Post-Fire Landscapes and Ecological Restoration



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Published: July 1, 2026

CANADIAN WILDLIFE FEDERATION

Technical Report

Canadian Wildlife Federation July 1, 2026

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Summary

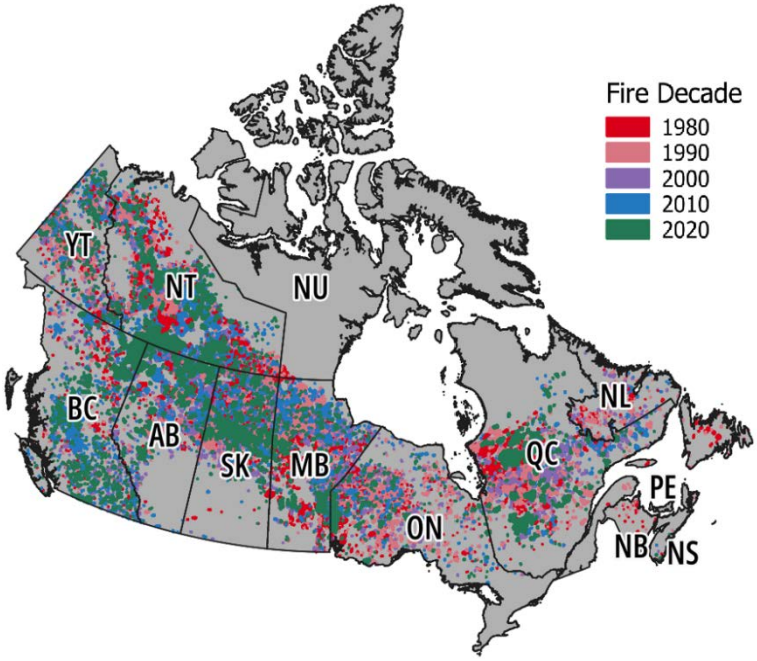
Wildfire is a natural disturbance process in forest ecosystems. The combined effects of climate change and fuel build up are now making fires larger and more intense. Within this context, fire severity is an important metric that affects recovery. In general, low-severity fires often leave living plants, seeds, and soil that allow forests to regrow naturally, whereas large higher-severity fires can variously damage soils, destroy seed sources, change water movement, and alter recovery. In some cases, restoration interventions may be necessary to support recovery or reduce hazards. In these instances, restoration should consider connected factors such as surviving plants and animals, soil and climate changes, water systems, and risks like debris flows that can extend beyond the burned area. As fire activity increases, maintaining a mix of burned and unburned areas and working with fire as a natural process will be essential for resilient forests, biodiversity, and community well-being.

1. Introduction

Forested ecosystems contain living and dead aboveground biomass, downed woody debris, and forest floor organic matter, including litter and detritus. During a fire, the extent to which these materials are consumed and ecosystems altered is largely determined by fire severity, which reflects the ecological impact of a fire (Agee 1993). Understanding how these attributes vary with fire severity is important since wildfire is a fundamental ecological process that shapes and rejuvenates ecosystems (Fig. 1). Fires achieve this by modifying vegetation structure, creating mosaics, enhancing biodiversity, preparing seedbeds, increasing light availability, and cycling nutrients (Agee 1993; Brown et al. 2025). By extension, fires also alter carbon fluxes, with rapid emissions occurring during combustion followed by gradual post-fire carbon sequestration and storage as the ecosystem recovers.

Wildfires burn either as ground, surface, or crown fires. Briefly, ground fires represent those events burning below the surface, smoldering in organic layers and killing roots and soil organisms. In contrast, surface fires consume aboveground fuels like litter and shrubs but do not involve the canopy, whereas crown fires involve spotty or continuous burning of the canopy. Of these, surface and crown are most prevalent in Canada, with ground fires often occurring in belowground peat layers. Regarding severity, surface fires are typically considered to be low-moderate, while crown fires are of higher severity.

In Canada, lower-severity fires were historically used by Indigenous peoples to enhance food resources, support hunting, reduce wildfire risk, and for other cultural purposes (Turner 1999; Brookes et al. 2021, Cardinal Christianson & Traverse 2026). These practices stopped after European



Large Fires in Canada

Figure 1. Distribution of large fires across Canada by decade (1980–2020) showing its widespread distribution as an ecological process. Fire polygons were obtained from the CWFIS Data & Service Catalogue (2026). This shows fire perimeters with colours classified by the decade in which the fires ignited. A large fire is one greater than 200 hectares.

settlement and were replaced by decades of fire suppression, which paradoxically allowed fuels to accumulate creating modern-day fire challenges. Today, lower-severity fires occur in both grasslands and open forests (Wong et al. 2003). They are also being deliberately applied through prescribed burning to reduce fuel accumulation to protect communities, resources, and other values (Francos and Úbeda 2021). This practice supports ecological restoration by reintroducing fire after a long interval of absence, enhancing regeneration and biodiversity, and promoting ecosystem health (Fig. 2). In contrast, higher-severity or stand-replacing fires, such as those that occur in subalpine (Hebda and Brown 2024) or boreal settings (Brown et al. 2024), typically remove most surface fuels and kill much of the canopy, leaving behind fire-killed stems and remnants of forest floor, while also facilitating the development of even-aged stands. These events impact ecosystems for longer intervals and can have cascading effects inside and outside burned areas. Higher-severity prescribed fires are also sometimes employed at smaller scales (i.e., circa 1–100's ha) to achieve stand-replacement objectives, including the creation of physical barriers to prevent future wildfire spread or to achieve ecological goals (R. Horrelt [Parks Canada], personal communication).

The incidence of wildfire disturbance is now increasing in Canada, driven by climate change and fuel build-up (Coogan et al. 2019; Hanes et al. 2019). Climate change is increasing forest flammability and creating more extreme fire weather (Romps et al. 2014; Jones et al. 2024). In response, fires are becoming larger and more intense (Jain et al. 2024). Following wildfire, sites regenerate via ecological succession, representing the process in which vegetation re-establishes on disturbed sites and gradually changes through time. However, as climate and fire regimes change, the post-fire environment and its recovery pathways are also becoming increasingly variable and unpredictable, augmented by changing weather patterns. For example, increasing fire frequency may result in seedling regeneration failures (Hart et al. 2018), thus altering ecosystems. Likewise, higher-severity burns can consume soil layers and seedbanks, impacting succession by



Garry Oak Forest

Figure 2. A low-severity surface fire in Garry oak (*Quercus garryana*) understory at Rocky Point, Vancouver Island, British Columbia. The goal of this prescribed burning program is to reduce the occurrence of invasive plant species and support the conservation of Garry oak landscapes and species.

Photo: K. Brown.

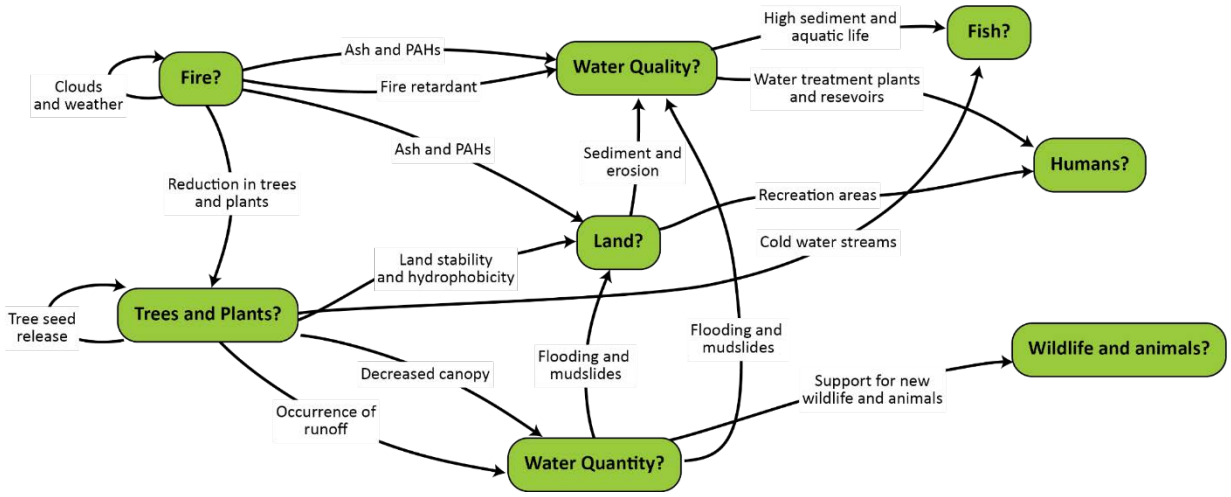


Figure 3. A simplified scheme showing the interconnected effects of wildfires. Each of these needs to be considered during community discussion when planning a post-fire recovery strategy. Image used with permission from Canada WaterPortal Society (https://waterportal.ca/).

favouring species that colonize mineral soils. Regarding burned area, larger fires increase the distance to unburned seed sources, slowing regeneration, with warmer and drier post-fire conditions further reducing seedling survival. Extreme post-fire precipitation events can also trigger various hydrological responses, creating debris flow, landslide, and flooding hazards. In response to these cumulative effects, coupled with other post-fire biogeochemical changes, some disturbed areas may require intervention to assist recovery and reduce undesired outcomes. In such cases, proactive restoration may be required to promote ecosystem recovery, restore ecosystem services, stabilize soils and slopes, prevent erosion and flooding, and build ecological and community resilience to future disturbances and climate change.

To provide background context for post-fire restoration, various aspects of the post-fire environment are shown in Fig. 3 and subsequently described. Fire-impacted components variously involve post-fire fuels, soil characteristics, and even changes in microclimate. Common post-fire hydrological and geomorphological changes are also explored. In addition to considering ecological succession, the effects of fire on a variety of organisms, including specialists and generalists, are also examined. To explore these topics in greater detail, see Brown et al. (2026), Tanney et al. (2026), and Murphy et al. (2026).

2. Post-fire Fuels and Environmental Change

2.1. Post-fire Fuels

Following a fire, any remaining fuels form the foundation of the post-fire fuel complex and interact with regenerating vegetation and other

biota. Considering that fire consumes biomass and reduces fuel loads, many forest types exhibit a period, lasting years to decades, during which reburning is unlikely (Parks et al. 2018). The magnitude and persistence of this effect is strongly modulated by spatial and temporal climate variability, and it can change (Whitman et al. 2022). As stands recover, both residual fuels and regenerating vegetation influence organic matter accumulation, with fire-generated snags contributing to surface fuel buildup as they shed branches and bark and eventually collapse, while new regrowth adds additional litter and sequesters carbon (Greene et al. 1999). The subsequent development of the fuel complex can vary through time, depending on the interacting influences of fire severity, fuel consumption, and patterns of regeneration and fuel accumulation (Agee 1993; Prescott et al. 2005; Keane 2015; Hopkins et al. 2025).

2.2. Soils

Beyond vegetation, wildfires can also alter the physical, chemical, and biological properties of soil (Agbeshie et al. 2022). While impacts from lower-severity fires are generally weaker and short-lived due to minimal canopy loss, limited production of wildfire ash, and less erosion, higher severity fires generate a greater range of stronger responses. For example, soil temperature can increase immediately post-fire in response to the loss of canopy cover and decreased albedo, with the former enabling greater amounts of light to reach the forest floor and the latter decreasing in response to the preponderance of dark charred material in burned areas. In addition, high-severity burning can degrade soil structure and induce hydrophobicity, reducing water infiltration (Farid et al. 2024). Combined with reduced canopy cover, which lowers rainfall interception and evapotranspiration, these changes result in increased overland flow and soil erosion.

Regarding chemical changes, effects are typically greater following high-severity fires compared to lower-severity burns (Fig. 4). Soil pH often increases after a fire due to the presence of base cations that are concentrated in wildfire ash. While total nitrogen is often reduced due to low-temperature volatilization (i.e., element loss to the atmosphere as gas during burning), erosion, and leaching, the thermal breakdown of organic matter also releases nitrogen, primarily as ammonium (NH_4^+), thus increasing nitrogen availability despite overall nitrogen losses. Over time, soil microbes convert ammonium to nitrate (NO_3^-; Covington and Sackett 1992), which can then be removed from burned areas through leaching and/or runoff (Murphy et al. 2006). In contrast to nitrogen, the volatilization temperature of phosphorus is higher, and thus its abundance generally does not decrease after a fire. In actuality, the bioavailable form (i.e., PO_4^{3-}) often increases post-fire.

Similarly, major plant nutrients like calcium (Ca), magnesium (Mg), and sodium (Na) likewise accumulate in soil after wildfire because their volatilization temperatures are also high (Roshan and Biswas 2023). While some of these elements can be removed from the burned area via leaching and erosion, much remains on site and is taken up by regenerating vegetation. Likewise, metals with high volatilization temperatures such as aluminum (Al), iron (Fe), and manganese (Mn) are typically retained in the soil, though manganese can be quickly mobilized (e.g., after rainfall). In contrast, trace elements can exhibit variable responses. For example, mercury (Hg) readily vaporizes during a fire event and is released into the atmosphere and

redeposited. In contrast, arsenic (As) and chromium (Cr) are chemically transformed, increasing their mobility and bioavailability.

2.3. Microclimate

While near-surface microclimatic changes associated with lower-severity burns are somewhat muted, they are more pronounced following higher-severity events that remove canopy cover (Wolf et al. 2021). In these cases, fire-induced decreases in vegetation lead to increases in solar radiation and heating at the surface. Consequently, near-surface air and soil surface temperature increase post-fire, with the former often increasing by a few degrees and soils >2 °C. Near-surface wind speed may also increase due to reduced surface roughness (Amiro 2001). Concurrently, the reduction in vegetation also lowers evapotranspiration, which increases soil moisture (Chambers et al. 2005). In terms of site regeneration, such changes in forest microclimate are important because they can affect the health and survival of young plants, which generally tolerate a narrower range of temperature and moisture conditions compared to mature individuals.

3. Hydrogeomorphology

3.1. Fire Effects on Rainfall–Runoff Pathways

Wildfires fundamentally alter the biological and physical state of watersheds, initiating changes that can alter the partitioning of hydrologic pathways and produce a cascade of hydrogeomorphic effects. The particular fire-induced changes that occur, as well as the degree to which they occur (commonly described using measures or indicators of burn severity), naturally vary across all spatial scales, from regional- or ecosystem-scale to plot-scale within an individual wildfire. When these effects occur at moderate to high-severity, the result can be a significant enhancement of runoff and erosion. In steep terrain, the cumulative effects of more severe fires can lead to the occurrence of natural hazards, such as floods, landslides, and/or debris flows. These hazards can pose significant local and downstream risks with potentially catastrophic impacts to life and property, critical infrastructure, freshwater ecosystems, and water resources (McGuire et al. 2024).



High-severity Fire

Figure 4. Wildfire ash, exposed mineral soil, snags, and downed wood following a high-severity fire in a *Pinus contorta* (lodgepole pine) forest, Chilcotin Plateau, British Columbia.

Photo: K. Brown.

To understand how wildfires change watershed dynamics and potentially cause such profound impacts, it is helpful to review the effects of fire along the hydrologic pathway from rainfall to runoff and streamflow. In the very first step of this pathway, fire can be responsible for reductions, or potentially the total loss, of canopy foliage. Any rainfall that reaches the soil surface must first pass through the canopy. Therefore, changes in canopy cover (i.e., the fractional ground area overlain by the tree crown) will influence the effective rainfall intensity at the soil surface (Tarboton 2003). Given that runoff generation can, in the simplest terms, be estimated as the difference between this effective rainfall intensity and the rate at which soil can absorb water (i.e., a process known as infiltration; Horton 1940), fire-related losses of canopy cover represent an important initial control on runoff.

The degree and extent of combustion of organic material on the forest floor, as well as below the subsurface, can also contribute to the post-fire hydrogeomorphic response. After the canopy, litter and duff on the forest floor serve as an important secondary buffer against rainfall, and the progressive removal of this ground cover with increasingly severe wildfire can have effects on runoff and erosion (Fig. 5). First, stripping the soil of this protective organic layer can enhance erosion both from direct raindrop impacts and runoff flowing across the exposed mineral soil surface (Certini 2005). While the loss of ground cover may increase the rate at which water reaches the soil surface, the combustion of litter, duff, and other aboveground



Figure 5. Comparison of an unburned forest (left) with a high-severity burn soon after wildfire (right). Both photos were taken in a dry mixed conifer forest outside of West Kelowna, British Columbia, following the McDougall Creek Fire (2023). In addition to the reductions in canopy foliage and surface vegetation, the high burn severity site demonstrates how wildfires reduce surface roughness and increase mineral soil exposure, factors that contribute to post-fire runoff and erosion and strongly influence the trajectory of post-fire restoration. Photo: B. Murphy.

vegetation can also lead to the deposition of thin ash layers on the soil surface. Ash is typically more absorbent than soil, but its fine particles can often work their way into surface soil pores, producing an effect known as surface sealing that can reduce soil infiltration. Therefore, the burning of ground cover, independent of the degree of combustion, typically has the effect of shifting the balance between effective rainfall intensity and soil infiltration further toward enhanced runoff generation.

As a fire burns, it will consume organic material below the surface as well, notably the fine and large roots that typically hold soil together and help resist erosion. Although dry mineral soil is generally a poor thermal conductor, the intense heat generated by fires can penetrate into the upper few centimetres of the soil surface. These two mechanisms of heat transfer into the subsurface can result in the combustion and loss of organic matter that is naturally mixed in with the topsoil (Parsons et al. 2010). In addition to increasing the soil erodibility, the combustion of subsurface roots and soil organic material can also produce small amounts of ash that may clog soil pores and further reduce the soil's infiltration capacity (Doerr et al. 2000).

The combustion of organic material during wildfires can also produce one of the most widely cited fire effects influencing post-fire runoff generation, the development (or enhancement) of soil hydrophobicity (Fig. 6). Plant materials (e.g., leaves, needles, roots) naturally contain water-repellent (i.e., hydrophobic) compounds, which are volatilized when these materials burn. In this gaseous state, the compounds can diffuse downward into dry soil pores, where they cool and condense, both coating soil grains and effectively blocking soil pores (Doerr et al. 2000). The lateral extent and degree to which this fire-induced hydrophobicity occurs is influenced by factors such as the degree of pre-existing soil hydrophobicity, the types of plants that burn, and the duration and temperature of the fire. When and where this phenomenon occurs, water repellent layers will develop either at the surface or typically



Hydrophobic Soils

Figure 6. A beaded water droplet on the mineral soil surface following a high-severity burn, illustrating the effect of fire-induced water repellency on soils. Water-repellent layers may develop at or near the soil surface from the combustion of vegetation, inhibiting water absorption into the soil and promoting more rapid runoff generation. Photo: B. Murphy (McDougall Creek Fire, British Columbia, 2023).

within the upper 10 centimetres of the mineral soil. The hydrophobic compounds can persist for many years in the soil, further contributing to reductions in soil infiltration (Debano 1981).

The combined effect of these fire-induced changes on the effective rainfall intensity and soil infiltration capacity can be dramatic shifts in rainfall partitioning, whereby even brief, low-intensity rainstorms can produce a large runoff response (Staley et al. 2020). Once overland flow initiates in a recently burned watershed, the loss of ground cover (e.g., herbaceous plants, woody debris, litter, and duff) can further amplify the hydrologic response by removing material that normally impede runoff and slow the velocity of water accumulating on the surface. Compounding the power of the amplified and unimpeded post-fire runoff is the enhanced erodibility due to extensive increases in mineral soil exposure and loss of root cohesion. As a result, sheetwash (i.e., thin, continuous layers of water flowing across hillslopes) can more easily erode and transport soil and ash downslope. As the sheetwash coalesces into more concentrated flow paths, hillslopes may begin to experience rill erosion (i.e., shallow, centimetre-scale channels eroded into the topsoil) and potentially gullying (i.e., metre-scale channels eroded into hillslopes), all of which will contribute more soil, ash, rock, and woody debris to the rapidly moving surface flows. Burned watersheds experience more rapid transitions along the entirety of the hydrologic pathway from rainfall to sheetwash to channelized flow, which can result in shorter lag times between peak rainfall and peak streamflow and possibly increased flood discharges.

3.2. Streamflow and Flooding

Despite the elevated potential for erosion after wildfire, if the concentration of soil, rock, and debris transported in the flow remains relatively low (<10%; Ebel 2024), then the fire's effects will typically not produce cascading natural hazards but instead translate to downstream changes in streamflow. While observations of post-fire streamflow response vary widely, the most frequently reported changes are with respect to flood (or peak) discharges, annual streamflow, and sometimes low-flows. Among these potential impacts, flood flows are often suggested to be the most common and pronounced (Moody and Martin 2001).

Changes reported between pre- and post-fire flood flows correspond to both increases in their magnitude and frequency (Shakesby and Doerr 2006), with studies suggesting this is driven largely by fire effects on soil infiltration capacity (Saxe et al. 2018; Wampler et al. 2023). In contrast, changes in annual streamflow are generally less pronounced and more variable. While some studies have reported no change or even decreased annual streamflows, in most cases, annual streamflows after wildfire are observed to increase, with changes ranging up to nearly two orders of magnitude and remaining elevated relative to pre-fire flows for an average of up to five years (Paul et al. 2022). The suggested influence of fires on low-flows is even more variable. In the short-term and in response to changes in evapotranspiration, infiltration, and groundwater recharge, low-flows may either increase or decrease after wildfire (Saxe et al. 2018; Cingolani et al. 2020), noting that there is presently no consensus regarding long-term effects.

3.3. Natural Hazards

When moderate-to-high severity wildfires occur in steep terrain, the myriad of fire effects on soil properties, rainfall-runoff partitioning,

and watershed dynamics can be exacerbated, leading to a potential cascade of natural hazards. Post-fire natural hazards can broadly be classified into three categories based on their initiation mechanism, including surface runoff, slope failure, and permafrost thaw. Notably, the period of elevated hazard risk (in terms of time since fire) varies between each of these initiation mechanisms due to different driving factors (McGuire et al. 2024).

The most frequent and characteristic natural hazards in burned watersheds are runoff-generated debris flows. Unlike conventional debris flows, which initiate as shallow slope failures, runoff-generated debris flows are initiated in channels, where they source the bulk of their material from deeply scouring the streambed (Cannon and Gartner 2005). These sediment-laden flows are capable of eroding and transporting substantial volumes of sediment (>100,000 m^3), which can fundamentally alter the physics of the flow itself to enable the transport of large boulders. Despite sediment concentrations in excess of 60% (Ebel 2024), debris flows can move at high velocity (5 – 15 m/s; Prochaska et al. 2008), making them extremely dangerous and destructive. Finally, demonstrating the degree to which fires alter infiltration and rainfall-runoff partitioning, nearly 100% of post-fire debris flows included in a study from across the western U.S. were reportedly triggered by sub-hourly rainfall intensities representative of storms with a recurrence interval of five years or less (Staley et al. 2020).

3.4. Water Quality

Wildfires can also disrupt the processes by which forested watersheds typically buffer and protect downstream water quality. The fire-induced increases in runoff and erosion across watersheds can contribute to an increase in both solid and dissolved pollutants that have the potential to contaminate critical downstream water resources (Hebda et al. 2024). Increased inputs of sediment, ash, organic material, nutrients, and metals into waterways have adverse impacts on turbidity, chemistry, aesthetics (e.g., taste), and other water quality measures, all of which present significant and costly challenges for treating and managing water supplies (Robinne et al. 2021).

The most consistently identified impacts on water quality after wildfire are elevated nutrient concentrations, specifically nitrogen (N) and phosphorus (P), both of which may remain high for many years after a fire and lead to eutrophication (Rust et al. 2018; Rhoades et al. 2019). Numerous metals and other compounds (e.g., arsenic, lead, mercury, cyanide) released during the combustion of vegetation and soils, are highly toxic, even at low concentrations, and can persist and accumulate in water, sediment, and aquatic organisms. While hazardous chemical contaminants can also enter water supplies due to fires in the wildland-urban interface (WUI) burning homes and other buildings (Proctor et al. 2020), the associated risks and impacts still require more investigation. Finally, the loss of riparian vegetation represents another potential water quality risk from wildfire. For example, increases in solar radiation and water temperature associated with the reductions in stream shade can affect the metabolism and reproductive success of freshwater fish and other aquatic organisms (Beakes et al. 2010).

Succession

Figure 7. Early seral succession with red-coloured paintbrush (*Castilleja*) and purple lupines *(Lupinus*) likely sprouting from root crowns following a high-severity fire, Chilcotin Plateau, British Columbia.

Photo: K. Brown.



4. Succession and Biotic Recovery After Wildfire

4.1 Ecological Succession as the Recovery Framework

Post-fire biological change unfolds through ecological succession, the process by which species composition and ecosystem structure reorganize following disturbance. Early post-fire communities are typically dominated by plants and animals that rapidly colonize disturbed sites. Many of these organisms are capable of tolerating heat, exploiting exposed substrates, and/or dispersing from nearby unburned areas. As time passes, vegetation structure and organic matter redevelops and habitat complexity and resource availability increase so that later-successional species are able to establish.

Successional trajectories depend on burn severity, spatial pattern, biological legacies (i.e., organisms surviving from before the fire), and post-fire climate. Patchy or lower-severity burns that retain live trees, coarse woody debris, and unburned refugia foster more rapid reassembly of structurally complex communities. High-severity or repeated fires shorten successional intervals, thus impeding the development of mature forest structure, disproportionately affecting species dependent on late-successional habitat. Within this successional framework, organismal traits determine which species persist, colonize, or decline following wildfires.

4.2. Plant Responses and Regeneration

Many plants possess adaptations that enable them to persist in fire-prone environments (Keeley and Pausas 2022). Several classes of fire-adaptation strategies are recognized, including, for example, resistors with thick bark, invaders that rapidly colonize disturbed sites, evaders with serotinous cones, endurers that resprout after fire, and avoiders that are largely restricted to areas where fire is infrequent. As a result, vegetation responses to wildfire vary widely and are shaped by fire intensity and severity, burn timing and

duration, fire frequency, plant community composition, and ecosystem type (Agee 1993). Of note, the Fire Effects Information System (FEIS; https://research.fs.usda.gov/feis/species-reviews), developed by the US Department of Agriculture and US Forest Service, is an easy to use high-value online resource that catalogues and characterizes numerous plant and animal responses to wildfire.

Fire-adapted Fauna



Figure 8. Black-backed Woodpecker (*Picoides arcticus*) using recently burned habitat following a prescribed fire at La Mauricie National Park, Quebec, Canada. Source: Parks Canada (https://parks.canada.ca/nature/science/especes-species/feu-fire).

In fire-adapted ecosystems, lower-severity fires typically modify stand structure and age composition by removing younger cohorts while more mature, fire-adapted trees survive (Harvey et al. 2017). Secondary succession is more strongly expressed where lower-severity fires burn in stands of fire-sensitive trees or following higher-severity fires that kill much of the overstorey. In these cases, regeneration commonly proceeds through resprouting and seed dispersal, supported by increased light availability and short-term nutrient pulses. Early fast-growing species often dominate initially, followed by deciduous trees and eventually conifers as succession progresses. (Fig. 7). Where severity is higher, regeneration depends more strongly on seed availability from on-site reserves or dispersal from unburned areas. As fire size increases, the distance to viable seed sources also increases. Long distances to sources may reduce post-fire stand density and alter species composition.

4.3. Trait-Based Responses of Microbes and Animals

Wildfire acts as a strong ecological filter through heat exposure, loss of organic substrates, altered microclimates, and modifications of soil and water chemistry (Dooley and Treseder 2012; Agbeshie et al. 2023). The intensity of this effect is governed by the severity, duration, and spatial extent of the wildfire, as well as by pre-fire structure and post-fire landscape configuration (Meigs and Krawchuk 2018). High-severity fires can eliminate surface organic horizons, kill overstorey vegetation, and homogenize large areas, consequently favouring early-successional and disturbance-adapted taxa while excluding species reliant on stable, shaded, or more structurally complex habitats

(Zwolak and Foresman 2007; Knaggs et al. 2020).

Responses differ consistently between late-successional specialists and disturbance-adapted or generalist taxa. Specialist species associated with mature forest structure, including many ectomycorrhizal fungi and mature-forest birds, often decline after severe fire (Schieck and Song 2006; Nelson et al. 2022). In contrast, generalists, opportunists, and pyrophilous (i.e., fire-adapted) taxa frequently show neutral or positive responses, benefiting from reduced competition, increased resource availability, and the creation of open habitat structure (Hutto et al. 2020; Fox et al. 2022).

Response strategies span a continuum. In mobile organisms, behavioural and demographic adjustments (e.g., movement, habitat selection, and resource tracking) dominate. Generalist mammals, such as deer mice and coyotes, often increase in early-seral habitats, whereas specialists, like Canada lynx, marten, and fisher, typically avoid recent burns and decline in abundance where late-successional habitat is lost (Zwolak 2009; Vanbianchi et al. 2017; Volkmann and Hodges 2024). Among landbirds, early-seral and cavity-nesting species benefit from increased insect prey and snag availability (Fig. 8), while mature-forest associates recover more slowly as structural complexity returns (Saab and Powell 2005; Hutto and Patterson 2016).

Microbial and invertebrate communities, by contrast, are structured primarily by tolerance and colonization traits. Examples include rapid post-fire proliferation of pyrophilous fungi such as *Pyronema* (Fig. 9), whose spores are heat-activated, and increases in saproxylic (i.e., dependent on dead wood) and fire-associated insects that exploit dead wood and reduced competition (McCullough et al. 1998; Bell 2023). Conversely, some groups, such as late-successional wood-decay fungi, may suffer immediate declines after a fire followed by increases due to enhanced woody substrates, while others like arboreal lichens may require decades to recover (Penttilä et al. 2013; Greuel et al. 2021).

Fungal Growth



Figure 9. Mass growth (white mycelia) and reproductive structures (orange discs) of the pyrophilous fungus *Pyronema omphalodes*on a burned soil surface, stimulated by a prescribed low-severity surface fire in a Garry oak (*Quercus garryana*) stand in Rocky Point, British Columbia. Photo: J. Miskelly.

4.4. Food-Web Dynamics

As species respond and adapt in different ways, these effects ripple through food webs

and ecosystem processes (Fig. 10). Food-webs reorganize on burned landscape mosaics structured by variation in fire severity, fuel distribution patterns, and microclimate. The increased abundance of fire-loving insects and early-seral herbivores can support insectivorous birds and generalist predators. Declines in late-successional prey, such as snowshoe hares and red squirrels, restructure higher trophic levels (Allard-Duchene et al. 2014; Bognounou et al. 2021; Furnas et al. 2022). For larger mammals, burn severity and fuel continuity shape snow cover, forage access, and movement costs, creating vegetation mosaics in which early-seral patches provide high-quality forage while residual forest patches offer thermal cover and refuge. These changes in habitat distribution alter herbivore–predator interactions and browsing pressure. In so doing, they change the distribution of key resources of the food web and, by implication, for humans too.

temporarily suppress some tree pathogens, fire-responsive species such as the pine fire fungus (*Rhizina undulata*) may exacerbate post-fire mortality (Gremmen 1961; Egger and Paden 1986; Day et al. 2020; Beals et al. 2022). Heat from wildfire or slash burns stimulate the germination of heat-resistant spores from this fungus, allowing it to infect adjacent regenerating seedlings and fine roots, potentially leading to localized disease hotspots in the years following fire (e.g., mortality up to 80% reported in Powell River, British Columbia; Callan 1993).

Notably, while much post-fire research has focused on terrestrial systems, responses to fire are also evident in aquatic and semi-aquatic environments linked by hydrology and riparian corridors. For example, wildfire alters

Figure 10. A simplified diagram of how fire events generate cascading ecological effects across forest ecosystems. Direct fire effects (direct injury, organic matter combustion, and vegetation loss) drive second-order responses in detritivores, decomposers, herbivores, and primary producers, which in turn shape the next level of consumer dynamics across detrital, soil, plant-based, and aquatic food webs. These new trophic, physiological, and biogeochemical pathways can the alter the type, quantity, and continuity of fuels and ultimately feedback and influence the intensity and frequency of future fire regimes.

Energy flow also shifts towards a source from dead organic material after fire. Microbial decomposition drives additional nutrient release from charred wood and litter and alters toxic compounds generated by the fire. The resulting microbial biomass binds soil particles while also providing substrates for algae, bryophytes, invertebrates, and other organisms (Carpenter et al. 1987; Filialuna and Cripps 2021). Regenerating tree health can also be directly affected by wildfire-microbial interactions (Seidl and Turner 2022; Johnson et al. 2023). While fire can

hydrology, water quality, and physical habitat in lakes, streams, and wetlands, driving changes in temperature, sedimentation, nutrient inputs, and food-web structure that affect aquatic and semi-aquatic biota (Carignan and Steedman 2000; Rengers and McGuire 2021; Erdozain et al. 2024). However, biological responses remain poorly documented, with limited studies on primary producers, invertebrates, and fishes, and even less attention to semi-aquatic taxa such as amphibians, turtles, waterfowl, and beavers that depend on fire-sensitive riparian habitats

(Robinne et al. 2020; Lesbarrères et al. 2014; Markle et al. 2020). Available evidence suggests highly context-dependent outcomes, ranging from short-term increases in productivity to negative effects driven by sedimentation, warming water, and contaminant mobilization (Gresswell 1999; Cooper et al. 2015). At this time, we are limited in our ability to generalize recovery pathways or assess risks to freshwater biodiversity under increasingly severe fire regimes. Having limited knowledge constrains the development of optimal recovery strategies.

5. Landscape Heterogeneity: Restoration and Management Implications

Varied patterns in the severity of a burn and the presence of unburned refugia support species with contrasting successional preferences and enhance biodiversity at broader scales (Meigs and Krawchuk 2018). Patch mosaics allow mature-forest specialists to persist locally while also creating opportunities for early-seral and disturbance-adapted species.

At regional scales, however, increasing fire frequency and reburn rates can reduce late-successional habitat availability, favouring generalists and disturbance-adapted taxa and affecting carbon storage and long-term ecological resilience (Prichard et al. 2017; Hessburg et al. 2021). The balance between local heterogeneity and regional habitat loss is therefore a central issue to planning for biodiversity under intensifying fire regimes.

Management interventions also influence post-fire recovery across trophic levels. For example, while salvage logging can provide some economic return and reduce hazards, it can also alter deadwood availability, disturb soil, and impact biological refugia, with cascading ecological effects (Leverkus et al. 2018; Bowd et al. 2025). Retaining structural legacies and unburned refugia can support recolonization by fungi, invertebrates, and vertebrates and maintain key ecosystem functions. Where regeneration is limited by seed availability, soil degradation, erosion risk, or repeated disturbance, active restoration may be required. Restoration actions may include assisted regeneration, erosion control, slope stabilization, and protection of hydrologic function and water quality.

As climate change drives increases in fire size, severity, and frequency, maintaining structural and successional diversity, including the preservation of unburned refugia will be central to sustaining ecosystem processes, conserving late-successional biodiversity, and supporting the long-term resilience of forest landscapes (Jain et al. 2024; Maron et al. 2015; Tanney et al. 2026).

6. Conclusion

Wildfire is a primary ecological process in many forest ecosystems. However, changing climate and fire regimes are producing increasingly variable and less predictable post-fire impacts and recovery trajectories. Within this context, fire severity is a key factor affecting ecological and other impacts. In contrast to lower-severity fires that retain biological legacies that support natural regeneration, higher-severity, larger, or repeated fires can disrupt soils, seed sources, and hydrology, leading to delayed or failed recovery. In consequence, active restoration may be required to prevent undesired outcomes. Within this context, restoration initiatives should consider the range of interconnected processes affecting succession (Figs. 3 and 10), including the size and

severity of the disturbance, surviving plants and animals, altered soil and microclimates, changes to forest hydrology, and development of hazards extending beyond the burned area perimeter. At broader scales, burn heterogeneity and unburned refugia are critical for biodiversity retention and recolonization. These various considerations highlight the importance of proactive, integrated restoration that considers biotic and abiotic linkages, stabilizes disturbed sites, and reduces the potential for hazards such as landslides after a fire. As fire size and intensity increase, driven by climate change, maintaining landscape heterogeneity and working with fire as an ecological process will be central to sustaining ecosystem function, biodiversity, and long-term forest resilience, representing values that are key to the well-being of communities.

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