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Impact of Wildfire on Soil Fauna Community Structure Post-Burning

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ABSTRACT

Wildfire represents one of the most significant disturbances affecting terrestrial ecosystems globally, with profound implications for soil faunal communities. This review synthesises current knowledge on the impact of wildfire on soil fauna, with a focus on the changes in multi-trophic community structure following burning events. We examine how wildfires affect heterogeneous landscapes, soil faunal activity patterns, and the loss of subterranean biodiversity. Evidence indicates that wildfire impacts vary considerably across different taxonomic groups, with immediate adverse effects on surface-dwelling fauna and variable recovery rates depending on fire severity, soil depth, and ecosystem type. Microarthropods, nematodes, and enchytraeids exhibit differential responses to fire disturbance, with some groups demonstrating remarkable resilience, while others experience prolonged population declines. The heterogeneous nature of burned landscapes creates a mosaic of microhabitats that influences recolonisation patterns and community assembly. This review highlights critical knowledge gaps and emphasises the need for long-term studies to understand the full implications of increasing wildfire frequency on soil biodiversity and ecosystem functioning.

Key words: Wildfire, Soil fauna, Biodiversity, Ecosystem disturbance, Post-fire recovery

INTRODUCTION

Wildfire frequency and intensity have increased globally due to climate change, altered land management practices, and human activities (Bowman et al. 2009). These disturbances have a profound impact on terrestrial ecosystems, with soil communities being particularly vulnerable due to their limited mobility and direct exposure to thermal stress (Certini 2005). Soil fauna represent a critical component of ecosystem functioning, contributing to nutrient cycling, organic matter decomposition, and soil structure maintenance (Bardgett and van der Putten 2014).

The multi-trophic nature of soil communities creates complex interaction networks that fire events can severely disrupt. Understanding these impacts is crucial for predicting ecosystem recovery and implementing effective post-fire management strategies (Neary et al. 1999). This review synthesises current knowledge on the effects of wildfires on soil fauna, examining changes in community structure, diversity patterns, and functional processes across different spatial and temporal scales.

METHODOLOGY

A comprehensive literature search was conducted using the Web of Science, Scopus, and PubMed databases, encompassing publications from 1990 to 2023. Search terms included combinations of "wildfire," "soil fauna," "soil invertebrates," "fire ecology," "post-fire recovery," and "soil biodiversity." Studies were selected based on their relevance to soil faunal responses to wildfire, with emphasis on quantitative assessments of community structure changes.

EFFECTS OF WILDFIRE ON COMMUNITY STRUCTURE

Soil community diversity and composition

Wildfires consistently alter the composition and diversity of soil communities across all trophic levels, though the direction and magnitude of response vary significantly among different biological groups. Fungal communities demonstrate extreme sensitivity to fire disturbance, often exhibiting more pronounced changes than bacterial communities. Research from subtropical forests has revealed that fire leads to a significant decline in the richness of fungi, protists, and invertebrates, while bacterial richness remains relatively unchanged (Zhou et al., 2024). This pattern was corroborated by a global meta-analysis of over 2,600 soil samples, which found that fungal diversity consistently decreased after fire. At the same time, bacterial communities maintained similar diversity levels but with shifted dominance structures toward fewer competitive taxa.

The differential response between microbial groups is further evident in specific taxonomic shifts. In karst forest ecosystems, wildfires led to a dramatic change in fungal composition, from Basidiomycota-dominated to Ascomycota-dominated communities. In contrast, bacterial communities exhibited significant increases in the relative abundance of Actinobacteria (Li et al. 2024). These fire-adapted bacterial taxa possess functional traits, including heat resistance mechanisms such as sporulation genes and heat shock proteins, as well as metabolic capabilities for utilising pyrogenic carbon, which provides them a competitive advantage in the post-fire environment (Nelson et al. 2022).

The complex multi-trophic networks in soil become significantly simplified following wildfires. Network analysis of soil communities reveals a consistent reduction in complexity, connectivity, and the number of keystone taxa ("hub microbiome") in burned soils compared to unburned soils (Li et al. 2024). This simplification of soil networks has profound implications for ecosystem resilience and recovery capacity following disturbance (Fig. 1).

Trophic-level responses and network reorganisation

Wildfires trigger a fundamental reorganisation of soil food webs, altering both the composition and interactions across trophic levels. Soil nematode communities serve as excellent bioindicators for these changes, with apparent trophic-level shifts observed following fires. Studies conducted across the Russian plain have demonstrated that fire consistently reduces the biomass and taxonomic richness of nematodes, with powerful effects on

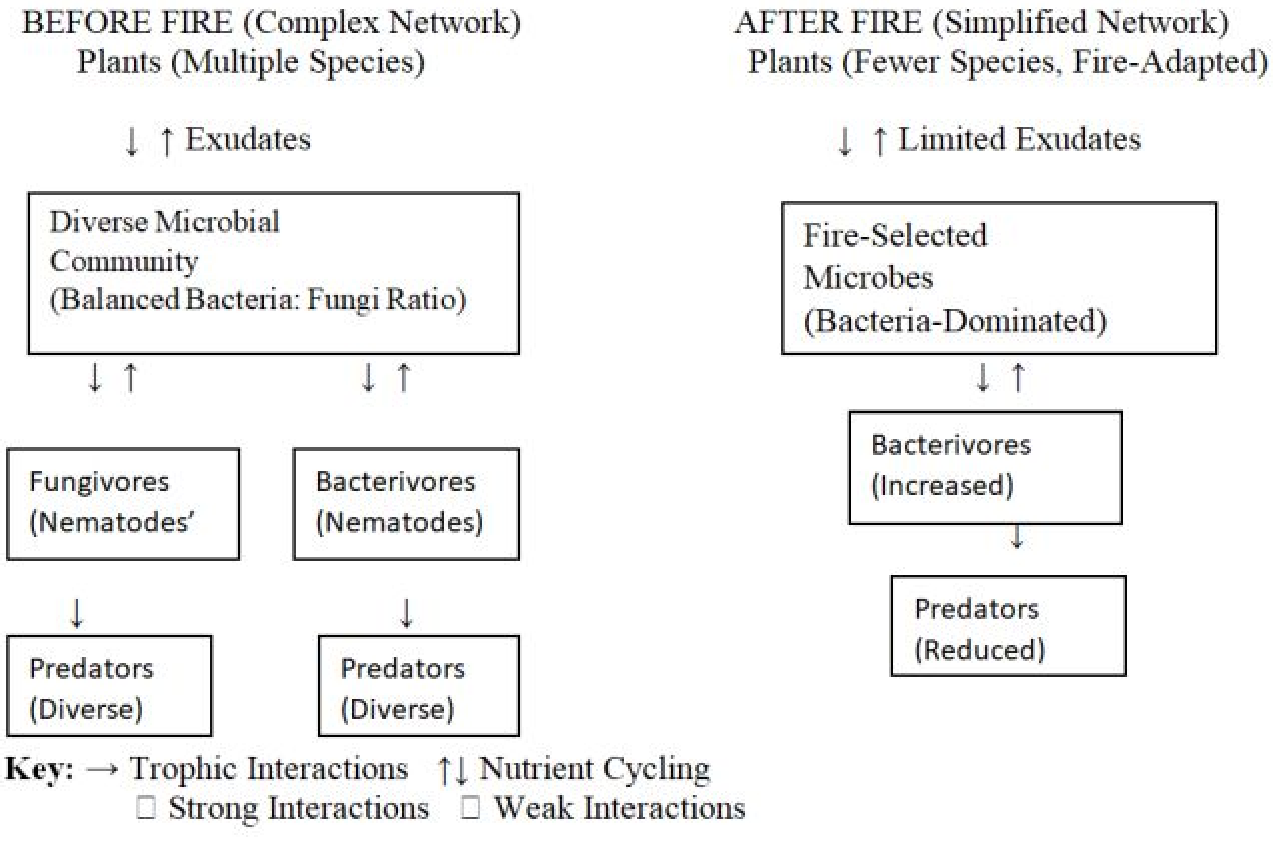

Figure 1. Conceptual diagram of wildfire effects on soil community structure (after Konstantin et al. 2017)

fungal-feeding and plant-parasitic nematodes, while bacterial-feeding nematodes tend to increase in relative abundance. This shift in nematode trophic structure reflects the broader transition from a fungal-based to a bacterial-based energy channel in the soil food web following wildfire.

The co-occurrence patterns among soil organisms across trophic levels show divergent responses to fire disturbance. While microbial networks (bacteria and fungi) typically experience simplification and reduced connectivity, invertebrate networks may actually increase in complexity following fire (Zhou et al. 2024). This discrepancy suggests that fire-induced changes operate through different mechanisms across trophic levels, with potentially compensatory dynamics emerging as some taxa fill ecological niches left vacant by fire-sensitive species. The functional potential of the soil microbiome undergoes significant restructuring after wildfires. Metagenomic analyses have revealed that fire-selected microbial taxa encode metabolic pathways for utilising pyrogenic carbon, oxidative stress tolerance, and thermal resistance (Nelson et al. 2022). Furthermore, functional predictions indicate an increase in the relative abundance of chemoheterotrophic bacteria and saprotrophic fungi following fire, suggesting enhanced capabilities for processing burned organic matter but reduced capacity for other ecosystem functions such as symbiotic relationships with plants (Li et al. 2024).

Mechanisms underlying

The changes observed in soil multi-trophic communities following wildfire can be attributed to a combination of direct temperature effects and indirect environmental modifications. Direct mortality from soil heating immediately eliminates heat-sensitive taxa, creating vacant ecological niches (Li et al. 2024). The differential heat tolerance among soil organisms explains much of the taxonomic sorting observed after fires, with spore-forming bacteria and specific fungal taxa exhibiting greater survival rates due to specialised resistance mechanisms such as thick cell walls, heat shock proteins, and sporulation capabilities (Nelson et al. 2022).

Following the initial direct impacts, indirect environmental changes become increasingly important in shaping the assembly of the soil community. The combustion of organic matter and vegetation alters soil chemical properties, increasing pH and initially boosting nutrient availability through ash deposition (Butenko et al. 2017). These changes create conditions that favour fast-growing, opportunistic taxa with simple nutrient requirements, particularly bacteria over fungi (Butenko et al. 2017). The loss of vegetation cover also alters the microclimate of the soil environment, increasing temperature fluctuations and reducing moisture retention, which in turn selects for desiccation-tolerant microorganisms (Nelson et al. 2022).

The simplification of ecological networks observed after fire likely results from the disruption of established environmental relationships and the reduction of niche diversity. Co-adapted species interactions, particularly those involving specialist taxa and obligate symbiotic relationships, are vulnerable to fire disturbance. The observed increase in microbial specialists after fire suggests a reduction in functional redundancy and a potential narrowing of the metabolic capabilities of the soil community, which may compromise ecosystem resilience to future disturbances (Butenko et al. 2017).

Functional consequences for ecosystem processes

The restructuring of soil multi-trophic communities following wildfire has profound implications for ecosystem functioning. The shift from fungal to bacterial energy channels alters fundamental nutrient cycling processes, potentially accelerating short-term nutrient availability but reducing long-term organic matter stabilisation (Butenko et al. 2017). Fungi, particularly mycorrhizal associations, play crucial roles in soil aggregation through their hyphal networks, and their reduction after fire can compromise soil structure, increasing susceptibility to erosion.

The simplification of trophic networks and reduction in cross-trophic interactions observed after fire may impair the stability of multiple ecosystem functions. Research has demonstrated that cross-trophic interactions become increasingly important for maintaining ecosystem multi-functionality under conditions of high resource availability. The post-fire environment typically experiences a pulse of nutrients from ash, making the loss of these complex interactions particularly detrimental to ecosystem recovery. Furthermore, the reduction in predatory and grazing pressure within simplified food webs can disrupt the top-down regulation of microbial communities, potentially leading to unbalanced decomposition rates and nutrient cycling (Zhu et al. 2023).

The functional homogenization of soil communities after fire may reduce the capacity of ecosystems to withstand subsequent disturbances or environmental changes. Diverse soil communities with high functional redundancy provide insurance against ecological variability, as different species contribute similarly to ecosystem processes but respond differently to disturbances. The observed increase in specialist taxa after fire suggests a narrowing of the functional breadth of the community, potentially limiting the range of environmental conditions under which essential ecosystem processes can be maintained.

Implications for ecosystem recovery and management

The lasting signature of fire on soil microbiomes highlights the importance of understanding microbial dynamics for ecosystem restoration. Traditional approaches to post-fire management have primarily focused on vegetation recovery and erosion control; however, our findings emphasise the need to incorporate soil biological components into restoration strategies. The slow recovery of fungal communities and mycorrhizal networks may represent a critical bottleneck for forest regeneration, particularly in ecosystems dominated by trees with obligate mycorrhizal associations.

The differential vulnerability of various trophic groups to fire disturbance suggests that ecosystem recovery depends heavily on the reassembly of a functionally complete soil food web. Management practices that promote the recovery of soil multi-trophic complexity, such as retaining unburned woody debris as refugia and inoculating with native microbial communities, may enhance the resilience of recovering ecosystems. The assessment of soil multi-trophic network structure can serve as a valuable bioindicator for evaluating the recovery trajectory and ecosystem health following wildfires (Zhou et al. 2024).

The context-dependent nature of fire effects - varying with fire severity, ecosystem type, and historical fire regime - underscores the need for tailored management approaches. In fire-prone ecosystems where natural fire return intervals have been disrupted, restoring appropriate fire regimes may help maintain soil communities adapted to periodic disturbance. In ecosystems where severe wildfires are novel disturbances, active management of soil biological communities may be necessary to support ecosystem recovery and prevent long-term

Immediate fire effects on soil fauna

Wildfire creates severe thermal stress that directly affects soil organisms through heat penetration and habitat destruction (DeBano et al. 1998). The immediate effects vary significantly with fire intensity, duration, and soil characteristics. Surface-dwelling fauna experience the most severe impacts, with mortality rates often exceeding 90% in the upper soil layers (Wikars and Schimmel 2001).

Temperature profiles during fire events show rapid increases that can exceed lethal thresholds for most soil organisms (Fig. 2). While temperatures at the soil surface can reach 800°C during intense fires, the buffering effect of soil typically limits temperature increases to 60-80°C at 5 cm depth (Campbell et al. 1995). Different taxonomic groups exhibit varying susceptibility to fire disturbance. Table 1 summarises the typical responses of major soil faunal groups to wildfire.

Vertical distribution changes

Fire impacts create distinct vertical gradients in soil faunal communities. Surface litter and organic horizons experience the most severe effects, while deeper mineral soil layers often serve as refugia (Malmström 2010). This vertical stratification becomes particularly important for understanding recolonisation patterns and community recovery trajectories.

IMPACT ON HETEROGENEOUS LANDSCAPE PATTERNS

Fire severity gradients

Wildfires create heterogeneous landscapes with varying fire severity patterns (Fig. 2), which

Table 1. Response patterns of major Multi-Trophic soil community to wildfire (after DeBano et al. 1998)

Taxonomic group	**Immediate impact**	**Recovery time**	**Key factors affecting recovery**
Collembola	Severe reduction (70-95%)	2-5 years	Fire severity, soil depth, vegetation recovery
Acari	Moderate to severe (50-90%)	1-3 years	Species-specific heat tolerance
Nematodes	Variable (20-80%)	6 months-2 years	Soil moisture, organic matter
Enchytraeids	Severe reduction (80-95%)	3-7 years	Soil pH changes, organic matter
Coleoptera larvae	Severe reduction (85-99%)	2-4 years	Habitat availability, dispersal ability
Diptera larvae	Moderate (40-70%)	6 months-1 year	Opportunistic colonization

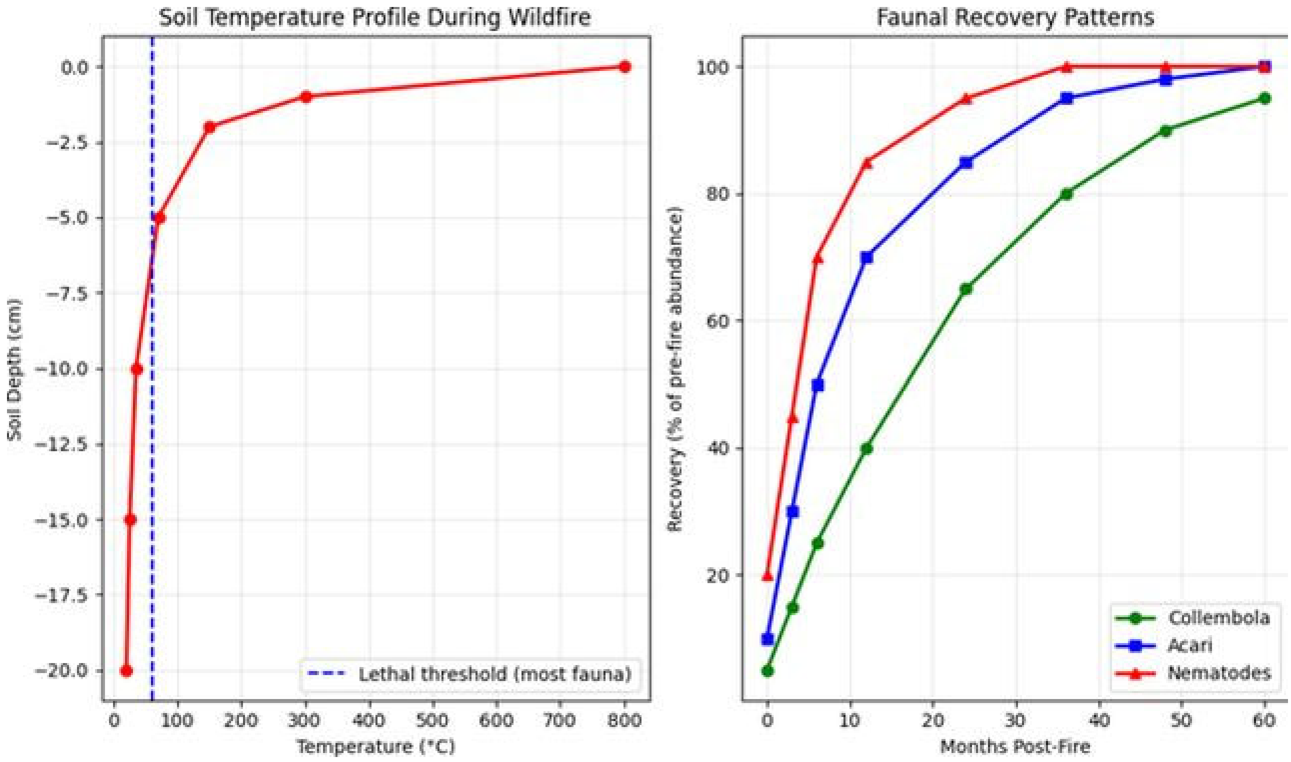

Figure 2. Soil temperature profiles during wildfire (After Campbell et al. 1994)

profoundly influence soil faunal communities (Turner et al. 1997). This heterogeneity arises from complex interactions among topography, fuel load, weather conditions, and fire behaviour. The resulting mosaic of burned and unburned patches creates diverse microhabitats that support different assemblages of soil organisms.

High-severity burn areas typically experience complete vegetation removal and significant soil heating, resulting in the near-complete elimination of surface-dwelling fauna (Penman et al. 2011). Moderate-severity areas maintain some vegetation structure and experience less soil heating, resulting in intermediate levels of faunal mortality. Low-severity burns and unburned patches serve as crucial refugia that facilitate recolonisation of severely burned areas.

Edge effects and connectivity

The spatial arrangement of burned and unburned patches creates significant edge effects that influence soil faunal recolonisation (Moretti et al. 2004). Areas adjacent to unburned patches typically recover faster due to immigration from refugial populations. The connectivity between these patches determines the rate and success of recolonisation processes.

Microhabitat diversity

Post-fire landscapes exhibit increased microhabitat diversity due to the removal of vegetation and exposure of mineral soil surfaces (Swanson et al. 2011). This creates opportunities for pioneer species and alters the competitive dynamics among soil organisms. Charcoal deposits, ash layers, and altered soil chemistry contribute to novel habitat conditions that may favour different faunal assemblages.

SOIL FAUNAL ACTIVITY CHANGES POST-FIRE

Fire disturbance significantly alters soil faunal activity patterns through multiple mechanisms. Direct thermal stress causes immediate mortality, while indirect effects include habitat modification, changes in food resources, and modified soil physical and chemical properties (Certini 2005). Surviving organisms often exhibit altered metabolic rates and behavioural patterns as they adapt to post-fire conditions. The functional diversity of soil communities undergoes significant changes following fire events. Table 2 presents the typical changes in functional group composition and activity levels.

Post-fire soil faunal activity exhibits distinct temporal patterns influenced by environmental conditions and resource availability (Wikars and Schimmel 2001). Initial activity levels remain extremely low due to high mortality and harsh environmental conditions. Recovery begins with the establishment of microbial communities, followed by rapid colonisation by opportunistic species (Fig. 3).

LOSS OF SUBTERRANEAN BIODIVERSITY

Species extinction and local extirpation

Wildfires can cause significant losses in subterranean biodiversity, particularly affecting endemic and specialised species with limited dispersal abilities

Table 2. Changes in soil faunal functional groups post-wildfire (after Certini 2005)

Functional group	Primary function	Fire impact	Activity change	Recovery pattern
Decomposers	Organic matter breakdown	Severe decline	-80 to -95%	Gradual, 2-5 years
Predators	Population regulation	Moderate decline	-60 to -85%	Variable, 1-3 years
Fungivores	Fungal regulation	Initial decline, then increase	-70%, then +50%	Rapid, 6-18 months
Bacterivores	Bacterial regulation	Moderate decline	-40 to -70%	Rapid, 3-12 months
Herbivores	Root/shoot consumption	Severe decline	-85 to -99%	Slow, 3-7 years

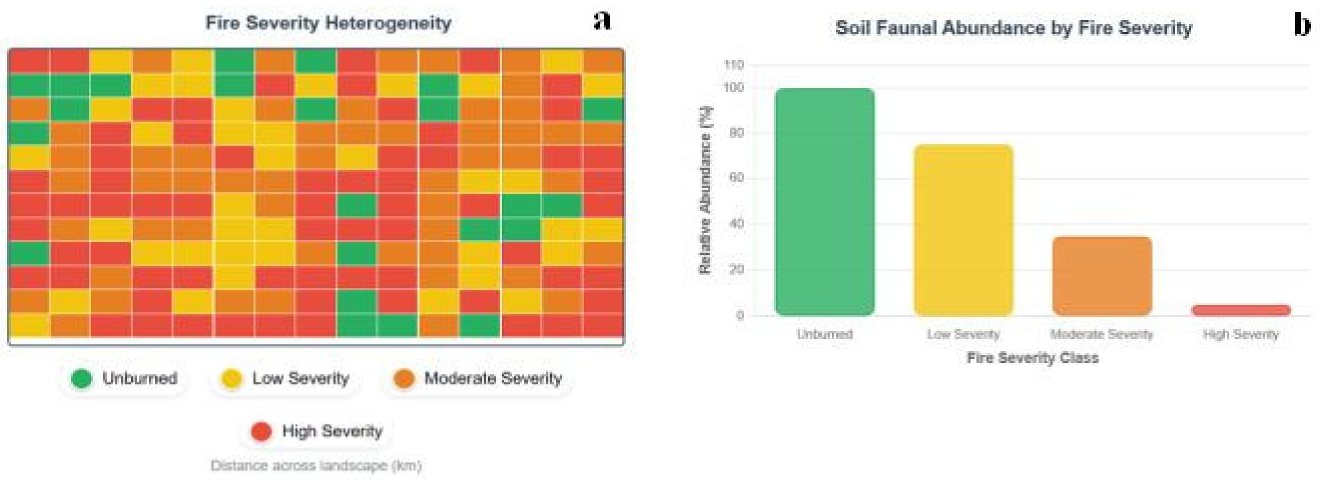

Figure 3. Heterogeneous fire effects on the landscape (after Wikars and Schimmel 2001)

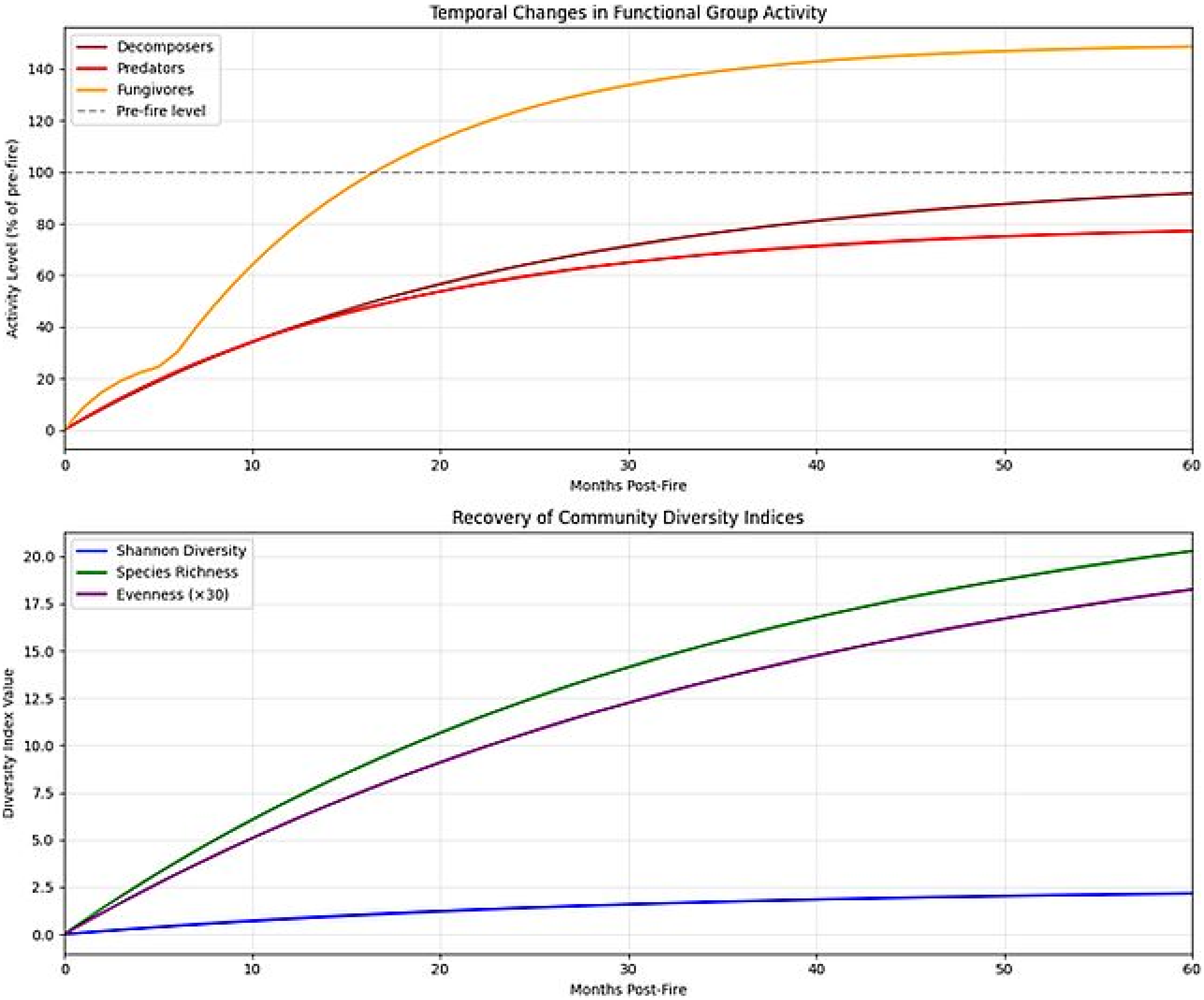

Figure 4. Temporal changes in soil faunal activity (after Harvey et al. 2011)

(Malmström, 2010). Local extirpations are common, especially for species adapted to stable soil conditions and specific microhabitat requirements. Endemic soil arthropods and highly specialised predators face the most significant extinction risk due to their narrow ecological niches and limited mobility (Fig. 4).

Rare and endemic species vulnerability

Rare and endemic soil fauna species are disproportionately affected by wildfire due to their restricted distributions and specialised habitat requirements (Harvey et al. 2011). These species often lack the dispersal capabilities necessary for rapid recolonisation. They may require decades for population recovery (Fig. 5). The loss of these species can have cascading effects on ecosystem functioning and stability.

Genetic diversity impacts

Fire-induced population bottlenecks can significantly reduce genetic diversity within surviving populations (Banks et al. 2011). This genetic erosion may compromise the long-term viability of populations and their ability to adapt to future environmental changes. Small, isolated populations are particularly vulnerable to genetic drift and inbreeding depression (Fig. 5).

RECOVERY MECHANISMS AND PATTERNS

Soil faunal recovery following wildfire occurs through multiple pathways, including survival in refugia, immigration from unburned areas, and aerial

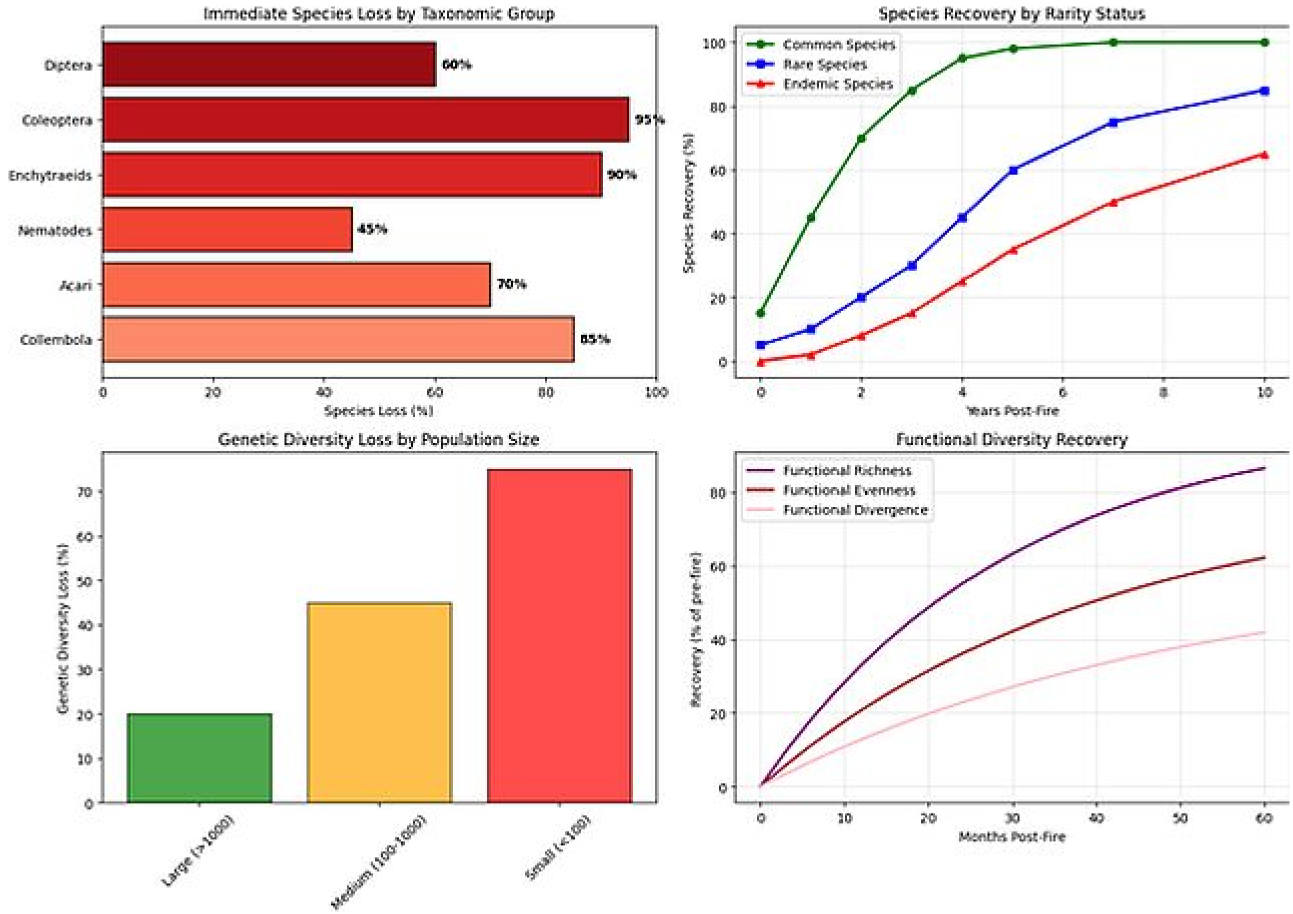

Figure 5. Biodiversity loss patterns (after Banks et al. 2013)

dispersal (Moretti et al. 2004). The relative importance of these pathways varies among taxonomic groups and depends on fire severity, landscape connectivity, and species-specific dispersal abilities.

Post-fire succession in soil communities follows predictable patterns, with opportunistic species typically dominating early stages and specialist species returning in later stages (Wikars and Schimmel 2001). High population growth rates, broad ecological tolerances, and effective dispersal mechanisms often characterise pioneer communities. Table 3 shows that multiple factors influence the rate and trajectory of soil faunal recovery, including fire severity, soil properties, climate conditions, vegetation recovery, and landscape connectivity.

ECOSYSTEM FUNCTIONING IMPLICATIONS

The loss of soil fauna has a significant impact on nutrient cycling processes, as these organisms play crucial roles in decomposition, mineralisation, and nutrient transport (Bardgett and van der Putten 2014). Reduced faunal activity can lead to slower decomposition rates and altered nutrient availability, which may impact plant recovery and ecosystem productivity.

Soil fauna contribute significantly to soil structure through bioturbation, aggregate formation, and pore creation (Lavelle et al. 1997). Fire-induced faunal losses can lead to reduced soil porosity, altered water infiltration rates, and increased susceptibility to erosion. These changes may persist for years or even decades, significantly impacting the long-term stability of ecosystems (Table 3).

Soil fauna mediate meaningful plant-soil interactions through herbivory, seed dispersal, and modification of rhizosphere conditions (Wardle et al. 2004). Disruption of these interactions can affect plant establishment and succession patterns, creating feedback loops that influence the trajectories of ecosystem recovery and regeneration.

Table 3. Factors influencing soil faunal recovery post-wildfire (after Moretti et al. 2004)

Factor category	Specific factors	Effect on recovery	Mechanism
Fire characteristics	Severity, Duration, Season	Strong negative correlation	Direct mortality, habitat destruction
Soil properties	Depth, Texture, Organic matter	Moderate positive correlation	Refugia availability, resource provision
Climate	Precipitation, Temperature	Strong positive correlation	Moisture availability, thermal stress
Vegetation	Recovery rate, Plant diversity	Strong positive correlation	Habitat structure, food resources
Landscape	Connectivity, Patch size	Moderate positive correlation	Immigration potential, source populations

MANAGEMENT IMPLICATIONS AND CONSERVATION STRATEGIES

Effective management of soil faunal diversity requires proactive planning that considers fire risk and potential impacts on the soil faunal diversity. Maintaining habitat heterogeneity, preserving refugial areas, and reducing fire severity through fuel management can help minimise biodiversity losses (Penman et al. 2011).

Post-fire restoration efforts should consider the recovery needs of soil fauna, including the protection of surviving populations, facilitation of recolonisation, and restoration of habitat conditions (Neary et al. 1999). Strategies include erosion control, the addition of organic matter, and maintaining landscape connectivity. Long-term monitoring programs are crucial for understanding the impacts of fires and their recovery patterns. Standardised sampling protocols and indicator species can help track ecosystem recovery and inform adaptive management strategies (Moretti et al. 2004).

RESEARCH GAPS AND FUTURE DIRECTIONS

There is a critical need for long-term studies that track soil faunal recovery over decades rather than years. Most current studies focus on short-term responses, limiting our understanding of complete recovery trajectories and potential alternative stable states. The interaction between wildfire and climate change represents a significant research frontier. Understanding how changing fire regimes and climatic conditions will affect soil biodiversity is crucial for predicting future ecosystem states. Advanced molecular techniques provide new opportunities to study cryptic species, changes in genetic diversity, and microbial community responses to fire. These approaches can provide insights into processes that are difficult to detect using traditional methods.

CONCLUSIONS

Wildfire represents a significant disturbance affecting soil faunal communities worldwide, with impacts that vary considerably across taxonomic groups, spatial scales, and temporal dimensions. This review demonstrates that while fire causes severe immediate losses in soil biodiversity, recovery patterns are complex and influenced by multiple interacting factors. The multi-trophic nature of soil communities creates cascading effects that can persist for years or decades following fire events.

Key findings include: (1) immediate fire effects cause severe mortality in surface-dwelling fauna while deeper soil layers provide refugia; (2) fire creates heterogeneous landscapes that influence recolonization patterns and community assembly; (3) functional group responses vary significantly, with some groups showing rapid recovery while others require years to decades for population restoration; (4) rare and endemic species face disproportionate extinction risks due to limited dispersal abilities and specialized habitat requirements.

Understanding these patterns is crucial for developing effective conservation strategies and predicting the responses of ecosystems to increasing fire frequencies under climate change. Future research should focus on the long-term dynamics of recovery, interactions with climate change, and the development of management strategies that promote soil biodiversity conservation in fire-prone ecosystems.

The conservation of soil biodiversity in fire-prone landscapes requires integrated approaches that consider both the immediate effects of fire and the long-term recovery processes. This includes maintaining landscape connectivity, protecting habitats, and implementing restoration strategies that facilitate natural recovery processes.

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