CLIMATE CHANGE, FOOD SECURITY, NATIONAL SECURITY and ENVIRONMENTAL RESOURCES

GLOBAL ISSUES & LOCAL PERSPECTIVES

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous climate change, food security, national security and environmental resources issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which climate change, food security, national security and environmental resources issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue climate change, food security, national security and environmental resources necessary in policy making process that will stimulate increase in food production and environmental sustainability.

Climate Change, Food Security, National Security and Environmental resources: Global issues and Local Perspectives is organized in four parts. Part One deals with Climate Change with Six Chapters, Part Two is concerned with Food Security with Nine chapters, Part Three deals with National Security with Five Chapters, while Part Four pertains Environmental Resources, has Five Chapters.

Ahmed Makarfi / Eteyen Nyong

April 2024

Chapter 3:

A Review of the Impact of Bush Burning on the Environment: Potential Effects on Soil Chemical Attributes

Chiroma, A. M. and Alhassan, A. B.,

Abstract

Bush burning, whether as a result of a wildfire or a controlled burn, has been shown to not only affect the appearance of the landscape but also the quality of the soil as well. Interest in gaining a proper understanding of the impact of fire on the ecosystem is particularly becoming increasingly important in the tropics given the fast-changing climatic regimes associated with climate change. However, climate change-induced changes in atmospheric processes influence the key factors that determine both the severity of fire regimes as well as the ecosystem's response. This is particularly so because climate change favours more extreme environmental conditions (e.g., low humidity, high temperatures, and high wind speed) that exacerbate the negative impacts of fire. Uncontrolled bushfires impact the soil in several ways with the magnitude of the disturbance largely dependent upon the fire intensity, duration and recurrence, fuel load, and soil characteristics. The impact on soil properties is complex, leading to different impacts based on these factors. Despite burning off the vegetation during land clearing for cultivation is a common farming practice among farmers in many parts of the tropics, very little is known by perpetrators of this practice about its impacts on the soil and its dwellers. This paper therefore reviews research findings from several works conducted across the globe to gain insight into the effects of wildfire and prescribed fire on the soil's chemical and biological attributes. The knowledge of soil response in terms of these two properties to fire events is useful in guiding the proper implementation of rehabilitation and restoration strategies in the short-term, medium-term, and long-term.

Keywords: Wildfires, Prescribed fire, Severity, Microbial biomass, Soil organic matter, Nutrient availability.

Introduction

Bush burning, defined as the removal of the natural vegetation cover that protects the soil surface through the use of fire has a detrimental effect on the environment, health, and the economy

(Otitoju *et al.,* 2019) (Fig. 1). Fires are considered a destructive factor in most forest ecosystems of tropical and temperate climates (Fernández-García *et al.* 2019a, b), and are viewed as global phenomena affecting most land areas (Bento-Gonçalves *et al.* 2012; Agbeshie *et al.,* 2022). Fires affect living organisms directly (causing their death) and indirectly, transforming their living environment (affecting food availability and quantity, heterogeneity of the environment, and pH increase) (Barreiro and Díaz-Raviña, 2021). The consequence of uncontrolled bush burning is most obvious in areas characterized by torrential rainfall, strong wind, and hot solar radiation (Otitoju *et al.,* 2019). This according to the authors is because even a slight disturbance of the vegetal mantle may have a considerable impact on organic matter content and vegetation biodiversity. In addition, bush fire reduces not only the plant species composition, abundance, richness, and biodiversity but also disrupts the natural soil fertility (Salim *et al.,* 2022). However, over the past 50,000 years, anthropogenic fires have been recurrently used in livestock and agriculture, but fire frequency, extent, and severity have greatly increased in the last few decades, bringing changes to the vegetation composition and soil nutrient stocks, particularly in the savanna ecosystems (Pellegrini *et al.,* 2021). Bush fires are key ecosystem modifiers affecting the biological, chemical, and physical attributes of forest soils. Change in soil properties after fire produces varying responses in the water, vegetation dynamics, and fauna of ecosystems. The wide range of effects is due to the inherent pre-burn variability in these resources, fire behaviour characteristics, season of burning, and pre-fire and post-fire environmental conditions such as timing, amount, and duration of rainfall (Clark, 2001; Verma and Jayakumar, 2012). Several studies have reported the impact of fire on soil chemical attributes (Table 1) with the extent of soil disturbance by fire largely dependent on fire intensity, duration and recurrence, fuel load, and soil characteristics (Agbeshie *et al.,* 2022). Table 1 summarizes the findings of different studies about the impact of fire on soils of various ecosystems across the world. The impact on soil properties is intricate, yielding different results based on these factors. Studies have revealed that African savannas which constitute roughly 50% of the global terrestrial ecosystems (Lehmann *et al.* 2011) has in the recent past undergone a rapid transformation through anthropogenic activities including the indiscriminate use of fire (Dwomoh and Wimberly, 2017; Amoako and Gambiza, 2019).

Fires, whether wild or prescribed defined as low-intensity fires used to achieve specific management objectives (Hiers *et al.* 2020; Francos and Úbeda, 2021) can have a marked effect on soil quality through its effect on the OM stock. This is evident because almost all OM which is the precursor of plant nutrients is consumed during fire thereby affecting long-term crop productivity and soil fertility (Tadesse, 2016). Since fire and traditional practices of soil burning remove OM and their colloid fractions, and since such materials furnish most of the microbiological activities and the base exchange sites in the soils, the removal of such essential particles and their colloids decreases the fertility of the soils (Assefa, 1978). Rates of nutrient loss from slash fires are among the highest of any fires (Kauffman *et al.*, 1995), and sustaining site fertility depends on a detailed understanding of the nutrient fluxes and losses that accompany such fires. Concerns about the threats posed by bush fire to the sustainability of low-input agriculture in many farming systems where the practice is prevalent are heightened by the current climate change predictions, coupled with more recurrent and prolonged droughts in many of these areas (Caon *et al.* 2014).

There have been several recent predictions on the possible increase in fire duration, intensity, and frequency in forested regions, especially in the tropics, because of higher temperatures (Zhang and Biswas, 2017; Auclerc *et al.* 2019; Addo-Fordjour *et al.* 2020). Therefore, increased fire risk will not only affect forest flora, but also the soil's physical, chemical, and biological properties (Romeo *et al.* 2020). Fire influences forest soils in complex ways but has not been studied as comprehensively compared to the effects of vegetation (Agbeshie *et al.* 2022). Fires on forest soils influence a wide range of processes, including organic matter loss (Knicker, 2007), nutrient availability and their dynamics (Cavard *et al.* 2019), and revival of vegetation after the fire (Rodríguez *et al.* 2018). Consequently, information on the changes to soil properties following wild or prescribed fire is key to finding sustainable and adaptable management practices for soils and forests (Zhang and Biswas, 2017). Despite its catastrophic effect on the ecosystem and physio-chemical properties of the soil, bush burning is among the several land-clearing management options employed by farmers in many parts of the tropics (Edem *et al.* 2013; Ubuoh *et al.* 2017; Ibitoye *et al.*, 2019). The practice is very common among the low-input farmers in Nigeria with little or no knowledge about the consequent effects of such practice on the soil (Ibitoye *et al.*, 2019). The objective of this paper is therefore to review the current knowledge regarding the impacts of fire on soil quality particularly as it relates to chemical and biological properties.

Impact of Fire on Chemical Properties of Soil

Potential impact on soil organic matter (SOM): SOM in agricultural soils is often concentrated on, or near, the soil surface and is made up of six easily recognized components: (1) the litter layer, consisting of recognizable plant litter; (2) the duff layer, composed of partially decomposed, but recognizable, plant litter; (3) the humus layer, consisting of extensively decayed and disintegrated organic materials, which are sometimes mixed with mineral soil; (4) decayed wood, consisting of the residual lignin matrix from decaying woody material that is on the soil surface or has been buried by the forest floor; (5) charcoal, or extensively charred wood mixed into the mineral soil; and (6) the upper mineral soil horizon (A horizon) of the underlying mineral soil (Harvey, 1982; DeBano, 1990). Nutrients in fuel and SOM are recycled by biological decomposition processes in environments where temperatures rarely approach 38°C and sufficient moisture is available to sustain active microbial activity (DeBano, 1990). Under these mild conditions, soil microorganisms decompose SOM and slowly release many of the essential nutrients over time. In contrast, during a fire the nutrients stored in fuels and SOM are subjected to severe heating and, as a result, undergo various irreversible transformations during combustion. During the fire, heat transfer from burning biomass on the surface and within the soil is directly responsible for the changes that occur (O'Brien *et al.* 2018). Generally, changes in SOC are variable and depend on fire duration, available biomass, moisture content, and fire type and intensity (Reyes *et al.* 2015; Agbeshie *et al.* 2022). Therefore, the effect on soil processes and their intensity influenced by fire are highly variable and no generalized tendencies can be suggested for most of the fire-induced changes in humus composition (Gonza´lez-Pe´rez *et al.*, 2004). Low-intensity prescribed fire usually results in little change in soil carbon, but intense prescribed fire or wildfire can result in a huge loss of soil carbon (Johnson, 1992). Charcoal can promote rapid loss of forest humus and belowground carbon during the first decade after its formation because charred plant material causes accelerated breakdown of simple carbohydrates (Wardle *et al.*, 2008). Fernandez *et al.*, (1997) suggested that in low-intensity fire, lipids are the least affected group whereas 90% of water-soluble cellulose, hemicelluloses, and lignin are destroyed.

Literature on the impacts of fire on soils is highly variable and suggests that low-intensity fires result in little or large change in the SOC, whereas high-intensity fires result in decreased SOC (Caon *et al.* 2014). Elsewhere, Alcañiz *et al.* (2016) and Liu *et al.* (2018) also recorded up to 19.4% and 11.2% increase in SOC after a low-intensity prescribed fire and a wildfire, respectively. Another study by Badía *et al.* (2014) showed a 27.9% reduction in SOC in the 1- cm soil layer after a highly severe fire. Similarly, Moya *et al.* (2019) recorded a 21.0% reduction in SOM at a moderate to high-intensity wildfire. Reduction in SOC after high-intensity fires may be due to several factors, including the combustion of SOM, increased rates of carbon mineralization, volatilization, and solubilization because of high pH (nutrient-rich ash) (RodriguezCardona *et al.* 2020). In contrast, Akburak *et al.* (2018) and Fernández-García *et al.* (2019a, b) did not observe any significant change in SOC following wildfire. Thus, low-intensity fires are associated with increased SOC due to increased pyrogenic carbon resulting from incomplete combustion of organic matter, decomposition of incomplete burnt biomass, and the addition of ash (Sánchez Meador *et al.* 2017; Santín *et al.* 2018; Hu *et al.* 2020). Studies suggest that low-intensity fires are associated with increased SOC due to increased pyrogenic carbon resulting from incomplete combustion of organic matter, decomposition of incomplete burnt biomass, and the addition of ash (Sánchez Meador *et al.* 2017; Santín *et al.* 2018; Hu *et al.* 2020; Agbeshie *et al.* 2022). The combustion of carbon and the ash produced during low-intensity forest fires are referred to as black carbon (BC) (Thomas *et al.* 2017; Gao *et al.* 2018). Black carbons are highly condensed carbons, resistant to microbial attacks that are generated after a fire (Agbeshie *et al.* 2022). Their presence in the soil has been associated with an increased SOM pool (Nave *et al.* 2011; Caon *et al.* 2014; Agbeshie *et al.* 2022).

Impact on nutrient dynamics: Nutrients contained in fuel (litter) and SOM are cycled by biological decomposition processes in environments where temperatures rarely exceed 38°C and sufficient moisture is available for sustaining active microbial activity (DeBano, 1990). Under these mild conditions, soil microorganisms decompose SOM and slowly release many of the essential nutrients over time. In contrast, during a fire the nutrients stored in fuels and SOM are subjected to severe heating and, as a result, undergo various irreversible transformations during combustion. Studies have shown that the responses of individual nutrients differ and each has its inherent temperature threshold. Threshold temperatures are defined as those temperatures where the volatilization of a nutrient occurs. For discussion purposes, these thresholds can be divided into three general nutrient categories: sensitive, moderately sensitive, and relatively insensitive. Nitrogen (Hosking, 1938) and Sulphur (Tiedemann, 1987) are considered sensitive because they have thresholds as low as 200 to 375°C, respectively. Potassium (K) and P are moderately sensitive, having threshold temperatures of 774 °C (Raison *et al.*, 1985). Magnesium (Mg), calcium (Ca), and manganese (Mn) are relatively insensitive, with high threshold temperatures of 1,107 °C, 1,484 °C, and 1,962 °C respectively (DeBano, 1990). However, because phosphorus is not readily mobile as nitrogen compounds, its concentration increases mainly in the ash and on, or near, the soil surface (DeBano 1989; DeBano and Klopatek 1988). However, the behaviour of micronutrients, such as Fe, Mn, Cu, Zn, B, and Mo, concerning fire is not well known because specific studies are lacking (Certini, 2005, Verma and Jayakumar, 2012).

Both wild and prescribed fires dramatically affect the nutrient cycling and other chemical and biological properties of the underlying soil. Burning increases the availability of most plant nutrients (Adejumobi *et al.,* 2021) even though substantial amounts of carbon (C), nitrogen (N), sulphur (S), and phosphorus (P) can also be lost to the atmosphere by volatilization during the combustion of litter and SOM (DeBano, 1990). Fire acts as a rapid mineralizing agent that releases nutrients instantaneously as contrasted to natural decomposition processes, which may require years or, in some cases, decades (St. John and Rundel, 1976). Organic matter acts as the primary reservoir for several nutrients and, therefore, is the source for most of the available P and S, and virtually the entire available N (DeBano, 1990). Studies have shown that concentrations of exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), P, and mineralized N ($NH4^{+}$ and NO^{3-}) increased with increasing fire intensity (Francos *et al.* 2019; Verma *et al.* 2019; Chungu *et al.* 2020). This increase in concentrations of the basic cations and phosphorus is a result of their high vaporization thresholds compared to $NH4^{+}$ and NO^{3-} (James *et al.* 2018). However, the increase in soil exchangeable cation concentrations following fire disturbance may be short-lived and may soon return to their pre-fire levels (Granged *et al.* 2011; Maynard *et al.* 2014; James *et al.* 2018). Due to their high vaporization thresholds, losses of exchangeable cations in soils may arise only from erosion of ash and leaching of cations, coupled with plant uptake during post-fire succession (Caon *et al.* 2014). In contrast, under cooler soil-heating regimes, substantial amounts of NH_4-N can be found in the ash and underlying soil (DeBano, 1990). Therefore, depending on the severity and duration of the fire, concentrations of NH_4-N may increase, decrease, or remain unchanged. The ash which is the principal product of burnt material although rich in phosphorous, nitrogen, and potassium can be easily washed away by rain.

Although the relationship between fire and soil nutrients is complex because of the interactions among many factors, fire intensity is usually the most critical factor affecting post-fire nutrient dynamics, with greater nutrient losses occurring with higher fire intensity (DeBano, 1990). Fire intensity both directly and indirectly impacts many of the mechanisms that affect nutrient pools and cycling. In the Southern part of Nigeria, slash and burn method of land clearing is an integral part of the traditional farming system, Ubuoh *et al.* (2017) investigated the effects of slash and burn method of land clearing on the soil nutrient dynamics of the upper 30 cm soil layer. The study revealed that at the upper 0-15 cm depth, the unburnt plot recorded a decrease in pH, and an increase in K and base saturation, while the burnt plot recorded an increase in SOM, Total N, Available P, Ca^{2+}, Mg^{2++}, Na^{+} and EC. At the depth of 15-30cm, the unburnt plot recorded a decrease in pH, Mg, and EC while the burnt plot recorded the highest values in other selected parameters than the unburnt plot. This and most other studies of slash-and-burn documented an increase in soil nutrient availability after burning (De Rouw, 1994). Post-burn increases in soil fertility (Tables 2 and 3) have generally been attributed to nutrient-rich ash in nearly all tropical forest types where slash-and-burn has been examined (Maass, 1995; Ubuoh *et al.* 2017; Numbere and Obanye, 2023)). Similarly, Muqaddas *et al.* (2015) and Francos *et al.* (2019) found increased soil pH in burnt soils following prescribed fire.

In grassland vegetation, many researchers have observed an increase in soil nutrients following a low-intensity wildfire (Inbar *et al.,* 2014; Hosseini *et al.,* 2017; Liu *et al.,* 2018). Low-intensity fires with ash deposition on soil surfaces cause changes in soil chemistry, including an increase in available nutrients and pH (Agbeshie *et al.* 2022). Under a low-intensity prescribed fire in a Q. frainetto forest, Akburak *et al.* (2018) also found significantly high Ca^{2+} and Mg^{2+} levels in the A horizon (upper 5 cm) immediately after burning. In addition, Johnson *et al.* (2014) reported an elevated and consistent Ca^{2+} content two years post-fire. However, other researchers have reported no change or a decline in exchangeable cations after fires. For example, in grassland vegetation, Liu *et al.* (2018) reported an insignificant amount of K^{+} between pre- and post-wildfire- affected soils. In contrast, Raison *et al.* (1986) reported a reduction in nutrient pools even with low-intensity fires. The study showed a decline of 50–75% of N, 35–50% of P, and 25–50% of Mg via volatilization and oxidation processes. Studies have shown that certain nutrients are also more vulnerable to fire than others. For example, levels of potassium (K), calcium (Ca), and magnesium (Mg) may be increased or unaffected by fire, while sulphur (S) and nitrogen (N) usually decline (Agbeshie *et al.* 2022). Some studies revealed that burned soils have lower nitrogen than unburned soils, higher calcium, and nearly unchanged potassium, magnesium, and phosphorus stocks (Neff *et al.,* 2005). In contrast, Dzwonko *et al.* (2015) reported significantly higher exchangeable cations in burnt plots over controls in a Scots pine forest when a high-severity wildfire occurred. Temperature specifically regulates the volatilization of nutrients within the soil. In organic matter, N begins to volatilize at 200 °C (Knicker, 2007), while Ca requires 1484 °C to vaporize (Johnston and Barati, 2013).

Impact of Fire on Biological Properties of Soil

Potential effects on soil macro-organisms: Soil-dwelling organisms, *m*ost of whom live in the uppermost soil layer where fire-imposed temperatures on the ground are the highest suffer numerous consequences of fire disturbance. A large part of soil-dwelling organisms resides in the surface layer, where the organic fraction, which comprises mainly plant residue, animal remains, and humic substances, often prevail over the inorganic inner materials. Whereas vertebrates can escape overheating death by running away, searching for wet niches, or burrowing deep into soil invertebrates and microorganisms, which have little or no mobility, succumb more easily to fire (Certini *et al.,* 2021). Generally, the direct effects of fire on soil-dwelling invertebrates are less marked than those on microorganisms, due to greater mobility which increases the potential for invertebrates to escape heating by burrowing deep into the soil (Certini, 2005). The general pattern of soil-borne organisms i.e. macroinvertebrate responses to fire is often driven by changes in habitat structure, or by changes in the amount or the quality of food resources. Whenever fire affects vegetation, temperature or moisture, or the nutrient status of soil, there is potential for impact on the soil invertebrate community (DeBano, 1990).

Some arthropod groups increased in abundance but most decreased soon after fire. A study of litter-dwelling and soil-dwelling macroinvertebrates showed that the density of macroinvertebrates was significantly reduced one year after a prescribed fire (Kalisz and Powell, 2000). The authors also reported a reduction in the number of beetle larvae following fire, and further proposed that repeated fire in a single location could potentially have long-term negative effects on beetle populations and on the functions these beetles perform within the system. Findings of several studies conducted in grassland soils in Kansas that focused on the responses of soil macroinvertebrates to fire revealed that earthworm populations are strongly affected by fire in tall grass prairie soils, and the usual pattern observed is for fire to increase the abundance of earthworms in undisturbed areas (James, 1995). However, in more disturbed areas (i.e. close to human habitations), fire also has the interesting effect of limiting the colonization of non-native earthworms into prairie soils (Callaham *et al.* 2003). Results of this study suggested that the native earthworms in grassland soils are adapted to the warmer soil conditions frequently found in burned prairie, and that because fire improves the performance of grasses, the native earthworms may have strong habitat preferences for soils with abundant grassroots. Several studies have reported decreased microarthropod abundance immediately following a fire (e.g. Sgardelis and Magaris, 1993). For example, Lussenhop, (1976) reported greater microarthopod abundance in a biennially burned prairie compared to an unburned prairie. Whereas a substantial resilience to fire in arthropod populations has also been documented in some studies. others found no effect of burning on microarthropod abundance. Coleman and Rieske (2006) examined the effect of early spring prescribed fires on forest floor arthropod abundance and diversity in mixed hardwood-pine of southeastern Kentucky (USA), and found that leaf-litter arthropod abundance, diversity, and richness did not differ among the pre-burned, unburned and single burned areas. The study by Swengel, (2001) suggests that leaf-litter and soil-dwelling arthropods might be directly affected by increases in temperature and exposure or indirectly affected through changes in habitat availability and quality. Findings from these and other similar studies suggest that there is no pattern of micro and mesofauna response to fire, instead, several factors are implicated in the responses of these organisms to fire (Mataix-Solera *et al.,* 2009).

Potential effects on soil micro-organisms: Microbial biomass reflects the microbial status of soil responsible for maintaining the nutrients and fertility of the soil and therefore, contributes to the biological properties of the soil (Mataix-Solera *et al.* 2009; Manral *et al.,* 2020). Microbes are generally known to be solely responsible for nutrient cycling and play a major role in the transformation of nutrients and therefore, act as soil health indicators (Singh *et al.,* 2021). Fire affects biological properties by directly killing or denaturing soil biota through combustion or indirectly by post-fire plant recovery or changes in soil organic matter (Knelman *et al.* 2015; Jonathan *et al.* 2016; Ibáñez *et al.* 2021). It has been suggested that the changes in the nutrient supply due to the loss of plant residues could also be a reason for the reduction in microbial biomass after fire (Mabuhay *et al.* 2003; Smith *et al.* 2008). Singh *et al.,* (2022) in their study on the impact of forest fire on soil microbial properties in the pine and oak forests of the Garhwal region of Uttarakhand Himalaya, India reported a reduction in microbial biomass (Cmic) of pine forests in Pauri and Tehri district were 61.7 and 17.4%, respectively, whereas in the oak forest, the percentage reductions of Cmic were much higher (75.8% in Pauri and 49.6% in Tehri district). The Cmic at the control and burnt sites of the oak forest was found to be greater as compared with the pine-dominated forest. This according to the authors could be attributed to the greater litter input with the oak forest which provides a greater carbon source pool for microbial utilization when compared to the pine forest. A similar reduction in microbial biomass after the fire has been reported in many studies (Strand, 2011; Holden and Treseder, 2013; GironaGarcía *et al.* 2018). Several other researchers have documented the impact of forest fires on soil biological properties (Table 4ab). These studies revealed that the different microbial properties (related to mass, activity, and diversity) showed a different sensitivity to detect fire impact as well as different trends over time (immediate, short-, medium-, and long-term). In general, microbial activity and biomass changes can be transitory, and their values can reach pre-fire ones (Barreiro and Díaz-Raviña, 2021). Studies also suggest that the loss of microbial biomass during a fire depends upon the intensity and duration of the fire (Girona-García *et al.* 2018; Lucas-Borja *et al.* 2019). Other studies attributed the observed reduction and diversity in soil microbial biomass after fire disturbance to factors such as the unavailability of soil carbon and nutrients (Zhou *et al*. 2018) as well as topographic positions such as ridge, middle slope, and valley bottom (Mabuhay *et al.* 2016; Girona-García *et al.* 2018).

In their review of prescribed burning on soil attributes, Alcañiz *et al.* (2018) noted that the temperature needed to kill most soil biological matter ranges from 50 to 120 °C. In other studies, Santín and Doerr (2016) also noted that temperatures from 50–150 °C result in the killing of fine roots, bacteria, fungi, and seeds within the soil. Microbial groups differ significantly in their sensitivity to temperature and nitrifying bacteria appear to be particularly sensitive to soil heating (Dunn *et al.* 1985). Aerobic heterotrophic bacteria, including the acidophilic and sporulating ones, were stimulated by fire while cyanobacteria, was depressed (Verma and Jayakumar, 2012). Another important group of soil microorganism that are particularly sensitive to soil heating during a fire are endo- and ectomycorrhizae. Because most ectomycorrhizae are concentrated in the organic matter on or near the soil surface, the loss of shallow organic layers may be at least partially responsible for the reported fire-related reductions. For example, the study by Stendell *et al.* (1999) showed that the total ectomycorrhizal biomass in the upper soil layer of the unburned plots did not change to appreciable level, while in the burnt site, the destruction of the uppermost organic layer resulted in an eight-fold reduction in total ectomycorrhizal biomass. Mycorrhizal biomass in the two mineral layers was not significantly reduced by the fire. In a related study, forest fire was found to affect the proliferation of arbuscular mycorrhizal (AM) fungi by changing the soil conditions (Rashid *et al.,* 1997). These workers also reported that compared with a nearby control area, the burnt site had a similar number of total spores but a lower number of viable AM fungal propagules. Regarding the impact of fire on soil microbial diversity, Castano *et al.* (2020) observed a decrease in the relative abundance of ectomycorrhizal species four years after a medium-severity prescribed fire. However, in the long term, a decrease in bacterial and fungal diversity was found 14 years after a wildfire (Huffman and Madritch, 2018). Long-term shifts in the composition of ectomycorrhizal fungal communities have been observed after wildfires and prescribed fires (Taudière *et al.,* 2017). The fire impact on soil and the following postfire recovery of the microbiota can differ depending on the fire recurrence. For example, a decrease in ectomycorrhizal fungal diversity (Pérez-Izquierdo *et al.,* 2020) or alteration of the microbial community structure and no effect on microbial biomass have been described as a consequence of changes in the fire recurrence (Lombao *et al.,* 2020; Barreiro and Díaz-Raviña, 2021). However, Barreiro and Díaz-Raviña, (2021) in their review of fire impact on soil microorganisms concluded that fire impact on soil microorganisms and the subsequent soil recovery depends on different factors such as the fire severity, the soil resilience, and the environmental conditions. They also asserted that the current situation of climate change favours more extreme environmental conditions (high fuel availability, low humidity, high temperatures, and high wind speed) that shift the fire regimes to more severe fires with a large impact on the soil microorganisms. Studies of the impacts of fire on soil microbial organisms revealed variable results depending on such factors as fire severity, postfire conditions, and time passed after the fire event. For example, some studies showed that the microbial biomass in the medium term can increase or decrease depending on the specific environmental conditions (Fernández-García et al., 2020). Similarly, Kang and Park (2019) observed a decrease in the microbial diversity and amounts three years after a prescribed fire, with an increase in the relative amounts of b-proteobacteria and firmicutes and a decrease in acidobacteria. However, other studies did not find significant differences in the fungi/bacteria ratio of a permafrost soil at the medium term and long term after a wildfire (Zhou *et al.,* 2019).

Summary and conclusions

Both wild and prescribed fires occur frequently in many parts of the tropics. These fires dramatically affect many of the soil properties including the physical, chemical, and biological attributes of the underlying soil. From the literature reviewed it is obvious that cultural practices such as slash and burn method have both beneficial and detrimental effects on soil quality with the effects largely dependent upon such factors as fire intensity, duration and recurrence, fuel load, and soil characteristics. Fires, depending on severity and duration generally increase soil temperatures and higher pH, which in turn affect the nutrient dynamics via the combined processes of mineralization and nitrification. During the combustion of soil organic matter some nutrients, such as N, P, and S, have low-temperature thresholds and are therefore easily volatilized. Part of the nitrogen, that is not completely volatilized, is mineralized to NH_4^+ -N to minimize its loss or can be further nitrifed to NO_3^- -N under favourable conditions. Potassium (K) and phosphorus (P) are moderately sensitive, having threshold temperatures of 774°C while magnesium (Mg) and calcium (Ca) are relatively insensitive, with high threshold temperatures of 1,107°C, and 1,484°C, respectively. As such, these nutrients are not readily volatilized from organic matter combustion temperatures. However, some studies suggest that low-intensity fires result in little change or an increase in available nutrients (K^+, Ca^{2+}, Mg^{2+}, $PO_4{}^{3-}$, $NH_4{}^+$) and pH due to ash deposition. It is also evident from the present review that soil heating directly affects the soil-borne organisms by either killing them directly or altering their habitats. Microbial groups in particular differ significantly in their sensitivity to temperature with the nitrifying bacteria in particular appearing to be sensitive to soil heating. The review suggests that the responses of soil microbes to fires range from minor detectable effects under low-intensity fires to total sterilization of the surface layers of soil under very intense fires. Studies have also shown that the impact of fire soil-dwelling organisms particularly soil microorganisms and the subsequent soil recovery depends on several factors such as the fire severity, the soil resilience, and the environmental conditions (fuel availability, humidity, temperature, etc.). This study posits that uncontrolled use of fire for hunting, charcoal production, or land clearing for crop production by most farmers in the tropics and other regions of the world has far-reaching implications for sustainable management of ecosystems resources in these areas.

Recommendations: Although little can be done to control SOM loss during wildfires, effort should be made to revegetate the site so that organic litter can again be restored on the site as quickly as possible; When one plans prescribed fires, care should be taken to avoid bums that consume large amounts of surface litter and soil humus; Likewise, the total combustion of large woody debris on the soil surface (logs, etc.) during prescribed burning may not be a desirable practice; Repeated use of fire at frequent intervals probably should be avoided on relatively infertile sites where OM production is inherently low (for example, as the case with coarse-textured soils found in most parts of drier environments); An integrated fire management approach that factors both the severity and complexity of the phenomenon is recommended; Further studies on the susceptibility resilience of soil bourn organisms to fire events is critical to understanding the microbial response to fire and the subsequent implementation of rehabilitation and restoration strategies in the short-term, medium-term, and long term as opined in several studies (see for example, Barreiro and Díaz-Raviña, (2021).

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Figure 1: Images of a low-intensity prescribed fire to burn stubble during land clearing preparatory to planting a crop

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire

AUTHOR(S)	VEGETATION TYPE	LOCATION	FIRE PROPERTIES	SOIL TYPE	SOIL PROPERTY	IMPACT	REASONS FOR IMPACT
INBAR *ET AL.* (2014)	*Pinus halepensis* and Pinus brutia forest	Northern Israel	Low-moderate severity, WP	Sandy clay loam, Lithic Xerorthenth	Organic matter (OM)	Increased	Mixing of incomplete burnt biomass in the soil exposed to direct fire increased its OM content
					CEC	Increased	Due to the increased OM content
					pH	Insignificant	-
					EC	Insignificant	-
MUQADDAS *ET AL.* (2015)	Wet sclerophyll forest	Queensland, Australia	Low intensity, 2 year burning regime, heat release rate of < 2500 KW m^{-1}, PF	Sandy, red to yellow Kandosols	Total N	Decreased	Due to N volatilization
					Total C	Decreased	Due to CO_2 emission following burning of biomass
					pH	Increased	Due to increased base cations
					Recalcitrant C, N	Decreased	Reduction of total C and N due to continuous burning
FRANCOS *ET AL.* (2019)	*Pinus halepensis* and	Northeast Spain	Temperature of 65 °C on soil surface, maxi-	Xerorthents	Total N	Decreased	N loss due to volatilization and uptake by surviving

	Quercus ilex forest		mum fire temperature of 435 °C, PF				shrubs and herbaceous plants
					Soil organic matter (SOM)	None	-
					pH	Increased	Heating caused denaturing of organic acid
					EC	Increased	Release of soluble inorganic ions and creation of black C after fire
					Extractable Ca	Increased	Higher base cations
					Extractable Mg	Increased	Increased base cations
					Extractable K	Increased	Increased base cations as a result of increased ash content
					Available P	None	-

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire (Continued)

AUTHOR(S)	**VEGETATION TYPE**	**LOCATION**	**FIRE PROPERTIES**	**SOIL TYPE**	**SOIL PROPERTY**	**IMPACT**	**REASONS FOR IMPACT**
LIU *ET AL.* (2018)	Grassland vegetation	Ningxia Hui Autonomous Region, China	Surface head fire, low intensity fire, WF	Calci-Orthic Aridisol	Soil organic carbon (SOC)	Increased	Increased pyrogenic C resulting from

				incomplete combustion
		Total N	Increased	Mixing of incomplete residual burnt material with soil
		NO_3^{-}	Decreased	Rapid revegetation with increased organic N uptake (NO_3^{-})
		NH^{+}	Increased	Higher ash deposition coupled with increased N mineralization as conditioned by temperature, pH and microbial activities
		Total P	None	-
		Extractable P	Increased	Mineralization of organic P to inorganic P
		Available K	Insignificant	-
		pH (IAB)	Insignificant	-

ALCAÑIZ *ET AL*. (2016)	*Pinus halepensis* forest	Montgrí Massif, Catalonia, Spain	Flame height < 2.5 m,324 °C, PF	Lithic Xerorthent	EC (IAB)	Increased	Release of soluble in-organic ions following burning
					Total C (IAB)	Increased	Formation of black C as a result of low fire(< 450 °C) and addi-tion of ash content to the soil
					Total N (IAB)	Increased	-
					Available P (IAB)	Increased	Addition of ash into the soil, transformation of organic P to inorganic P, and burning of vegetation
					Extractable cations (IAB)	Increased	Low fire severity, and addition of ash and its subsequent mixing in the soil

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire (Continued)

AUTHOR(S)	VEGETATION TYPE	LOCATION	FIRE PROPERTIES	SOIL TYPE	SOIL PROPERTY	IMPACT	REASONS FOR IMPACT
BADÍA *ET AL.* (2014)	Aleppo pine (*Pinus halepensis)* forests	Montes de Zuera, Northeast Spain	Moderate to high or high burn severity	Rendzic Phaeozem	SOC	Decreased	Soil losses resulting from severe burning
					pH	None	-
					EC	Increased	Addition of basic cations
					NO_3^-	Increased	Organic N transformation
					NH_4^+	Increased	Mineralization of organic N to mineral N
					CEC	Increased	Due to the increased OM content and inorganic ions
					Available P	Increased	Mineralization of organic P and dissolution of P from ashbeds
DZWONKO *ET AL.* (2015)	Scots pine moist forest	Southern Poland	High severity, WF	Sapri-Dystric Histosol	Total N	Decreased	Losses through volatilization
					pH	Increased	-
					S	Decreased	-
					OM	Decreased	Complete oxidation and

							volatilization of minor compounds
					Base cations	Increased	Burning of organic matter
MERIA-CASTRO *ET AL.*(2015)	*Pinus pinaster* vegetation	Northern Portugal	Fire spread 10–15 m h^{-1}, PF	Umbric Leptosol and Umbric Cambisol	pH	None	-
					SOM	None	-
GOBERNA *ET AL.* (2012)	Shrubland (*Rosmarinus officinalis)* vegetation	Valencia, Spain	Fire temp. of 611 °C, soil surface temp. of 338 °C, PF	Humic Leptosols	pH	None	-
					Total OC	None	-
					NO_3^-	Increased	Increased nitrification
					NH_4^+	Increased	Mineralization of organic N
					Available P	Increased	Mineralization of organic P
BENNETT *ET AL.* (2014)	Eucalyptus forest	Victoria, Australia	High intensity, 259 kW m^{-1}, PF	Kandosols and Der-mosols	Carbon stocks	decreased	Combustion of organic matter

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire (Continued)

AUTHOR(S)	VEGETATION TYPE	LOCATION	FIRE PROPERTIES	SOIL TYPE	SOIL PROPERTY	IMPACT	REASONS FOR IMPACT
		Istanbul, Turkey			Total N	None	-

AKBURAK *ET AL.* (2018)	*Quercus frainetto* forest		Low intensity, burning for 20 min (857.95 g m^{-1} ofbiomass), PF	Loamy clay, Luvisol	SOC	None	-
					pH	increased	Due to increased base cations
					EC	None	-
					Base cations	increased	Increased OM and inorganic ions
HOSSEINI *ET AL.* (2017)	*Pinus pinaster* forest	North-central Portugal	Moderate severity fire, WF	Humic Cambisols and Epileptic Umbrisols	N	increased	Not discussed
					P	increased	Addition of ash and higher clay content which increase P sorption in soils
DOWNING *ET AL.* (2017)	Alpine moorlands	Mount Kenya, Kenya	High intensity, WF	Dystric Histosols and partly humic Andosols	CEC	increased	Addition of ash and inorganic ions
					OC	None	-
					pH	None	-
					OM	None	-
VALKÓ *ET AL.* (2016)	Grassland	East Hungary	PF	Gleyic Solonetz	OM	None	-
					pH	None	Less combustion leading to small ash availability
					Available K	None	-
HEYDARI *ET AL.* (2017)		Ilam, Iran	Mixed intensity, WF	-	OC (high intensity)	Decreased	Not discussed

	Oak (*Quercus brantii*) forest				EC (low intensity)	None	-
					pH (high intensity)	increased	Release large quantities of basic cations after burning
					NO^{-} (moderate intensity)	increased	Release of NO^{-} N into the soil as leaf litter decomposition or burning
					CEC (high intensity)	increased	Reduced thickness of the soil organic layer after burning and subsequent addition of ash to the mineral layer

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire (Continued)

AUTHOR(S)	VEGETATION TYPE	LOCATION	FIRE PROPERTIES	SOIL TYPE	SOIL PROPERTY	IMPACT	REASONS FOR IMPACT
SCHARENBROCH *ET AL.*(2012)	Oak forest	Illinois, USA	Low intensity, 120–230 °C, PF	Alfisols and Mollisols	Available P	None	-
					Total C	Increased	Less heat to oxidize OM

					Total N	Increased	Considerable amount of organic N can with stand low-grade fire
FERNÁNDEZ-GARCÍA *ET AL.* (2019A, B)	*Pinus pinaster* forest	Spain	High burn severity, WF	Haplic Umbrisol, Dystric Regosol	Available P	Increased	transforms organic P into orthophosphate
					pH	None	Removal of ash by erosion
					EC	None	leaching or transported by runoff
					OC	None	-
					Total N	None	-
MOYA *ET AL.* (2019)	*Pinus halepensis* forest	Spain	Moderate-high intensity, WF	Aridisols (Lithic Haplocalcids)	OC	Decreased	--
					N	None	-
					Available P	Increased	Combustion of the organic part of fuel load and the deposition of ashes
					pH	None	-
					CEC	Increased	Increase in exchangeable cations from ash

FERNÁNDEZ-FERNÁNDEZET AL. (2015) **FULTZ *ET AL.* (2016)**	*Pinus pinaster* forest Grassland	Northwest Spain Texas, USA	PF Low-moderate, PF	- Acuff and Amarillo	pH	None	-
					NO_3 –N	Decreased	Decrease net nitrification following fire
					CEC	None	-
					NH_4 $^+$–N	Increased	-
					NO_3 –N	None	Low nitrification due to low moisture
CERTINI *ET AL.* (2011)	*Pinus pinaster* forests	Calambrone, Italy	Highly to very highly severe.WF	Endogleyic Arenosols	pH	Increased	Incorporation of ash
					C	Increased	Due to charred litter and biomass incorporation
					C/N ratio	Decreased	Nitrogen is preferentially immobilised during charring

Table 1: Summary of results from the reviewed articles on Soil chemical properties affected by forest fire (Continued)

Author(s)	Vegetation type	Location	Fire properties	Soil type	Soil property	Impact	Reasons for impact
					pH	None	-

Certini *et al*. (2011)	*Pinus pinea* forests	Migliarino, Italy	Highly to very highly severe WF	Endogleyic Arenosols	C	Increased	Due to charred litter and biomass incorporation
					N	Decreased	Nitrogen is preferentially immobilised during charring
Switzer *et al*. (2012)	Douglas-fir forest	British Columbia Canada	40–853 °C, PF	Orthic Eutric Brunisol	Total C	None	-
					Base cations	Increased	Increased inorganic ions following combustion of partially burned vegetation

Source: Agbeshie *et al.*, (2022). WF, PF and IAB indicates wildfire, prescribed fire, and immediately after burning, respectively.

Table 2: The mean soil quality parameters for burnt and un-burnt land at different soil depths in the study area

SOIL INDICATORS	UN-BURNT PLOT	BURNT PLOT	UN-BURNT PLOT	BURNT PLOT
	0-15 cm	15.30 cm	0-15 cm	15.30 cm
SOIL PH (H_2O)	5.58	7.2200	5.1200	6.3500
SOIL PH (HCL)	4.8633	6.50	4.246	5.8900
SAND (G KG^{-1})	73.01	67.2	62.5333	64.5333
SILT (G KG^{-1})	8.0333	6.6667	8.000	6.0000
CLAY (G KG^{-1})	18.1333	26.1	29.4667	29.4667
SOIL ORGANIC CARBON (SOC) (G KG^{-1})	2.3100	2.73	1.5567	1.9633
SOIL ORGANIC MATTER (SOM) (G KG^{-1})	3.9933	4.7267	29.4667	3.5367
TOTAL NITROGEN (TN) (G KG^{-1})	0.1967	0.666	0.1300	0.7200
AVAILABLE PHOSPHORUS (AVAIL. P) (MG KG^{-1})	2.5400	3.45	29.4667	1.4
CALCIUM (CA) (CMOL KG^{-1})	2.5333	2.6667	2.533	2.2667
MAGNESIUM (MG) (CMOL KG^{-1})	1.6000	1.966	1.4667	1.7667
POTASSIUM (K) (CMOL KG^{-1})	1.8567	0.593	0.1333	0.600
SODIUM (NA) (CMOL KG^{-1})	0.1300	0.1567	0.1633	0.2033
EXCHANGEABLE CATION (EC) (CMOL KG^{-1})	5.0200	5.38	5.16333	4.8637
BASE SATURATION (BS) (%)	82.5667	82.20	52.1633	82.8000

Source: Ubuoh *et al.* (2017)

Table 3: Mean concentration of metals in burnt and unburnt soils at Eagle Island, Niger Delta, Nigeria

SOIL TYPE	METALS (MG/KG)					
	Ca	Fe	Mg	NO_3^-	$PO4^{3-}$	K
BURNT	241.69 ± 55.96	10743.75 ± 15.39	650.18 ± 145.74	85.06 ± 22.63	284.75 ± 42.73	171.54 ± 27.40
UNBURNT	234.22 ± 86.02	8854.02 ± 1734.86	497.12 ± 116.22	60.93 ± 10.35	193.38 ± 50.49	135.95 ± 14.80

Source: Numbere and Obanye, (2023).

Table 4a: Summary of results from the reviewed articles concerning the fire effects on soil biological properties of samples taken mainly in the 0–5 cm of the A horizon top layer (part 1).

FIRE TYPE/ECOSYSTEM/CLIMATE	**TIME AFTER FIRE**	**MICROBIAL PARAMETER**	**CHANGE (RESPECT TO UNBURNED)**	**REFERENCE**
WILDFIRES FOREST/MEDITERRANEAN CLIMATE	3 days/10 months	Enzyme activities: Acid and alkaline phosphatases, arylsulfatase, beta-glucosidase, and leucine-aminopeptidase	Decrease, recover after 10months	Borgogni *et al.*, 2019
		Bacterial and fungal communities (DNA)	Decrease, recover after 10 months	
		Microbial biomass	None	
PEATLAND/EQUATORIAL CLIMATE	14/28 days	Soil respiration	Decrease	Wasis *et al.*, 2019
		Viable cells (plate counting)	Decrease	
CONIFER CATCHMENT/ALPINE CLIMATE	18 days	Enzyme activities:		Fairbanks *et al.*, 2020
		a-glucosidase, b-xylosidase, leucine-aminopeptidase, acid phosphatase	None	
		b-1,4-glucosidase, b–D-cellobiohydrolase, b-1,4,N-acetylglucosaminidase	Decrease	

PINE FOREST/MEDITERRANEAN CLIMATE	1 month/1 –3 years	Viable bacteria and fungi (plate counting)	Increase	Rodriguez *et al.*, 2018
		Bacterial diversity (DNA)	Decrease (recovery 1 year)	
		Soil respiration (SIR)	Increase	
		Enzyme activities: glucosidase, cellulase, invertase, urease, b-N-acetylglucosaminidase, acid and alkaline phosphatases	None/increase (phosphatase)	
FOREST AND SHRUBS/ MEDITERRANEAN AND TEMPERATE CLIMATE	2 months	Richness and diversity of bacterial communities (DNA)	Decrease	Sáenz *et al.*, 2020
WETLAND/SUBTROPICAL WETCLIMATE	2 months	Microbial biomass (PLFA)	Increase (decrease in Fungi)	Zhang *et al.*, 2019
		Microbial C utilization (CLPP)	Incre	
FOREST/TEMPERATE MONSOONCLIMATE	6 months	Bacterial and fungal richness, diversity (DNA)	Decrease (fungi more sensitive)	Qin and Liu, 2021
FOREST/TEMPERATE OCEANICCLIMATE	1 year	Bacterial and fungal communities (DNA)	Change in structure, bigger impact in bacteria than infungi	Brown *et al.*, 2019
FOREST/BOREAL CLIMATE	1 year	Fungal richness and diversity (DNA)	Decrease	Day *et al.*, 2019]

WETLAND/SEMIARID CLIMATE	1/2 years	Enzyme activities: invertase, urease, catalase	Decrease	Semenenko *et al.*, 2020
OAK-PINE FOREST/HUMID SUBTROPICAL CLIMATE	1/14 years	Enzyme activities: cellobiohydrolase, b- glucosidase, leucine aminopeptidase, phenol oxidase, peroxidase, urease	None/decrease (urease)/ increase phenol oxidase	Huffman and Madritch, 2018
		Soil respiration	Decrease (1 year)	
		Bacterial and fungal diversity (DNA)	Decrease	
PINE FOREST/SEMIARID CLIMATE	2 years	Soil respiration	Decrease	Allam *et al.*, 2020
		Microbial biomass (SIR)	Decrease	
PINE FOREST/SEMIARID CLIMATE	3 years	Viable bacteria and fungi (plate counting)	Decrease in bacteria	Olejniczak et al., 2019
FOREST/BOREAL CLIMATE	3 years	Fungi/bacteria (DNA)	None	Zhou *et al.*, 2019
		Microbial biomass (fumigation)	None	
		Microbial C, N, P	Decrease	
		Enzyme activities:		Fernández-García *et al.*, 2020
		b-glucosidase, urease	Increase/decrease (site specific)	
		Acid-phosphatase	Increase	
		Microbial biomass C	Increase/decrease (site specific)	
FOREST/BOREAL CLIMATE	50 years	Microbial biomass (PLFA)	None	Cavard *et al.*, 2019

Table 4b: Summary of results from the reviewed articles (part 2)

FIRE TYPE/ECOSYSTEM/CLIMATE	TIME AFTER FIRE	MICROBIAL PARAMETER	CHANGE (RESPECT TO UNBURNED)	REFERENCE
PRESCRIBED FIRES SHRUBLAND/MOUNTAIN CLIMATE	1 day/1 –5 years	Microbial biomass C	Decrease (recovery after 5 years)	Armas-Herrera *et al.*, 2018)
		Enzyme activities (b-D-glucosidase, acid phosphatase), soil respiration	Decrease	
FOREST/MEDITERRANEAN CLIMATE PINUS	2/6 months	C-substrate utilization	Increase	Moya *et al.*, 2020
PLANTATION/SUBTROPICAL CLIMATE	1 year	Bacterial fungal diversity	None	Wang *et al.*, 2019; 2020
		Bacterial–fungal relative abundance	Shift	
		Microbial biomass C	Decrease	
LARCH FOREST/BOREAL CLIMATE	3 years	Microbial diversity and richness	Decrease	Kang and Park, 2019
SHRUBLAND/MEDITERRANEAN CLIMATE	4 years	Fungal community composition	Decrease mycorrhizal fungi	Castaño *et al.*, 2020
SHRUBLAND/TEMPERATE CLIMATE	4 years	Microbial biomass (PLFA)	Decrease	Díaz-Raviña et al., 2018
		Enzyme activities (b-glucosidase)	None	

		Enzyme activities (urease)	Decrease	
		Microbial biomass C	Decrease	
		Soil respiration	Decrease	
		Bacterial growth	None	
PINE FOREST/SEMIARID CLIMATE CONTROLLED EXPERIMENTS	15 years	Ectomycorrhizal fungi	None	Hart *et al.*, 2018
ARABLE LAND/HUMID CONTINENTAL CLIMATE (LABORATORY HEATING, DEGREE-HOUR METHOD)	1 day	Enzyme activities: catalase, dehydrogenase	Decrease	Kazeev *et al.*, 2020
		Microbial biomass	Decrease	
		Viable N fixing bacteria	Decrease	
PINE FOREST/TEMPERATE CLIMATE (LABORATORY HEATING UNDER DIFFERENT SOIL WATER CONTENT, DEGREE-HOUR METHOD)	1 day/1 month	Microbial biomass	Decrease	Barreiro et al., 2020
		Bacterial activity	Decrease	
SHRUBLAND/TEMPERATE CLIMATE (LABORATORY HEATING, SEVERITY AND RECURRENCE, DEGREE-HOUR METHOD)	1 day/2 months	Microbial C utilization (CLPP)	None/increase (soil specific)	Lombao et al., 2020]
		Microbial biomass (PLFA)	Decrease	
		Microbial community structure (PLFA)	Shift	
PINE FOREST/MEDITERRANEAN CLIMATE (HEATING OF SOIL MONOLITHS)	7 days	Microbial biomass	None	Lucas-Borja *et al.*, 2019
		Bacterial composition	Modified	
PINE FOREST/BOREAL CLIMATE (GREENHOUSE)	1 year	Fungal communities	None	Beck *et al.*, 2020

		associated to pines		
POSTFIRE MANAGEMENT				
FOREST/TEMPERATE CLIMATE (MULCH MATERIAL AMENDMENT)	2 months	Bacterial activity	Increase (straw)/decrease (initial with eucalyptus)	Barreiro *et al.*, 2016
		Fungal activity, soil respiration	Increase/none (coconut fiber)	
		Microbial biomass	Increase (fungi)	
FOREST/MEDITERRANEAN CLIMATE (LOGGING)	6 months	N cycling bacteria abundance	Decrease	Pereg *et al.*, 2018
GRASSLAND/CONTINENTAL CLIMATE (FERTILIZER APPLICATION AFTER YEARLY PRESCRIBED FIRE)	1 year	Bacterial and fungal biomass	None	Carson and Zeglin, 2018
		Bacterial community Composition	Decrease/increase (specific phyla)	

PLFA: Phospholipid fatty acids; CLPP: Community Level Physiological Profiling; SIR: Substrate Induce Respiration

Source: Barreiro and Díaz-Raviña, (2021).