *et al.* 2015; Hohner *et al.* 2019). Post-fire debris flows are a particularly hazardous consequence of wildfire in steep terrain owing to their potential for sudden and undetected triggering in remote areas, rapid progression downslope and ability to damage infrastructure and homes (Kean *et al.* 2011). In recent decades, droughts due to climate change and rebound effects of legacy land management have increased the frequency and intensity of wildfire (Westerling *et al.* 2006; Abatzoglou and Williams 2016; Jones *et al.* 2022), making it critical to improve our understanding of the effects of wildfire on geomorphic systems.

How post-fire geomorphic processes manifest across a landscape varies with climate, topography, soil characteristics, vegetation, land management legacies, fire history, and both soil and vegetation burn severity (Moody *et al.* 2013; Santi and Rengers 2022; McGuire *et al.* 2024). Recent reviews on post-fire landscape change have highlighted impacts to erosion, sediment transport and slope stability (Santi and Rengers 2022; McGuire *et al.* 2024; Vahedifard *et al.* 2024), and impacts on reservoir sedimentation

Collection: Establishing Directions in Postfire Debris-Flow Science

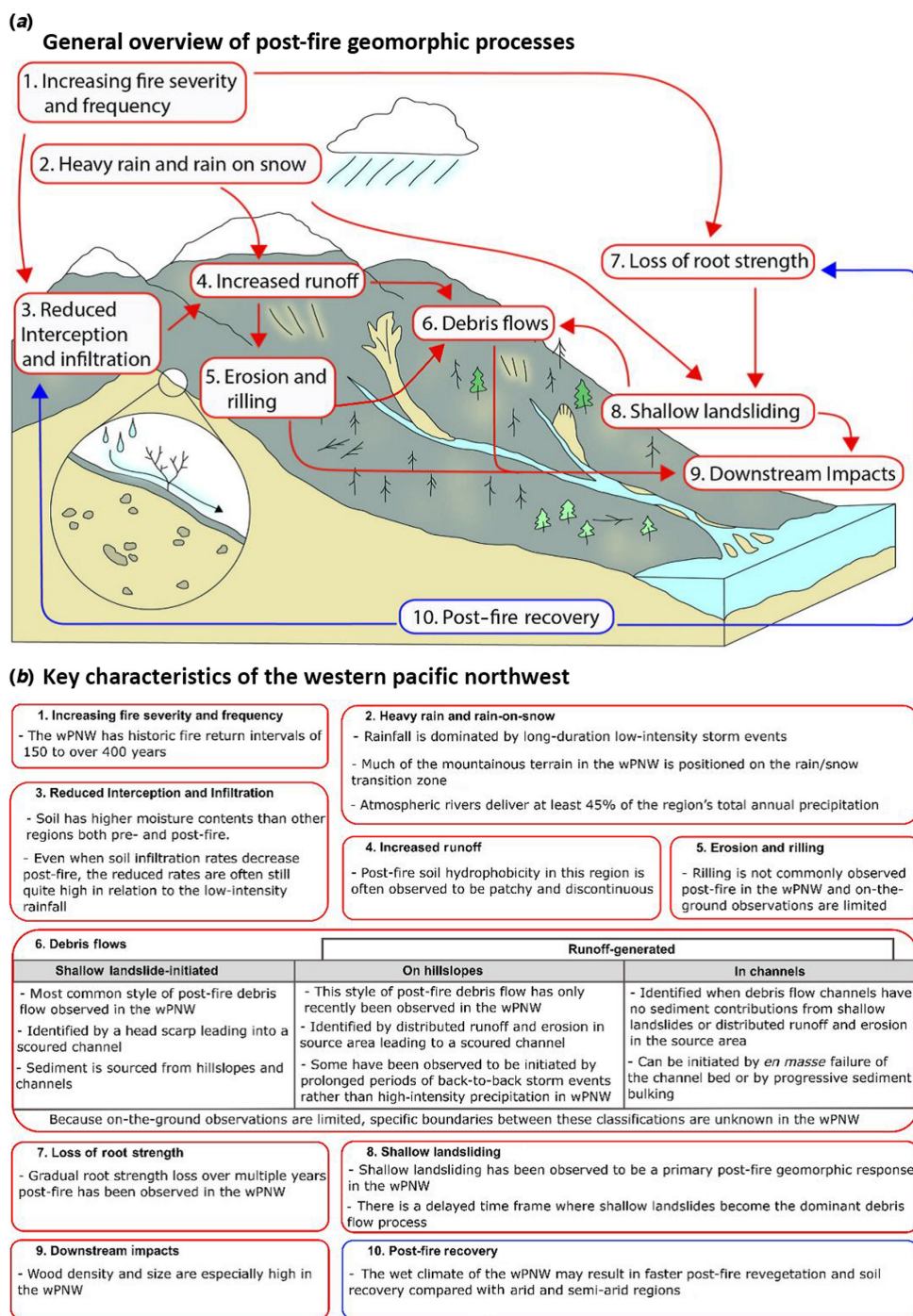


Fig. 1. (a) Conceptual overview of post-fire geomorphic processes (red arrows). Blue arrows indicate opposing processes. (b) Overview of the key characteristics of post-fire geomorphic processes in the wPNW and how they may differ compared with more studied, frequently burned regions.

(Moody and Martin 2004), water quality (Paul *et al.* 2022; Murphy *et al.* 2023; Clark *et al.* 2025; Wall *et al.* 2026) and hydrologic processes (Ebel *et al.* 2026). However, current understanding of post-fire geomorphic processes mostly derives from regions where wildfires have a frequent to moderately frequent and recently documented history on the landscape. Such regions include southern California and the Rocky Mountains in the western United States (US), the Mediterranean area of Europe and the Middle East, and much of Australia (Shakesby and Doerr 2006;

Cannon *et al.* 2010; Mataix-Solera *et al.* 2011; Nyman *et al.* 2015; Staley *et al.* 2017). In these regions, post-fire geomorphic processes are strongly influenced by short-duration, high-intensity rainfall that often exceeds soil infiltration rates, together producing excess overland flow and runoff-triggered debris flows following fire (Moody *et al.* 2013; Santi and Rengers 2022). The increasing prevalence of wildfire in a broader set of geographies, however (Pechony and Shindell 2010; Prichard *et al.* 2017; Jones *et al.* 2022), especially in wet temperate forests around the

world (Whitlock *et al.* 2015; Urrutia-Jalabert *et al.* 2018; Halofsky *et al.* 2020; Benyon *et al.* 2023), drives a need to better understand variation in post-fire processes and to construct geographically appropriate predictive tools for mitigating post-fire hazards, particularly in regions with wetter climates (Wall *et al.* 2023; Gorr *et al.* 2024; Selander *et al.* 2025).

Post-fire geomorphology has been understudied in the temperate rainforest setting to the west of the Cascades Mountains crest in the US states of Washington and Oregon, which we refer to as the western Pacific Northwest (wPNW; Fig. 2; Selander *et al.* 2025). The region's humid-submediterranean climate is characterized by long-duration, low-intensity winter-season precipitation, and soil infiltration rates are notably high (Jackson and Roering 2009). In the wPNW region's steep, highly dissected terrain, debris flows may be a dominant landscape-shaping geomorphological process (Stock and Dietrich 2006). Documentation of post-fire debris flows in this region may be more limited by a lack of large, high-intensity fires over the past century, post-European colonization, than by an actual lack of debris flow potential (Wiley 2000; May and Gresswell 2004; Reid *et al.* 2016; Wall *et al.* 2020; Burns *et al.* 2025; Selander *et al.* 2025). Recent reviews have generally not included observations from the seasonal temperate rainforests of the Coast Range and western Cascade Mountains of the wPNW and instead have used observations from the eastern Cascades and Rocky Mountains to represent the PNW (e.g. McGuire *et al.* 2024). These reviews have therefore not explicitly addressed how post-fire geomorphic processes differ in the steep, wet forests of the wPNW compared with more studied regions that burn more frequently (McGuire *et al.* 2024; Vahedifard *et al.* 2024).

Despite hosting one of the wettest climates in the US, the forests of the wPNW can still burn when summer conditions are sufficiently dry and fire is known to be a key landscape process over long timescales in this region (Halofsky *et al.* 2020; Reilly *et al.* 2021). Recent severe fires, most notably the five large, simultaneous 2020 'Labor Day Fires' in the western Cascades (Fig. 2b), which burned larger areas and at higher intensity than other fires in this region in recent history, have underscored the critical need to better understand post-fire landscape responses in this unique climate. Although the majority of observed post-fire mass movements in this region have been initiated by shallow landsliding (Selander *et al.* 2025), runoff-generated debris flows have recently been observed (Wall *et al.* 2020; Burns *et al.* 2025; Selander *et al.* 2025). Increasing wildfire frequency and severity in this region due to climate change (Reilly *et al.* 2017, 2022; Halofsky *et al.* 2020; Jones *et al.* 2022) raises questions about how wildfire may influence geomorphic processes and community resilience into the future. The aims of this review are to (1) collect and synthesize current post-fire geomorphic knowledge for the

wPNW, (2) identify gaps in existing data and understanding of post-fire geomorphic processes in the wPNW, and (3) identify where findings from other regions may not apply to the unique landscape, ecology and climate of this region. Better understanding post-fire geomorphic processes in the wPNW can help inform how other landscapes with similar wet climates and infrequent fire histories, globally, may respond to fire in the future.

Western Pacific Northwest, US

Regional overview and historical fire regimes

The focus of this review is on the forested regions of the wPNW (Fig. 2), which are characterized by high annual precipitation, exceptional forest biomass density and a highly seasonal climate. The majority of drinking water in this region is sourced from surface water in forested watersheds and is therefore particularly vulnerable to post-fire erosion (Robichaud and Padowski 2024). The wPNW is predominately underlain by volcanic rocks, with some marine sedimentary and metamorphic rock layers (O'Connor *et al.* 2021; Selander *et al.* 2025). Elevations span up to 4300 m, and slopes in the Cascades and Coastal Ranges are steep (Fig. 2a). Forests within the study region are dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) at low to middle elevations, with grand fir (*Abies grandis*), western red cedar (*Thuja plicata*) and Sitka spruce (*Picea sitchensis*) near the coast, and Pacific silver fir (*Abies amabilis*), subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*) at higher elevations. Many forests in the wPNW have an extensive history of timber harvest, which results in very different forest structures between intensively managed private timberlands and public forests (Spies *et al.* 2019; Dunham *et al.* 2023).

Historical fire regimes in the wPNW have varied with local conditions ranging from frequent, low-intensity fires in drier areas like the Willamette Valley (surrounding the cities of Portland, Salem and Eugene; Fig. 2) to infrequent, stand-replacing fires in the cooler, wetter zones of the Coast Range and western Cascades (Fig. 2a; Reilly *et al.* 2021). In these wet forests, fire return intervals were historically >200 years (USGA, USDA 2016), but projected higher temperatures, decreasing summer precipitation and increasing drought are expected to increase the frequency, extent and intensity of future fires (Fig. 1; Halofsky *et al.* 2020). In September 2020, five megafires (>40,000 ha), known as the Labor Day Fires, burned across western Oregon (Fig. 2). The Labor Day Fires were consistent in size and severity of vegetation loss with the largest historical fires in this area over the last millennium, the last of which, the Tillamook Burn, occurred in western Oregon in 1933, which reburned several times in the following two decades (Reilly *et al.* 2021, 2022). These now-reactivated

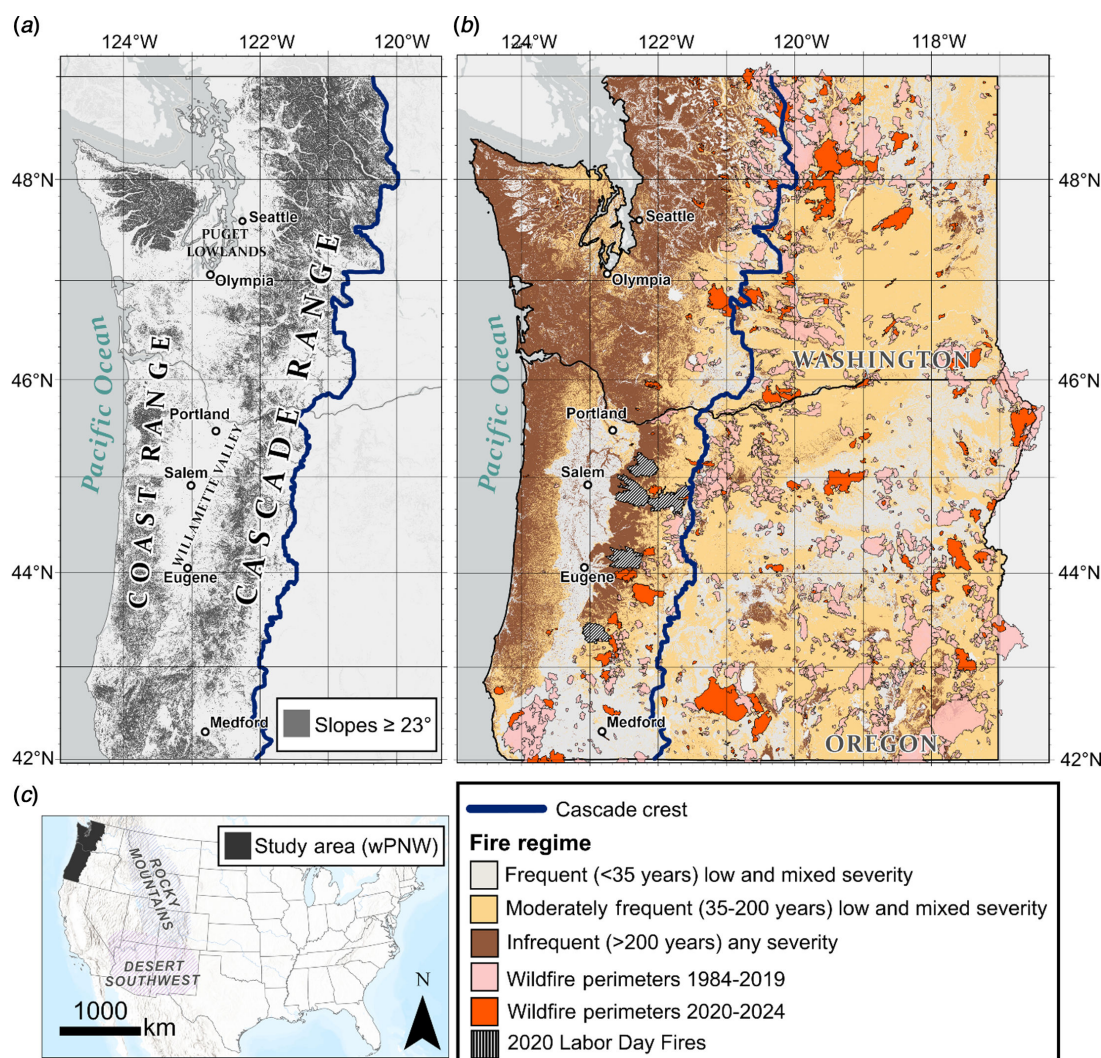


Fig. 2. (a) Map of study region where slopes are equal to or greater than 23 degrees, which may have increased susceptibility to post-fire debris flows when burned (Staley *et al.* 2017). Our study region, the wPNW, is the area to the west of the Cascade Crest (blue line). (b) Map of wildfire perimeters since 1984 in the states of Oregon and Washington (Eidenshink *et al.* 2007). Base map shows fire regimes based on frequency and severity classifications (USGA, USDA 2016). Our study region is the area to the west of the Cascade Crest (blue line). (c) Map of the continental United States with our study region shaded in grey. Figure modified from Selander *et al.* (2025).

historical fire regimes, combined with emerging drought patterns, declining snowpacks and growing population density further support the need to better understand how landscapes respond to fire in the wPNW.

Climate and precipitation of the western Pacific Northwest

The wPNW hosts one of the wettest climates of the US, with 180 to >400 cm of annual precipitation in the Coast Range and western Cascades Mountains. In the intervening Willamette Valley, Puget Lowlands and mountain foothills, annual precipitation totals 100–180 cm (Reilly *et al.* 2021).

The precipitation regime in this region is dominated by long-duration, low-intensity rainfall and strong seasonality, with mostly winter precipitation and dry summers (Markham 1970; Wondzell and King 2003). Compared with the interior western US, the wPNW experiences fewer convective storms in the summer, and short-duration rainfall intensities in the region are lower than elsewhere in the continental US, though prolonged winter events deliver more total precipitation (Fig. 1b; Arkell and Richards 1986).

Atmospheric rivers (ARs), which are corridors that transport moisture from the tropics poleward (Payne *et al.* 2020) and have peak seasonal occurrence between November and January, account for the majority of each year's extreme

precipitation events in the wPNW (Fig. 1; Rutz *et al.* 2014; Collow *et al.* 2020). Within the cool and wet season, ARs contribute at least 45% of total precipitation, bringing extreme rainfall to low elevations, snowfall to high elevations and possible rain-on-snow events near the snowline. Sustained rainfall from ARs lasts, on average, 24 hours (Rutz *et al.* 2014; Collow *et al.* 2020) and follows the late summer and early fall (autumn) fire season (Payne *et al.* 2020; Oakley 2021). ARs can cause significant geomorphic, hydrologic and water quality impacts in burned regions (Wetherell *et al.* 2021). ARs are an important driver of debris flows, landslides and other mass-wasting processes (Oakley *et al.* 2017; Cordeira *et al.* 2019; Darrow *et al.* 2022), including in the wPNW (Lancaster *et al.* 2012; Gillett *et al.* 2022; Sepúlveda *et al.* 2023; Davidson *et al.* 2024; Hancock and Włodarczyk 2025), but characteristics of triggering storms, including synoptic and meso-scale storm conditions are not well described in this region.

Drought is another dimension of the wPNW climatology that influences fire behavior and post-fire landscape response. The intense seasonality of precipitation in this region results in dry summers, but drought intensification, both seasonally and in terms of multiyear droughts, is expected to heighten future fire risks and demand corresponding hazard-preparedness efforts (Cartwright *et al.* 2020; Halofsky *et al.* 2020). Hyper-dry soil conditions, as a result of drought, have also been found to increase watershed vulnerability to flooding and large debris flows after fire (Moody and Ebel 2012). Severe droughts occurred in the region during the 1930s, 1970s, early 2000s (Xiao *et al.* 2016), and in the months preceding and following the 2020 Labor Day fires (Abatzoglou *et al.* 2021; Reilly *et al.* 2022; White *et al.* 2023).

In combination, the concentration of precipitation in the winter, annual summer drought, moderate temperatures and large altitude range place the wPNW in a humid-submediterranean, temperate to cool-temperate oceanic climate zone (e.g. Rivas-Martínez *et al.* 2011; Belda *et al.* 2014; Xu and Lauenroth 2025). However, the sheer magnitude of annual precipitation in the wPNW distinguishes forests in this region from geographically or climatically adjacent regions such as: Mediterranean areas of Africa, Europe and the Middle East, western Australia, northern Chile, and central and southern California, and from more continental climates such as of the US Rocky Mountains and eastern Cascades. The seasonally dry summers also distinguish the wPNW from other humid temperate areas without a pronounced dry season such as southern Chile, central-northwestern Europe, eastern South Africa, southern Japan, Tasmania, New Zealand and south-eastern mainland Australia (Canadell *et al.* 2021; Jones *et al.* 2022; Benyon *et al.* 2023).

Climatologically, the wPNW can be most directly compared with southeast Australia (Bradstock 2010; Duff *et al.* 2018) and north-central Portugal (Ferreira *et al.* 2000), which host highly flammable and mostly sclerophyllous eucalypt forests; with central Chile around Temuco, which

hosts broadleaf evergreen and deciduous temperate forest and drier mediterranean sclerophyllous forest and scrub (Balocchi *et al.* 2023; Duarte *et al.* 2024), and with the humid sub-mediterranean bioclimate areas of eastern Liguria in Italy (Pesaresi *et al.* 2014). Whereas all of these regions qualify as having a 'Mediterranean' climate with moderate temperatures, a pronounced dry season and high total amount of precipitation, the wPNW has a particularly high ratio of average annual precipitation to average annual potential evapotranspiration.

Climate change in the western Pacific Northwest

Climate change is expanding the elevation range in which high-intensity wildfires occur (Alizadeh *et al.* 2023). The impact of wildfire as it relates to snowpack characteristics and the influence on rain-on-snow events is poorly constrained (Wilson *et al.* 2021; Koshkin *et al.* 2022; Ebel 2025). Changes to fire regimes, especially in regions with seasonal snowpack, may result in a shift from historical patterns of triggering landslides and debris flows (Hatchett *et al.* 2023; Keck *et al.* 2025). The location of the steep slopes of the wPNW in the rain-snow transition zone makes this region particularly vulnerable to climate change (Buma *et al.* 2019).

Climate change in the wPNW is expected to increase annual average temperatures and to result in a decline of ~25% snow water equivalent by 2050 (Mote and Salathé 2010; Berghuijs *et al.* 2014; Siirila-Woodburn *et al.* 2021; Roberts-Pierel *et al.* 2024). Although annual precipitation is not expected to change appreciably (Mote and Salathé 2010), climate change is expected to redistribute seasonal precipitation (Chang and Jung 2010), increasing AR intensity (Payne *et al.* 2020), and increasing and lengthening summer drought (Halofsky *et al.* 2020). Potential changes to the frequency of rain-on-snow events, including those generated by ARs, are not yet well understood, although these extreme events have the potential to trigger widespread flooding, erosion and landsliding (McCabe *et al.* 2007). As the timing of snowfall and snowmelt changes, the direction of trends may vary locally: some areas may experience more frequent rain-on-snow events, while others with less snowpack may see declines in rain-on-snow flooding and landsliding (Cohen *et al.* 2015; Rhoades *et al.* 2024; Keck *et al.* 2025).

Although the potential for post-fire precipitation to drive landscape change by triggering surface erosion, landslides and debris flows is widely recognized, below-normal post-fire precipitation and drought intensification associated with climate change may also influence post-fire landscape responses in complex ways (Busby and Wilcox 2024). Post-fire drought could decrease erosion associated with post-fire precipitation and floods, but could also prolong or otherwise alter above-and below-ground vegetation

recovery in a manner that extends post-fire recovery time scales and subsequent hazards (Davis *et al.* 2019; McGuire *et al.* 2019).

Geomorphic contributing factors: post-fire vegetation and land surface change

Root strength loss and vegetation change

Vegetation stabilizes soil-mantled hillslopes, particularly by providing mechanical reinforcement (Waldron 1977; Wu *et al.* 1979; Wu and Sidle 1995). Although the mechanisms by which roots reinforce soil are complex, roots generally anchor otherwise unstable near-surface (0–2 m) soil and debris to stable surrounding bedrock (Roering *et al.* 2003; Pollen and Simon 2005; Schwarz *et al.* 2010). Following tree mortality from timber harvest, land-use change, or wildfire, root-strength decay may result in increased shallow landslide susceptibility and frequency (Fig. 1; Swanson and Swanson 1976; Burroughs and Thomas 1977; Sidle 1992; Imaizumi *et al.* 2008; Vergani *et al.* 2016; Barik *et al.* 2017; Persichillo *et al.* 2017). These effects may be amplified by loss of forest canopy and attenuated evapotranspiration, which alter the hydrological forcing of shallow landslides (Ghestem *et al.* 2011). The decay of tree roots and their lateral slope reinforcement after tree mortality may be countered by vegetation recovery and associated root regrowth (Sidle 1992; Imaizumi *et al.* 2008), but the trajectories of recovery are variable as a function of early seral environment, species, vegetation management, soils and climate, among other factors (Swanson *et al.* 2011).

Vegetation recovery and post-fire root decay timescales are specific to climate, topography and ecological setting, yet how wildfire alters vegetation dynamics in the heavily forested wPNW is poorly understood. This is especially pertinent as stand-replacing fires can result in conversion from forest to non-forested ecosystem types (Halofsky *et al.* 2020). Exacerbated by regional climate change, changes to forest structure and density (Reilly *et al.* 2017) may reflect different magnitudes of root strength, rainfall interception and evapotranspiration and, in turn, altered rates of shallow landslides and debris flows. Both wildfire and land cover change may also alter the frequency of reburns (Halofsky *et al.* 2020), the implications of which remain unclear.

The implications of wildfire in the wPNW for root strength and slope stability loss are poorly constrained. Wildfire may result in loss of canopy and tree structure (Parsons *et al.* 2010), which suggests a loss of root strength and a potential increase in shallow landslide rates (Lanini *et al.* 2009; Thomas *et al.* 2021). Wildfire may also result in trees that are stressed and dying, but are not immediately dead, which is known as delayed mortality (Reilly *et al.* 2022; Busby *et al.* 2024) and which may modify the onset of root strength loss. Sampling of smaller roots

(<7 mm diameter) in burned areas in Oregon has shown a gradual decrease in root strength following wildfire, with total strength loss of approximately 70% within 4 years (Jackson and Roering 2009), and Gehring *et al.* (2019) found that loss of root strength may last for up to 40 years following wildfire. Whether overall root strength can fully recover to pre-fire conditions in stand-replacing fires remains unknown (Perry *et al.* 2011). These unknowns yield questions about the timescales over which shallow landslides and debris flows may persist after severe wildfire in the wPNW (Thomas *et al.* 2023). The various roles of salvage logging, accelerated revegetation and planting, and natural regeneration in persistence or mitigation of post-fire geomorphic hazards in the wPNW on both public and private forestlands are also largely unknown, as are the effects of multiple successive wildfires (Busby *et al.* 2020). Very high severity fire or multiple wildfires that affect the seed bank (Larson and Franklin 2005) may limit vitality and diversity of revegetation (Maia *et al.* 2012; Duijvenvoorden *et al.* 2024) such that the timeframe and magnitude of vulnerability to mass wasting may be protracted and amplified.

Dry ravel

The combustion of vegetation on steep slopes can mobilize colluvium as dry ravel, moving sediment or organic material downslope by rolling, sliding, or bouncing (Gabet 2003; Wondzell and King 2003). Roering and Gerber (2005) showed that after fire, the efficacy of disturbance processes increased and the angle at which transport occurs decreased, which resulted in substantial increases in soil transport and erosion, consistent with observations of abundant dry ravel activity in the Oregon Coast Range (Jackson and Roering 2009). Observations from burned hillslopes suggest that fire not only initiates dry ravel via debutting or destabilizing vegetation, but also facilitates ravel movement by removing vegetative roughness elements that would otherwise impede downslope movement (Jackson and Roering 2009). The downslope transport of this material depends on slope angle, surface roughness and grain size. The combined influence of these factors dictates whether transport is friction-dominated, where particles are more likely to become trapped, or inertia-dominated, where particles tend to accelerate before coming to rest in low-gradient areas (Roth *et al.* 2020). Consistent with dryland settings where dry ravel is observed, the accumulation of both pre- and post-fire colluvium in valleys of the wPNW contributes to the potential for debris flows with significant entrainment and volumetric growth, downstream runoff and inundation (Reid *et al.* 2016; Rengers *et al.* 2018, 2021).

Empirical models that account for the pre-fire volume of colluvium accumulated and stored behind vegetation have been developed for dry shrubland settings (Lamb *et al.*

2011, 2013; DiBiase and Lamb 2013, 2020), but have not been adapted to the densely forested wPNW steeplands, where dense understory and stochastic post-fire treefall make pre-fire volumes and post-fire disturbances difficult to quantify. The contribution of post-fire material to the long-term accumulation of sediment in high-order valley networks remains unclear (May and Gresswell 2004). Furthermore, the timescale over which colluvium is reloaded following fire is uncertain for these wet forested steeplands, owing to significant variability in the pace and scale of soil production and transport processes (Gabet and Mudd 2010; Roering *et al.* 2010).

Burned soil

Fire significantly alters the physical and hydraulic soil properties on which slope, sediment and channel stability depend (Fig. 1). Effects are positively related to the total fire energy output in a location, or fire intensity, which relates to fire temperature and duration and can be categorized as the observed soil burn severity (SBS; e.g. as estimated by BARC (Burned Area Reflectance Classification) in the US; Parsons *et al.* 2010), vegetation burn severity (e.g. as archived by MTBS (Monitoring Trends in Burn Severity) in the US; MTBS 2026), or ecosystem response (Keeley 2009; Fernández-García *et al.* 2023). The three most significant effects of fire on soils with respect to post-fire erosion are: (1) the combustion of organic matter and killing of soil organisms, beginning at temperatures as low as 50°C for fine roots, bacteria, fungi and leaves; (2) the frequent (but not universal) creation of fire-induced soil water repellency (SWR) when fire volatilizes organic matter beginning at 150–200°C, which then recondenses as hydrophobic hydrocarbon coatings onto cooler soil particles at soil depths of 1–5 cm; and (3) above temperatures of 300–500°C, the destruction of SWR, degradation of soil aggregate structures, combustion of even moderate-to-large roots, collapse of clay minerals (DeBano 1981, 2000; Ice *et al.* 2004; Neary *et al.* 2005; Shakesby and Doerr 2006; Mataix-Solera *et al.* 2011; Bodí *et al.* 2014; Alcañiz *et al.* 2018; Agbeshie *et al.* 2022).

Soils can have widely varying contributions to post-fire geomorphology and debris flow risks depending on soil type and burn severity; specific effects will covary with soil factors including soil texture, cohesion, moisture and SWR conditions, with vegetation factors including canopy, root and soil organic matter removal and recovery, and with landscape setting and management. The magnitude and depth of soil heating, fire-induced SWR and fire's other effects are greatly affected not only by fire intensity but also by pre-fire soil moisture content, fuel load, fuel type, fuel moisture and antecedent surface SWR (Doerr and Thomas 2000; Moody *et al.* 2009, 2019), such that post-fire conditions are notoriously spatially and temporally variable. In dense mixed-conifer forests such as in the wPNW,

the substantial remaining soil organic matter, live roots and rapid vegetation regrowth (Parsons *et al.* 2010) are expected to limit fire-related erosion and mass failure after low-severity and prescribed fire. In moderate-SBS patches, more extensive vegetation and duff removal, surface and fine root scorch, and possible black ash deposition (Parsons *et al.* 2010) tend to reduce surface roughness and may induce SWR in the top ~0–3 cm of soil (DeBano *et al.* 1979; Parsons *et al.* 2010; McGuire *et al.* 2024). These effects then promote overland flow, surface erosion (by flow entrainment or dry ravel), and possible runoff-dominated sediment and debris floods or flows (DeBano *et al.* 1979; Wall *et al.* 2020; McGuire *et al.* 2021; Hancock and Włodarczyk 2025).

With high SBS, mid-sized (and even large) roots and surface fuels, soil organic matter, shallow SWR and cohesive soil structure will have been substantially consumed to depths of ~3–5 cm or more, light or white ash may be deposited, and underlying mineral soils oxidized in dense mixed-conifer forests (Parsons *et al.* 2010). These factors, in various settings and combinations, can produce a variety of hydrogeomorphic effects in wildfire-prone ecosystems. In some cases, high SBS promotes greater soil water absorption and short-time infiltration in the top few centimeters of soil. At the same time, high SBS can also be related to lower overall vertical hydraulic conductivity and total infiltration where a subsurface SWR layer has been induced by the high temperatures (e.g. at >2.5 to 15 cm depth; DeBano *et al.* 1979, 2000; Doerr *et al.* 2000, 2006; Parsons *et al.* 2010). In other instances, high SBS can correlate with increased vertical hydraulic conductivity and sorptivity, despite increased surface bulk density and surface gravel fraction and decreased organic content; yet together these changes may have little net effect on soil moisture (Wieting *et al.* 2017; Ebel *et al.* 2018). Where increased infiltration promotes increased subsurface pore pressure and moisture post-fire (Cardenas and Kanarek 2014), steep terrain may exhibit bulk sloughing of the surface wettable layer (DeBano *et al.* 1979), increased subsurface stormflow (Stoof *et al.* 2014), slope and channel instability (Hancock and Włodarczyk 2025), and increased risk of landslide-generated or in-channel runoff-generated debris flows (Jordan 2016). One key to reconciling these disparate observations may be temporal sequencing: dry, high-SBS soils and ash with no surface SWR may initially absorb and store substantial water during the first wetting event after fire (Ebel *et al.* 2022a), but a succeeding event in the days or weeks before the soil has thoroughly dried may then produce the deleterious overland runoff, sloughing, rilling and associated geomorphic risks (Doerr *et al.* 2006). Overall, higher soil burn severities are thus expected to produce more (e.g. Cannon *et al.* 2010; Staley *et al.* 2017) and larger (e.g. Gartner *et al.* 2008, 2014; Gorr *et al.* 2024) post-fire debris flows. However, differences in post-fire responses in the wPNW compared with other regions suggest a need for

further study and a deeper understanding of the range of geomorphologically relevant effects of fire on soils in the wPNW.

The wPNW may be distinct in terms of post-fire soil recovery, particularly compared with the neighboring, drier, well-studied systems of California and the Interior PNW. Such differences can be attributed to the wPNW's high soil infiltration capacities both before and after fire, extreme burn severities due to high biomass and long fire return intervals, variable and seasonally concentrated intense precipitation with some snow-dominated areas, rapid vegetation growth and high variability in soil depths. It is not yet known if fire soil alterations in the wPNW will take months or decades to recover, as observations differ widely from this region (e.g. Jackson and Roering 2009; Niemeyer *et al.* 2020; Pimont 2024) and from climatically adjacent, drier locations such as the US Rocky Mountains (e.g. Huffman *et al.* 2001; MacDonald and Huffman 2004; Ebel 2020), Spain (Cerdà and Doerr 2005), Israel (Tessler *et al.* 2016) and other Mediterranean-climate areas (Wagenbrenner *et al.* 2021). The recovery rates of vegetation, hydrology, soils and geomorphic stability are not necessarily monotonic (Chen *et al.* 2020; Hoch *et al.* 2021; Wagenbrenner *et al.* 2021; Ebel *et al.* 2022b) or synchronized post-fire (Cerdà and Doerr 2005; Kinoshita and Hogue 2011; Ebel *et al.* 2022a, 2022b), and temporary intensifications of climatically typical annual summer drought or atypical short-interval reburns may delay forest regeneration (e.g. Busby *et al.* 2020; Coop *et al.* 2020). The higher soil moisture contents prevalent in the wPNW, compared with other fire-prone regions, may also reduce the continuity or prevalence of SWR following fire compared with expectations based on other regions (Wondzell and King 2003; Jackson and Roering 2009), although when present, patchy post-fire SWR over depths ~1 to 10 cm may be typical (Jackson and Roering 2009; Weatherholt and Johnson 2024). Some post-fire catchment hydrology in the wPNW has been reasonably simulated by decreasing soil hydraulic conductivity and increasing bulk density with increasing burn severity relative to unburned conditions (Wampler *et al.* 2023) but others have found no hydraulic change between unburned and burned soils (Pimont 2024) or catchments (Owens *et al.* 2013). The particularities of the wPNW climate may also contribute to multiple possible alternative stable states of soil moisture and vegetation regrowth post-fire (Clark 2018), as has been observed in some dryland systems (Obrist *et al.* 2004; Dzwonko *et al.* 2015).

The most critical gaps in our knowledge regarding post-fire soil changes and recovery are: (1) how to relate pre-fire soil moisture, texture, organic matter, vegetation and physiographic setting to post-fire soil hydrogeomorphological consequences in a generalized, predictive way (Acevedo

et al. 2023); (2) how to adjust hillslope soil parameterizations to accurately capture slope hydrological and geomorphological behavior after fire; and (3) how long to maintain altered landscape expectations (and parameterizations) after fire, until returning to the pre-fire baseline (McGuire *et al.* 2019; Wagenbrenner *et al.* 2021; Ebel *et al.* 2022b). These gaps remain persistent challenges in part because post-fire impact assessments typically lack baseline data on pre-fire conditions and are not sustained for the years to decades that may be required to understand post-fire landscape responses. More long-term pre- and post-fire field studies and mechanistic laboratory studies and models are needed (Ebel and Moody 2013; Ebel 2022; Ebel *et al.* 2022b). Modeling studies are also limited by the lack of comprehensive data sets in the wPNW to parameterize appropriate post-fire soil properties and recovery timescales (Acevedo *et al.* 2023).

Hillslope runoff and surface erosion

How watersheds respond to wildfire is influenced by multiple factors, including the spatial and temporal extent of fire and SBS, hydrologic landscape factors and climatic factors (Wampler *et al.* 2023). Four interrelated hydrologic consequences tend to follow wildfire: (1) substantial reduction of evapotranspiration following vegetation removal (Collar *et al.* 2022; Rey *et al.* 2023); (2) reduced snow-water storage and earlier snowmelt (Gleason *et al.* 2013; Gleason and Nolin 2016; Uecker *et al.* 2020); (3) decreasing surface infiltration and increasing surface runoff (Fig. 1; Ice *et al.* 2004; Larsen and MacDonald 2007); and (4) increased streamflows with shorter time-to-peak flow after storms (Cerdà and Doerr 2005; Collar *et al.* 2022; Romero-Cuelar *et al.* 2025). Post-fire streamflow reflects changes in hillslope hydrology, including reduced infiltration, ponding space and surface roughness, and associated increases in the efficiency of runoff delivery from upstream contributing areas (Loáiciga *et al.* 2001).

Post-fire soil changes can shift runoff processes from subsurface flow to infiltration-excess overland flow, which can lead to hillslope runoff, rilling and surface erosion (Fig. 1; Ice *et al.* 2004; Larsen and MacDonald 2007; Lanini *et al.* 2009). These post-fire erosional processes have commonly been reported in southern California, the Rocky Mountains and the desert Southwest of the US (Wondzell and King 2003; Santi *et al.* 2008; Hoch *et al.* 2021; McGuire *et al.* 2021) and have been observed to increase sediment yields by over two orders of magnitude compared with pre-fire conditions (Potts *et al.* 1985; Robichaud and Brown 1999; Santi and Rengers 2022). Increases in surface erosion post-fire can degrade water quality and aquatic habitat and can reduce reservoir storage capacity (Landsberg and Tiedemann 2000; Moody and Martin 2004; Bixby *et al.* 2015;

Wall *et al.* 2026). Sheetwash erosion and rilling can load channels with unstable material following fire, which can increase debris flow initiation risk and magnitude (Kean *et al.* 2013; McGuire *et al.* 2017).

In the wPNW, however, where pre-fire soil infiltration rates and antecedent soil moisture are both high, post-fire runoff, rilling and surface erosion have less commonly been observed than in dryland systems. In some cases where post-fire soil hydrophobicity has been observed, surface runoff has not been generated owing to patchy hydrophobic layers (Jackson and Roering 2009) or because even with these hydrophobic conditions, soil infiltration rates remained high in relation to the rainfall intensities of the region (Schmidt 1995). After the 2020 Labor Day Fires in the western Cascades, patchy rainsplash erosion and sheetwash erosion were observed, but not rilling (Hammer 2022; Busby and Wilcox 2024). After the 2017 Milli Fire in the western Cascades, widespread rill erosion was triggered by a 2 to 5-year return-interval storm in the year following the fire, and was primarily found in areas that had burned at high SBS (Wall *et al.* 2020), but such observations of extensive runoff-induced erosion in the region have been infrequent. The lack of observed rilling in the wPNW could be a result of the region's notably high soil infiltration rates paired with relatively low-intensity rainfall that is characteristic of this region (Wondzell and King 2003). It could also be due to the region's steep slopes promoting debris flows initiated within channels without incising rills (Burns *et al.* 2025; Sanders *et al.* 2025); it could be due to rapid revegetation limiting or hiding inter-vegetation rilling (Owens *et al.* 2013), or the lack of observed rill erosion in the wPNW could be because this process is truly uncommon in this region (Roering and Gerber 2005; Wall *et al.* 2020).

After the 2020 Labor Day Fires, increases in annual runoff ratios, which are the ratio of streamflow to precipitation for each water year, were found in catchments burned at high severity (Kang *et al.* 2024), while event runoff ratios did not increase in the same catchments (Long and Chang 2022). These contrasting findings suggest that considering water year type and seasonality is important for assessing post-fire stream flow response (Canham *et al.* 2025). The Labor Day Fires were also projected to increase streamflow more at the headwater scale than the basin scale (Wampler *et al.* 2023). Although some studies across the broader PNW have found no changes to streamflow post-fire (Owens *et al.* 2013; Surfleet *et al.* 2014), an investigation into burned watersheds across many bioclimate zones of the continental US found that the portion of post-fire stream flow increase attributable to fire seemed much greater in the PNW than in any other region (Hallemma *et al.* 2018). Little post-fire overland

flow yet high post-fire streamflow increases suggest a dominance of subsurface flowpaths in this region, but more research is needed to understand what factors increase susceptibility to runoff and rill erosion and to landslides and debris flows in the wPNW.

Post-fire geomorphic hazards

Post-fire debris flows are the dominant hazard following wildfire in steep terrain. The generation and process can vary widely, operating along a continuum that is driven by spatial sources of hydrologic inputs and sediment, as well as by temporal factors. In this paper, we classify post-fire debris flows into two broad categories depending on these components, namely: shallow landslide-initiated and runoff-generated debris flows. Shallow landslide-initiated debris flows are identified by a head scarp leading to a scoured channel (Burns *et al.* 2025; Selander *et al.* 2025). This type of debris flow is initiated via soil saturation and sediment is sourced from both the hillslope and channel (Dietrich and Dunne 1978). Runoff-generated debris flows can be initiated on the hillslope, within the channel, or a combination of the two. We identify runoff-generated debris flows initiated on the hillslope as those where there is evidence of distributed runoff and erosion on the hillslope source area that leads to scour (e.g. Alesio *et al.* 2021). These result from infiltration-excess overland flow and sediment is sourced from both hillslopes (i.e. sheetwash, rilling and gullying) and channels. Runoff-generated debris flows that begin in the channel (in-channel-initiated debris flows) are identified when debris flow channels do not have sediment contributions from shallow-landslides or distributed runoff and erosion in the source area; instead, the initiation point corresponds to the uppermost point in the evacuated channel (Rengers *et al.* 2024; Selander *et al.* 2025). This type of debris flow can be initiated via an array of hydrologic inputs, such as during high baseflow and discharge in the channel from a storm event or increased post-fire runoff (Takahashi 1978; Prancevic *et al.* 2014; Jordan 2016; Palucis *et al.* 2021). Unlike hillslope-initiated debris flows, in-channel-initiated debris flows source sediment predominantly from the channel, such as from the channel bed or from a colluvium-filled valley, and temporal factors such as channel recharge rates can play an important role in their initiation. Because of limited on-the-ground observations of post-fire debris flows in the wPNW, there is not yet a clear understanding of the boundary between runoff-generated debris flows that are initiated on the hillslope versus within the channel for this region. For the sake of simplicity, we have chosen to use shallow landslide and runoff-generated post-fire debris flow

classifications to follow those previously defined in the literature (Santi and Rengers 2022; Rengers *et al.* 2024; Burns *et al.* 2025; Selander *et al.* 2025).

Shallow landslides

Shallow landslides refer to the mobilization of unconsolidated soil or colluvium typically with a thickness of less than 4 m (Fig. 1). In these types of landslides, soil shear strength from cohesion and friction is often augmented by root reinforcement (Schmidt *et al.* 2001; Roering *et al.* 2003; Sousa *et al.* 2026), and failure most often occurs when saturation of the soil matrix elevates pore pressures and decreases the shear strength (Montgomery *et al.* 2009; Ebel *et al.* 2010). These shallow failures are often initiated in topographic convergent zones (i.e. hollows) that accumulate soil over >100 year timescales, concentrate shallow subsurface stormflow over hourly to seasonal timescales, and experience cycles of infilling and evacuation via shallow landslides according to the rate of soil transport and accumulation and the frequency of storms that generate elevated pore pressure (Dietrich and Dunne 1978). Both shallow landslide and debris flow failures can also occur where storm-fed artesian groundwater flows out of fractured bedrock, causing locally high pore pressures in thin overlying soil and saprolite on steep slopes, as observed and simulated in the southern Oregon Coast Range (Montgomery *et al.* 2002; Ebel *et al.* 2008), and as may be more likely in areas of more friable underlying lithologies in the region (Bywater-Reyes *et al.* 2017).

Following wildfire, altered soil hydrological and mechanical properties, loss of root strength, canopy interception and evapotranspiration, groundwater recharge, amplified sediment transport and localized erosion may all accelerate the rate and activity of various landslide processes. For example, following the 2017 Eagle Creek wildfire in Oregon's Columbia River Gorge, the rate of shallow landsliding increased more than tenfold (Burns *et al.* 2025). Conceptual frameworks have proposed that following fire, there may be a delayed timeframe where shallow landslides become dominant (Thomas *et al.* 2023), and recent observations in southern California recorded this switch in process on the order of 5 years following a wildfire (Thomas *et al.* 2025). Rainfall occurring over hours to a day (Baum and Godt 2010; Selander *et al.* 2025), or rapid snowmelt that infiltrates quickly into the soil mantle (Smoot and Gleason 2021) may elevate porewater pressures, and may trigger shallow landslides (Baum *et al.* 2010). However, isolating these triggering intensities is a challenge owing to the heavily seasonal pattern of precipitation in the wPNW and the predisposition for higher hourly intensities to occur during atmospheric rivers that span days. Fire-induced vegetation loss, changes in hydrology (Niemeyer *et al.* 2020; Vahedifard *et al.* 2024) and

loss of root strength (Sousa *et al.* 2026) may exacerbate these instabilities. Shallow landslides may exhibit significant mobility in some instances, depositing debris in downstream channels or transitioning directly into debris flows (Iverson *et al.* 1997).

Shallow landslides translate into debris flows when shear failure causes grains to contract and elevates pore pressure, leading to fluidization and downslope flow (Iverson 2000). This transformation generates highly mobile flows that travel through steepland channel networks before stopping at acute junctions or low angle slopes (<5–10°; Benda 1990). As a result, shallow landslide-initiated debris flows are responsible for shaping the relief structure of unglaciated wPNW watersheds and can impact public safety, sediment delivery and habitat disturbance (Stock and Dietrich 2006; Penserini *et al.* 2017). Selander *et al.* (2025) suggest that wildfire may affect the frequency of shallow-landslide initiated debris flows by changing the rainfall threshold associated with failure. Their work, paired with other observations of post-fire sediment production in steepland valleys in the region (e.g. Jackson and Roering 2009), highlights that shallow landslide-initiated debris flow volume and inundation area may increase following wildfire.

Runoff-generated debris flows

Runoff-generated debris flows are the primary post-fire debris flow process reported in the literature (McGuire *et al.* 2024). They are classified based on runoff processes leading to their initiation, which includes overland flow entraining individual grains from hillslopes and channels, as well as saturation of channel colluvium by channelized flow leading to discrete failures. These events are variously identified by upslope rill and gully networks that contribute sediment to the channel network, progressive bulking within the channel, or by an in-channel initiation scarp (Cannon *et al.* 2001; Santi and Rengers 2022; Selander *et al.* 2025), but all include mobilization and failure triggering related to convergent water runoff. We make the distinction between predominantly hillslope sediment-sourced and predominantly channel-sourced runoff-generated debris flows in the following sections, following previous post-fire debris flow compilations (i.e. Selander *et al.* 2025).

Hillslope–channel connections: progressive sediment bulking

Runoff-generated debris flows can initiate on a hillslope via progressive sediment bulking. They can result from distributed runoff that gradually mobilizes sediment, leading to increased entrainment capacity as the flow converges into higher-order channels (Cannon *et al.* 2001; Gabet and Bookter 2008). Sediment input from rilling and surficial erosion have been found to be an important factor in

the progressive sediment bulking that leads to debris flow generation (Kean *et al.* 2019; Santi and Rengers 2022). Although the distributed contribution of sediment from the hillslopes into the channels is a key characteristic of this initiation mechanism, the relative volumes of sediment supplied from the hillslope versus the channel are variable (Santi *et al.* 2008; Jordan and Covert 2009). Sediment supplied from hillslopes via progressive sediment bulking can also load low-gradient sections of channels, where it can be temporarily stored, later promoting the generation of in-channel erosion-initiated debris flows that initiate either via *en masse* failure of the channel bed or grain-by-grain sediment bulking (see next section; Kean *et al.* 2013; McGuire *et al.* 2017).

Studies of burned temperate to dry forests and shrublands, such as in the US southwest and Rocky Mountains have identified soil burn severity, slope steepness, soil characteristics and rainfall intensity to influence runoff-generated debris flow initiation and sediment yield (Cannon *et al.* 2010; Staley *et al.* 2017, Staley *et al.* 2020; Hoch *et al.* 2021; Thomas *et al.* 2024). Owing to post-fire soil changes, runoff-generated debris flows can be triggered by short-duration rainfall (often <1 h) and modest rainfall intensities in these drier regions, particularly when antecedent soil moisture is low (Cannon *et al.* 2008; Kean *et al.* 2011; Staley *et al.* 2020), as soil aridity increases effective SWR regardless of the presence or absence of hydrocarbon-based SWR (Doerr and Thomas 2000; MacDonald and Huffman 2004). Post-fire runoff-generated debris flows initiated on the hillslope have only recently begun to be systematically catalogued in the wPNW. Wall *et al.* (2020) observed a runoff-generated post-fire debris flow in the western Oregon Cascades triggered by the first summer storm in the year following fire, when antecedent soil moisture was low. Erosion and rilling initiated on high SBS slopes and converged into channel networks where the bulk of the sediment was entrained. Selander *et al.* (2024, 2025) found an increase in the frequency of hillslope-sourced runoff-generated debris flows post-fire within the 2020 Labor Day Fires. They observed that these debris flows in their inventory were not necessarily triggered by high-intensity rainfall but rather by prolonged periods of successive storm events, and proposed that these runoff-generated debris flows may have occurred owing to a unique saturation-excess overland flow-initiation process, rather than from infiltration-excess overland flow as observed in other regions (Selander *et al.* 2025).

In channel: channel erosion-initiated debris flows

Runoff-generated debris flows can also initiate from within the channel without significant hillslope contributions (Tang *et al.* 2019). There are two dominant in-channel debris flow initiation mechanisms recognized in the literature: (1) channel bed failures along a discrete plane (i.e. *en*

masse failures), and (2) progressive grain-by-grain entrainment within the channel (Takahashi 1978; Kean *et al.* 2013; McGuire *et al.* 2017; Tang *et al.* 2019). Although the hydrologic conditions of grain-by-grain entrainment and *en masse* failure initiations are hydrologically similar, they differ in relative thresholds required for failure. The bed failure mechanism occurs as a result of relatively constant baseflow and/or discharge that saturates the channel bed and overcomes the critical slope of the bed sediments (Takahashi 1978; Palucis *et al.* 2021), which is comparable with shallow landslide hollow failures (Rengers *et al.* 2024). Grain-by-grain bulking requires sufficiently high discharge to overcome the critical Shields stress of and entrain surficial bed sediment (Prancevic *et al.* 2014).

In-channel debris flows typically occur in reaches of the stream network with slopes that exceed ~15 degrees, which marks approximately the transition between dominantly granular sheetflow and dominantly debris flow processes (Prancevic *et al.* 2014; Palucis *et al.* 2018). Thus, these events are prevalent across steep, rocky landscapes, where the relative proportion of runoff to infiltration during a precipitation event is high owing to a prevalence of low permeability outcropping bedrock (Kean *et al.* 2013), which in some field sites lacks abundant hillslope-sourced sediment to entrain (Tang *et al.* 2019; Neely *et al.* 2024). These landscapes typically have relatively high sediment production rates and, thus, sediment recharge rates into channel networks (e.g. Godt and Coe 2007; Coe *et al.* 2008; Kean *et al.* 2013; Burns *et al.* 2025). Observations of channel erosion-initiated debris flow frequencies have revealed the ability of steep landscapes to recharge available in-channel sediments sub-annually (Kean *et al.* 2013) through freeze-thaw processes (Rengers *et al.* 2020), rock-fall (Kean *et al.* 2013) and channel bank collapse (Burns *et al.* 2025).

Wildfire-related surficial changes have been shown to increase susceptibility to in-channel initiated debris flows due to similar feedback described in the previous section that promote overland flow, as well as increase sediment availability. Loss of vegetation feeds back into increased discharge through decreased interception, decreased evapotranspiration and potential decreases in infiltration rates due to the formation of SWR. The sudden incineration of vegetation also increases sediment transport rates into channels by physical removal releasing dammed sediments that can be transported as dry ravel immediately (or soon) after the fire (Jackson and Roering 2009; DiBiase and Lamb 2013, 2020; Palucis *et al.* 2021; Neely *et al.* 2024). Dry ravel may decrease entrainment thresholds, as observations across the southwestern US have revealed that post-fire sediment load may be finer than sediments in the channel pre-fire, especially for patchy bedrock landscapes (Neely *et al.* 2024). Fining sediment distributions decrease the Shields stress threshold for progressive bulking and provide a sediment-laden flow that can more easily entrain larger

grains (DiBiase and Lamb 2013; McGuire *et al.* 2017; Palucis *et al.* 2021; Neely *et al.* 2024). The relative increase in discharge due to decreased infiltration rates then increases the likelihood for post-fire *en masse* in-channel failures as well (Palucis *et al.* 2021; Rengers *et al.* 2024). Field observations from the literature revealed the interplay of both *en masse* failure and grain-by-grain bulking mechanisms occurring during the same storm event in steep, rocky landscapes (Tang *et al.* 2019; Palucis *et al.* 2021).

Documentation of channel erosion-initiated debris flows following wildfires in the wPNW is also just beginning to be assembled. For burned areas in the western Cascades, the inventory of Selander *et al.* (2024, 2025) showed an unchanged proportion of channel erosion-initiated events pre- and post-2020 Labor Day Fires. They also observed a prevalence of in-channel initiated debris flows occurring below rocky outcrops, which is in line with observations in southern California and the Intermountain West where channels plunging over bedrock steps or cliffs can initiate *en masse* failures through scouring sediment at the base of the plunge, also known as the ‘firehose’ mechanism (Johnson and Rodine 1984; Coe *et al.* 2008; Kean *et al.* 2013; Palucis *et al.* 2021). In the steep, rocky Columbia River Gorge in Oregon, a debris flow inventory was compiled following the 2017 Eagle Creek Fire and revealed an increase in the relative proportion of channel bed failures compared with pre-fire conditions (Burns *et al.* 2025). Rapid sediment recharge rates were observed along channels during the pre-fire period, and in-channel debris flows were initiated from unburned and severely burned catchments during the same debris flow-triggering storm event (Burns *et al.* 2025; Sanders *et al.* 2025). Thus, the isolated effect of fire on the triggering thresholds in these burned, rocky catchments remains unclear, yet the incineration of understory vegetation and reduced root strength due to tree mortality likely led to increased debris flow volumes observed in the burned watersheds (Sanders *et al.* 2025). The lack of an exceptional increase in the Cascade Range events and the unchanged triggering thresholds in the Columbia River Gorge suggest these events may be relatively less sensitive to post-fire conditions in the wPNW compared with other debris flow initiation mechanisms in the wPNW. However, further study is merited to investigate the prevalence of these events in wPNW landscapes, the hydrologic triggering mechanisms initiating these events, and whether fire modulates triggering thresholds for these debris flow mechanisms.

Major gaps in wPNW post-fire debris flow research

Because of the wPNW’s unique climate, soils and vegetation, more research is needed to better understand post-fire debris flow processes in this region. Few studies have explicitly compared precipitation thresholds and timing,

storm-antecedent soil conditions, stabilizing roles and root decay rates of different vegetation types, hillslope colluvium and in-channel sediment storage and recharge, channel bank stability and groundwater contributions with triggering debris flows before and after fire in the wPNW. Process-based studies that characterize the influence of the wPNW’s specific climate are also needed to better understand post-fire geomorphology and compounding hazards in this region. In particular, investigations into how fall and winter AR events, rain-on-snow processes, changing snowpacks and snowmelt, increasing precipitation intensity and summer drought compound with wildfire in this region are essential for understanding future impacts of climate change on post-fire geomorphology in the wPNW.

One of the main factors that sets the wPNW apart from other more studied regions is that landscapes in the wPNW are susceptible to multiple types of debris flows pre- and post-fire, which include shallow landslide-initiated debris flows and runoff-generated debris flows that can initiate via different mechanisms either on hillslopes or in channels (Burns *et al.* 2025; Selander *et al.* 2025). In a recent major geographically focused cataloging effort, Selander *et al.* (2024), Selander *et al.* 2025 found that debris flow frequency in the wPNW increased after wildfire and shifted in initiation mechanism. Of the 144 observed post-fire debris flows cataloged between 2020 and 2022 within the 2020 Labor Day Fires’ burned areas in the western Oregon Cascades, 24% were initiated by runoff on hillslopes, 26% by channel erosion and failure, 51% by shallow landslides and 0% by deep landslides. In contrast, of the 875 debris flows they cataloged pre-fire from 1995 to 2020 in the same geographic footprints, only 2% initiated via runoff on the hillslope, 27% were by channel erosion and failures, 68% were by shallow landslides and 3% were by deep landslides. Therefore, findings and assumptions made from post-fire debris flow studies where runoff-generated debris flows are the primary process (e.g. southern California and the Rocky Mountains of the US) may not apply in this region (Selander *et al.* 2025).

One particular challenge for applying current debris flow likelihood models trained from data in other regions (e.g. Staley *et al.* 2017) to burned areas in the wPNW is that these models are built under the assumption that short-duration, high-intensity rainfall is what triggers post-fire debris flows. In contrast, the rainfall intensities that triggered debris flows in western Oregon after the 2020 Labor Day Fires, observed by Selander *et al.* (2025), were lower than those predicted by the US Geological Survey M1 post-fire model (Staley *et al.* 2017) and were much lower than those that have been observed to trigger post-fire debris flows in other regions of the western US (Fig. 3; Gorr *et al.* 2025; Selander *et al.* 2025). It is possible that the debris flows observed by Selander *et al.* (2025) differ from post-fire debris flows studied in other regions, because they occurred in the winter following consistent

precipitation, rather than after a single high-intensity storm event. Therefore, models trained for debris flows triggered by high-intensity storms, such as the M1 model, cannot be applied to all initiation styles of post-fire debris flows in the wPNW.

Empirical rainfall triggering studies typically rely on either characterizing rainfall intensity over varying timescales, antecedent rain or soil saturation, or storm duration. Approaches for evaluating local or regional triggering thresholds vary widely (Segoni *et al.* 2018), which complicates efforts to compare pre- and post-fire landslide susceptibility. Most commonly, post-fire debris flow risk calculations performed by the M1 model and post-fire debris flow volume model, apply a 'design storm' as a trigger, with a 15-min precipitation intensity of 24 mm/h (Gartner *et al.* 2014; Staley *et al.* 2016). Characterization of post-fire debris flows after the 2020 Labor Day Fires shows low rainfall intensities (measured over short durations) triggered debris flows, but that longer duration intensities would be more applicable; additionally, the M1 Model overpredicted the rainfall intensities required for triggering debris flows (Selander *et al.* 2025). Because shallow landslide-initiated debris flows are one of the more common initiation styles of post-fire debris flows in the wPNW (Selander *et al.* 2025), we hypothesize that longer timescales of intense rainfall (hours rather than minutes) may be required to trigger post-fire debris flows and that antecedent precipitation or saturation may be an important predictive variable. Recent studies in unburned temperate rainforests of southeast Alaska showed that 3-h rainfall intensity was the best predictor for infiltration-driven debris flows (Patton *et al.* 2023), as opposed to the 1-h rainfall intensity derived from post-fire debris flow inventories in southern California and the Intermountain West (Kean *et al.* 2013; Staley *et al.* 2020). Patchy hydrophobicity and deep, organic-rich soils in burned wPNW forests may respond similarly to intense rainfall as in southeast Alaska. Currently used (e.g. Burns *et al.* 2025) precipitation threshold conditions for 'fast-moving landslides', inclusive of debris flows, in western Oregon merit updating and refinement for predictive purposes where fire, roads and timber harvest history complicate landscape responses (Barik *et al.* 2017). The Wiley (2000) threshold for western Oregon, which does not explicitly consider wildfire, suggests landslide triggering after (1) ~20 cm of antecedent rain since the end of September (the typical start of the rainy season), and (2) 24 hour rainfall exceeding 40% of mean December rainfall. More research is needed to both investigate the characteristics of triggering rainfall for post-fire debris flows in the wPNW and to construct geographically specific post-fire debris flow likelihood and volume models based on those findings.

Although the mechanisms and occurrence of post-fire SWR and other direct physical soil alterations by fire are observed in the wPNW (Jackson and Roering 2009; Wall

et al. 2020), the magnitudes, controls on and timescales of consequences from these alterations, as well as the factors influencing the spatial distribution of runoff and rill erosion, are not understood at this time. Furthermore, post-fire dry ravel is observed in steep wPNW landscapes (Jackson and Roering 2009); however, too few observations exist to determine the controls on this mechanism and its contributions to debris flow hazards. Timber cultivation and harvest in the wPNW may alter landscape vulnerability to fire (Reilly *et al.* 2021). More research is needed to understand how burn severity, topography, land use, soil type, vegetation, bedrock and precipitation dynamics contribute to debris flow initiation in the wPNW. The recovery timeline for post-fire landscapes in the wPNW is also unclear, as the recovery period of forests, deep root systems and streamflow is on the order of decades (Jackson and Roering 2009; Niemeyer *et al.* 2020), and the effects of reburns (e.g. Clark 2018) and delayed forest mortality are poorly constrained. Overall, future research needs to directly address post-fire debris flow initiation thresholds, the key predictors of initiation and sediment yield, and recovery timelines for burned catchments in this region.

Channel change and downstream consequences

The extent to which wildfires and post-fire hydrogeomorphic processes affect stream channels, both in burned areas and farther downstream, depends on SBS and extent, post-fire precipitation, dominant runoff mechanisms, and vegetation and soil characteristics (Fig. 1). Channel responses to wildfire also depend on antecedent channel morphology (gradient, bed and bank composition, confinement) and network arrangement (drainage density, tributary junctions; Benda and Dunne 1997; Morell *et al.* 2021; Florsheim *et al.* 2024). These effects can be evaluated in the context of the net effect of fire on the force balances shaping channels. On the one hand, where post-fire precipitation and runoff produce floods and associated increases in sediment transport capacity, channels may coarsen, incise and/or widen following fires. On the other hand, where fires and post-fire hillslope processes increase the supply of wood and sediment to channels, channels are likely to experience increases in roughness, bed-material fining and aggradation (Florsheim *et al.* 1991; Keller *et al.* 1997; Minshall *et al.* 1997; Florsheim *et al.* 2017; Busby and Wilcox 2024; Florsheim and Chin 2024).

In the wPNW, wood density and size are especially high compared with other regions (Swanson and Lienkaemper 1978; Gurnell *et al.* 2002; Montgomery *et al.* 2003), such that post-fire wood recruitment and retention may be particularly important influences on channel processes. Wood can be supplied to channels in the aftermath of fire by multiple processes, such as debris flows or direct mortality and

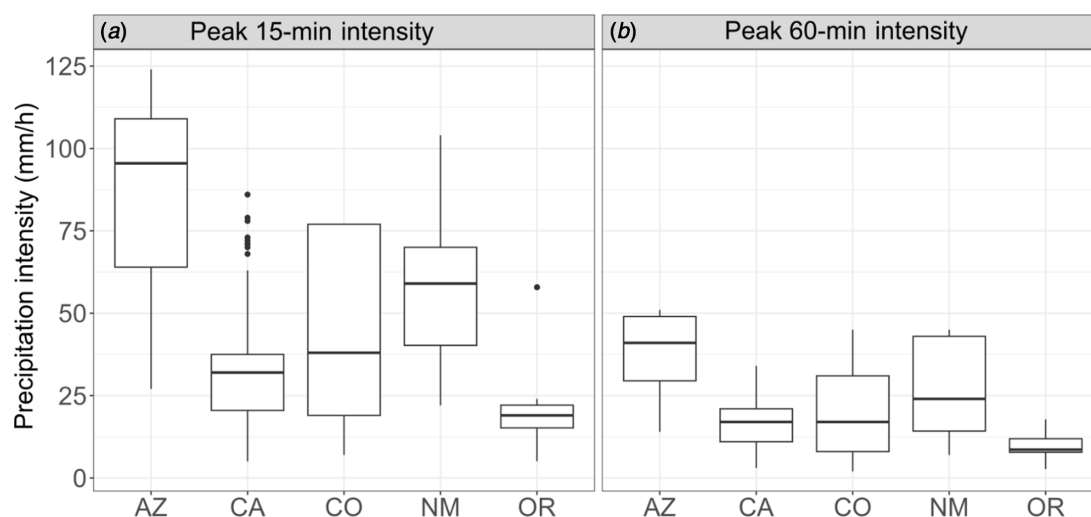


Fig. 3. Comparison of the triggering precipitation intensity for post-fire debris flows across the western US. Data for post-fire debris flows in Arizona (AZ), California (CA), Colorado (CO) and New Mexico (NM) are sourced from [Gorr *et al.* \(2025\)](#). Data for post-fire debris flows in Oregon (OR) are sourced from [Selander *et al.* \(2024\)](#). (a) Peak 15-min precipitation intensity. (b) Peak 60-min precipitation intensity.

toppling, and at varying post-fire time scales, from during the fire to years after ([Benda and Sias 2003](#)). The spatial and temporal variability of effects of in-stream wood on post-fire channel processes depends on wood size, density and organization (e.g. individual pieces versus jams; [Zelt and Wohl 2004](#); [Wohl *et al.* 2010](#); [Eaton *et al.* 2012](#); [Wohl and Scott 2017](#)). Although large wood supplied to headwater channels following wildfire in the wPNW can be expected to have long-lasting geomorphic, sediment storage and habitat-creation effects, few studies have investigated the mediating effect of wood on channel response in post-fire environments in the region. [Coble *et al.* \(2023\)](#) found that within 1 year of the 2020 Labor Day Fires, a set of Oregon streams exposed to different fire severities showed no significant changes in wood volume, which they attributed to low rainfall in the period since the fires, and highlighted that post-fire wood effects may not manifest immediately. Because of the potential role of in-stream wood in promoting negative feedbacks following fire, dampening downstream sediment routing and creating habitat complexity, multiyear studies of in-stream wood characteristics and channel morphology are key to understanding the resilience of stream channels to post-fire changes.

Post-fire responses of individual stream reaches within a network cumulatively influence sediment transport in burned watersheds. Post-fire sediment transport often shows strong size dependence ([Rathburn *et al.* 2018](#)) and can be influenced by the incision, remobilization and transport of pre-existing fans and/or initially deposited sediment ([Elliott and Parker 2001](#); [Moody *et al.* 2008](#)). Even when erosion thresholds to trigger debris flows or to mobilize coarse bed materials are not exceeded, surface erosion on burned hillslopes can deliver fine sediment to streams that increases

transport of sand and finer size fractions and increases turbidity, with impacts extending far downstream of burned areas ([Busby and Wilcox 2024](#)). Post-fire changes in channel morphology, physical habitat and downstream sediment transport can be considered in the context of connectivity between hillslopes and channels and between upstream and downstream reaches of channel networks ([Wohl *et al.* 2019](#); [Gilbert and Wilcox 2020](#)). Additional work should investigate which predictive models, such as indices based on high-resolution topography (e.g. [Cavalli *et al.* 2013](#)), best quantify connectivity to evaluate how fire influences sediment propagation through channel networks and to predict post-fire sensitivity of stream channels to fire in this region. These investigations will allow improved forecasting of how wildfire, and subsequent post-fire geomorphic processes, will impact aquatic habitat and essential infrastructure downstream.

Data and monitoring gaps

Maintaining and expanding networks of environmental data collection with high spatiotemporal resolution is critical to improving our understanding of post-fire geomorphic impacts in the wPNW. In particular, high-quality weather observations are sparse throughout the complex terrain of the wPNW, with few maintained weather stations and limited radar coverage, and there are only outdated and limited data available for precipitation frequency and duration for this region ([NOAA 2025](#)). Although these limitations have been recognized for years (e.g. [Ralph *et al.* 2014](#); [Daly *et al.* 2021](#)), significant gaps in data coverage remain a key limitation for predictive modeling and empirical studies.

Rainfall data are particularly limited along the central and southern Oregon coast (NOAA 2025) and into the central Cascades. There is a critical need for strategically placed data collection in sparsely monitored areas (e.g. remote and steep terrain) and *in situ* weather observations (precipitation, snow water equivalent, wind, temperature), improved radar coverage, and improved precipitation frequency and duration estimates. High temporal resolution rainfall data are essential for the development of regionally specific debris flow likelihood and volume models in the wPNW.

Impact inventories are also critical for regional-scale understanding of the probability, timing, spatial extent and persistence of post-fire geomorphic change. For example, documentation of debris flows following the 2017 Eagle Creek and 2020 Labor Day Fires in Oregon has substantially informed understanding of landscape response to those fires and geomorphic processes in the wPNW (Selander *et al.* 2024, Selander *et al.* 2025; Burns *et al.* 2025). The amount we have relied on findings from these studies for this review underscores the need for expanded inventories of post-fire debris flows in this region. The scarcity of data in the wPNW makes it even more essential that post-fire geomorphic studies and data are promptly published or shared to inform future research in this region. Further support for inventories of geomorphic disturbance necessitates coordination between local, state, federal and academic partners to systematically record the type, location and timing of geomorphic disturbances including landslides, debris flows, sedimentation, floods and their impacts on humans and infrastructure.

Conclusions

Most post-fire geomorphic studies have been conducted where fires have been frequent, such as in dry-Mediterranean and temperate climates, and less in wet forests where wildfire is now expanding with climate change. As wildfire burns greater areas at higher severities across the globe, many questions arise about how wildfire may influence geomorphic processes. This synthesis effort provides an overview of how wildfire has influenced the priming factors that contribute to post-fire hazards in the wPNW, such as reduced soil infiltration rates, root strength decline and dry ravel. This review also provides an overview of post-fire hazards in the wPNW, which include post-fire debris flows and downstream channel changes. Overall, there are significant gaps in data coverage for this region and future research needs to directly address post-fire debris flow initiation thresholds, predictors of debris flow initiation and volumes, and recovery timelines for burned catchments in the wPNW.

The gaps in existing data and understanding of post-fire geomorphic processes in the wPNW, and the opportunities for future work highlighted by this paper, can be applied to other regions globally. These include regions with similar

climate and/or fire history to the wPNW, and more generally to regions whose fire, hydroclimate and landscape conditions are not represented by the current body of post-fire geomorphology knowledge. Complexities in how soils, vegetation, hydrology, topography and climate combine to produce post-fire landscape responses highlight the need for geographically specific research into post-fire erosion and post-fire hazards, in the wPNW and more broadly, to appropriately assess and mitigate the impacts from post-fire geomorphic processes in the future.

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