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A Review of Wildfire Effects on Forests Soil Properties in China

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Abstract: The increasing frequency and intensity of wildfires pose significant threats to forest ecosystems, particularly in China's diverse climatic regions. This review focuses on the impacts of wildfires on forest soil properties in China, highlighting changes in soil physiochemical properties, nutrient cycles, enzyme activities, and microbial communities. Wildfires often lead to the loss of soil organic matter, disruptions in nutrient availability, and alterations in microbial dynamics, which are essential for nutrient cycling and ecosystem recovery. The severity of these impacts is closely linked to fire intensity, soil depth, and post-fire management practices. While short-term recovery of soil properties is possible, long-term effects on soil health, especially on microbial diversity and nitrogen cycling can persist for years. This review underscores the importance of region-specific research and long-term monitoring to better understand the complex interactions between soil and vegetation post-fire. Future research should focus on the influence of climate change on wildfire patterns, the role of innovative restoration techniques, and the development of comprehensive management strategies tailored to China's unique forest ecosystems.

Keywords: wildfire, forest soil properties, soil microbial communities, nutrient cycling, ecosystem recovery.

1. Introduction

Wildfires are increasingly recognized as a critical factor shaping forest ecosystems worldwide, particularly under the influence of climate change[1,2,3]. In China, forests play a vital role in maintaining ecological balance, supporting biodiversity, and contributing to global carbon cycles[4,5]. However, with the rising frequency and intensity of wildfires, the impacts on forest soil properties in China have garnered significant attention[6]. Forest soils are not only fundamental to plant growth but also central to nutrient cycling, microbial activity, and ecosystem recovery after fire disturbances[7].

Soil serves as the foundation of forest ecosystems, providing essential nutrients and physical support for plant life[8]. It regulates water availability, stores organic matter, and sustains a complex network of microorganisms that drive nutrient cycling[9,10,11]. The interactions between soil, plants, and microorganisms are crucial for maintaining ecosystem stability and resilience, particularly in the face of disturbances such as wildfires[12,13,14]. Transformations in soil characteristics, including alterations in nutrient composition, structure, or microbial diversity, can exert significant and

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enduring effects on forest regeneration and overall ecosystem health[15,16,17]. Wildfires disrupt this delicate balance by altering the physical and chemical properties of the soil. In particular, the combustion of organic matter during fires can lead to significant losses in soil carbon and nitrogen, which are essential for plant growth and microbial activity[18]. In addition, fire-induced changes in soil pH and moisture content can influence the composition and function of microbial communities, further affecting nutrient availability and soil health. Soil enzyme activities, which are critical for the decomposition of organic matter and nutrient cycling, are also highly sensitive to fire-induced changes in temperature and soil structure[19]. The recovery of soil health after a wildfire, therefore, plays a pivotal role in determining the speed and success of ecosystem recovery.

The unique geographical and climatic conditions in China—ranging from the subtropical forests in the south to the cold-temperate forests in the north—result in varied responses to wildfires. Pine forests, especially those in northern China, are particularly susceptible to fire due to their resin-rich composition, which increases flammability. The effects of wildfires on forest soils in China include alterations in soil carbon and nitrogen cycles, changes in moisture levels, pH shifts, and disruptions to soil enzyme activities and microbial communities[20]. These impacts have cascading effects on vegetation recovery, long-term soil health, and ecosystem resilience[21].

Given the increasing frequency of wildfires in China, understanding their impact on soil properties is essential for developing effective management and restoration strategies. Current research has predominantly focused on short-term impacts, but there is a growing need for long-term studies that investigate the complex interactions between soil and vegetation post-fire. The objective of this review is to synthesize recent findings on the effects of wildfires on soil properties in China's forests, highlighting the challenges and opportunities for future research and management.

2. Material and methods

2.1. Literature Search Strategy

The article for this review was sourced primarily from the Web of Science Core Collection (SCI-E), using the keywords “wildfire,” “soil properties,” and “China”. The search was limited to articles published from 2010 onwards to focus on recent developments in the field. The search aimed to identify research articles specifically examining the effects of wildfires on soil properties within China. Boolean operators (AND, OR) were applied to refine the search results and ensure that all relevant studies were included. All of the articles were in English. Studies from the last 20 years were prioritized to focus on recent developments in the field.

2.2. Inclusion and Exclusion Criteria

A total of 75 articles were initially retrieved. One thesis was excluded due to restricted access, leaving a final selection of 74 articles. The inclusion criteria focused on peer-reviewed journal articles that explored the relationship between wildfire disturbances and soil properties such as carbon, nitrogen, pH, and microbial activity. Studies that did not focus on wildfire impacts or did not address soil-related parameters were excluded. Additionally, reviews and articles that did not provide empirical data or lacked methodological detail were not considered.

2.3. Data Extraction and Analysis

For each included article, key information was extracted, including the study’s geographical location, soil properties analyzed, fire intensity, and the specific effects of wildfires on soil conditions. These studies were then categorized based on the soil properties they investigated and the specific impacts reported. The extracted data were synthesized to identify common trends, knowledge gaps, and

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variations across different regions and fire intensities in China. This synthesis forms the basis of the comparative analysis presented in this review. To ensure the review was comprehensive yet focused, specific inclusion and exclusion criteria were applied. Studies that directly investigated the effects of fire on soil physical and chemical properties, soil microbial communities, and plant traits were included. These included both empirical research articles and review papers. Excluded from the review were studies that did not focus on fire disturbances or soil and plant interactions, as well as articles that were not peer-reviewed or lacked sufficient methodological details. Older studies published before the year 2010 were excluded unless they were considered foundational or highly cited in recent research.

3. Results and Discussion

3.1. Increasing Publications on “wildfire” and Research Focus

In recent years, with the increasing frequency of climate change and extreme weather events, the impact of wildfires on ecosystems has attracted growing attention. In particular, wildfire research in China has made significant progress, as reflected in the steady rise of published literature in the field from 2014 to 2023 (Figure 1), indicating sustained interest and research investment. From 2014 to 2020, the number of published articles remained relatively stable, averaging 2 to 3 articles per year. Although early research was somewhat limited, there has been a growing interest in studying the impact of wildfires on soil physiochemical properties and ecosystems. By 2021, the number of published articles had risen significantly to 6, followed by 13 articles in 2022 and 23 in 2023. This upward trend reflects China's increasing research focus on fire ecology, particularly in areas such as the effects of wildfires on soil microbial communities, nutrient cycles, and vegetation recovery. This rapid increase not only highlights the growing emphasis on wildfire science but also demonstrates China's policy direction in addressing climate change and wildfire risks. Globally, researchers are increasingly focusing on the long-term effects of wildfires on soil systems, employing multidisciplinary approaches to address ecological restoration and soil management challenges.

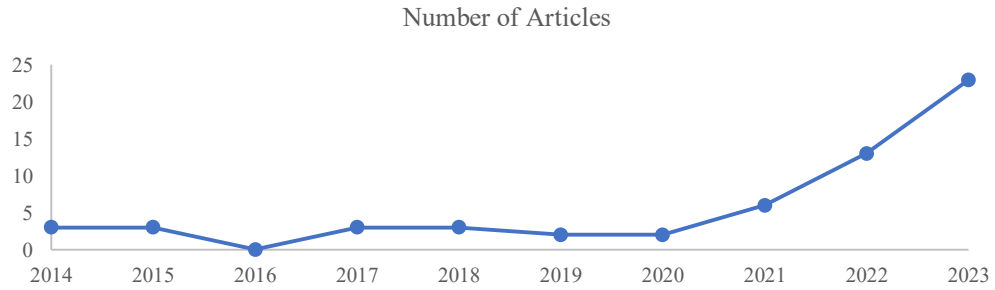


Figure 1: The number of articles on the topic of “wildfire” published from 2014 to 2023 in China.

The soil environment generally refers to the continuous layer of soil covering the Earth's land surface, which is shaped by the combined effects of climate, organisms, topography, parent material, and time[22]. In the context of China’s diverse landscapes and forest ecosystems, the impacts of wildfires on soil properties are especially important due to the unique climatic and ecological conditions found across different regions[23]. Depending on the research focus, the indicators used to evaluate soil environments can vary. In most studies related to China’s forest ecosystems, soil physiochemical properties, nutrient cycle, enzymes and microorganisms are considered critical due to their direct influence on vegetation recovery after wildfires[24]. Recent research on wildfire effects in China has made significant progress, particularly in understanding how fire disturbances alter the soil environment. The following sections will examine the relationship between wildfire disturbances

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and soil properties in China, with a particular focus on four key areas: soil physiochemical properties, nutrient cycles, enzyme activities, and microbial communities. These aspects are crucial for understanding how wildfires affect soil health, nutrient availability, and the long-term recovery of forest ecosystems in China.

3.2. Wildfire Effects on Soil Physiochemical Properties

Wildfires have been demonstrated to result in substantial disruptions to soil moisture levels, which in turn affect the hydrological balance of forest ecosystems. Research by Shi et al. on the dynamics of forest fuels in Xiuwu, Henan, highlighted that wildfire-induced reductions in soil moisture are exacerbated by the increased presence of dry, flammable organic matter, which decreases the soil's water-holding capacity and accelerates evaporation[25]. Li et al. found that wildfires accelerate permafrost thawing, leading to changes in the hydrological cycle[26]. In their study of the permafrost in the Qinghai-Tibet Plateau, the degradation of permafrost after wildfire events increased soil drainage and reduced moisture retention, ultimately affecting vegetation regeneration. This is especially critical in high-altitude regions where the loss of soil moisture can have cascading effects on soil structure and water availability. Moreover, Cheng et al., studying light and moderate fire sites in taiga forests of northeastern China, noted that arbuscular mycorrhizal fungi (AMF) diversity and soil moisture were closely linked[27]. Post-wildfire reductions in soil moisture significantly altered the microbial environment, further destabilizing the soil ecosystem. As AMF is crucial for plant nutrient uptake, the decreased soil moisture impeded the recovery of the forest ecosystem, particularly in regions affected by moderate fires. In conclusion, wildfires drastically reduce soil moisture, with long-lasting impacts on ecosystem recovery. Effective management strategies that focus on mitigating moisture loss are essential for promoting the regeneration of fire-affected forests and maintaining long-term soil health.

Meanwhile, wildfires can lead to significant alterations in soil pH, with the effects varying over time as ecosystems recover. In the early stages of recovery, the hydrolysis of alkaline cations in ash produced by the fire typically results in an initial increase in soil pH, making the soil more alkaline. However, as recovery progresses, Li et al. found that soil pH decreased significantly and eventually became acidic[28]. This shift was attributed to enhanced root respiration in recovering plant communities, the increased release of organic acids from plant roots, and the microbial decomposition of dead plant material. In their study on forest fire smoke deposition, Zhu et al. noted that while smoke deposition did not lead to significant pH changes, it altered other soil properties such as carbon and nitrogen content, which may indirectly affect soil acidity in the longer term[29]. In contrast, Zhao et al. demonstrated that elevated temperatures during wildfires in contaminated soils increased soil pH due to the decomposition of organic matter and changes in the mobility of heavy metals such as chromium[30]. This resulted in a shift toward more alkaline soil conditions, particularly in areas with high fire intensity. Overall, the effects of wildfires on soil pH are complex and depend on multiple factors, including fire intensity, soil type, and the stage of ecosystem recovery.

3.3. Wildfire Effects on Soil Nutrients Cycle

Wildfires are typically categorized into underground, surface, and crown fires, each impacting the soil environment in different ways[31]. Surface fires, the most common type, primarily affect the soil by altering the availability of key nutrients such as carbon and nitrogen. High-intensity fires can significantly disrupt nutrient cycles, depleting soil organic matter and leading to nutrient losses through volatilization and erosion. As a critical component of ecosystem recovery, these nutrients play a vital role in supporting post-fire vegetation regrowth and maintaining soil fertility.

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Wildfires play a critical role in the dynamics of soil carbon (SOC), often causing both immediate carbon losses through combustion and long-term changes to carbon cycling in affected ecosystems. Research from boreal forests in northeastern China demonstrates that the loss of SOC after a wildfire can be significant, particularly in surface soil layers. Weng et al. reported that in the Dahurian larch forests, fires reduced water-soluble organic carbon (WSOC) concentrations in the litter layer, with recovery dependent on the time since the fire event and post-fire ecological succession[32]. This study highlights that WSOC in the Oi layer of the litter was particularly affected, emphasizing the critical role of post-fire vegetation dynamics in regulating soil carbon recovery[32]. Additionally, the research conducted by Zhang et al. in wildfire-perturbed soils observed that pyrogenic organic matter (PyOM) plays a significant role in post-fire carbon stabilization[33]. The PyOM produced during wildfires contributed to the formation of heterogenous microhabitats, which in turn influenced bacterial community assembly and carbon dynamics in these soils. The presence of PyOM not only increased soil organic carbon stability but also contributed to the long-term retention of carbon in the ecosystem. In contrast, Qin and Liu documented significant losses in SOC following severe wildfires in the artificial *Pinus tabulaeformis* forests of North China[34]. Their study found that SOC losses were particularly pronounced in the top 5 cm of soil, with the post-fire recovery period extending beyond the first rainy season. These findings underline the variable impact of wildfires on soil carbon across different ecosystems and underscore the need for targeted post-fire management strategies to support soil carbon recovery.

Wildfires significantly disrupt nitrogen (N) dynamics in forest ecosystems, leading to both immediate nitrogen losses through volatilization and longer-term alterations in nitrogen cycling. Research conducted in different regions of China reveals that the recovery of soil nitrogen after wildfires is a slow and complex process, with factors such as fire intensity, soil texture, and post-fire ecosystem management playing critical roles. In a study conducted by Kang et al. on cold-temperate coniferous forests in northeastern China, it was found that nitrogen forms such as ammonium (NH_4^+-N) and nitrate (NO_3^--N) were significantly affected by fire[35]. Ammonium levels initially spiked following the wildfire, reflecting the rapid release of nitrogen from organic matter, but returned to pre-fire levels after nine years. This slow recovery suggests that nitrogen cycling in these ecosystems remains disrupted for nearly a decade, with seasonal fluctuations further modulating nitrogen availability. Similarly, Wang et al. examined nitrogen mineralization processes in boreal forests and discovered that fire had a profound impact on microbial-driven nitrogen retention[36]. Their study highlighted the role of soil texture in nitrogen dynamics, with fine-textured soils retaining more nitrogen compared to sandy soils. This indicates that soil properties, combined with fire severity, significantly influence nitrogen availability and recovery post-fire. Their research also showed that even nine years after a wildfire, soil nitrogen levels remained lower than in unburned areas, emphasizing the long-term consequences of severe fires on nitrogen cycling. The slow recovery of nitrogen suggests that it may take decades for nitrogen levels to fully return to pre-fire conditions, especially in fire-prone regions. In addition to soil processes, Huang et al. explored how plants absorb nitrogen directly from wildfire smoke deposition[37]. Their findings demonstrated that plants contribute to nitrogen recovery by absorbing nitrogen compounds from smoke, providing an additional nitrogen input to the post-fire ecosystem. However, the efficiency of this recovery process depends heavily on the intensity of the fire and subsequent ecosystem management practices. Overall, these studies underscore the complexity of nitrogen dynamics following wildfires. While nitrogen is initially lost through volatilization, long-term recovery depends on various factors, including soil texture, microbial activity, and the regrowth of vegetation, making post-fire management crucial for restoring nitrogen balance in forest soils.

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3.4. Wildfire Effects on Soil Enzyme Activity

Wildfires significantly influence soil enzyme activities, which are essential for nutrient cycling and overall soil health. Enzymes such as β-glucosidase, urease, and acid phosphatase are crucial indicators of soil microbial activity and the biochemical processes occurring in post-fire environments. Hu et al. conducted a study on subtropical-warm temperate forests and found that post-fire soil extracellular enzyme activities, including β-glucosidase (involved in carbon cycling), remained suppressed for an extended period after the fire[38]. This suppression was linked to changes in the microbial community structure and a decrease in soil organic matter content. The researchers emphasized that the re-establishment of vegetation played a critical role in gradually restoring enzyme activities, as vegetation regrowth provided fresh organic matter to the soil, supporting microbial recovery. In a related study, Yang et al. explored the successional trajectories of fungal communities in cold-temperate forest soils following wildfire[39]. They observed that soil enzyme activities were heavily affected across different soil horizons, with surface layers showing the most significant reductions. However, enzyme activities in deeper soil layers exhibited greater resilience and recovered faster. The study highlighted the importance of fungal community recovery in driving the restoration of enzyme functions, which are critical for nutrient cycling, particularly in the deeper soil layers. Earlier research by Xue et al. in a Pinus massoniana forest in South China revealed that wildfire caused a sharp decline in soil enzyme activities immediately after the fire[40]. Urease activity, essential for nitrogen cycling, decreased by 53% to 65%, while acid phosphatase activity, crucial for phosphorus cycling, dropped by 59% to 66%. These declines were primarily attributed to the loss of organic matter and microbial biomass caused by the intense heat. Despite partial recovery over the subsequent seven years, enzyme activities did not fully return to pre-fire levels, indicating long-term impacts on soil health. In conclusion, wildfires result in substantial, long-lasting reductions in soil enzyme activities. The recovery of these enzymes depends heavily on microbial community resilience and vegetation regrowth, both of which are vital for re-establishing nutrient cycling in post-fire ecosystems.

3.5. Wildfire Effects on Soil Microbial Community

Wildfires have profound and often long-lasting effects on soil microbial communities, which play a key role in nutrient cycling and ecosystem recovery. The changes in soil properties, such as pH, nutrient availability, and organic matter content, induced by wildfires, can drastically reshape microbial populations, leading to both immediate losses and long-term shifts in microbial structure and function. Liu et al. investigated the impact of wildfire-perturbed soil environments on bacterial communities in *Pinus tabulaeformis* forests in North China[31]. Their research highlighted that the heterogeneity of microenvironments created by wildfire severity had a direct effect on bacterial diversity. They found that bacterial phyla such as *Acidobacteriota* and *Actinobacteriota* responded differently to fire-induced changes in soil pH and nutrient levels. Fire intensity and soil depth were critical factors in determining the resilience and recovery of these bacterial communities. In grassland ecosystems, Mao et al. observed that fire-induced nutrient loss led to significant changes in microbial community composition[41]. The redistribution of key bacteria involved in nitrogen cycling was particularly affected, which, in turn, influenced plant growth and overall ecosystem function. This study underscored the dual role of fire in both reshaping aboveground vegetation and altering belowground microbial dynamics, showing the interconnectedness between soil microbes and nutrient availability. Qin et al 2021 explored the effect of wildfire on microbial communities across different soil depths in North China's *Pinus tabulaeformis* forests[34]. They found that microbial diversity was most severely impacted in the topsoil layers immediately following the fire, with significant reductions in bacterial populations. However, subsoil microbial communities

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demonstrated greater resilience, with a gradual recovery over time as environmental conditions stabilized. Their study emphasized that the effects of fire on microbial communities are highly depth-dependent, with distinct recovery patterns emerging in different soil horizons. In conclusion, wildfires induce complex changes in soil microbial communities, with their effects varying by fire intensity, soil depth, and ecosystem type. The recovery of microbial diversity and function is closely tied to post-fire environmental conditions and management strategies, which are essential for promoting ecosystem resilience and restoring soil health.

4. Conclusion

This review highlights the profound and multifaceted effects of wildfires on forest soil properties in China, particularly in pine-dominated ecosystems. The unique climatic and ecological conditions in China shape the way wildfires influence soil physiochemical properties and nutrient cycles, including, soil moisture, pH levels, carbon and nitrogen content. These alterations have cascading effects on soil enzyme activities and microbial communities, which are critical for nutrient cycling and ecosystem recovery. Research specific to China reveals that while short-term recovery of soil properties may occur, long-term impacts—particularly on nitrogen cycling, microbial diversity, and enzyme activity—persist for years after fire events. The severity of these effects is closely linked to fire intensity, soil texture, and post-fire management practices, all of which are highly variable across China's diverse forest ecosystems. To mitigate the adverse effects of wildfires and promote the recovery of China's forest ecosystems, comprehensive management strategies must be developed. These strategies should be informed by long-term studies that consider the unique characteristics of Chinese forests, the role of human-induced fires, and the interactions between soil and vegetation.

Although significant progress has been made in comprehension of wildfire impacts on forest soils in China, several key areas require further research. Firstly, there is a need for longitudinal studies that monitor the recovery of soil properties over extended periods, particularly in relation to microbial communities and enzyme activities, which play critical roles in ecosystem function. Such studies will help clarify the long-term ecological consequences of wildfires and inform more effective restoration strategies. Secondly, more region-specific studies are necessary to account for China's diverse ecosystems, ranging from the subtropical forests in the south to the cold-temperate forests in the northeast. Research should aim to uncover how different fire regimes influence soil recovery processes in these distinct environments. Lastly, climate change is expected to exacerbate the frequency and intensity of wildfires in China. Future research should investigate how changing fire patterns might interact with soil properties, including carbon sequestration potential and nutrient cycling. Additionally, there is a need to explore novel restoration techniques, such as biochar application or reforestation with fire-resistant species, to enhance post-fire soil resilience. By addressing these research gaps, future studies will provide valuable insights into the complex interactions between wildfires and soil properties, ultimately supporting more sustainable management and conservation efforts in China's forest ecosystems.

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