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Abstract

The impacts of wildfire on vegetation and soil erosion have been studied for decades aiming to bring back ecosystems after fire perturbance. However, the influence of fires on above and belowground biodiversity remains far less understood. Biodiversity is critical for supporting ecosystem function, and this data scarcity is hampering managers in adopting effective practices for a proper restoration of burned ecosystems. This limitation could be overcome by future research that should focus post-fire diversity of plants and soil biota, by (i) analysing the environmental factors driving post-fire evolutionary trends; (ii) exploring their interrelations across different spatial and temporal scales; (iii) identifying the variability across fires of different severities and frequency; (iv) ascertaining the post-fire response of individual plant species and soil taxa to fire with or without application of post-fire restoration actions.

Keywords: Plant diversity; soil microbiomes; fire disturbance; post-fire evolutionary trend; ecosystem restoration strategies

1. Ecosystems in a context of fires and global change

Fires are large ecosystem engineer's naturally shaping the biodiversity and function of terrestrial ecosystems worldwide (Pellegrini et al., 2018; Feng et al., 2021). Human influence has further stoked these fires through the interaction of land abandonments and fuel accumulation with warming and drought-associated climatic changes. As such, more severe and frequent fires are expected over the next decades with still poorly described consequences for the maintenance of terrestrial ecosystems, and the multiple ecosystem services they provide to humankind. From experiments and observational studies, we know that fires can affect almost all components of agro-forest ecosystems, such as soil, vegetation, air, and surface and water (Niemeyer et al., 2020). However, much less is known about the influence of fires on the biodiversity of above and belowground communities.

Vegetation, topography and climatic conditions as well as the burning dynamics generate spatial and temporal variations in landscape with fire-related patches, which produce a biological and environmental heterogeneity driving plant biodiversity at the local scale (He et al., 2019). Thus, the influence of fire on ecosystems depends on its characteristics, environmental conditions of the burnt areas, and post-fire weather dynamics (Bodí et al., 2012), and these changes can be transient or permanent depending on fire severity and frequency (Caon et al., 2014). Burning removes ground vegetation and litter cover, and, for high-severity fires, also tree crowns, while high temperatures during burning severely alter the properties of soils compared to the pre-fire conditions (Agbeshie et al., 2022). The strong impacts of fire on physical, chemical and biological characteristics of soil produce huge effects on short- to medium-term soil biodiversity (Lopes et al., 2020), including microbial communities and processes. These still poorly understood fire-induced changes in plant and soil dynamics play an essential role in ecosystem services, including water resource availability, quality of water bodies, erosion and flood control, and biodiversity maintenance (Vieira et al., 2018).

In this letter, we discuss new research directions toward a better understanding of the future and recovery of plant and soil biodiversity in a world subjected to more fires of greater intensity, severity and frequency. The information used in this research comes from 466 journal articles we found using the ISI Web of Science and the China National Knowledge Infrastructure database (CNKI) with the following key word combinations: ("fire" or "burn" or "wildfire" or "prescribed fire") and ("soil") and ("carbon" or "nitrogen" or "phosphorus" or "soil respiration" or "nutrient" or "carbon flux" or "soil organic matter" or "SOM decomposition" or "microbial biomass" or "PLFA" or "bacteria" or "fungi" or "biogeochemistry") from 1950 to 2023. According to Labouyrie et al. (2023), vegetation cover, climate and soil properties are the major determinants significantly affecting spatial patterns of microbial communities. Wildfires may directly and indirectly alter vegetation and soil properties (Bodí et al., 2012), thus also modifying soil biology. Both short- and long-term changes on soil environment and microbial communities need to be evaluated along different environmental gradients. This knowledge is critical to ensure the rewilding of ecosystems to support critical ecosystem services such as carbon sequestration, waste decomposition and water and climate regulation.

2. Responses of plant and soil biodiversity to fire

The importance of plant species richness for ecosystem function and sustainability is undoubted, since a variety of species supports a balanced production of food and water for living beings, control of climate and disease, enhancement of nutrient cycles and oxygen production as well as recreational benefits (MEA, 2005). Similarly, soil micro-organisms are essential for decomposition of organic matter (Fairbanks et al., 2020), nutrient cycling and energy flow (Verma and Jayakumar, 2012), plant nutrition and reproduction (Neary et al., 2005) and formation of mutualistic relationships with plant roots that improve their survival (Hart et al., 2005). However, both plants and soil biota are sensitive to environmental changes (Fairbanks et al., 2020), and especially fire is a severe factor of disturbance that decreases diversity of plants and microorganisms (Fig. 1) (Reilly et al., 2006; Sáenz De Miera et al., 2020).

Fires may directly and indirectly affect several ecological mechanisms and plant communities. The way that fire interacts with vegetation and soil is generally function of local conditions as for example forest structure, tree density, fuel moisture, topography and weather conditions (Liang and Hurteau, 2023). While high-severity fires generally homogenise species composition, creating landscapes dominated by disturbance-tolerant or rapidly colonizing species, low severity fires may generate a mosaic of habitats supporting species with different environmental tolerances and dispersal traits (Burkle et al., 2015). For example, Small-scale and patchy low-severity burning (e.g., prescribed fires, increases α-diversity in burned patches, and decreases β-diversity at the landscape level (Zema and Lucas-Borja, 2023)), while general reductions in α-diversity and increases in β-diversity are recorded after high-severity fires (Pastro et al., 2011).

Fire also affects soil microbiome (archaea, bacteria, fungi, and protists) by decreasing biomass and altering community composition of microorganisms (Köster et al., 2021). The impacts of fire on soil biological communities are direct (due to suppression or severe damage of microorganisms) or indirect (due to long-term influences on plant succession and soil transformations) (Alcañiz et al., 2018). These effects are immediate after burning, leading to mortality of microorganisms and shifts in species composition of survivors, due to the direct effect of soil heating when peak temperature of soil noticeably exceeds the range of microbe survival (DeBano et al., 1998). In general, fire impacts on soil biology generally produce modifications of amount and composition of microbial communities, even with a slight stimulation of microbial population size and activity after fire (Neary et al., 2005).

Both impacts on plant and soil biota are extremely site-specific (depending on the pre-fire environmental characteristics), and are affected by a noticeable post-fire variability in space and over time. Therefore, understanding the impacts of fire on plant communities and soil microbial communities is a very hard task, and the complexity of the associated biological processes requires targeted investigation at several temporal and spatial scales.

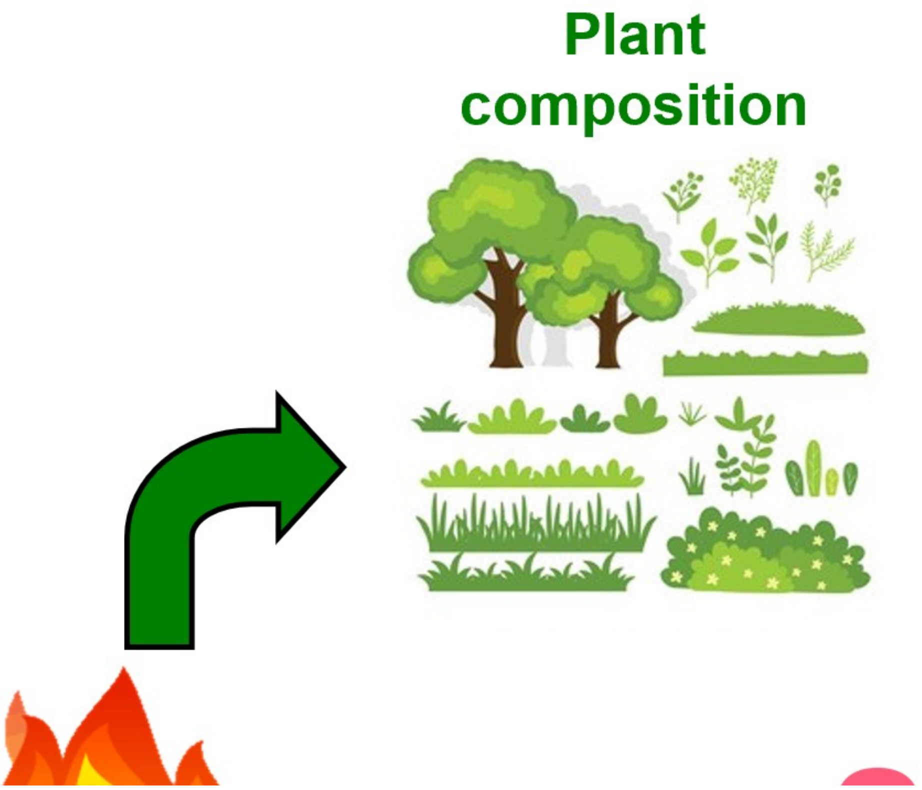

Fig. 1. Research needs for knowing plant and soil biodiversity in post-fire environments.

As a result, land-use changes and disruption of historical fire regimes can alter how climate, fire and vegetation interact going forward. In this context, wildfires may induced changes in different environment characteristics that affect biological organisms by changes in habitats, food supply, competition, and other impacts on post-fire reestablishment and succession of plants and animals (Neary et al., 2005). In fact, wildfires are key factors influencing the creation and maintenance of landscape heterogeneity, with post-fire successional changes influencing vegetation structure and biota for decades or even centuries (Burton et al., 2008). But before wildfire long-term impacts, immediate plant and soil biology changes after fire may play a key role in ecosystems recovery. It has been shown that heating glowing combustion with consequent killing or severe injuries to the organisms could directly trigger great negative effect in wildfire affected ecosystems. Moreover, post-fire ecosystem conditions, a diverse range of outcomes may arise, from almost no change to landscape to very relevant soil erosion events, debris flows and landslides, or even severe floods. The combined effect of wildfire and severe drought or intense rainy events will drive the feedback between the ecosystem functions and fire (Kelly et al., 2020). Increasingly, ongoing climate change is influencing wildfire activity and how fire interacts with the plant and soil ecosystems. Finally, differences among postfire hillslope treatments may also generate changes in the vegetation features, such as plant cover or community composition. By trapping seeds or generating higher soil moisture near the postfire management structures in the treated areas, forest structure after wildfires. But again, plant and soil microorganisms diversity in any given area will be in accordance to different potential drivers such us burnt fuel, weather pattern, soil morphology, plant physiology and evolution of soil-dwelling microorganisms (Jhariya and Raj, 2014).

3. Gaps of knowledge and research needs on post-fire biodiversity

The potential ecological consequences of biodiversity loss have raised considerable interest and controversy. Decreased biodiversity could impair many natural ecosystem functions, such as food production, carbon sequestration and nutrient cycling, which may thus diminish the number and quality of services they provide. Providing empirical evidence of the relationship between above-belowground diversity and functions in highly post-fire ecosystems and across different soil types ranging in biotic and abiotic factors (e.g. pH, texture, etc.) is critical for predicting changes in the soil health and microbial functioning. In general, in-situ persistence of a diversity of soil and plant species will allow ecosystems to properly respond to wildfires and climate change effects, thus providing an opportunity for ecosystem reassembly to occur from remaining soil and plant species (Liang and Hurteau, 2023). However, although we have gained much knowledge about the individual effects of post-fire on biodiversity or ecosystem functions, knowledge about how biodiversity affect multiple ecosystem functions are rare. Indeed, along many different bibliographic research about the wildfire effects on ecosystem features at the global scale made by authors, we have found that, whereas physical and chemical properties of burnt soils are measured in 99.6% and 100.0% of studies, respectively, soil biology is focused only in 38.5% and even plant morphology and diversity in less than 12% of cases (Figure 2).

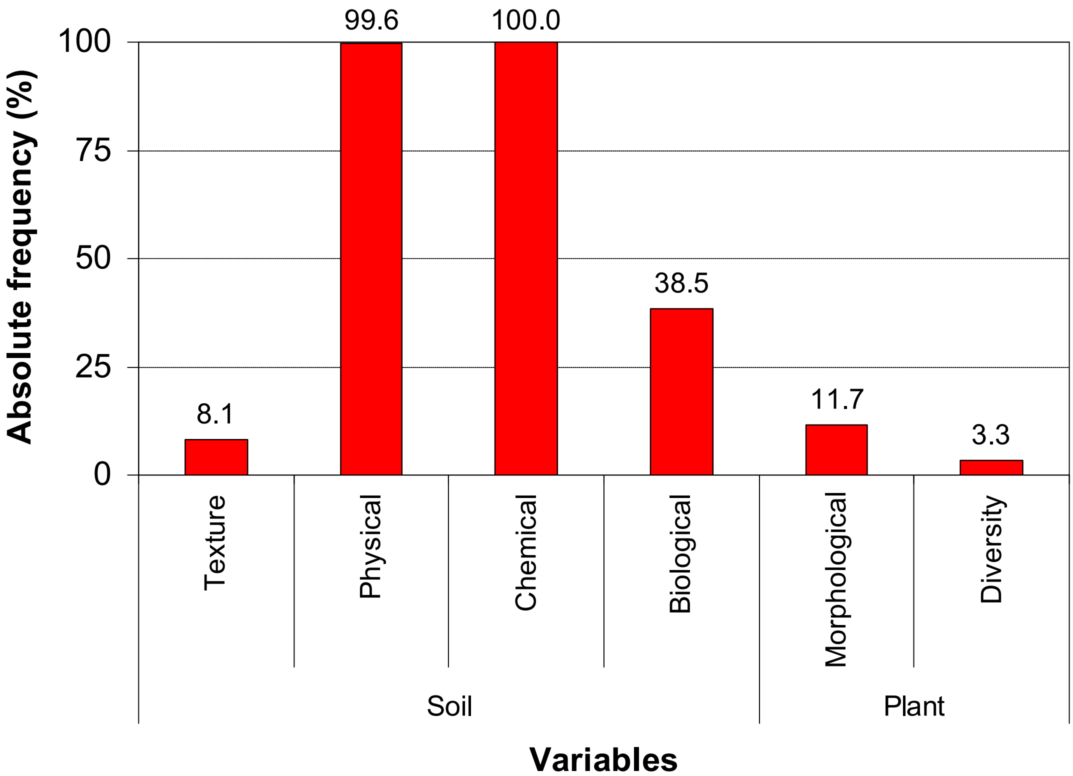

Fig. 2. Absolute frequency of measurements of soil and plant characteristics in 466 academic papers reviewed by the authors (source: Own data).

From above, it results that our capacity to understand the impact of heterogeneity of post-fire biodiversity is limited, since few studies have investigated variations in plant community composition in response to fire (Burkle et al., 2015), and moreover the major differences in species composition due to fire disturbance have not explored in depth (Verma and Jayakumar, 2012). These scarce evidences limit managers in developing fire prescriptions towards a minimization of damage to soil biota (Neary et al., 2005).

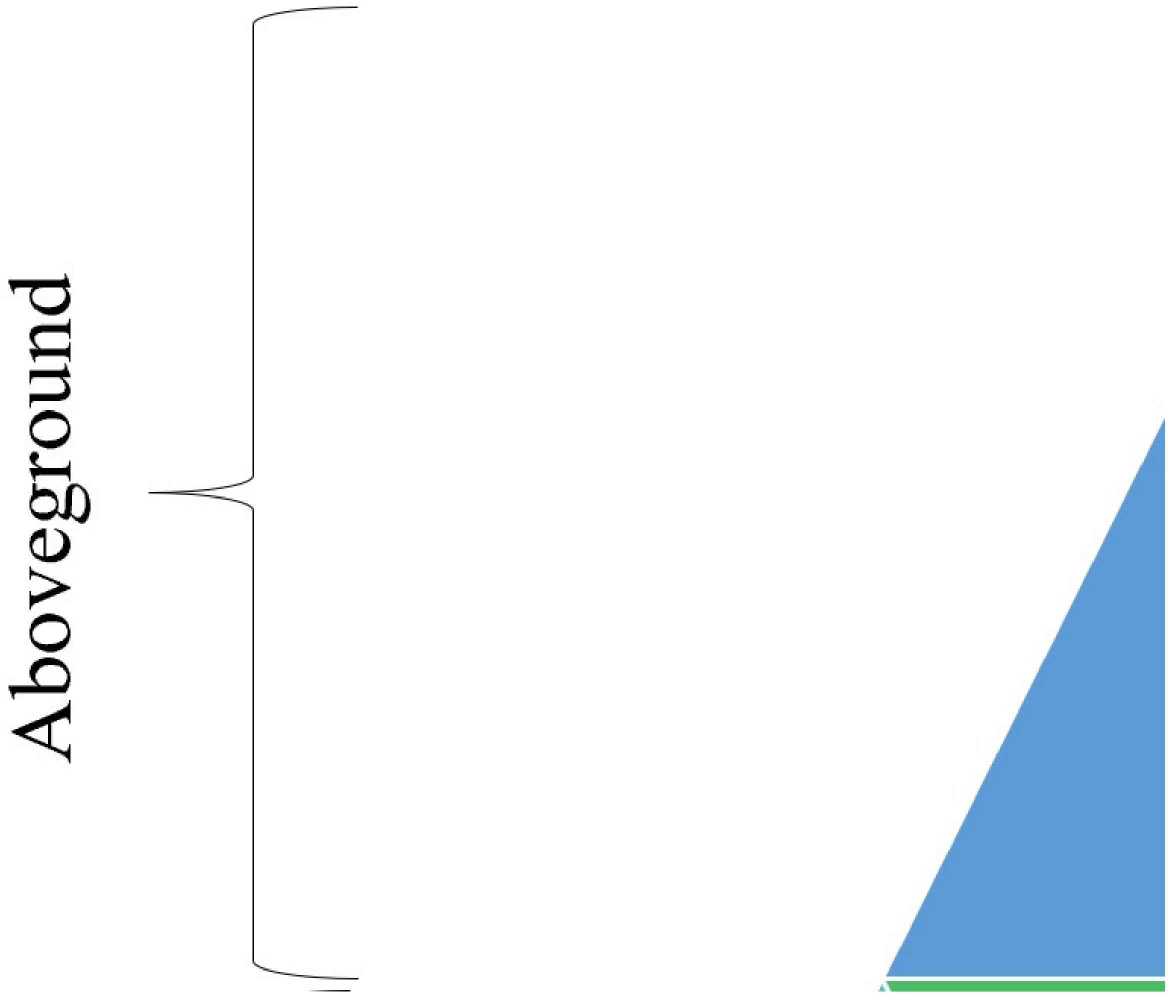

Figure 3 - Example of the indicators found in the bibliographic research on 466 academic articles about the wildfire effects on ecosystem features at the global scale (Source: source: Own data).

Regarding plant diversity, this limited knowledge also affects current fire-management practices, which rarely consider the ecological and evolutionary roles of fire in maintaining biodiversity (He et al., 2019). The response of vegetal species to fire regimes is needed, in order to support an ecologically-sustainable management, but it is essential to understand how the spatial and temporal patterns of fires influences the post-fire regrowth and composition of recruiting plants, and how fire interacts with the other ecological processes (Driscoll et al., 2010). A detailed identification of species with different fire-regime requirements may allow a suitable fire management, indicating which species may support the most rapid and ecologically-effective land restoration processes (He et al., 2019).

Post-fire evolution of soil-dwelling organisms has been even overlooked compared to those on vegetation and wildlife (Certini et al., 2021), and the recovery of microbial communities after fire has not been comprehensively investigated (Dai et al., 2021). It is true that there is a growing number of articles dealing with soil biota evolutionary trends following fire have been published, but the activity and dynamics of soil microorganisms is so complex that many other studies and robust data are needed to infer universal laws, if there are any (Certini et al., 2021).

The fact that fire changes microbial population size and activity has been highlighted in literature, but less knowledge exists about the variability and unpredictability of microbial responses in time and space as well as its dependency on environmental conditions and fire characteristics. For instance, it is known that extremely-intense wildfires play severe and often long-lasting effects on microbial population, while the impacts of low-severity burning are generally much lower and often negligible (Neary et al., 2005). What is lacking is a clear understanding of post-fire size, diversity, and functions of microbial communities after burning at intermediate severity as well as slash-and-burn fires. Another research gap is the knowledge of microbial diversity after single fire events, while the evolutionary trends of soil biota have not analysed in ecosystems affected by recurrent fires and increasing frequency of burning, which is expected to increase considering the forecasted effects of climate change (Certini et al., 2021).

Moreover, the response of soil microorganisms to fire and other environmental stressors is not alike, and past studies have explored the fire effects on microbial life, as the latter was only a function of soil temperature and food availability (Neary et al., 2005). Certini et al., (2021) suggest a long-term and continuous monitoring of post-fire soil biological community (Guerra et al., 2021), extending the investigations to different environments and to as many microbial taxa as possible. These monitoring activities should ascertain: (i) the environmental factors that most affect the post-fire recovery paths of each species as well as community composition (Whitman et al., 2022); (ii) the reciprocal interactions between taxa in the evolutionary phase following fire (Certini et al., 2021); (iii) the identification of key soil bacterial groups that more quickly recover together with the possible restoration actions to enhance this recovery until the pre-fire values (Prendergast-Miller et al., 2017).

4. Concluding remarks

Overall, while an ample body of literature has explored the effects of fire on post-fire vegetation cover dynamics and changes in physico-chemical properties of soil, there is much less knowledge about diversity in vegetation and microbial communities following fire with different severity. Future research activities should be targeted to (i) comprehensive and mechanism-based analysis of environmental factors driving post-fire evolutionary trends of vegetal complexes and microbial communities as well as the resulting effects on abundance and diversity of various plant species and microbial taxa by comparisons between fire-affected and undisturbed sites; (ii) focus these interrelations across different spatial (from individual sampling points to catchment scale) and temporal (seasonal to multi-year observations) scales, in order to capture the relevant variability; (iii) explore the variability of plant and soil diversity to disturbance across fires at different severities as well as frequent burning events; (iv) ascertain the post-fire response of individual plant species and soil taxa to fire under environmental conditions with or without application of post-fire restoration actions, in order to identify the ecological components (tree, shrub and grass varieties as well as microbial taxa) with recovery or survival strategies adapted to fire. Addressing these research needs would support landscape managers in their complex and hard actions towards conservation of pre-fire plant and soil-dwelling communities, and for this purpose research should go beyond scientific publications to reach broader stakeholders' communities, including politicians and media.

Acknowledgments

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