Post-fire soil management

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Abstract

Soils are an important natural capital and can be negatively affected by high severity fires. The capacity of soil to recover from the degradation caused by fire disturbance depends on fire history, ash properties, topography, post-fire weather, vegetation recuperation and post-fire management. These factors are interdependent, and can increase or decrease the effects of high severity fires on soil degradation. Normally, ecosystems are resilient to fire disturbance and a scenario of no intervention should be considered. Post-fire management should be carried out in specific areas that are more susceptible to degradation. Post-fire interventions such as mulching are important to decrease soil degradation, whereas salvage logging increases it. Overall, the management options that we choose can trigger or reduce positive and negative impacts on soil.

Keywords: Soil degradation, high fire severity, post-fire management

Highlights

- Soils are vulnerable after high severity fires
- Soil capacity to recover is dependent on natural factors and human management
- Post-fire management should consider no intervention scenario
- Post-fire management can trigger or reduce soil degradation

Introduction

Soils are the base of life on earth and directly or indirectly affect all forms of life. They provide an important number of ecosystem services essential to human life and fundamental to address future global challenges such as climate change, water scarcity, loss of biodiversity, air pollution, land degradation, human health, and food security. The soil resource is not renewable at human time scales, is the world's largest active carbon pool, acts as a water filter and reservoir, and is the basis for vegetation growth, food production and multiple human activities [1].

Fire is a global phenomenon that shapes ecosystems that depend on the vegetation growth that would not be possible without soils. With the exception of the Artic and Antarctic environments, fire visits the world's ecosystems more or less regularly. Throughout history, ecosystems adapted to this disturbance and created mechanisms of protection from this disturbance. Fossil evidence shows that fire appeared in the Silurian period (420 million years ago) with the appearance of vascular land plants. Fire was used by hominins in Africa 1.6 million years ago, and became part of their technological repertoires around 300.000 -400.000 years ago. The homo manipulation of fire introduced unprecedented changes in the earth's ecosystems, including soils. Fire is considered the seventh soil-forming factor and was an important tool used to create agriculture and grazing fields. Some ecosystems (e.g Mediterranean) cannot be understood without the presence of fire. Despite the importance of fire to several ecosystems, since the beginning of the 20th century, and especially since the 1950s-1960s, strong and effective suppression policies were established to protect ecosystems and human properties from fire. These measures coupled with rural exodus contributed to an increase in the accumulation of fuel in wildland areas. Land abandonment in the countryside led to investment in industrial monospecific plantations with extremely flammable species (e.g Pinus and Eucalyptus) and an increase in the frequency, duration and intensity of summer drought periods increased the vulnerability of wildlands to fire. A combination of all these factors is responsible for the high frequency of mega-fires with high severity, responsible for the loss of human lives and millions of euros of direct and indirect losses [2,3,4*].

Ecosystems adapted to rely on fire disturbance. However, the increase of fire recurrence and the high severity of these fires reduced the capacity of vegetation to recover. One of the most important factors that hampers this recuperation is the status of soils that may be highly affected by fire, especially in areas where high severity fires are frequent [5]. In this work, we will provide an overview of the impacts of fire on soil, the factors that influence post-fire ecosystem recuperation, the methods used for restoration, and the impacts of these practices.

Fire impacts on soils

Fire impacts on soil properties can be direct or indirect. Direct impacts are related to heat. With the exception of smoldering fires and burning logs and piles, the direct impact of fire on soil properties is usually short. Because soils are a poor conductor of energy, the heating induced by fire is restricted to the first few centimeters of the soil [6]. The exact effects depend on the type of soil, texture, pre-fire conditions (e.g. moisture content), type and structure of vegetation (e.g. density and connectivity), the ecosystem, fire intensity, severity, and recurrence, meteorological conditions during the fire and topography (e.g. slope and aspect) that influences fire behavior [7,8]. The indirect impacts of fire are related to the ash-bed effects, degree of vegetation recuperation, post-fire weather patterns, topography and post-fire management (discussed in the next section).

Low severity fires can have beneficial impacts on soil properties, since the temperatures reached are not high and the loss of nutrients by volatilization and with smoke are reduced. Good examples of these types of fires are grassland fires [9] or prescribed fires carried out during the autumn and winter seasons for landscape management [10]. The impact on soil cover is minimal and soil heating is negligible, therefore, overland flow and soil erosion are reduced compared to high severity wildfires [11]. As a consequence of the production of ash rich in carbon, there is an increase of soil organic matter, pH, electrical conductivity and extractable cations such as calcium, magnesium, sodium and some forms of nitrogen such as ammonia, important for vegetation recuperation [10]. The incorporation of ash is more effective in sandy soils and the impacts extend to deeper layers than in finer textured soils [12]. A potential negative impact of low severity fires is the production of hydrophobic ash that can temporarily increase soil water repellency until the hydrophobic compounds are leached [13].

Contrary to low-severity fires, high-severity fires combust a large amount of fuel and have extremely negative impacts on soil. One of the most important impacts is the large reduction in soil cover [14] (Figure 1). High temperatures at the soil surface reduce the quantity of organic materials and induce important transformations in organic matter composition [15]. The major changes in soil organic matter composition occur at temperatures between 250-450 °C [16]. The combustion of soil organic matter is also responsible for the destruction of soil aggregates. However, high temperatures may increase aggregation as a consequence of recrystallization of some iron and aluminum oxyhydroxides, if present in the burned soil. [17] (Figure 1). The oxidation of iron minerals at high temperatures increases soil redness and the proportion of sand [18]. Fire can increase soil hydrophobicity as a consequence of the volatilization of hydrophobic compounds from organic matter that are condensed onto soil particulates, increasing water repellency. Burning process decrease the aliphatic series of alkanes and alkenes and increase the relative content of aromatic compounds and fatty acids, increasing the soil hydrophobicity after heating [19]. However, at high temperatures, hydrophobicity disappears. Below 175 °C no changes are observed in water repellency, with repellency increasing at temperatures around 200 °C. At temperatures between 280-400 °C hydrophobicity is destroyed [20]. High severity fires can destroy hydrophobicity in previously water repellent soils [21] (Figure 1).

Severe wildfires volatilize high amounts of carbon and nitrogen since these nutrients start to vaporize at temperatures of about 200 °C. Carbon and nitrogen are totally lost in soils that burned at temperatures higher than 550 °C [22] (Figure 1). Wildfire temperatures can be as high as 1100 °C, thus nutrients such as calcium, magnesium, aluminum or manganese that need higher temperatures to be volatilized can only be lost by evacuation with ash and smoke. Other elements with low temperatures of volatilization such as potassium (>774°C), sodium (>880°C) and phosphorous (>700°C) may be lost by direct volatilization [23,24].

High severity fires increase soil pH because of organic acid denaturation and the increase of sodium and potassium oxides, carbonates and hydroxides [25] and electrical conductivity as a consequence of the mineralization of organic matter [23]. Soil extractable anions, that are highly soluble in burned material, are leached. The increase in pH favours the solubility of some cations such as calcium, magnesium, sodium and potassium, and reduces others such as cooper and zinc [26] (Figure 1). Phosphorous solubility is limited following high severity wildfires as the pH increases above 8, which limits the solubility of this element, and if in solution, it is easily precipitated with calcium, aluminium, or iron. Soil microbes are very sensitive to high severity wildfires, especially in the topsoil, where soil heating is more intense. The thermal shock induced by fire changes the activity, size and composition of the microbial biomass. At temperatures higher than 70-80 °C, the majority of the soil microbes are destroyed and at temperatures between 115 and 150 °C they disappear completely [7,27,28] (Figure 1).

Post fire soil management: natural vs human factors

Pre-fire land use and management is a crucial aspect to understanding the degree of the impacts of a wildfire on soil. The highest wildfire severities and the highest environmental, economic and social damages occur in areas where there was a lack of management or in existing industrial plantations of Pinus and Eucalyptus. Soil degradation is high in these areas because of the impacts of the high temperatures on the volatilization of nutrients and negative impacts on soil biological and physical properties, which in turn will limit the capacity of the ecosystem to recover. Ecosystems with high biodiversity are less vulnerable to wildfire impacts, recover faster, and act as a barrier to fire spread [29].

Post-fire impacts on soil degradation extent and magnitude depends on the fire history, environmental conditions of the fire affected area and the human management. These interactions are very difficult to generalize because they are interdependent (Figure 1). Fire history has important implications on soil properties. For example, high fire frequencies increase the flammability of vegetation [30]. This increases the vulnerability of those areas to wildfire occurrence creating a fire recurrence cycle that can be disastrous for soils in these ecosystems and induce a negative trend in soil fertility [31]. Areas affected by high fire recurrences have lower quantity and quality of soil organic matter and store fewer nutrients such as nitrogen and carbon [31**]. It has also been reported that high fire recurrences decrease soil biota [32] and increase total runoff, the amount of nutrients present in overland flow, organic matter losses and sediment transport [33,34]. On the other hand, high fire recurrence may decrease soil water repellency, which can reduce overland flow and soil erosion [35]. However, this may not be considered a positive, because the loss of organic matter is extremely negative for soil quality. Hydrophobicity occurs naturally in several types of soil, and to some degree, is not considered a negative since it can increase key soil aspects such as aggregate stability [36]. In addition, the study of Keesstra et al. [35] was carried out in the Mediterranean environment and may not be applicable to other ecosystems (Figure 1).

After a fire, ash covers the soil surface and provides temporary protection against erosion processes. However, the capacity to protect the soil depends on the severity at which the ash is produced. Normally the ash created at high temperatures is very fine and can be incorporated into the soil profile, which clogs soil pores, reducing water infiltration. Since the ash produced at high fire severities is light, it is also easy to remove, which can increase the bare soil surface area. In other words, ash produced by high severity fires often does not provide efficient protection. In addition, the ash produced at high temperatures is rich in carbonates that create a crust on the topsoil upon wetting, increasing overland flow. These factors all contribute to soil degradation. On the other hand, the ash produced at high severity is very hydrophilic and can retain water. It can also introduce important nutrients into the soil profile. In post-fire environments, increased soil nutrient levels are often attributed to ash, which has a positive impact on ground cover reestablishment [12,14] (Figure 1).

Soil is more vulnerable to degradation on steep slopes, especially after high-severity fires. Steep slopes are the most vulnerable to the effects of flames, especially if the fire line heads upslope, since convection of heat from the fire has the capacity to pre-heat the fuel, reducing moisture content before combustion. These effects are especially important on dry south facing slopes that are also the most vulnerable to soil erosion. This is aggravated by slow vegetation recovery [37]. On the other hand, a high rock fragments cover on the soil surface can mitigate soil erosion and micro depressions retain ash, facilitating the incorporation of nutrients into the soil profile [14, 38] (Figure 1).

Post-fire wind and rainfall intensity influence the degree of soil degradation in fire-affected areas. Ash and soil erosion and nutrient losses are high when intense rainfall (normally accompanied by strong winds) occurs in the period immediately after a fire. During this time, soils are very sensitive to any kind of disturbance, especially because vegetation has not yet started to recover. The lack of soil protection and the sparse ash cover increases the impacts of raindrops on soil compaction and facilitates sediment detachment. These conditions are very common in Mediterranean environments because of the occurrence of high intensity and short duration summer thunderstorms and intense autumn rainfalls. The impact of wind and raindrops on topsoil is intensified if the tree crown is totally combusted [39, 40]. High intensity precipitation events are also responsible for large mass movements such as debris flows and geomorphic changes [41*]. On the other hand, aridity changes post-fire microbial activity, reducing the carbon mineralization rate and availability of nutrients [42]. Post-fire aridity also increases the probability of debris flow occurrence, since it is associated with low infiltration rates as a consequence of an increase in soil water hydrophobicity and high runoff [43*]. In this context, both excess and lack of rainfall may increase soil degradation in soils affected by a high severity fire. Low intensity rainfall events can be beneficial reducing soil degradation because the capacity to compact the soil and create sediment detachment is reduced, soil moisture increases rapidly, and soil water repellency is destroyed, facilitating water infiltration, input of nutrients from ash, and microbial and vegetative recovery (Figure 1).

High fire severities affect seed abundance in the soil. This is especially observed when high temperatures are combined with prolonged periods of contact. Normally, there is a reduction in seed germination rate with increasing temperature, and at 300 °C most of the seeds are killed [44,45]. The existence of large bare soil areas increases the vulnerability of seed to erosion [46]. In addition to seed destruction by soil heating and erosion, a high post-fire soil pH as a consequence of ash leachates decreases the rate of seed germination capacity [47]. This is intensified by the occurrence of drought periods [48]. High fire recurrences decrease the capacity of vegetation to recover and dramatically change plant community diversity and composition [5]. All these aspects contribute to soil degradation.

Despite the reduction of seeds in the soil, the seeds of some species can resist high temperatures and be stimulated by heat and smoke, especially shrubland and heathland vegetation [49]. This can be enhanced by the release of nutrients (after pH decrease from high alkaline levels) into the soil profile from ash. The impacts of soil heating are complex and can be different according to the ecosystem affected. Mediterranean species are more adapted than other ecosystems, likely due to the long presence of fire in these ecosystems [50]. Another important aspect that reduces soil degradation after high severity wildfires is the capacity of some plants to resprout. This is a key adaptation of plants to fire disturbance, allowing the rapid recovery of vegetation, which is evidence of the high resilience of some ecosystems to this disturbance [51*] (Figure 1).

Ecosystems have developed strategies to respond to high severity fires and mitigate the effects of fire on soil degradation. This disturbance is temporal and the recuperation depends upon the resilience of the given ecosystem. For this reason, in many cases no intervention in burned areas is the most appropriate way to reduce soil degradation in fire affected areas. This does not mean that intervention cannot successfully be used in specific areas where there is a high risk of soil erosion, debris flows, or potential environmental, economic and/or social losses downstream. Several types of interventions are applied in fire-affected areas such as salvage logging, site preparation (post-fire mounding, ripping, and tree plantation), mulching (e.g. straw, wood chips, hydromulching), seeding, erosion barriers, and channel treatments. Tables S1a and S1b (supplementary material) summarize the impacts of post fire managements on soil properties during the first year after experimental and wildland fires, when the soil is most vulnerable to disturbance. The restoration techniques carried out in areas where experimental fires were applied showed no improvement in the majority of cases. Some major cation nutrients increased in mulched plots. This shows that the investment in these techniques in areas affected by low or moderate fire severity usually had little or no effect on soil properties.

If some intervention is needed, this should be carried out in areas affected by high fire severity. However, some interventions can be disastrous for soil and increase their degradation. In many cases salvage logging is carried out in the period immediately after a fire to provide some economic benefit to the owner, since the wood value decreases with time. However, these economic benefits depend on market conditions and the investments need to remove the wood [75]. These apparent benefits can be overwhelmed by the subsequent soil degradation (e.g. soil compaction, aggregate stability and organic matter loss, reduction of carbon sequestration, increased soil erosion) and the negative impacts on vegetation recuperation, richness and diversity (Figure 1, Table S1b and S2 Supplementary material) [62*]. Another practice that is detrimental for soil is site preparation, which substantially increases soil erosion rates and reduces vegetation recuperation capacity [76]. These practices always represent a negative disturbance to the soils. On the other hand, mulching practices are a sustainable practice to reduce high severity fire impacts on soil degradation. The impacts of mulching are not so evident in soil chemical properties, but improvements have been observed in soil microbiology (especially with a low dose of wheat straw). Organic amendments are more appropriate to restore soil nutrients. Mulching has a high capacity to reduce overland flow and soil erosion. Post-fire management practices such as wood removal should be carried out when vegetation show signs of recuperating, if possible one or two years after the fire (Figure 1, Table S1b and S2).

Final remarks and conclusion

Fire can have major impacts on soil. Low fire severities can be beneficial to soil properties, while high fire severity can produce long-term negative impacts and induce soil degradation. The degree of impact is very dependent on the pre-fire land use and is most visible where there was a lack of management and in areas where there are large areas of monospecific plantations. In these areas, high severity fires have highly negative impacts on soils. The effect of high severity fires on soil degradation depends upon the fire history of the site, the type of ash produced, topography, post fire weather, and degree of vegetation recuperation. These factors are interdependent and can increase or mitigate the effects of fire. However, the fact is that many ecosystems are resilient to fire and recover fast. This raises the question, what scenarios allow no intervention to be considered? This does not mean that intervention is not needed in specific situations. Human intervention and the way that we manage areas affected by high severity fires is crucial in determining whether fires will lead to an increase or decrease in soil degradation. Sustainable measures such as mulching can improve soil conditions, contrary to salvage logging techniques that cause soil degradation. Overall, post-fire management options can trigger or reduce soil degradation in areas affected by high severity fires.

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Figure Captions

Figure 1: High severity fire effects and factors that control post-fire recuperation. This figure was based on [4*,5,6,7,8,12,13,14,18,22,23,24,25,26,28,31**,33,34,35,37,38,42,43*,45,47,51*,52,55,57,62*,66-74]

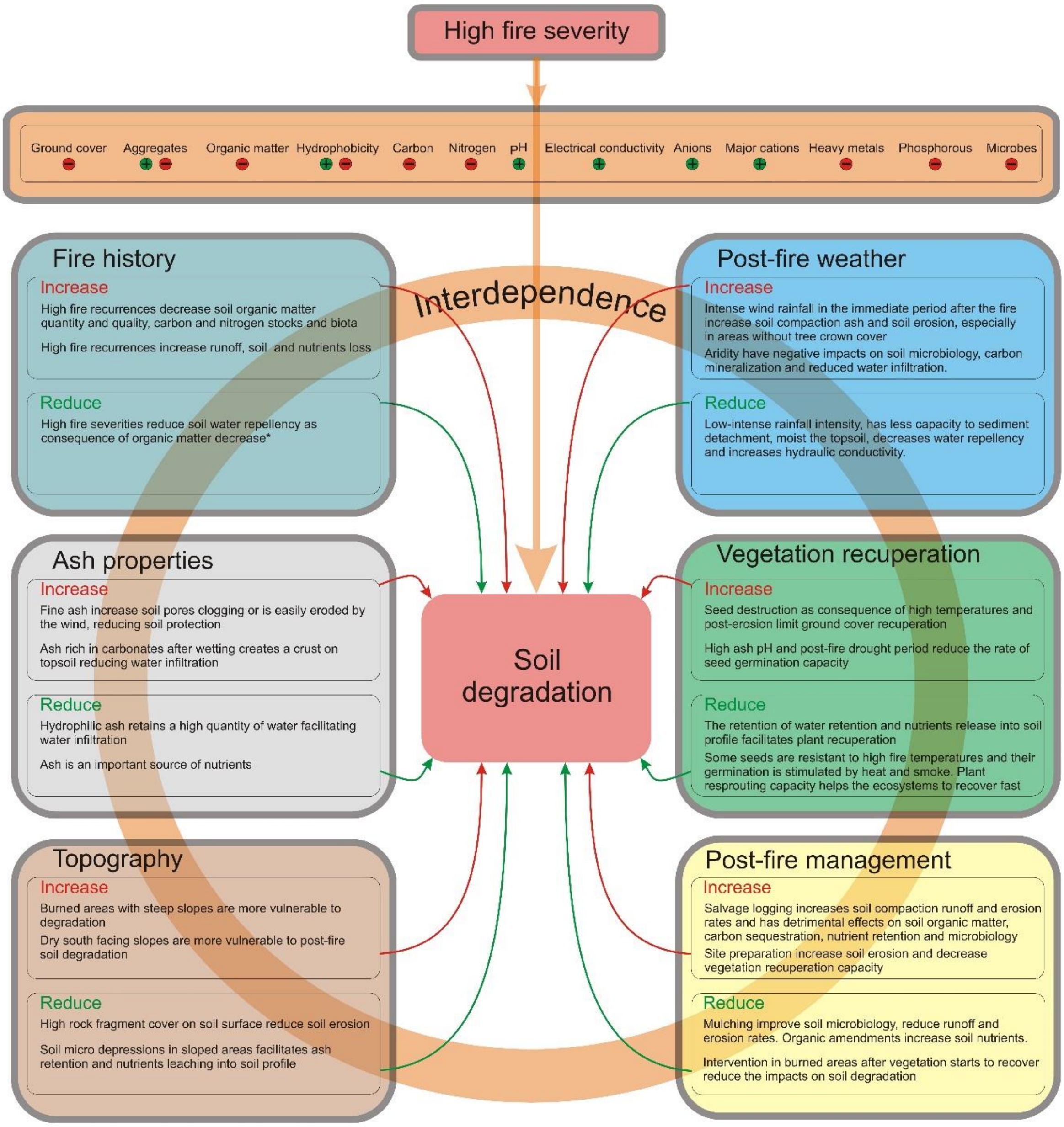
High fire severity
Ground cover
Aggregates
Organic matter
Hydrophobicity
Carbon
Nitrogen
pH
Electrical conductivity
Anions
Major cations
Heavy metals
Phosphorous
Microbes
Interdependence
Fire history
Increase
High fire recurrences decrease soil organic matter quantity and quality, carbon and nitrogen stocks and biota
High fire recurrences increase runoff, soil and nutrients loss
Reduce
High fire severities reduce soil water repellency as consequence of organic matter decrease*
Post-fire weather
Increase
Intense wind rainfall in the immediate period after the fire increase soil compaction ash and soil erosion, especially in areas without tree crown cover
Aridity have negative impacts on soil microbiology, carbon mineralization and reduced water infiltration.
Reduce
Low-intense rainfall intensity, has less capacity to sediment detachment, moist the topsoil, decreases water repellency and increases hydraulic conductivity.
Ash properties
Increase
Fine ash increase soil pores clogging or is easily eroded by the wind, reducing soil protection
Ash rich in carbonates after wetting creates a crust on topsoil reducing water infiltration
Reduce
Hydrophilic ash retains a high quantity of water facilitating water infiltration
Ash is an important source of nutrients
Soil degradation
Vegetation recuperation
Increase
Seed destruction as consequence of high temperatures and post-erosion limit ground cover recuperation
High ash pH and post-fire drought period reduce the rate of seed germination capacity
Reduce
The retention of water retention and nutrients release into soil profile facilitates plant recuperation
Some seeds are resistant to high fire temperatures and their germination is stimulated by heat and smoke. Plant resprouting capacity helps the ecosystems to recover fast
Topography
Increase
Burned areas with steep slopes are more vulnerable to degradation
Dry south facing slopes are more vulnerable to post-fire soil degradation
Reduce
High rock fragment cover on soil surface reduce soil erosion
Soil micro depressions in sloped areas facilitates ash retention and nutrients leaching into soil profile
Post-fire management
Increase
Salvage logging increases soil compaction runoff and erosion rates and has detrimental effects on soil organic matter, carbon sequestration, nutrient retention and microbiology
Site preparation increase soil erosion and decrease vegetation recuperation capacity
Reduce
Mulching improve soil microbiology, reduce runoff and erosion rates. Organic amendments increase soil nutrients.
Intervention in burned areas after vegetation starts to recover reduce the impacts on soil degradation

Table S1. Post-fire managements impact on soil properties according to different managements in the immediate period after (0-1/1.5 year). A) Experimental fires and B) Wildland fires. Comparisons (impact) related to no intervention (control plot). Significant decrease (red), no changes (yellow) and significant increase (green). Only studies after 2010 were considered.

A

Ecosystem	Severity	Burned species	Treatment	Soil property	Impact	Reference
Mediterranean Scrubland	Moderate	*Ulex europaeus* L., *Pteridium aquilinum* (L.) Kuhn., *Ulex* gallii Planch., *Daboecia cantabrica* (Huds.) K. Koch and *Pseudoarrenhaterum longifolium* Rouy	Seeding	pH		[52]
				Electric conductivity		
				Water retention		
				Total carbon		
				Soluble carbon		
				Total nitrogen		
				Inorganic nitrogen		
				Total biomass PLFA		
				Fungal PLFA		
				Bacterial PLFA		
				Bacterial PLFA		
				Bacterial PLFA G+		
				Fungal/bacterial PLFA		
				Bacterial G−/G+ PLFA		
				Cyclopropyl/monoenoic precursors		
				Saturated/monounsaturated		
			Straw mulch	pH		
				Electric conductivity		
				Water retention		
				Total carbon		
				Soluble carbon		
				Total nitrogen		
				Inorganic nitrogen		
				Total biomass PLFA		
				Fungal PLFA		
				Bacterial PLFA		
				Bacterial PLFA		
				Bacterial PLFA G+		
				Fungal/bacterial PLFA		
				Bacterial G−/G+ PLFA		
				Cyclopropyl/monoenoic precursors		
				Saturated/monoun saturated		
Mediterranean Scrubland	Moderate	*Ulex europaeus* L., *Pteridium aquilinum* (L.) Kuhn., *Ulex* gallii Planch., *Daboecia cantabrica* (Huds.) K. Koch and *Pseudoarrenhaterum longifolium* Rouy	Mulching	pH water		[53]
				pH KCl		
				Total carbon		
				δ13carbon		
				Total nitrogen		
				δ15Nitrogen		
				Ammonium		
				Nitrate		
				Extractable Aluminium		
				Extractable Sodium		
				Extractable Potassium		
				Extractable Magnesium		
				Extractable Calcium		
				Extractable Phosphorous		
				Extractable Iron		
				Extractable Managanese		
				Extractable Copper		
				Extractable Zinc		
				Extractable Barium		
				Extractable Cobalt		
			Seeding	pH water		
				pH KCl		
				Total carbon		
				δ13carbon		
				Total nitrogen		
				δ15N		
				Ammonium		
				Nitrate		
				Extractable Aluminium		
				Extractable Sodium		
				Extractable Potassium		
				Extractable Magnesium		
				Extractable Calcium		
				Extractable Phosphorous		
				Extractable Iron		
				Extractable Managanese		
				Extractable Copper		
				Extractable Zinc		
				Extractable Barium		
				Extractable Cobalt		

Continuation

Ecosystem	Severity	Burned species	Treatment	Soil property	Impact	Reference
Temperate	Low	*Ulex europaeus* L., *Pteridium aquilinum* (L.) Kuhn., *Ulex* gallii Planch., *Daboecia cantabrica* (Huds.) K. Koch and *Pseudoarrenhaterum longifolium* Rouy	Seeding	Moisture		[54]
				pH water		
				Electric conductivity		
				Water retention at field capacity		
				Total carbon		
				Microbial carbon[1]		
				Microbial Carbon[2]		
				Basal respiration		
				Glucosidase		
				Urease		
				Phosphatase		
				AWCD[3]		
				MR[4]		
				H′[5]		
			Straw mulch	Moisture		
				pH water		
				Electric conductivity		
				Water retention at field capacity		
				Total carbon		
				Microbial carbon[6]		
				Microbial Carbon[7]		
				Basal respiration		
				Glucosidase		
				Urease		
				Phosphatase		
				AWCD[8]		
				MR[9]		
				H′[10]		

[1] Fummigation extraction
[2] Substrate induced respiration
[3] Average well color development
[4] Microbial richness
[5] Shannon–Weaver diversity index
[6] Fummigation extraction
[7] Substrate induced respiration
[8] Average well color development
[9] Microbial richness
[10] Shannon–Weaver diversity index

B

Ecosystem	Severity	Burned species	Treatment	Soil property	Impact	Reference
Mediterranean	Moderate to High	*Pinus sylvestris* L. plantation and shrubs (*Erica* spp., *Vaccinium myrtillus* L., *Pterospartum tridentatum* Willk. and *Cistus* spp)	Mulching	pH water		[55]
				pH KCl		
				Ammonium		
				Nitrate		
				Extractable Sodium		
				Extractable Potassium		
				Extractable Magnesium		
				Extractable Calcium		
				Extractable Phosphorous		
				Extractable Aluminium		
				Extractable Iron		
				Extractable Managanese		
				Extractable Copper		
				Extractable Zinc		
				Extractable Cobalt		
			Seeding	pH water		
				pH KCl		
				Ammonium		
				Nitrate		
				Extractable Sodium		
				Extractable Potassium		
				Extractable Magnesium		
				Extractable Calcium		
				Extractable Phosphorous		
				Extractable Aluminium		
				Extractable Iron		
				Extractable Managanese		
				Extractable Copper		
				Extractable Zinc		
				Extractable Cobalt		
Mediterranean	High	*Pinus sylvestris* L. plantation and shrubs (*Erica* spp., *Vaccinium myrtillus* L., *Pterospartum tridentatum* Willk. and *Cistus* spp)	Straw mulch	Moisture		[56][11]
				Aggregate stability		
				Water repellency		
				Water retention at field capacity		
				pH water		
				pH KCl		
				Electric conductivity		
				Organic carbon		
				Total nitrogen		
				Microbial carbon		
				Respiration		
				qCO2		
				Bacterial activity		
				Urease activity		
				Glucosidase activity		
			Rye seeding	Moisture		
				Aggregate stability		
				Water repellency		
				Water retention at field capacity		
				pH water		
				pH KCl		
				Electric conductivity		
				Organic carbon		
				Total nitrogen		
				Microbial carbon		
				Respiration		
				qCO2		
				Bacterial activity		
				Urease activity		
				Glucosidase activity		
Mediterranean	High Severity	Shrubland (dominated by *Ulex* spp.)	Mulching. Wheat straw (low-dose)	Soil respiration		[57]
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Wheat straw (low-dose)	Soil respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Coconut fibre (low-dose)	Soil respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		

[11] Results from 16 weeks after the fire

Continuation

Ecosystem	Severity	Burned species	Treatment	Soil property	Impact	Reference
Mediterranean	High Severity	Shrubland (dominated by *Ulex* spp.)	Mulching. Coconut fibre (low-dose)	Respiration		[57]
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Coconut fibre (high-dose)	Respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Eucalyptus bar strands (low-dose)	Respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Eucalyptus bar strands (high-dose)	Respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Eucalyptus wood chips (low-dose)	Respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
			Mulching. Eucalyptus wood chips (high-dose)	Respiration		
				Fungal growth		
				Bacterial growth		
				Fungal biomass		
				Total PLFA		
				Fung PLFA		
				Fungal/bacterial PLFA index		
				G^-/G^+		
Mediterranean	High	Herbaceous (*Bituminaria bituminosa* L. and *Lotus* species), woody species (*Cistus monspeliensis* L., *Calycotome spinosa* L. and *Erica arborea* L.) and *Quercus suber* L.	Young compost	Total organic carbon		[58][12]
				pH water		
				Total nitrogen		
				Total phosphorous		
				C/N ratio		
				C/P ratio		
				Ammonium		
				Nitrate		
				Phosphate		
				Microbial biomass		
				Respiration		
			Intermediate compost	Total organic carbon		
				pH water		
				Total nitrogen		
				Total phosphorous		
				C/N ratio		
				C/P ratio		
				Ammonium		
				Nitrate		
				Phosphate		
				Microbial biomass		
				Respiration		
			Old compost	Total organic carbon		
				pH water		
				Total nitrogen		
				Total phosphorous		
				C/N ratio		
				C/P ratio		
				Ammonium		
				Nitrate		
				Phosphate		
				Microbial biomass		
				Respiration		
			Young compost	Catabolic diversity		[59][12]
				AWCD		
			Intermediate compost	Catabolic diversity		
				AWCD		
			Old compost	Catabolic diversity		
				AWCD		

[12] Results from 10 months after compost amendment

Continuation

Ecosystem	Severity	Burned species	Treatment	Soil property	Impact	Reference
Mediterranean	High	*Pinus Pinaster* and *Pinus nigra*	Salvage logging	Respiration		[60]
			Cut and plus lopping			
		Pinus sylvestris	Salvage logging			
			Cut and plus lopping			
Mediterranean	High	*Pinus sylvestris*	Salvage logging	Carbon sequestration		[61]
Mediterranean	Moderate	*Pinus halepensis* and shrubs (*Quercus coccifera*, *Rosmarinus officinalis*, *Thymus vulgaris* and *Brachypodium retusum*)	Salvage logging	Aggregate stability		[*62]
				Field capacity		
				Organic matter		
				Nitrogen		
				Phosphorous		
				Microbial biomass carbon		
				Respiration		
				Total DNA		[63]
				16S rRNA gene		
				nifH gene		
				nosZ gene		
				nirK gene		
				nirS gene		
				amoA-Arch gene		
				amoA-B		
Temperate	Moderate to High	*Pinus pinaster* Ait., *Eucalyptus globulus* Labill. and *Pinus radiata* D. Don. Understory (*Ulex* sp., *Erica* sp. and *Pterospartum tridentatum* (L.) Willk.).	No Mulching[13] +Savage logging	Shear strenght		[64]
			Mulching[2] +Savage logging	Penetration resistence		
Mediterranean (Eucalyptus plantation)	Moderate	Eucalyptus	Salvage logging (skid low)[14]	Bulk Density	0-5 cm	[65]
					5-10 cm	
				Penetration resistence		
				Shear strenght		
			Salvage logging (skid low)[15]	Bulk Density	0-5 cm	
					5-10 cm	
				Penetration resistence		
				Shear strenght		

[13] Eucalypt bark strands
[14] *"skid trails by the forwarder tractor with two passes"* [65]
[15] *"with skid trails resulting from several passes by both the forwarder tractor and the feller-buncher"* [65]

Table S2. Impacts of wildfire on overland flow and soil erosion according to different post-fire managements in the immediate period after (0-1/1.5 year). Comparisons (impact) related to no intervention (control plot). Significant decrease (green), no changes (yellow) and significant increase (red). Comparisons related to no intervention. Studies form 2010.

Type of fire	Ecosystem	Severity	Plot /catchment size	Treatment	Overland flow	Soil erosion	Reference
Experimental fire	Temperate	Moderate	300 m^2	Straw mulching	-		[66]
				Seeding	-		
Wildfire	Mediterranean (Eucalyptus plantation)	Moderate	0.28 m^2 (control) and 0.27 m^2 (mulched)	Mulching		-	[67]
			83 m^2 (control) and 128 m^2 (mulched)	Mulching		-	
Wildfire	Mediterranean (Eucalyptus plantation)	Moderate	0.28 m^2	Mulching			[68]
				Polyacrylamide			
Wildfire	Mediterranean	High	500 m^2	Straw mulching	-		[69]
				Wood-chip mulch	-		
				Cut-shrub barriers	-		
Wildfire	Mediterranean	High	80 m^2	Straw mulching	-		[57][16]
				Rye seeding	-		
Wildfire	Temperate	Moderate to high	80 m^2	No Mulching[17] +Savage logging	-		[70]
				Mulching[4] +Savage logging	-		
Wildfire	Temperate	High	500 m^2	Straw mulching	-		[71]
				Eucalyptus bark strands	-		
Wildfire	Temperate	High	80 m^2	Straw mulching	-		[72]
				Erosion barriers	-		
Wildfire	Mediterranean (Eucalyptus plantation)	Moderate	18 m^2	Salvage logging (skid low)[18]			[65]
			17 m^2	Salvage logging (skid high)[19]			
Wildfire	Hayman (Ponderosa pine and Douglas-fir), Hot Creek (Douglas-fir and Subalpine fir), Myrtle Creek (Douglas-fir and Ponderosa Pine) and School (Douglas-fir and Grand fir)	High	22-282 m_2 (average range)	Straw mulch	-		[73][20]
				Wood	-		
				Hydromulch	-		
Wildfire	Hayman	High	Straw mulch (3.3 ha)	Straw mulch			[74]
			Hydromulch (5.2 ha)	Hydromulch			
	Cedar (Mediterranean)		Fully treated (2.1 ha)	Fully treated[21]			
			Partially treated (2.6 ha)	Partially treated[22]			

[16] Results from 16 weeks after the fire
[17] Eucalypt bark strands
[18] *"skid trails by the forwarder tractor with two passes"* [65]
[19] *"with skid trails resulting from several passes by both the forwarder tractor and the feller-buncher"* [65]
[20] This work was carried out in different environments and the results presented correspond to the average of the different treatments in all study sites.
[21] Hydromulch of wood and paper fiber with non-water soluble binder
[22] Hydromulch of wood and paper fiber with non-water soluble binder applied in 30 m contour strips