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Review

The Effect of Repeated Prescribed Burning on Soil Properties: A Review

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Abstract: Prescribed burning is a tool that is frequently used for various land management objectives, mainly related to reduction of hazardous forest fuels, habitat management and ecological restoration. Given the crucial role of soil in forest ecosystem processes and functions, assessing the effects of prescribed burning on soil is particularly relevant. This study reviews research on the impacts of repeated prescribed burning on the physical, chemical and biological properties of soil. The available information shows that the effects are highly variable, rather inconsistent and generally minor for most of the soil characteristics studied, while a number of soil properties show contrasting responses. On the other hand, ecosystem characteristics, differences in fire severity, frequency of application and the cumulative effect of treatment repetition over time, have possibly made it more difficult to find a more common response in soil attributes. Our study has also revealed some limitations of previous research that may have contributed to this result, including a limited number of long-term studies, conducted at a few experimental sites, and in a limited number of forest ecosystems. Research issues concerning the effects of prescribed fire on soil are presented. The need to integrate such research into a broader interdisciplinary framework, encompassing the role of the fire regime on ecosystem functions and processes, is also highlighted.

Keywords: controlled fires; frequency; soil properties; soil mesofauna

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1. Introduction

Prescribed burning is commonly used to modify fuel quantity and continuity and thus to reduce the potential occurrence and extent of high-severity wildfires in fire-prone areas [1–3]. Prescribed burning is also used for ecological restoration in an attempt to emulate historical fire-regimes in fire-adapted landscapes to promote ecological functions and enhance biodiversity [4–8]. It has also been proposed that prescribed fire can be used to mitigate greenhouse gas emissions [3]. However, the application of prescribed fire is hampered by difficulties in determining windows of suitable meteorological conditions within which the operational objectives can be achieved without damaging the ecosystem. Fire can affect soils physical, chemical and biological properties in different ways depending on the fire severity and frequency. The impact of single fires on soil properties has been widely studied [9–11], and prescribed burning has generally been found to have a limited effect on soil due to its typically low-severity, as a consequence of reduced soil heating and the protective effect of the remaining soil organic cover [12–14]. Since fuels accumulate over time, fuel reduction techniques such as prescribed burning need to be applied periodically to maintain fuel hazard at tolerable levels, which may exacerbate the fire effect on soil. However, the impact of repeated prescribed fires has scarcely been investigated and the results are very variable [11,15]. Most of the information comes from North America [16] and extrapolation of the findings to other ecosystem types is questionable. Moreover, there is no clear relationship between fire prescribed conditions, fire frequency and changes in soil properties. The lack of knowledge is of concern, especially in fire-prone areas such as in southern Europe where there is almost no information about the consequences of repeated prescribed fires and potential changes in ecosystem services [17]. Planned field experiments aimed at studying the impact of repeated prescribed burning on soil properties are rare in Europe, and the available information is provided by experimental burns that induce medium- or high- rather than low-severity fires [18]. There is an urgent need for guidelines regarding the planning of prescribed burning that make fire management objectives compatible with environmental sustainability.

In the present review we summarize information on the effects of repeated prescribed burning on key soil properties. The objectives of the review were to: (1) identify common responses of the soils physical, chemical and biological properties caused by repeated prescribed burning and (2) detect knowledge gaps and suggest research topics to help understand the role of frequency of low-severity prescribed fires in soil.

The manuscript contains, in addition to the introduction (Section 1), two other sections: (2) changes in soil properties after repeated prescribed fires and (3) some reflections on the information analysed and research needs. Section 2 includes 4 sub-sections: (1) physical properties, (2) chemical properties, (3) microbiological properties and (4) soil mesofauna. These sub-sections contain comparative tables of the properties considered, indicating the vegetation type, the frequency of prescribed fire application, the sampling time and the change in relation to unburned soils. Section 3 presents a summary of the results presented in the tables, comparing the responses observed in the different studies.

2. Changes in Soil Properties after Repeated Prescribed Fires

There is a considerable amount of information available about the effects of prescribed fires on soil properties, but most of the research is restricted to the effects of single fires. The treatments involved are generally low to moderate severity fires that have less marked and shorter-lived impacts on the soil than wildfires. However, a wide variety of responses to prescribed fire are documented depending on numerous factors, such as the vegetation present, initial site characteristics, fire severity, weather and conditions under which the burning is conducted, e.g., [11]. In addition, prescribed fire frequency can determine the resilience of the ecosystems (and hence the soil system) to these perturbations. Studies investigating the consequences of repeated fires on soils physical, chemical and biological (microbiota and mesofauna) properties are summarized in Tables 1–9. The tables show information about the frequency of fire, duration of the study and the most marked changes in relation to unburned soil. The references have been ordered by vegetation type.

2.1. Physical Properties

Regarding the soil properties investigated, information on the physical soil condition is scarce (Table 1) relative to information on chemical and biological properties, despite the importance of physical properties for water retention, soil conservation and soil erosion risk. Soil structure determines organic C accumulation, infiltration capacity, movement and storage of gases, water and nutrients, emergence of vegetation and root growth, and microbial community activity. Relative to unburned soils (0–10 cm), Scharenbroch et al. [19] did not observe any differences in soil texture, aggregate stability or hydrophobicity after annual and biannual low-severity burns carried out during a period of 23 years in *Quercus* forests in Illinois (USA). Similarly, other authors have not observed any changes in soil texture after repeated prescribed fires with a 1–4 year frequency in a humid subtropical tallgrass prairie [20]. These results may be attributed to the typically low temperatures associated with prescribed fires, which are not sufficient to cause changes in soil mineral particles (sand, silt and clay) [21]. However, it has been found that a high burning frequency (every 2 years) decreases the clay content, while no effects have been detected after less frequent burning (every 4 years) in sandy soils located on a wet sclerophyll forest in Australia [22]. Slight reductions in porosity, infiltration and moisture holding capacity have also been recorded in soils repeatedly subjected to prescribed burning [23]. In the case of bulk density, different responses have been recorded depending on the ecosystem, depth of soil and frequency of burning. Therefore, some studies have reported a lack of change in this parameter which is consistent with the low severity of prescribed fires, relatively minor changes in soil carbon content and slight reduction in the thickness of the organic horizon [24,25], whereas other authors have recorded higher values after repeated prescribed fires in different ecosystems which may be attributed to the repeated destruction of soil organic matter (SOM) by heating [23,26–28]. In contrast, the decrease in bulk density after 12 years of annual burning in an Arkansas tallgrass prairie is related to increased soil organic matter inputs [20]. The authors attributed that response to the mechanical effect of the inputs as root biomass and partially charred SOM. In general, significant changes are observed in the topsoil layer (0–5 or 0–10 cm), while effects at lower depths are negligible [22,23].

Table 1. Studies including the effects of repeated prescribed fires on soil physical properties: texture, aggregate stability (AS), water repellency (WR), moisture holding capacity (MHC) and bulk density (BD). UB: unburned soil; yr: year; IAF: immediately after fire.

Soil Property	Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change (Relative to UB)	Reference
Texture, AS, WR	Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	No change	[19]
Texture (sand, silt, clay)	Humid subtropical prairie (USA)	Annual for 12 yr	≈3 months	0–10	No change	[20]
Clay content	Eucalypt forest (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [1]	Decrease No change	[22] [2]
MHC	Pine forest (USA)	Every 2 yr for 16 yr	6 months	0–5, 15–20	Decrease	[23]
BD	Pine forest (USA)	Every 2 yr for 16 yr	6 months	0–5 15–20	Increase No change	[23]
BD	Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	No change	[24]
BD	Oak-pine forest (USA)	Every 1, 2, 3,4 yr for 12 yr	≈8 months, 1 yr	0–10	No change	[25]
BD	Oak forest (USA)	Every 2 yr for 20 yrEvery 4 yr for 20 yr	2.5 yr	0–10	Increase No change	[26]
BD	Pine-grassland forest (USA)	Every 1, 2 yr for 40 yr	2 yr	0–10	Increase	[27]
BD	Tropical savanna (Zimbabwe)	Every 1, 3, 5 yr for 50 yr	4, 16, 28 or 52 months	0–5	Increase	[28]
BD	Humid subtropical prairie (USA)	Annual for 12 yr	≈3 months	0–10	Decrease [3]	[20]

[1] Soil depths: 0–10, 10–20, 20–30 cm; the results included in the table refer to 0–10 cm. [2] Study performed in wet and dry sclerophyll sites; the results refer only to wet sites. [3] Relative to pre-fire values.

2.2. Chemical Properties

Among the soil chemical properties considered, the changes in soil carbon (C) that occur after fires are particularly relevant because of the overwhelming influence of soil C on a myriad of the soils physical, chemical and microbial properties and the sensitivity of soil C to fire-induced heating, which leads to thermal decomposition and combustion of the soils organic matter, e.g., [29,30]. After repeated prescribed fires (Table 2), a few increases [19,20,31,32] or decreases [28] in soil C content have been observed, some of them dependent on fire frequency [33] or season [34–36]. Most decreases have been recorded in eucalypt and pine forests in Australia [22,37–40] but all of them were dependent on fire interval, with more frequent fires causing a reduction in C but less frequent fires resulting in fewer effects or no change; this pattern was also observed in oak forests [26]. However, the total lack of change [23–25,41–48] is the most frequent response, especially in oak and pine forests. The effect of the frequency of prescribed fires varies depending on the ecosystems and the conditions under which the burning is conducted. Thus, in some cases the C response is found to be independent of the prescribed fire frequency [19,25,41,42,45,46], whereas in other cases fire interval affected this variable [22,26,33,37–40]. A more marked response to a shorter fire interval has been attributed to the cumulative combustion of the soils organic matter, litter consumption and other fire-related C inputs [26,38] and the lack of time for complete recovery between prescribed fires [39,40]. In contrast, increases in C immediately or shortly after prescribed fires, similar to the findings of a meta-analysis by Johnson and Curtis [49], have been related to the addition of necromass to the soil, or to incomplete combustion of organic matter due to low temperatures reached in the top first centimetre of mineral soil during burning [19]. In addition, the season of application of prescribed fire can also influence the response of the soil C content. Thus, the changes are generally greater after repeated autumn fires than after repeated spring fires [34,38,44], due to the more severe drought conditions in autumn which result in more severe fires and greater consumption of the organic horizon. The effects of low to moderate severity fires, such as prescribed fires, are typically confined to the upper soil layers [10] because mineral soil is a poor conductor of heat [50,51]. As a result, changes in soil C are therefore usually more marked in the upper few centimetres of soil. This response has been found after repeated prescribed burns [22,33,37,44,48], although generalisation is difficult owing to the different soil depths considered in the various studies. In contrast, the C stock usually suffers a more pronounced impact in the soil organic horizon than in the mineral soil surface [33,38,44,47] due to the partial or total combustion of the organic horizon during burning. On the other hand, when prescribed fires are combined with other fuel treatments, such as mechanical clearing of understory shrubs, e.g., [43,52], these treatments may have similar or greater effects on soil C content than the fire alone. The greater effect of the combined mechanical-fire treatment than fire-only or mechanical-only treatments was attributed by Boerner et al. [52], in their meta-analysis study, to the greater fire severity (based on proportional fuel consumption) in the first case. Additionally, Dukes et al. [43] found that a combined cut and burn treatment produces a greater reduction of most fuel components than the burn-only treatment.

Table 2. Studies including the effects of repeated prescribed fires on soil total or organic carbon (TC, OC). UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in TC or OC (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	Increase	[19]
	Annual for 30 yr	14 months	0–5, 5–15		[32]
	Every 2 yr for 20 yr Every 4 yr for 20 yr	2.5 yr	0–10	Decrease No change	[26]
	Every 1, 4 yr for 45 yr	1, 5 months	0–15	No change	[41]
Oak-hickory forest (USA)	Every 1, 2 yr for 4 yr	1 month or 1 yr	0–15 cm of A + Oa horizon	No change	[42]
Oak-pine forest (USA)	Every 1, 2, 3, 4 yr for 12 yr	≈ 8 months, 1 yr	0–10	No change	[25]
	Four fires in 18 yr	3 yr	0–10		[43]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	No change	[24]
Pine forest (USA)	Annual for 20 yr Four fires in 20 yr	IAF	0–5, 5–10	Increase after annual fires at 0–5 cm	[33]
	Every 2 yr for 5 yr Spring and autumn fires	12 or 20 months	0–30	Decrease after autumn fires	[34]
Pine forest (USA)	Every 1, 2, 4, 7 yr for 10–65 yr	Not indicated	0–5 or 0–8 [1]	In general, no change	[44]
	Every 2, 3, 6 yr for 19 yr	3, 7 or 10 yr	0–10	No change	[45]
	Every 1.5, 2, 3 yr for 12 yr Every 2 yr for 37 yr	IAF	0–10		[46]
	Every 5, 15 yr for 18 yr	2 or 3 yr	0–15		[47]
	Every 2 yr for 16 yr	6 months	0–5, 15–20		[23]

Table 2. *Cont.*

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in TC or OC (Relative to UB)	Reference
Pine forest (Australia)	Four fires in 10 yr	IAF	0–2.5 2.5–7.6	Decrease after 3rd fire No change	[48]
Eucalypt forest (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [2]	Decrease No change	[22] [3]
	Every 3 yr for 13 yr Every 10 yr for 13 yr	1 or 4 yr	0–2, 2–5 [4]	Decrease No change	[37]
	Every 3 yr for 27 yr Every 10 yr for 27 yr	4–8 yr 3–6 yr	0–30	Decrease No change	[38]
	Every 2 yr for 35 yr Every 4 yr for 35 yr	3.5 yr 5.5 yr	0–10	Decrease No change	[39]
	Every 2 yr for 39 yr Every 4 yr for 39 yr	3.5–4 yr 5.5–6 yr	0–10	Decrease No change	[40]
Shrubland (Spain)	Two fires in 9 yr	3 yr	0–5	Increase	[31]
Shrubland (France)	Every 1 and 2 yr for 5 yr Spring and autumn fires	IAF	0–5	Increase after autumn fires	[35]
	Every 1 and 2 yr for 9 yr Spring and autumn fires	IAF	0–5		[36]
Humid subtropical prairie (USA)	Annual for 12 yr	≈3 months	0–10	Increase	[20]
Tropical savanna (Zimbabwe)	Every 1, 3 and 5 yr for 50 yr	4, 16, 28 or 52 months	0–5	Decrease	[28]

[1] Soil sampling at several depths, depending on the study site, up to 40–50 cm; the results included in the table refer to 0–5 or 0–8 cm. [2] Soil depths: 0–10, 10–20, 20–30 cm; the results refer to 0–10 cm. [3] Study performed in wet and dry sclerophyll sites; the results refer only to wet sites. [4] Soil depths: 0–2, 2–5, 5–10, 10–20 cm; the results refer only to the depth indicated.

In addition to the response of soil carbon content to different types of fires, it is important to consider that the quality of soil C may also be greatly affected in the long term, becoming more recalcitrant to decomposition [29,30]. Although pyrogenic carbon formation after prescribed fires is generally lower than after wildfires, these new compounds show an increased resistance to the degradation, and thus can be considered a long-term C sink, although its longevity is still debated [30,53,54]. They may also have other positive effects on burned soils, such as improving soil moisture retention and nutrient uptake [55]. Matosziuk et al. [47] found that repeated prescribed fires conducted in pine forests in autumn increased the concentration of pyrogenic carbon in the mineral soil, relative to that in unburned controls, whereas no changes were detected after spring fires; the authors attributed the response to the greater severity of autumn burns. However, in a study of a 20-year chrono sequence of repeated prescribed fires in shrublands, Alexis et al. [56] observed that soil organic matter composition was not strongly modified by fire and that pyrogenic carbon did not dominate soil organic matter composition and underwent significant degradation within decades. These authors also concluded that after several years of fires the soils organic composition may be driven by the ecosystem recovery through above- and below-ground litter production.

Studying the effects of fire on soil nitrogen (N) is important because N is one of the most limiting nutrients in terrestrial ecosystems and is easily lost during combustion of organic matter [57–59]. The impact of fire on the soil N content is complex, with many influencing factors potentially having opposite effects. For example, N losses can occur when the soil temperature during fire exceeds 200 °C; however, if the soil temperature is lower, as is common in prescribed fires [57], the N may be unaffected or may even increase due to the deposition of N-rich materials from partial combustion of vegetation and incorporation of ash into the soil [11,19,33,59]. On the other hand, decreases in N have been directly related to fuel consumption during burning [15,24,60]. Indeed, the scientific literature regarding the impact of repeated prescribed burning on soil N reports contrasting results (Table 3), including increases [19,20,32,33,48], no changes [22–26,31,33,34,37,39,40,43–48,61–63] and decreases [22,24,37,39–41,48,63], being the absence of changes the predominant tendency. Focusing on the fire return interval, in most of the reviewed studies that analyzed different fire frequencies, the response was independent of fire recurrence [19,25,26,41,45–47,61,62], while in others a higher frequency of fires was associated with a greater number of changes or changes of greater magnitude [22,33,37,39,40]. Differences in the response of soil N in eucalypt forest stands in Australia in wet (decreases) and dry sclerophyll (no change) sites subjected to repeated prescribed fires were attributed by Guinto et al. [22] to different site qualities and previous fire history in the two ecosystems. The absence of significant reductions in soil N levels demonstrated in some long-term studies on prescribed fire in the south-eastern region of the USA, as a result of increasing fire frequency, has been associated with the low-intensity and low-severity of fire, as well as with the type of vegetation present and initial soil characteristics [44,62]. Changes in soil N are also influenced by the soil depth analysed, being greater in the organic horizon and in the upper few centimetres of mineral soil [33,47,48,61,63], which the authors explained in a similar way to that discussed for C.

Table 3. Studies including the effects of repeated prescribed fires on total or organic nitrogen (TN, ON). UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in TN or ON (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	Increase	[19]
	Annual for 30 yr	14 months	0–5, 5–15		[32]
	Every 2, 4 yr for 20 yr	2.5 yr	0–10	No change	[26]
	Every 1, 4 yr for 45 yr	1, 5 months	0–15	Decrease	[41]
Oak-pine forest (USA)	Every 1, 2, 3, 4 yr for 12 yr	≈ 8 months, 1 yr	0–10	No change	[25]
	Four fires in 18 yr	3 yr	0–10		[43]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	No change Decrease	[24]
Pine forest (USA)	Annual for 20 yr Four fires in 20 yr	IAF	0–5, 5–10	Increase No change	[33]
	Every 2 yr for 5 yr	12 or 20 months	0–30	No change	[34]
	Every 1, 2, 4, 7 yr for 10–65 yr	Not indicated	0–5 or 0–8 [1]		[44]
	Every 2, 3, 6 yr for 19 yr	3, 7 or 10 yr	0–10		[45]
	Every 1.5, 2, 3 yr for 12yr Every 2 yr for 37 yr	IAF	0–10		[46]
	Every 5, 15 yr for 18 yr	2 or 3 yr	0–15		[47]
	Every 2 yr for 16 yr	6 months	0–15, 15–30		[23]
	Every 1 to 4 yr for 20 yr	16 months	0–5, 5–15		[61]
	Every 1, 2, 3, 4 yr for 30 yr	1, 2, 3 and 1 yr, respectively	0–10, 10–20		[62]
	Every 2 yr for 24 yr Every 4 yr for 24 yr	1 yr	0–10	No change Decrease	[63]
Pine forest (Australia)	Three and 4 fires repeated every 3 yr	IAF	0–2.5 2.5–7.6	Increase Decrease	[48]

Table 3. *Cont.*

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in TN or ON (Relative to UB)	Reference
Eucalypt forest (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [2]	Decrease No change	[22] [3]
	Every 3 yr for 13 yr Every 10 yr for 13 yr	1 or 4 yr	0–2 [4]	DecreaseNo change	[37]
	Every 2 yr for 35 yr Every 4 yr for 35 yr	3.5 yr 5.5 yr	0–10	Decrease No change	[39]
	Every 2 yr for 39 yr Every 4 yr for 39 yr	3.5–4 yr 5.5–6 yr	0–10	Decrease No change	[40]
Shrubland (Spain)	Two fires in 9 yr	3 yr	0–5	No change	[31]
Humid subtropical prairie (USA)	Annual for 12 yr	≈ 3 months	0–10	Increase	[20]

[1] Soil sampling at several depths, depending on the study site, up to 40–50 cm; the results included in the table refer to 0–5 or 0–8 cm. [2] Soil depths: 0–10, 10–20, 20–30 cm; the results refer to 0–10 cm. [3] Study performed in wet and dry sclerophyll sites; the results refer only to wet sites. [4] Soil depths: 0–2, 2–5, 5–10, 10–20 cm; the results refer only to the depth indicated.

Total soil nitrogen includes mineral N, which is the main form of N that can be directly taken up by plants, so that conservation of N and the ecosystem capability to transform N organic sources in N mineral form is critical for the maintenance of biogeochemical cycles and the sustainability of the system. Therefore, it is essential to determine how soil N mineralization is affected by fire. Increases in soil ammonium (NH_4^+) availability have often been found immediately after fire, while effects on soil nitrate (NO_3^-) are neither immediate nor always occurring, since it must be mineralized by nitrifiers, which will depend on labile C and moisture levels. The increases have been attributed to the thermal degradation of vegetation and soil organic matter and leaching of NH_4^+ and NO_3^- into mineral soil, enhanced microbial mineralization due to improved microenvironmental conditions, increased nutrient availability and decreased uptake of mineral N caused by root mortality [64,65]. Specifically, increases in NH_4^+ are considered to be a direct product of combustion by immediate pyromineralisation of the remaining matter, whereas increases in NO_3^- have been related to stimulation of biologically-mediated nitrification [19]. That response has been found after repeated prescribed burning (Table 4) by some authors that reported increases in NH_4^+ or NO_3^- levels and N mineralization after prescribed fires of different frequency in oak and pine forests [19,26,66]. However, opposite effects to the above have also been found, with reduced levels of extractable NH_4^+ and NO_3^- and/or N [22,63,65,67–72], especially after very frequent fires [22,72]. These results may be a consequence of the adverse effect of long-term burning on substrate quality, loss of soil total nitrogen or significant reductions in soil microbial activity and slow recovery of nitrifying bacterial community following fire [73]. Vance et al. [65] attributed the decrease in N mineralization to the fact that N immobilization was favoured by high C/N ratios and increased aromatic N forms that occurred after high severity fires. In other studies, repeated prescribed fires had no effect on NH_4^+ (or NH_3^+) and NO_3^- levels [24,26,69,70,74,75] or N mineralization [24,42,61]. In addition to the previously mentioned factors affecting inorganic N levels and N cycle transformations, vegetation type, initial site characteristics, changes in litter decomposition rate and vegetation mortality also play important roles in these dynamics [59,76,77] and references therein.

Table 4. Studies including the effects of repeated prescribed fires on inorganic N (concentration of extractable N-NH_4^+ and N-NO_3^-) and N mineralization (Nmin). UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in Inorganic N (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	Increase in NO_3^- and Nmin after 19 months	[19]
Oak forest (USA)	Every 2, 4 yr for 20 yr	2.5 yr	0–10	No change in NH_3^+ or NO_3^-	[32]
Oak forest (USA)	Annual for 30 yr	14 months	0–5 5–15	No change in NH_4^+ and increase in NO_3^-. Increase in Nmin	[26]
Mixed-oak forest (USA)	Every 1, 2 yr for 4 yr	1 month or 1 yr	0–15 of the A + Oa horizon	No change in Nmin or nitrification	[42]
Oak-hickory forest (USA)	Every 1, 4 yr for 30 yr	6 times between IAF and 1 yr later	0–5	Decrease in NH_4^+ and Nmin and no change in NO_3^-	[65]
Oak savanna forest (USA)	From 0.13 to 0.81 fires/yr for 32 yr	1–6 months	0–15	Decrease in N min	[67]
Oak savanna forest (USA)	Every 1.25 yr for 37yr Every 2–3 yr for 37 yr	1, 2 yr	0–10	Decrease in NH_4^+ and NO_3^- availability	[68]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr	0–2	No change or decrease in NH_4^+ and no change in NO_3^- and Nmin	[24]
Pine forest (USA)	Every 4 yr for 20 yr	16 months	0–5, 5–15	No change in potential Nmin	[61]
Pine forest (USA)	Every 2 and 4 yr for 24 yr	1 yr	0–10	Decrease in Nmin and nitrification	[63]
Pine forest (USA)	Every 1, 2 yr for 10 yr Every 4 yr for 10 yr	7 months, 1 yr or 2 yr	0–5, 5–15	Increase in NH_4^+ Increase in NH_4^+ and NO_3^-	[66]
Pine forest (USA)	Every 2 yr for 20 yr	1, 2 yr	0–15	No change in NH_4^+ and NO_3^- and decrease in Nmin	[69]
Pine-wiregrass savanna (USA)	Annual for 2 yr	IAF 1, 6 months	0–5	Decrease in NH_4^+ and no change in NH_4^+ and NO_3^-	[70]
Subalpine eucalypt forest (Australia)	Every 2–3 yr for 15 yr Every 7 yr for 15 yr	18, 22, 24 months	0–10	Decrease in Nmin	[71]
Eucalypt forest (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [1]	Decrease in Nmin No change in Nmin	[22] [2]
Eucalypt forest (Australia)	Every 2 yr for 32 yr Every 4 yr for 32 yr	3 months > 2 yr	0–10	No change in NH_4^+ or NO_3^-- and decrease in Nmin No change	[75]
Shrubland (USA)	Two fires in 4 yr	1 yr	0–5	No change in soil mineral N	[74]

[1] Soil depths: 0–10, 10–20, 20–30 cm; the results included in the table refer to 0–10 cm. [2] Study performed in wet and dry sclerophyll sites; the results refer only to wet sites.

Many studies addressing the effects of prescribed fire on soil nutrients have focused on changes in available or exchangeable phosphorus (P). This is because P, in addition to N, is considered one of the most limiting nutrients in many forest ecosystems. Increases in P have been observed in different ecosystems after prescribed fires applied with different frequency and seasonality (Table 5) [22,24,44], which have been related to the duration of heating of the organic horizon, addition of ash and thermal mineralization of organic P [22,24,59]. P enhancement may also be related to overall P status of the ecosystem: forests and shrublands on coarse grained, sandy soils typically cycle P very efficiently and little may be released from consumed litter (e.g., some sites in Australia) [78]. However, most authors have reported the absence of such changes in oak and pine forests in USA burned at a frequency of every 1 to 4 years [19,23,32,33,43,46,61,62], in eucalypt forests in Australia burned between 2- and 10-year intervals [22,37] and in shrublands in Spain and France burned every 1 to 9 years [31,36]. These findings have been related to the low severity of the fires or to the characteristics of the soils analysed. Although a less common response, decreased P levels have also been observed [20,41] and attributed to volatilisation and wind erosion.

Table 5. Studies including the effects of repeated prescribed fires on soil extractable or exchangeable phosphorus (P). UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in P (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	No change	[19]
	Every 1, 4 yr for 45 yr	1, 5 months	0–15	Decrease	[41]
	Annual for 30 yr	14 months	0–5, 5–15	No change	[32]
Oak, hickory and pine forests (USA)	Four fires in 18 yr	3 yr	0–10	No change	[43]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	Increase No change	[24]
Pine forest (USA)	Every 2 yr for 16 yr	6 months	0–10	No change	[23]
	Annual for 20 yr Four fires in 20 yr	IAF	0–5, 5–10	Increase after winter annual fires at 0–10 cm	[33]
	Every 1, 2, 4, 7 yr for 10–65 yr	Not indicated	0–5 or 0–8 [1]	No change, but increases after some fires	[44]
	Every 1.5, 2, 3 yr for 12 yr Every 2 yr for 37 yr	IAF	0–10, 10–20	No change	[46]
	Every 1 to 4 yr for 20 yr	16 months	0–5, 5–15		[61]
	Every 1, 2, 3 and 4 yr for 30 yr	1, 2, 3 and 1 yr, respectively	0–10		[62]
Eucalypt forest: wet sclerophyll site (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [2]	No change	[22]
Eucalypt forest: dry sclerophyll site (Australia)	Annual for 41 yr Every 2 or 3 yr for 20 yr	2 yr 5 yr		Increase No change	
Eucalypt forest (Australia)	Every 3, 10 yr for 13 yr	1 or 4 yr	0–2, 2–5 [3]	No change	[37]
Shrubland (France)	Every 1 and 2 yr for 9 yr	IAF	0–5	No change	[36]
Shrubland (Spain)	Two fires in 9 yr	3 years			[31]
Humid subtropical prairie (USA)	Annual for 12 yr	≈3 months	0–10	Decrease	[20]

[1] Soil sampling at several depths, depending on the study site, to 40–50 cm; the results included in the table refer to 0–5 or 0–8 cm. [2] Soil depths: 0–10, 10–20, 20–30 cm; the results refer to 0–10 cm. [3] Soil depths: 0–2, 2–5, 5–10, 10–20 cm; the results refer only to the depth indicated.

It is generally agreed that soil pH increases after wildfires and prescribed fires, see reviews [9,10], although these changes are usually of a short duration. The increase in soil pH has been mainly attributed to the release of cations calcium (Ca), magnesium (Mg) and potassium (K) that can buffer soil acidity. This release is associated with burn severity and fuel consumption. Rainfall and other soil characteristics, such as soil carbon content and clay content, also regulate that response in the medium term. Soil pH increases have also been observed after repeated prescribed fires [19,22,33,39] despite most studies reporting no change in soil pH (or temporarily small increases) independently of the fire return interval (1–9 years) [20,24,26,31,41,44,45,48,62] (Table 6). In studies involving different fire frequencies, there is a greater tendency for more frequent fires (annual or biannual) to cause an increase in soil pH relative to less frequent fires (repeated every 3 to 7 years) [22,25,33,39,44]. Summer prescribed fires may lead to higher changes in soil pH because burning under drier soil conditions may result in greater fuel consumption [25].

Table 6. Studies including the effects of repeated prescribed fires on soil pH. UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in pH (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	Increase	[19]
	Every 2, 4 yr for 20 yr	2.5 yr		No change	[26]
	Every 1, 4 yr for 45 yr	1, 5 months	0–15		[41]
Oak-pine forest (USA)	Every 1, 2, 3, 4 yr for 12 yr Spring and summer fires	≈8 months, 1 yr	0–10	Increase after annual summer fires	[25]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	No change Increase	[24]
Pine forest (USA)	Annual for 20 yr Four fires in 20 yr	IAF	0–5 5–10	Increase at 0–5 and no change at 5–10	[33]
	Every 1, 2, 4, 7 yr for 10–65 yr	Not indicated	0–5 or 0–8 [1]	No change	[44]
	Every 2, 3, 6 yr for 19 yr Winter and summer fires	3, 7 or 10 yr	0–10		[45]
	Every 1, 2, 3, 4 yr for 30 yr	1, 2, 3 and 1 yr, respectively			[62]
Pine forest (Australia)	Four fires in 10 yr	IAF	0–2.5, 2.5–7.6		[48]
Eucalypt forest: wet sclerophyll site (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [2]	Increase No change	[22]
Eucalypt forest: dry sclerophyll site (Australia)	Annual for 41 yr Every 2 or 3 yr for 20 yr	2 yr 5 yr	0–10, 10–20	Increase No change	
Eucalypt forest (Australia)	Every 2 yr for 35 yr Every 4 yr for 35 yr	3.5 yr 5.5 yr	0–10	Increase No change	[39]
Shrubland (Spain)	Two fires in 9 yr	3 yr	0–5	No change	[31]
Humid subtropical prairie (USA)	Annual for 12 yr	≈3 months	0–10		[20]

[1] Soil sampling at several depths, depending on the study site, up to 40–50 cm; the results included in the table refer to 0–5 or 0–8 cm.
[2] Soil depths: 0–10, 10–20, 20–30 cm; the results refer to 0–10 cm.

Small and short-lived increases in the concentrations of the major cations (potassium, calcium and magnesium) after fire have been reported in different ecosystems [10]. Several mechanisms have been proposed to explain this response. During the flame phase of the fire, temperatures are generated that can lead to nutrient loss by volatilisation [58,60]. Since Ca and Mg have high volatilisation temperatures (1484 °C and 1100 °C, respectively), and given the short duration of the flame phase, it is assumed that the amount lost of these cations by this mechanism is small and lower than those of K, which has a lower volatilisation temperature (774 °C). On the other hand, losses through particulate matter and wind dispersion of ash may result in larger losses of these nutrients. However, even if there are nutrient losses, there may be increases due to ash deposition and incorporation of ash into the soil profile [19,20]. This, and the lower mobility of divalent cations (Ca, Mg), usually results in larger increases in these nutrients than in K. Different patterns have been observed following recurrent prescribed fires (Table 7); thus, while Ca and Mg tend to increase, K either does not change or decreases [22,33,44,46]. However, other responses have also been reported: an increase in all these three nutrients [19,24], in some cases in the upper layer [33,48], no change after annual to quadrennial prescribed fires [20,25,43,61,62] and decreases three years after a second prescribed fire [31]. Some studies have also indicated different responses depending on the type of ecosystem [22] and fire frequency [22,46]. In the reviewed literature (Table 7), the most common response of soil nutrients to recurrent prescribed fires is an increase in the levels or no change.

Table 7. Studies including the effects of repeated prescribed fires on soil macronutrients (extractable or exchangeable potassium -K-, calcium -Ca- and magnesium -Mg-). UB: unburned soil; yr: year; IAF: immediately after fire.

Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change in K, Ca and Mg [1] (Relative to UB)	Reference
Oak forest (USA)	Every 1, 2 yr for 23 yr	12, 19, 24 months	0–10	Increase	[19]
Oak-pine forest (USA)	Every 1, 2, 3, 4 yr for 12 yr	≈ 8 months, 1 yr	0–10	No change	[25]
	Four fires in 18 yr	3 yr	0–10		[43]
Oak-hickory, oak-hickory-pine and pine savannas (USA)	Annual for 2 yr	1 yr	0–5	No change in K and increase in Ca	[79]
Pine forest (Spain)	Two fires in 4 yr	IAF, 1 yr IAF	0–2 0–5	Increase	[24]
Pine forest (USA)	Annual for 20 yr Four fires in 20 yr	IAF	0–5 5–10	At 0–5: no change in K and increase in Ca and Mg At 5–10: no change	[33]
	Every 1, 2, 4, 7 yr for 10–65 yr	IAF	0–5 or 0–8 [2]	No change (increase in Ca and Mg after some fires)	[44]
	Every 1.5, 2, 3 yr for 12 yr Every 2 yr for 37 yr	IAF	0–10, 10–20	Increase in Ca and decrease in K with frequency	[46]
	Every 4 yr for 20 yr	16 months	0–5, 5–15	No change	[61]
	Every 1, 2, 3, 4 yr for 30 yr	1, 2, 3 and 1 yr, respectively	0–10	No change in K and Ca	[62]
Pine forest (Australia)	Four fires in 10 yr	Not indicated	0–2.5 2.5–7.6	Increase after 3rd fire No change	[48]
Eucalypt forest: wet sclerophyll site (Australia)	Every 2 yr for 20 yr Every 4 yr for 18 yr	3 yr 5 yr	0–10 [3]	No change	[22]
Eucalypt forest: dry sclerophyll site (Australia)	Annual for 41 yr Every 2 or 3 yr for 20 yr	2 yr 5 yr	0–10 [3]	No change in K and Mg and increase in Ca No change	
Shrubland (Spain)	Two fires in 9 yr	3 yr	0–5	Decrease	[31]
Humid subtropical prairie (USA)	Annual for 12 yr	≈ 3 months	0–10	No change	[20]

[1] If not indicated, the results included in the table refer to K, Ca and Mg. [2] Soil sampling at several depths, depending on the study site, up to 40–50 cm; the results refer to 0–5 or 0–8 cm. [3] Soil depths: 0–10, 10–20, 20–30 cm; the results refer to 0–10 cm.

2.3. Soil Microbiological Properties

Assessing how soil microorganisms are affected by prescribed fire is important because of the crucial role these organisms have in a multitude of soil processes and functions. In addition, microbial communities are highly sensitive to disturbances such as fire, which makes them good indicators of soil damage and resilience [80–83]. However, the response of soil microorganisms to repeated prescribed fires is not constant, owing to differences between ecosystems (mainly soil types) and fire characteristics and also to the wide variety of methods used to assess the responses (biomass, activity, diversity and composition of microbial communities). Nonetheless, after repeated prescribed fires, negative effects or slight changes are more frequent than positive effects, although the responses are usually short-lived (Table 8). Regarding the former, decreases have been observed in microbial biomass C (C_{mic}) [41,71], microbial biomass N (N_{mic}) [71], enzyme activities [41,62,84], soil respiration [27] and total phospholipid fatty acids (PLFA) and functional diversity (CLPP) [85]. These negative responses have been attributed to the soil temperatures reached during fires [41], decreases in C and N [71] and changes in nutrients and substrate availability [79], variations in soil and organic layer properties [27], and changes in organic matter quality [84]. The lack of responses in C_{mic}, N_{mic}, microbial biomass P (P_{mic}), enzyme activities, soil respiration, total PLFA and fungal richness reported by several authors [19,26,32,79,86] may be related to the low temperatures reached during fires and the low impact of prescribed fire on other soil properties [19]. Taylor et al. [32] reported increases in N_{mic}, but no change in microbial biomass C or P, after prescribed fires repeated annually for 30 years in an oak forest in the USA. The different response was attributed to the possible dominance of bacterial over fungal communities induced by repeated burning, due to the greater sensitivity of fungi to soil heating [87–90]. Studies involving different genomic techniques and performed in Australian sclerophyll forest soils reported differences in the structure and diversity of mycelial communities of ectomycorrhizal fungi, below-ground basidiomycetes, and cellulolytic fungi after biennial prescribed fires, but not after quadrennial fires [72,91,92]. Other authors [45] found that while recurrent prescribed fires (every 6 years) do not affect the richness and diversity of fungal communities, more frequent fires (at intervals of 2 and 3 years) maintain fire-selected soil fungal communities that may support adapted plant communities or fire tolerant species that dominate the frequently burned areas. Regarding the effect of repeated prescribed fires on soil bacterial communities, Shen et al. [93] reported higher values of bacterial diversity and greater differences in bacterial community structure after biennial prescribed fires than after quadrennial fires, in the above ecosystem. They attributed this finding to the changes in several soil chemical properties (pH, soil C/N ratio) most affected by the more frequent fire treatments. The response is consistent with findings indicating that the medium-term post-fire changes in some soil properties favour bacteria more than fungi [94]. Overall, the responses of microorganisms to fire recurrence can vary widely, as changes in microbial communities may involve numerous indirect, potentially interactive effects. Among these effects, post-fire alterations in soil physical and chemical properties, as well as changes in plant community composition and plant biomass [80,88,95] may play important roles.

2.4. Soil Mesofauna

Soil fauna exerts a greater role in above and below ground processes than is usually perceived, affecting other ecosystem components (plant and microbial communities) and organic matter decomposition at both global and biome scales [96–98]. In general, fire has a detrimental effect on soil organisms, although the responses are highly variable [10,80,90]. To evaluate the impact of fire on soil biological quality, the presence of soil mesofauna (particularly microarthropods) has recently been included in a biotic index that may be useful for post-fire management programmes [99]. Prescribed fires usually result in a decrease in abundance and changes in mesofauna community composition [100–102], with the responses often being dependent on the taxa considered [103,104]. However, the effect of repeated burning has seldom been addressed in relation to edaphic organisms [105] and few studies have considered the impact of prescribed fire frequency on mesofauna; this is very important because the recovery period may be longer for invertebrates if the sites are burned more than once [106].

The majority of studies have shown that microarthropod populations are scarcely affected by frequent prescribed burning, although most only recorded ordinal abundances and not species composition (Table 9). Prescribed fires are often of low-intensity, causing less direct damage to mesofauna [107] but also to the vegetation, which provides food and refuge [108,109]. Furthermore, heterogeneity within a burned area is key to soil fauna recovery [110] and low-severity burning usually leaves unburned patches where organisms can survive and later repopulate the burned areas [19,111]. Most studies indicate that repeated prescribed fires do not affect mesofauna [112–120]. However, some authors have reported that recurrent treatments have a positive effect on microarthropod density [121,122], which may be related to an increase in above-ground living biomass and the diversity of grass species [122] or to root growth stimulation [123] and greater microbial biomass [124–126], as suggested by Lussenhop [121]. In some other cases the burning seemed to be detrimental to microarthropods [127–132] although this may be partly explained by the effect of seasonality on edaphic populations rather than by the direct consequence of fire [127,133]. It is therefore advisable to conduct sampling several times throughout a period of some years after prescribed burning, e.g., [117–120] rather than in a single period [128], in order to better capture the temporal responses of populations. In addition, a high-frequency of fires can cause changes in the structure and arrangement of the organic layer, creating lower habitat complexity without accumulation of litter, duff and freshly fallen leaves, which may explain some of the observed decreases in microarthropod populations [128,129]. The studies reviewed suggest that soil fauna seems to be highly resilient to very frequent burning in some ecosystems, such as savannas [134], but it appears that mesofauna needs a few years to recover to pre-burn population numbers and/or species composition in other biomes [19,111,127,129–132]. Moreover, there is a lack of information about other meso-faunal groups (e.g., enchytraeid worms) which also have strong effects on soil processes and are highly vulnerable to fire [135–137]. It also seems advisable to include information about functional traits to enable assessment of whether or not ecosystem processes will change after repeated prescribed fires [138,139].

Table 8. Studies including the effects of repeated prescribed fires on soil biochemical and microbial properties: microbial biomass C (C_{mic}), microbial biomass N (N_{mic}), microbial biomass P (P_{mic}), enzyme activities, soil respiration, community level physiological profiles (CLPP), phospholipid fatty acid (PLFA), soil fungal community composition and structure and bacterial community diversity. UB: unburned soil; yr: year; IAF: immediately after fire.

Soil Property	Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change (Relative to UB)	Reference
C_{mic}	Oak forest (USA)	Every 1 and 4 yr for 45 yr	1, 5 months	0–15	Decrease	[41]
		Annual for 30 yr	14 months	0–5, 5–15	No change	[32]
	Pine forest (Italy)	Two fires in 5 yr	IAF, 1, 3, 6, 12 months	0–5	No change	[86]
	Eucalypt forest (Australia)	Every 2–3 yr for 15 yr: frequent burns (FB) Every 7 yr for 15 yr: recurrent burns (RB)	18, 22, 24 months	0–2.5 2.5–5 5–10	At all depts.: RB > UB > FB	[71]
N_{mic}	Oak forest (USA)	Every 1 or 2 yr for 23 yr	12, 19, 24 months	0–10	No change	[19]
		Annual for 30 yr	14 months	0–5, 5–15	Increase	[32]
	Eucalypt forest (Australia)	Every 2–3 yr for 15 yr Every 7 yr for 15 yr	18, 22, 24 months	0–2.5 2.5–5 5–10	Decreases largest near surface	[71]
P_{mic}	Oak forest (USA)	Annual for 30 yr	14 months	0–5, 5–15	No change	[32]
Enzyme activities	Oak forest (USA)	Every 1 and 4 yr for 45 yr	1, 5 months	0–15	Decrease in acid phosphatase, α-glucosidase, β-glucosidase and sulphatase and urease	[41]
		Annual for 30 yr	14 months	0–5, 5–15	No change in acid phosphatase, β-glucosidase and N-acetyl-β-d-glucosaminidase	[32]
	Oak-hickory forest (USA)	Every 1 and 2 yr for 4 yr	5 months	0–15	Decrease in acid phosphatase and β-glucosidase, increase in phenol oxidase and no change in chitinase	[84]
	Pine forest (USA)	Every 1, 2, 3 and 4 yr for 30 yr	1, 2, 3 and 1 yr, respectively	0–10	Decrease in acid phosphatase more pronounced after biennial fires	[62]

Table 8. *Cont.*

Soil Property	Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Soil Depth (cm)	Change (Relative to UB)	Reference
Soil respiration	Oak forest (USA)	Every 1 or 2 yr for 23 yr	12, 19, 24 months	0–10	No change	[19]
	Pine forest (Italy)	Two fires in 5 yr	IAF, 1, 3, 6, 12 months	0–5	No change	[86]
Soil respiration	Pine-grassland forest (USA)	Every 1 or 2 yr for 40 yr	1, 2 months	0–8	Decrease	[27]
CLPP	Wet sclerophyll eucalypt forest (Australia)	Every 2 yr for 34 yr Every 4 yr for 34 yr	21 months 45 months	0–10	Decrease in the use of C-substrates No change	[85]
PLFA	Oak forest (USA)	Every 2 yr for 20 yr Every 4 yr for 20 yr	2.5 yr	0–10	Decrease in Gram-negative bacteria after biennial fires. No change in total PLFA, fungal and bacterial PLFA biomass	[26]
	Oak-hickory, oak-hickory-pine and pine savannas (USA)	Annual for 2 yr	1 yr	0–5	No change in total PLFA. Increase in Gram-positive and Gram-negative bacteria and decrease in fungal PLFA	[79]
	Wet sclerophyll eucalypt forest (Australia)	Every 2 yr for 34 yr Every 4 yr for 34 yr	21 months 45 months	0–10	Decrease in total PLFA and reduction of bacterial PLFA similar to fungal PLFA after biennial fires	[85]
Soil fungal community composition [1]	Pine forest (USA)	Every 2, 3, 6 yr for 19 yr Winter and summer fires	3, 7 or 10 yr	0–10	No changes in richness and diversity. More frequent fires maintain fire-adapted fungal communities	[45]
Soil fungal community structure [2]	Eucalypt forest: wet sclerophyll site (Australia)	Every 2 yr for 30 yr Every 4 yr for 30 yr	3 months >2 yr	0–10, 0–20	Differences in structure No change	[72]
Below-ground basidiomycete fungal communities [2]		Every 2 yr for 30 yr Every 4 yr for 30 yr	3 months 2 yr	0–10, 0–20	Differences in structure Minor change	[91]
Cellulolytic fungi [3]		Every 2 yr for 34 yr	3 months	0–10, 0–20	Reduction in diversity	[92]
Bacterial community diversity [4]		Every 2 yr for 38 yr Every 4 yr for 38 yr	2 yr 4 yr	0–10, 0–20	Increase in in the topsoil and changes in community structure after biennial fires	[93]

[1] Method: denaturing gradient gel electrophoresis (DGGE). [2] Method: terminal restriction fragment length polymorphism (T–RFLP). [3] Method: RNA stable isotope analysis. [4] Method: DNA analysis.

Table 9. Studies including effects of repeated prescribed fires on soil mesofauna. UB: unburned soil; yr: year.

Faunal Group; Method [1]	Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Change (Relative to UB)	Reference
Microarthropods [2]; B-T	Grassland (USA)	Every 2 yr for 20 yr	7 months	Increase in abundance and richness	[121]
Collembola; P	Savanna (Australia)	Annually for 5 yr	2 months	No change in abundance	[112]
Mites; B-T	Savanna (Australia)	Every 4 yr for 32 yr	Not indicated	No change in abundance or diversity	[113]
	Savanna (Ivory Coast)	Two consecutive yr	1 month		[114,115] [3]
Collembola; P	Savanna (Brazil)	Annual for 12 yr Every 1–3 yr for 12 yr	1 yr 3 yr	Increase in abundance	[122]

Table 9. *Cont.*

Faunal Group; Method [1]	Vegetation Type (Country)	Frequency	Sampling Time after the Last Fire	Change (Relative to UB)	Reference
Collembola; P	Eucalypt forest (Australia)	Every 2 or 4 yr for 40 yr	3 yr	No change in abundance	[116]
Microarthropods; P		Twice in 3 yr	2 yr		[117]
		Twice in 5 yr			[118]
		Every 3 yr for 6 yr			[119]
		Twice in 10 yr			[120]
Microarthropods; B-T		Every 3 yr for 20 yr	2 yr	Decrease in abundance	[128]
Microarthropods; B-T	Oak forest (USA)	Every 1, 2 or 3 yr for 23 yr	2 yr	No change in abundance	[19]
		Annual for 30 yr Every 3–4 yr for 30 yr	1 yr 2 yr	No change in abundance; decrease in mite diversity	[127]
Collembola; B-T		Annual for 16 yr	6 months	No change in total abundance; change in composition	[111]
Microarthropods; B-T	Oak-pine forest (USA)	Twice in 3 yr	1.5 yr	Decrease in mite abundance	[129]
	Oak-hickory forest (USA)	Annual for 4 yr Twice in 4 yr	2.5 months	Decrease in abundance No change	[130]
	Pine forest (USA)	Annual for 20 yr Every 5–8 yr for 20 yr	1 yr 4 yr	Decrease in abundance after annual fires; change in composition	[131,132]

[1] Method: Berlese–Tullgren funnels or similar dry extractor (B-T) and pitfalls (P). [2] Microarthropods include mites and Collembola. [3] Relative to pre-fire values.

3. Some Reflections on the Information Analysed and Research Needs

While there are a large number of studies on the immediate and medium-term effects of a single application of prescribed fire on soil, see references in [11,49,59,90,95], the above review shows that there are as yet few studies assessing the effect of repeated applications, in particular in the long term. This largely limits the ability to assess adequately the real effects of such treatment and constitutes an obstacle to its use which represents an important gap in understanding of the impact of repeated as opposed to single prescribed fire events [140].

The information analysed reveals a picture of high variability in the response, where small effects predominate for most of the soil characteristics studied, with recovery time generally relatively short. In fact, although most of these effects appear minor and clearly less than those caused by wildfire, the contradictory results suggest that there is a risk of overlooking subtle short- to medium-term changes that could later lead to appreciable cumulative effects in soil [92,116,141–143]. In addition, the response pattern differs depending on the type of ecosystem and soil property considered, with inconsistency of response being the most frequently observed pattern. Despite this great variability some conclusions can be elucidated, but it should be noted that this review is not a meta-analysis and no statistics were performed on the results, therefore only some patterns that emerge when comparing the studies are highlighted here. When comparing the different soil variables to evaluate which ones are more sensitive, more than half of the studies show no changes in carbon, nitrogen and macronutrients contents and pH after repeated prescribed fires; this number increases if considering the studies where the largest fire interval resulted in no effect on these properties. Phosphorus content also seems to be very resilient to burning and 12 of 16 studies that include this element did not find any change in its concentration. In contrast, inorganic N content and N mineralization showed a great variation with increases, decreases and no changes that also depended on the soil layer (forest floor or mineral soil), frequency and season of burning or the form of N considered. Although there is not a comparable amount of information on the effect of repeated prescribed fires on the soil properties studied (there is much more information on chemical properties than on physical properties), the studies reviewed show that, in general, physical properties are less affected than chemical properties and chemical properties less affected than microbiological properties. Regarding different ecosystems, pine forests seem to be highly resilient to low severity fire, in terms of soil chemical properties (carbon, nitrogen, phosphorus, pH and macronutrients), with most studies showing no change on their values after repeated prescribed burning, even after long periods of time experiencing annual burns. This seems consistent with pine ecosystems that evolved in a natural regime of frequent low intensity fires such as longleaf pine or ponderosa pine [5,144,145]. However, some increases and decreases in certain properties are observed, depending on the studied soil layer, fire frequency or burning season. In the case of eucalypt forests, the more frequent the fires, the more pronounced the effects. Therefore, annual or biennial prescribed fires seem to have a detrimental effect on soils physical (clay content), chemical (carbon, nitrogen, phosphorus, pH and nutrients) and microbial properties (use of carbon, PLFA, diversity, structural changes) whereas no change in soil properties is detected when burning frequency is decreased to (at least) 4 years. In contrast, mesofauna abundance is hardly affected in these eucalypt forests despite short fire intervals (every 2–3 years). Most authors in deciduous forests applied burning regimes from 1 to 4 years for decades which resulted in such a great variation and inconsistency in responses that it impeded them from making any generalisation. However, the results from one of the studies that compared two burning frequencies (every two vs. four years) may indicate that some soil properties in these ecosystems (bulk density, carbon and microbial PLFA) need more than two years to return to pre-fire values. The remaining studies developed in shrublands, prairies or savannas and the results about physical or biological properties are too few and diverse to make any conclusion, except for the already mentioned great resilience of mesofauna in savannas.

The biomes where the studies have been conducted represent only a small proportion of the extant fire-prone ecosystems of potential interest. In fact, more than 75% of the ones included in this review were performed in forests (mostly pine forests, followed by eucalypt and oak forests), whereas only a few of them refer to shrublands (four) or grasslands (two). In addition, most research was performed in the USA (35 references) and Australia (20 references) but only five studies were developed in southern Europe, three of them in shrublands. This limitation restricts our understanding of the ecological role of fire and constraints the use of prescribed burning as a management tool in other ecosystems. More specifically, this also brings up an interesting question concerning to what extent the tabulated results, basically from the North American and Australian forests, are transferable to other regions such as southern Europe or elsewhere where prescribed fire is applied often to "modified" shrublands and introduced tree species in plantations on land (and therefore soil) that has often been subject to long-term degradation (by millenary lad use of grazing or intensive agriculture practices) and probably land use change over hundreds or even thousands of years. On the other hand, human impacts on North American forests have been compressed into the last 200 years or so, and are different from southern Europe. This, in turn, leads to other connected questions such as whether, for instance, it is ecologically coherent for the application of prescribed fire in some European forest species as Aleppo pine, considered as a fire evader species [146–148], evolutionarily shaped by intense replacement crown fires. Indeed, we need to increase our knowledge about these questions and future research should investigate in a larger number of representative ecosystems, which would allow a broader perspective on ecosystem response and particularly to elucidate soil resilience to repeated disturbances under across a wide range of environmental conditions and land use histories. It could also help to test the applicability of some hypotheses that currently support fire ecological restoration efforts [149–152]. Additionally, these expanded experiments would also be useful for refining adaptive management in these areas or in fire regime restoration efforts [153,154].

Indirectly, our review has revealed limitations in the extent and designs of the experiments carried out that may be useful for future investigation, building on what has been carried out so far. Frequently, studies have been conducted with a small number of replicates. For instance, 63% of the studies considered in this review have ≤ 5 replicates which makes it difficult to find statistically significant differences in soil parameters that have frequently undergone only minor changes. This has also been previously underscored [105,155,156]. Furthermore, although the lack of pre-fire data is explicable in long term studies that began decades ago, in future studies an effort should be made to have information prior to the application of fire both in control and areas to be treated.

The objectives of long-term studies on the effects of prescribed burning need to be broadened to the full range of prescribed burning regimes. Frequency has been the fire regime factor that has received more attention until now, contrasting with seasonality, addressed in only 20% of the studies reviewed. Still, other features of prescribed burning regimes need to be considered. Fire intensity and severity, time since last fire, size of burn area and the total number of burn applications may be determinant in the long-term response of some soil properties and their effects need to be explored in greater detail [143,157]. In our review, less than 10% of the studies considered the comparison between different fuel treatments or the combined effect of prescribed fire with thinning, mechanical mastication, understory clearing or grazing. The broad scale of the treatments carried out in the US for ecological restoration of past fire regimes and the frequent use of combined treatments in that approach are providing relevant information on this point [52,158,159].

A particularly important issue is the scan (or lack of) quantification of variables related to fire behaviour, and other associated variables, detected in most of the studies analysed. Only in about one third of them is their reference merely qualitative, on the meteorological conditions and fuel moisture content during a burn. This is also the same for other fuel characteristics such as its initial load, structure and continuity and fuel consumption. Even more infrequent is the quantification of fire behaviour parameters such fire rate of spread, flame length or fire line (less than 10% of cases). Good examples of quantitative description of these variables can be found in Bennet et al. [38] and Santín et al. [160]. Fire severity descriptors are also rarely used. Although in recent years more attention has been paid to fire intensity and fire severity in relation to studies on effects of repeated fire on soil [107,161–163], there continues to be a lack of information on the relationship between these two important components of the fire regime and their effects on soil. However, both variables are critical to understand the above effects and probably to explain seemingly contradictory results of past studies, which may be partially due to differences in these two variables not being properly quantified. An example of a detected shortcoming that illustrates this point is the lack of information on the fire ignition technique used during prescribed burning in more than 80% of cases. Fire ignition is crucial to control fire behaviour use [164–167] and, accordingly, its effects on soil [168]. Future experiments could pay more attention to quantifying the components of prescribed fire regimes and fire behaviour-related variables to link their spatial variability within the burned area to the variability in soil properties [105]. The spatial variation of thermal regime in the soil during burning can have a pronounced impact on the recovery of a number of soil properties and particularly on mesofauna [161]. This, together with information recorded in medium- and long-term studies, should enable researchers to relate the observed effects on soil to different temporal patterns of burning and types of ignition techniques under predetermined windows of meteorological and fuel conditions. Furthermore, these variables are also central in achieving a more efficient planning and implementation of prescribed fire treatments, thus minimizing possible adverse effects on the ecosystems concerned. Additionally, that information would be useful to make an adaptive fire management more ecologically sustainable.

More interdisciplinary and comprehensive approaches are needed to unravel the relationships between fire characteristics and fire effects. This linkage is vital for a better understanding of the ecological role of fire but also for the sustainable use of fire [169,170].

Although soil occupies a central position in the storage and recycling of nutrients in the ecosystem, studies are needed that consider prescribed burning effects on soil within a more comprehensive framework from which our knowledge of the long-term effects on soil would then benefit. Vegetation and soil response to fire are inextricably linked [171]. The response to prescribed burning of capital processes in nutrient cycling such as nutrient resorption, litterfall and decomposition, accumulation of organic soil horizons, lixiviation through the soil profile, impacts on deep soil horizons, need to be addressed and related to atmospheric deposition of nutrients, and free and symbiotic N fixation and the nutrient uptake by vegetation. We have too static and compartmentalized a picture of the changes occurring in the soil as a consequence of fire and the interaction between abiotic and biotic soil components is critical to understand the ecosystem response to repeated application of prescribed fire.

Concerns about the long-term impact of prescribed burning in forest soil and the entire ecosystem are long-standing and seem far from being allayed [15,58,172] and they are inseparable from forest and fire management issues. Basically, land managers are required to meet multiple objectives, including the protection of human life and property from wildfires and the conservation of biodiversity [7,170] while making them compatible with the sustainable use of natural resources. All this in a scenario of global change, where the reduction of CO_2 is a priority and where fire-regimes change is the rule, while the wildland-urban interface expands and the demand of protection from inhabitants grows [170]. It certainly seems to be no easy task. Consequently, reconciling these different perspectives and objectives is becoming increasingly necessary [173,174]. Prescribed burning is a fundamental tool for wildfire risk management [140,175], although it can also be useful for some of the objectives in the above scenario and, given that soil occupies a central position in all ecosystem processes, research on the complex relationships between soil and fire is also crucial. Indeed, research on prescribed fire is not only necessary, but may provide an opportunity to find a trade-off between seemingly disparate objectives, thus helping to ensure sustainable use of resources while contributing to biodiversity conservation at an acceptable level of impact.

While the long-term response to prescribed fire on a myriad of soil properties and the relationships between ecosystem compartments continues to be examined through targeted research, results so far show that generally an increase in fire interval appears to give the system a chance to recover from the unfavourable cumulative effects of burning. This conservative approach could become an interim guiding principle for managers to combine with adaptive management based on the continuous monitoring of ecosystem health indicators.

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