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How Long Is Long? A Bibliographic Review of What Is Meant by the *Long-Term* Effects of Fire on Soil Properties

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Wildfires pose one of the greatest threats to the world's forests soils. After exposure to fire, forests lose many of their ecological functions; moreover, the repercussions can extend well beyond the forest itself, as the erosive processes attributable to the combustion of vegetation and the soil's lack of protection against rainfall are likely to impact any areas of a catchment, contaminating reservoirs, estuaries and aquifers. A forest fire is not solely, therefore, an environmental issue, but also a social and economic problem. The recovery of a forest is heavily dependent on just how the soil has been affected and how rapidly the latter can be restored. Fire intensity is critical in understanding the temporal evolution of the forest, while its location—a clear determinant of its climate and the ecosystem it occupies—can undermine the functionality of the forest system and is critical in determining the duration of the effects of the fire episode. This paper undertakes a review of the literature with the aim of understanding what might be understood when studies speak of the *long-term* effects of fire on the soil and when a soil might be considered to have recovered from these effects. What is evident is that many variables have a role to play and that not all soil properties recover at the same rate; indeed, some may never be restored to pre-fire levels.

Keywords: fire intensity, climate change, soil recovery, prescribed fire, forest management

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STATE-OF-ART

What exactly is understood by *the long-term* effects of wildfire on forest soils is worthy of some consideration. One interpretation is that the main effects of the fire will still be observed after a period of some years; however, this begs the question as to how many years these effects can remain evident. When does the forest recover its pre-fire characteristics? Just how long is *long term* when we refer to the modifications that have been suffered by the forest ecosystem and its soil characteristics? While the literature seems to have a fairly clear idea of what it means when it speaks of the *long-term* impacts of a fire, here we seek to highlight some of the uncertainties that inevitably underpin any attempt at definition.

The impact of a forest wildfire is conditioned by a wide range of variables and, importantly, varies across different time scales. The bio-climatic region, the type of ecosystem, the plant species, soil type, fire regime (including the season), topography, intensity and severity of the fire, recurrent fires, and post-fire meteorological conditions, especially as regards timing, intensity, and duration (of, for example, rainfall and wind) are all variables that determine the response of ecosystem components and processes to a fire episode (Pereira et al., 2018). A heavy rainfall event, for instance, in the aftermath of a wildfire may cause severe erosion and lead to the most lasting effects over time, simply because of massive soil loss (Francos et al., 2016). Despite a considerable body of research that has examined these variables, there are insufficient long-term data to understand the consequences of climate change on the recovery of soil properties and the recovery of a soil's ecological functions (Halofsky et al., 2020).

Studies have been published in which the authors assume that *long-term* post-fire effects can persist for a different number of years (e.g., 11, 27 or more), but they fail to consider all the variables that might influence the trajectory of this post-fire recovery. Yet, many stakeholders, including land managers and water providers, need an answer to the question as regards the time frame in which the *long-term* effects of fire have to be considered. Clearly, there is no one answer that can be applied to all fire-affected areas and ecosystems of the world. Moreover, we also need to determine just when a forest can be considered to have fully recovered from a fire disturbance—assuming that the forest soil and vegetation have the necessary resilience—and, more relevantly, how we can measure the recovery of variables to their pre-fire state, especially under variable climate conditions (McGee et al., 2022). As DeBano (1991) pointed out towards the end of the 20th century: The key here is to ensure the sustained productivity of ecosystems despite fire-induced soil alterations.

The forest should be seen as a unit comprising a huge set of variables (each of its soil properties, for example,), which may or may not have suffered the same fire-induced effects (Úbeda and Outeiro, 2009). Indeed, the *long-term* effects of the same fire will only be *long term* in the case of certain variables: at some point, some properties will have recovered and others not. The *long-term* recovery from the effects of a fire, be it a wildfire or a prescribed fire, cannot be defined in the same number of specific years given the multiplicity of variables.

OBJECTIVES AND METHODS

The objective of the current paper is to undertake a review of studies that have purported to analyse the effects of fire on soil properties in a timeframe stated as *long term*. In so doing, we have separated these studies in two groups: those that focus on the most influential external variables related to the intensity of the fire episode and those that concern themselves with the soil's internal properties. In performing this review, we first conducted a literature search for scientific articles published, primarily in English, over the last two decades (2004–2023) in the Scopus database. In some instances, however, earlier studies were included because of the explanations and discussion they provide of given dynamics.

The search terms used were the combination of Long-term effects + Wildfire effects on soil; Fire-induced changes in soil properties; Soil heating by fire; Soil erosion after wildfires; Soil water repellency after wildfires; Soil compaction after wildfires; Soil nutrient losses after wildfires; Soil rehabilitation after wildfires; Soil carbon losses after wildfires; Soil microbial activity after wildfires; Soil organic matter decomposition after wildfires; Wildfires; Fire; Wildfire management; Wildfire prevention; Fire ecology; Fire effects; Fire severity; Fire behaviour; Fire regime; Fire disturbance; Burn severity; Burned area emergency response; Fire-adapted ecosystems; Fire-suppression; Fire-fighting; Soil structure; Soil texture; Soil acidity; Soil nutrients; Soil pH; Soil organic matter; Soil biology; Post-fire recovery; Soil carbon sequestration; Soil water repellency; Soil aggregate stability; Soil compaction; Soil microbial diversity; Soil microbial ecology; Soil microbial biomass; Soil erosion control; Soil erosion prevention; Soil remediation; Soil restoration techniques; Prescribed fire effects; Soil heating; Nutrient cycling in soil; Soil nutrient availability; Soil nutrient management.

In all, a total of 102 references were identified; however, we opted only to include those that specified exactly the number of years that had elapsed after the wildfire or the prescribed fire (**Table 1**).

EXTERNAL VARIABLES: FIRE INTENSITY, FIRE SEVERITY AND CLIMATE TYPE

Fire intensity has been identified as being of critical importance when seeking to understand the effects of fire on soil properties. Hurteau and Brooks (2011) examine carbon sequestration in the temperate forests of the western United States and conclude that the key factor in determining whether the carbon sequestered is subsequently restored is the intensity at which the forest burns. They argue that, in a high-intensity fire, more carbon is lost and the recovery of the forest is slower; indeed, in many instances, it is unlikely to recover its pre-fire carbon stock as the vegetation structure may well have changed, becoming bushy and even more herbaceous. Thus, these authors do not propose a specific time period as corresponding to the expression *long term*, but rather report that the effects of a fire can be drawn out indefinitely over a long period of time. They conclude that avoiding the fire risk in forests altogether is largely futile and that the best strategy has to be forest management practices that mitigate the risk of high-intensity fires, whose *long-term* impact can be great. Yet, to do so requires, for example, prescribed burning that will release carbon periodically into the atmosphere. In short, carbon stocks should not be seen as the most important aspect, but rather they should be considered as just one more element in the suite of ecosystem services.

Ibañez et al. (2022) investigate the effect of fires on soil nitrogen (N) concentrations in a Swedish boreal forest in which post-fire management takes the form of salvage logging. They claim that while much is known about what happens in the immediate aftermath of a fire, less is understood about the *long-term* effects. The authors report that, in response to high fire severity, gross N mineralization and consumption rates per unit carbon (C) increased by 81% and 85%, respectively, and that nitrification rates per unit C basis fell by 69%, while net N mineralization was unresponsive. They also found that,

TABLE 1 | Summary of the studies developed in this work, arranged chronologically.

Authors	Type of fire and location	Dominant vegetation	Time after fire	Parameters analysed	Overall effects
Ffolliot and Guertin (1990)	Prescribed fire in Arizona (United States)	*Pinus ponderosa*	22 years	Litter, duff and humus layers	Decrease of litter and duff
Slaughter et al. (1998)	Wildfire in Minnesota (United States)	*Taiga*	23 years	Cmass	Almost total recovery
Roscoe et al. (2000)	Wildfire in Southeast Brasil	Cerrado	20 years	Stocks of C and N	Similar in soil but less stocks of C and N in litter
Johnson et al. (2005)	Wildfire in Sierra Nevada, California (United States)	*Pinus jeffreyii*	20 years	C, N, P, K, Ca, Mg, S	P, K and S has not differences. N, Ca, Mg increase and C decrease in the burnt area
De Luca et al. (2006)	Wildfire in Montana (United States)	*Pinus ponderosa*	17 years	Charcoal, N, microbialactivity	Charcoal avoid a higher decrease of microbial activity
Yermakov and Rothstein (2006)	Wildfire in Michigan (United States)	*Jack pines*	72 years	N, organic horizons	Depending of climate there is recovery or not after a long term sequence
Capogna et al. (2009)	Wildfire in Castel Volturno (Italy)	*Phillyrea angustifolia L.*	3 years	C, N, P_2O_4, Ca, Mg, Na,K, microfungal variables	Increase in photosynthetic activity, particularly in the high-intensity fire plots
Fflolliot et al. (2009)	Prescribed fire in Arizona (United States)	*Pinus ponderosa*	43 years	Litter, duff and humus layers	Recovery of these layers
Kaye et al. (2010)	Wildfire in Garraf massif, (Spain)	*Quercus coccifera* and *Pinus halepensis*	30 years	Cstock	Increase just after fire, decreased with time and not recovery after 30 years
LeDuc and Rothsein (2010)	Wildfire in Canada	*Jack pines*	46 years	N	Recovery in 22 years and increase after 46 years
Hurteau and Brooks (2011)	Wildfires in Oregon (United States)	*Pinus ponderosa*	35, 100 and 200 years	Cstock	Decrease immediately after wildfire, recovering with time, although the non-managed forest result in high intensity wildfire than reduce again the Cstock
Longo et al. (2011)	Wildfire in Patagonia (Argentina)	*Nothofagus pumilio*	10 years	pH, C, N, P	Increase of pH and decrease of C, N, P
Johnson et al. (2012)	Wildfire in Sierra Nevada, California (United States)	*Ceanothus velutinus* *Pinus jeffreyii*	46 years	pH, C, N, P, K, Ca, Mg, S	C and N are similar in the burnt and unburnt soil. P similar in *Pinus jeffreyii* plot. Ca, Mg, K and S are increasing while P is decreasing in *Ceanothus velutinus* plot
Bennett et al. (2014)	Prescribed fire in Victoria (Australia)	*Eucalyptus obliqua* L'Her.	27 years (3 and 10 years frequency of burning)	Cstock in above-ground biomass, dead wood, Litter and soil	Decrease of the Cstock in all the analysed organic variables and frequency of burning
Alcañiz et al. (2016)	Prescribed fire in Montgrí massif, (Spain)	*Pinus halepensis*	9 years	EC, P_2O_4, pH, C, N, Ca, Mg, K	EC, P_2O_4 increase; pH, C, N, Ca, Mg, K decrease
Muñoz-Rojas et al. (2016)	Wildfire in Western Australia	Grassland	14 years	C, N, Soil microbiology	Partial recovery
Francos et al. (2018)	Wildfire in Cadiretes massif, (Spain)	*Pinus pinaster* and *Quercus suber*	18 years	C, N, C/N, SOM, Ca, Mg, Na, K	Similar to control for N, Ca, Mg, Na. Decrease of C, SOM in Low severity. Similar to control for N, Na, K. Decrease of C, SOM, Ca, Mg in High severity
Francos et al. (2019)	Prescribed fire in Tarragona (Spain)	*Pinus pinea*	13 years	EC, P_2O_4, pH, C, N, Ca, Mg, K, SOM	Decrease in N, SOM, P_2O_4
Francos et al. (2020)	Wildfire in Ódena, Barcelona (Spain)	*Pinus halepensis*	30 years	EC, P_2O_4, pH, C, N, Ca, Mg, K, SOM	Recovery in areas with forest management
Robichaud et al. (2020)	Wildfire in Colorado (United States)	*Pinus ponderosa*	10 years	Erosion	No differences with unburned after 4 years
Sadeghifar et al. (2020)	Wildfire in Zagros monuntains (Iran)	*Quercus brantii* Lindl.	10 years	qCO_2, microbal biomass, C	Increase of qCO_2 and Cmic:Corg decrease of C
Li et al. (2021)	Meta-analysis		10 years	C, N, PyC, PyC/TOC	Recovery of C and N after 10 years. Increases in PyC and PyC/TOC
Pérez-Quesada et al. (2021)	Wildfire in Chiloé (Chile)	*Drimys winteri* Jordan Forst.	50 years	Soil CO_2	The unburned forest is still a source of CO_2
Dove et al. (2022)	Wildfire in Central Sierra Nevada (United States)	*Pinus ponderosa*	More tan 25 years	Different soil microbes, C, N	Not recovery of microbial community, affecting C and N cycles after high severity fires
Follmi et al. (2022)	Wildfires in Águeda catchment (Portugal)	Majoritary Eucaliptus, pines and shrub vegetation	41 years	Soil erosion	Decreasing with time and equal than non-burnt areas in some places after 41 years. Erosion increases after wildfires and its higher depending fire severity and fire recurrence

(Continued on following page)

TABLE 1 | (*Continued*) Summary of the studies developed in this work, arranged chronologically.

Authors	Type of fire and location	Dominant vegetation	Time after fire	Parameters analysed	Overall effects
Ibañez et al. (2022)	Wildfire in Central Sweden	Conifer forest	4 years	Different forms of N and C	Net N was unresponsive. Gross N mineralization and consumption rates per unit carbon (C) increased by 81% and 85%
Kastridis et al. (2022)	Wildfire in Thessaloniki (Greece)	*Pinus brutia*	25 years	Erosion	Increasing after fire and decreasing with time but remaining higher than in control
Margiorou et al. (2022)	Wildfire in Thessaloniki (Greece)	*Pinus brutia*	30 years	Erosion	Not recovery
McGee et al. (2022)	Wildfire in Utah (United States)	*Temperate coniferous forest*	20 years	Soil fungal communities	Recovery
Orumaa et al. (2022)	Wildfire in Estonia	Scots pine	From 12 to 181 years	Fungal community, C and N	Similar quantity after 181 years but differences in the species composition over the years
Voropay et al. (2022)	Wildfire in Baykal region (Russia)	Pine forest	10 years	Soil temperature	Increase until the 8 years
Liu et al. (2023)	Meta-analysis		Different years considered “long term”	SOM	Recovery of SOM at long term
Taylor et al. (2023)	Prescribed fire in Florida (United States)	*Pinus palustris* Mill.	60 years	Soil horizons	Increase of the A horizon

regardless of burn severity, the rate of N immobilization exceeded the rates of N nitrification and, as such, immobilization was the dominant pathway of gross N consumption. The study shows that soil N transformation rates were more strongly affected by changes in fire severity than by salvage logging, and that 4 years after the fire many aspects of the N cycle in burned and unburned stands did not differ, suggesting substantial resilience of the N cycle to fire and salvage logging.

In the tropical climate of Brazil, Roscoe et al. (2000) study the differences in three areas of forest—two of them burned at low intensity and one at high intensity—after 20 years. They find that fire intensity is responsible for the difference in the recovery of C and N content. Thus, in the two low intensity plots the stock of C in the litter was lower than that in the unburned area, but that this was not the case in the mineral soil. In the most heavily burned area, the stocks of C and N were lower than those of the control area while significant differences were seen with the other two plots.

In the Mediterranean, the most intense erosion is a short-term phenomenon, that is, it occurs immediately after a fire, given that the many plant species that colonize the burned area protect the soil from erosive processes. And yet, Follmi et al. (2022) show that although erosion in a Portuguese forest is reduced over time, it remains more important in the *long term* in areas that have been burned than in those that avoided the effects of fire. To achieve this goal, the authors build a landscape evolution model and find that over a 41-year timespan erosion rates in the burned area were 5.95 ton compared to 0.58 ton ha^{-1} $year^{-1}$ in the non-burned area. The authors conclude that burn severity is the most important variable here, but that the topography should not be underestimated given that it can concentrate erosion hotspots, coinciding with the creation of rills and gullies. Likewise, Kastridis et al. (2022) report that, 25 years after a fire in Greece, erosion is greater in a burned area; however, the infestation of the forest by the bark beetle *Tomicus piniperda* impedes soil recovery because of the logging and removal of infected trees. The authors show that these variables are determining factors of the rates of erosion in disturbed and undisturbed areas of the forest. Margiorou et al. (2022) study erosion rates in Greece in basins in which check-dams were built some 20 years ago to prevent soil loss, some 3 years after the fire. The authors find that the average annual erosion rate for the pre-fire period was 0.0419 t/ha/year, rising to 0.998 t/ha/year 3 years after the fire but remaining at 0.08 t/ha/year 20 years afterwards, that is, twice as high as in the unburned control. As such, the forest has yet to fully recover. The authors attribute this to a very thin soil depth, the high intensity fire and the geomorphology of the basin, which favours erosion.

In the continental climate of the state of Colorado in the United States, Robichaud et al. (2020) found that the burned control plots of a forest presented high sediment flux rates until post-fire year 3, when they fell significantly to a level that was statistically no longer higher than those of the unburned reference plots in post-fire years 4 and 10. The authors stress the importance of the climate and its relationship with the rates at which existing vegetation are allowed to regenerate and, hence, to determine the duration of the erosive processes. In this instance, the authors identify the need to reduce erosion in the immediate aftermath of the fire using mulch treatments, such as the application of straw and wood.

In Spain, in the Cadiretes Massif, Francos et al. (2018) studied the long-term (18-year) impact of a wildfire on two areas affected by low and high fire severity regimes, comparing outcomes with the characteristics of an unburned control (**Figure 1**). The authors concluded that 18 years on, many of the respective soil properties differed and that the intensity of the episode could be considered largely responsible. Vegetation regrowth was rapid although it differed in density and species type, factors that appeared to explain the evolution of the soil parameters. After 18 years the decrease in the soil organic

FIGURE 1 | Recent sample from the high severity of the Cadiretes Massif study area in 1994. It is clear how the organic layer was burned. After the first rains, this layer was eroded. Picture by Xavier Úbeda.

FIGURE 2 | A prescribed fire in Montgrí Massif in 2022. Picture by Eduardo García-Braga.

matter (SOM), C and N values in the high severity area was more accentuated than that in the low severity area. In the same Mediterranean ecosystem, Francos et al. (2020) observed the influence of long-term forest density after a wildfire. The authors compared high and low density areas with a control forest and detected the positive effects of a management action conducted almost 20 years after a wildfire. However, they identified problems in the recovery of certain physicochemical soil properties in high density areas, stressing the need to study forests in a context of global change.

Not all studies dedicated to the analysis of the long-term effects of burning focus their attention on wildfires; some interest themselves in the impact of prescribed burning (**Figure 2**). This is the case of Bennett et al. (2014) who examine the effects on total soil C of a prescribed fire in a temperate climate zone of Australia. In general, the authors report a decline in C stocks following such an episode, not only in the soil, but also in the vegetation. They identify fire intensity as well as frequency as the most important variables in this regard; moreover, the effects are evident 27 years after the first burning, being greater when the frequency factor (every 3 or 7 years, depending on the fire intensity) is added. Another factor that the authors show to be important is the time of year when the fire treatment is administered, with carbon stock decreases being greater in the dry autumn season than in the wet spring season when greater burning intensities can be achieved. Such studies serve to demonstrate how frequently fire should be used as a management tool to avoid negative soil effects.

In other studies of the use of fire as a tool for managing forests, Alcañiz et al. (2016) found that pH levels, C, N and available phosphorus (P) were significantly lower 9 years after a prescribed fire in a *Pinus halepensis* forest than their pre-fire values, while the rest of the variables analysed did not present a statistically significant difference. In this forest, the vegetation burned was the *Quercus coccifera* L. shrubland, but the fact that the fire intensity achieved during the prescribed burning was not great explains, according to the authors, why the effects were not greater after 9 years. Francos et al. (2019), among others, have evaluated the impact of prescribed fire on soil chemical properties, in this particular instance in a wildland-urban interface in the Mediterranean environment. The authors report that the burning sought specifically to eliminate the continuity of plant fuel, and, therefore, the prescribed fire was of a higher intensity than in other cases; indeed, controlling the intensity of the fire during the execution of a prescribed fire is, they stress, critical. Thirteen years after the burn, they conclude that the inhabited area has been successfully protected from fire risk. However, even after this period of time, they report impacts on soil chemical properties that still need to be monitored. Ffolliott and Guertin (1990), in a study conducted in a forest of Ponderosa pine in Arizona, found that the forest floor (litter and duff) failed to recover its original depth even 22 years after a fire. In short, the objectives of a prescribed fire, and its consequences, must be very clearly determined, which means a good understanding of the effects of fire in each site is fundamental so as not to harm the soil and its functions (Alcañiz et al., 2018; Francos and Úbeda, 2021). Ffolliott et al. (2009), in line with others, point out that after 40 plus years the effects of a prescribed fire disappear, making it necessary to repeat the measure less than every four decades to maintain the effects and avoid a detrimental impact on the ecosystem.

Historically, fire, both natural and anthropogenic, has not been as recurrent in the easternmost forests of the United States. For this reason, Miesel et al. (2012), who undertake an analysis of the forests of the Lake States region, conclude that there have been few studies of post-fire dynamics in this area of the country. According to these authors, climate is decisive in understanding the effects and, in particular, the *long-term* effects—10 years being deemed sufficient, although they offer no concrete reasons as to why—on the composition and structure of vegetation and on soil properties. They also stress that the recovery of forest soils differs from one ecosystem to another, the characteristics of which are determined primarily by climate factors. The authors conclude that in the Lake States there have been insufficient *long-term* studies to draw any safe conclusions about the role played by the variables analysed and, moreover, call for the inclusion of more physical parameters in future studies. However, they are able to show that the *long-term* effects differ in the coldest forests of the Lake States from those in the westernmost forests of the United States In none of the cases reviewed are the authors able to verify that there are no longer term effects of fire on soils than those reported in a 10-year period after the fire episode.

A further example of the effects of fire in a temperate climate is provided by Longo et al. (2011) in a study of wildfires that occurred 6–10 years earlier in Argentine Patagonia. In what the authors describe as a *long-term* study (having stressed that most studies are conducted in the immediate aftermath and very few more than 5 years on), they show that in all study plots, the soils present different rates of decrease in their C, N and P concentrations and different degrees of increase in pH. They attribute these differences essentially to the time elapsed, which in all instances is insufficient for the parameters to have returned to their pre-fire values. In this Patagonian forest, the authors suggest that the evolution in the development of ectomycorrhizas in the soil can be directly related to such elements as N and P. The climate, they argue, is also important, given that at higher temperatures the recovery of certain parameters, especially biological, such as fungi, is faster than that in colder climates, and that this biological recovery is determined by the recovery in the accumulation of SOM.

McGee et al. (2022) study the *long-term* effects on soil fungal communities over a 20-year chronosequence in Utah. The authors report that at the end of this period the fungal community has recovered, but that the rate of recovery is dependent on the temperature—a difference of as little as just 2°C making a difference—and annual precipitation. In addressing climate change in alpine areas, the authors believe that as temperatures increase, forest fires are also increasing with all the ramifications this might have; yet, in these new scenarios, fungal recovery time should be cut.

Another example of the way in which climate and soil type can respond differently to wildfires is provided by Yermakov and Rothsein (2006). In more northerly ecosystems (in this instance, in Michigan), where the accumulation of N in surface organic layers can constrain plant productivity, wildfires induce ecosystem rejuvenation and increase N cycling rates. In contrast, N availability, in drier, sandy places with a very thin O horizon, a fire can actually consume the main nutrient pool. In soils of this type, the restoration of pre-fire N levels is much longer.

Some forests will never recover their pre-fire state. New climate situations are likely to prevent a forest from recovering its structure and composition in the way it would have done decades earlier when exposed to the same kind of fire event (Halofsky et al., 2020).

INTERNAL SOIL VARIABLES

Shifting the focus more specifically to a soil's internal variables, Johnson et al. (2012) conducted a study in California, in which they compared the evolution over time of two plots that had burned 46 years earlier. The authors detected differences in the respective forest soil parameters but the degree of these differences varied. They attributed the variations in certain soil chemicals to the vegetation that had emerged after the fire, with some species providing better fixation, for example, of P and N. They also attributed higher concentrations of major cations in burned areas to the greater accumulation of burned material above the soil surface. However, they stress that the substrate type had been decisive in producing these different soil parameters, specifically, in the *long term*, they recorded higher concentrations of P in areas of andic parent material.

Carbon is one of the most frequently measured elements in studies of this type, given the importance of carbon sequestration by forests for mitigating the effects of atmospheric emissions. In a study conducted in a southern boreal climate, it was found that in the five immediate post-fire years there was a general loss of C throughout the forest from the soil to the vegetation (Slaughter et al., 1998), with losses peaking in the fourth year; however, 23 years later, the forest had recovered 91% of its entire pre-fire C mass. Similar results were reported by Roscoe et al. (2000) in native *cerrado* (savannah) ecosystems in Brazil, where 21 years after an intense fire, the soils' C and N values had been restored, albeit the quantities of C and N were lower in the litter horizon than in the control forest. Likewise, Kaye et al. (2010) reported an increase in soil C after a fire in a Mediterranean forest, but concentrations had fallen to pre-fire levels after 10 years. The authors conclude that the type of vegetation to emerge after a fire can be decisive in determining soil C storage. If there is vegetation recovery, the authors determine that in the organic horizon (LF) there are no significant differences after 30 years. However, they find differences in the organic H horizon after 15 years and report that these can be maintained even after 30 years. In the mineral horizon, they found significant differences with the unburned area, with the C content being higher in this latter area.

Johnson et al. (2005) conducted a study in a Californian forest some 20 years after a fire and found that the soil contained less C and more N than that of the adjacent forest ecosystem. They attribute this to the fact that one species, *Ceanothus velutinus* Dougl, has helped N fixation not only in the organic horizon, but also in the mineral horizon. They found no differences in ecosystem P, K and S, while exchangeable K^{+}, Ca^{2+}, and Mg^{2+} were greater in the burned zone. The authors speculate that the large increase in the soil and ecosystem Ca content resulted from the release of these elements by the ash and the rapid absorption and recycling of Ca by vegetation after the fire. LeDuc and Rothstein (2010) found similar results for different forms of N availability in a jack pine forest in Canada. They reported that in the first 10 years after the fire the uptake of N forms beneficial for vegetation (amino-acid N) was lower than that of pre-fire values; however, a rapid increase was recorded 15–22 years post-fire, reaching values that exceeded those before the fire after 46 years. Li et al. (2021) carried out a meta-analysis focused on the loss and subsequent recovery of soil C and N concentrations in the wake of a fire, on the understanding that these elements determine soil health and ecosystem services at the global scale. After reviewing 3,173 publications, the authors conclude that although the intensity of burning determines the losses of soil C and N, geographical variables determine both wildfire severity and soil recovery. Thus, greater negative impacts on soil C and N were found in tropical and temperate climates than in Mediterranean and subtropical climates, while stronger effects were found in forest ecosystems than in non-forest ecosystems. Yet, on average, the authors conclude that pre-fire levels can be recovered after 10 years.

One of the main ecosystem services provided by forest soils is their ability to serve as C sinks and so minimize greenhouse gases (GHGs). Pérez-Quezada et al. (2021), in a study conducted on the island of Chiloé in Chile, compared CO_2 emissions in a forest that had not suffered a fire with an adjacent forest that burned more than 50 years earlier. Starting from the premise that the greatest quantities of CO_2 are released into the atmosphere during the combustion event, once the fire has burnt out, the time of year, as well as temperature and humidity can be deemed decisive in understanding annual GHG variations. The authors conclude that in the net ecosystem exchange of CO_2, the unburned forest is a sink, while the burned site is a source of GHGs, although more than 50 years have passed, these differences can still be observed. Pellegrini et al. (2022) make an important contribution regarding the complexity of soil carbon content after impacts such as wildfires, based on a review of studies conducted in different types of ecosystem. The authors consider that fire affects soil C content in quite a different fashion, given that most of this C is found in SOM. Fire can mean that soil C occurs in a much more stable form that persists over time and that the effect of fire on the decomposition of SOM would appear to be important for understanding the *long-term* changes in soil C storage and fluxes. They conclude that perhaps, by means of prescribed fires, climate change could be mitigated since the stability of this organic matter seems to increase.

It is clear, as discussed above, that not all ecosystems behave in the same fashion when exposed to fire, the response depending on the climate zone in which it is located and, arguably even more so, on its characteristic soil type. Taylor et al. (2023), in a study conducted at Spodosols in Florida, show that A-horizon thickness is greater in places that have been managed for more than 60 years with prescribed burning than in those that have not been exposed to any management practices. They attribute the greater thickness to the fact that in burned soils, with a thinner O horizon, there is likely to be more movement of particles towards the A horizon. The authors report differences in thickness of more than 2.5 cm between a soil that has been burned recurrently for 60 years and another that has not been burned. They also report that fire can cause changes to the bulk density of burned plots because of the inputs of ash. This means the A horizons tend to be less dense, thus influencing their thickness. The authors conclude that, following a fire, the C of the organic matter is better protected in this A horizon than in the organic horizon which is more prone to burning.

Closely related to horizon thickness and the effects of fire is the importance that the increase or decrease in temperature can have on altering a soil's physicochemical and biological processes. In a study undertaken in the south-western area of the Baykal region, Voropay et al. (2022) found that, 10 years after a fire, increases and decreases in soil temperature differed. The authors conclude that the burned forests need to be managed to ensure these temperature dynamics do not take so many years to recover. They report that differences in average monthly temperatures at the surface began to decrease 8 years after the fire; however, trends have yet to be studied at greater depths.

Other authors, most notably Orumaa et al. (2022), have studied the short- and long-term effects of fire on fungal communities and soil properties. These latter authors conducted a study in Scots pine stands in the hemiboreal climate of Estonia, where fires had occurred at various times between the last 12 and 183 years. In this chronosequence, soil saprotrophs and ectomycorrhizal fungi (EcM) were predominant. The authors report marked differences in the species composition of EcM fungi, with *Piloderma sphaerosporum*, *Pseudotomentella* sp. and *Clavulinaceae* sp. being the most abundant EcM operational taxonomic units in the most recently burned stand while *Clavulinaceae* sp. and *Cortinarius* sp. were the most abundant in the three oldest burned stands. Soil C and N stocks were lower in the most recently burned stand, but the differences with the other stands were not statistically significant. Soil pH had a significant effect on fungal species composition, with the older stands presenting a substantially lower pH than that of the more recently burned areas. It should be noted that the forests have not undergone any type of forest management. As discussed, it is evident that not all soil properties evolve in a similar fashion over time, nor are they affected in a similar fashion by fire. What is important—as many researchers in this field have been at pains to point out—is the relationship between the different variables. Capogna et al. (2009) highlight the close relationship between a soil's biotic and abiotic soil components, above and below the ground. The authors observe that the more intense the fire, the more important these relationships and interconnections are. They highlight the importance of soil fungal components and their relationship with the reserve and translocation of chemical elements in the soil in a Mediterranean forest 10 years after a fire. This also means that the plants have higher nutrient stocks and are able to emerge more vigorously after the fire.

Soil microbiology is critical for ensuring that degradation of organic matter and mineralization occur at rates that safeguard the proper functioning of the C and N cycles and provide sustenance for the vegetation and the structural stability of the soil's most superficial layers (Muñoz-Rojas et al., 2016). The same authors report that 14 years after a forest fire in a semi-arid grassland ecosystem of Western Australia, the recovery of soil properties continued to be only partial, but given their interconnections it was impossible to identify which were the most important. They also stress how a soil's physical and organic properties are critical for its capacity to retain water, the latter being a basic element for many of the functions of the soil system and its relationship with plants.

Dove et al. (2022) have studied high-intensity burned forests in the western United States and find that the recovery of soil microbial communities can take more than 25 years. They report, moreover, that not all communities recover at the same rate and that changes may occur in the microbiome composition. As wildfires tend these days to be more severe, the authors claim that post-fire management is necessary to speed up rates of recovery and so favour biogeochemical dynamics. Similarly, Liu et al. (2023), based on an analysis of 371 works studying the impact of fire on microbial properties, conclude that the effects are highly variable depending on the location and soil type, but given that the majority constitute short-term studies, what may occur in the *long term* is largely unknown. These authors report that their review of the literature suggests that SOM is not affected in the *long term*, although the biological properties may be impacted. However, they stress that there is a relationship between the effect and the intensity of the fire. In the short term, reported outcomes show that fires significantly increase microbial metabolic quotient (qCO_2) by an average of 19.45%, and reduce soil microbial and fungal biomass carbon by 8.41% and 27.17%, respectively.

In a similar vein, Sadeghifar et al. (2020), in a study conducted in the Zagros Mountains, report that not all microbial eco-physiological indices behave in the same way, both as regards their impact and their recovery time. They find an increase in some properties after the fire—the case, for example, of the eco-physiological indices, including the ratio of respiration to qCO_2 and the ratio of microbial biomass to soil organic carbon (Cmic: Corg); however, some parameters had not recovered 10 years after the fire—the case of acid phosphatase (ACP) activity and, unlike the previous study, the amount of Corg had not recovered, being up to 21% less than in the unburned control plot.

FOREST MANAGEMENT

Post-fire forest management (e.g., mulching, salvage logging, reforestation, etc.) can affect soil properties even in the long term. It is therefore essential to take into account the existence or absence of intervention in an area to determine its natural recovery or whether it has been intervened or favoured by humans. According to some studies (e.g., Mitchell et al., 2009), forest management can help some types of forest recover from the impact of a wildfire more quickly and without any detrimental effects to any of the ecosystem services. Such management initiatives might centre on clearing the post-fire vegetation combined with the felling of some individuals (Stephens and Ruth, 2005). These management practices are of benefit at the ground level, given that not as many nutrients and as much water are extracted and so recovery is likely to be quicker. They also have the benefit of minimizing the risk of a large forest fire in the event of a future outbreak. However, Mitchell et al. (2009) claim that in forests with little accumulation of forest mass—such as, monospecific forests or forests with a highly dominant species (e.g., the Douglas fir)—management strategies that promote logging can be counterproductive, since they undermine a forest's carbon sequestration capacity.

However, each ecosystem needs to be considered in isolation. For example, DeLuca et al. (2006), in a study carried out over a 17-year period, highlight that in fires in boreal forest ecosystems one of the few products produced is charcoal. Charcoal is of particular importance in environments of this type as a *long-term* driver of ecosystem processes and, specifically, of N cycling. The authors report that post-fire forest management and road construction can result in the disappearance of this passive form of C, leading to soil impoverishment and alterations to the nutrient cycles.

CONCLUSIONS

The authors of this review believe that a study might assume that the years that have elapsed since the fire episode is sufficient to offer conclusions, but this is often determined by the actual opportunity a team has to conduct its study (often dictated by funding or availability of team members). Thus, the literature is full of studies conducted after varying numbers of years simply because the authors believed the *long-term* effects of the fire might still be evident; indeed, knowing with any degree of certainty when the effects are no longer visible is largely impossible.

A review of the extant literature fails to reveal just how many years might be understood to constitute *long* when considering the *long-term* effects of fire on soil properties. Indeed, the variation in responses is high. However, the review does identify two key variables that seem to determine the prolonged impact of fire on soils: first, the intensity of the fire and the consequent severity of the burning, and, second, the climate, closely associated with the forest's ecosystem, insofar as prevailing temperatures and levels of precipitation, and the vegetation type that prospers in each place, are decisive.

The literature also highlights that not all soil properties recover at the same rate and that not all effects remain visible over time. Moreover, certain soil properties can impact others, thus modifying soil system dynamics.

The literature, likewise, stresses the importance of *long-term* studies because there has been a change in the global fire regime, characterised today by more severe, more recurrent fires that are likely to occur throughout longer periods of the year. These changing circumstances emphasise the need to conduct studies of these characteristics. Undoubtedly, the changes in the world's fire regimes—above all, their increasing severity—can be attributed to the effects of climate change, a phenomenon that the literature reviewed here constantly associates with the difficulties faced in recovering soils.

Clearly, both pre- and post-fire management practices need to be the object of very careful study: the former to prevent the proliferation of more severe fires, which as we have documented here are increasing in number, and the latter to minimize the effects of severe burning on a temporal scale. Disseminating the findings of this research to forest managers and administrators must be the ultimate goal of these studies.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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