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REVIEW

Fire impacts on soil and post fire emergency stabilization treatments in Mediterranean-climate regions

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ABSTRACT

Wildfires are non-controlled large-scale fires of various vegetation types that have long affected the Mediterranean-climate regions, but their increased frequency and severity has led to the degradation of the ecosystems. Particularly in Chile, 147 major wildfires in 2017, were responsible of burning 546 678 ha, which included 28 729 ha of traditional small-scale non irrigated agricultural systems, highlighting the vulnerability of these agricultural soils to wildfires. Soil biological properties are more sensitive to heating than physicochemical properties. Thus, a reduction of microbial communities and associated enzyme activities generally occur in low-intensity fires (< 200 °C). Most significant changes in physicochemical properties of soil occurring in moderately intense fires (250 to 450 °C) are increases of soil pH, nutrient availability, bulk density and soil water repellency, whereas soil aggregate stability and water holding capacity generally decrease. When vegetation cover is completely destroyed by fire, emergency stabilization treatments such as mulching and seeding provide an immediate ground cover to reduce soil erosion and preserve nutrients. Therefore, it is important to define the impacts of wildfire on soil properties of agricultural lands to establish a roadmap to implement an adequate and viable restoration.

Key words: Erosion, fire, Mediterranean-climate, mulching, seeding, soil properties, wildfire.

INTRODUCTION

Fire intensity relates to temperature and fire duration (residence time) and represents the energy output from a fire. Thus, fire intensity mainly depends on fuel amount and flammability, weather conditions and topography (Keeley, 2009; Mataix-Solera et al., 2011). Low intensity fires reach surface temperature of up to 250 °C, whereas moderate and high intensity fires reach surface temperature up to 450 and 650 °C, respectively (Araya et al., 2016).

Because fire intensity is often not known for most wildfires, fire severity is used to describe how fire intensity affected ecosystems. Fire severity emphasized the degrees of organic matter loss or decomposition both aboveground and belowground and is positively correlated to fire intensity but also depends on the type of vegetation and soil characteristics and conditions (texture, water content and organic matter) (Keeley, 2009; Mataix-Solera et al., 2011). Fire severity can be assessed using burn severity mapping (spectral indices) (Fernández-García et al., 2019b) and/or ground variables such as coloration of ash, twig diameter on terminal branches and charring depth among other metrics (Keeley, 2009; Francos et al., 2018). Ground variables differ depending on the ecosystem but in general, severity varies from low severity fires (light) where non woody vegetation cover is consumed, ash is black and charring is limited to a few millimeters depth, to high severity fire (deep burning) where all vegetation is killed, ash is white/gray and charred organic matter reach several centimeters depth (Keeley, 2009).

Wildfires or uncontrolled fires generally occur in the presence of an abundant and dry fuel load (Certini, 2005). In Mediterranean-climate regions the frequency of wildfires is related to fuel flammability conditions and that is projected to increase around the globe if climate variables were the only driver (McWethy et al., 2018; Urrutia-Jalabert et al., 2018; Gómez-González et al., 2019).

Particularly, in Chile more than 95% of the wildfires occur in the Mediterranean-climate (warm summer) region between 33° and 42° S lat (Figure 1), i.e., the South-Central region (Sarricolea et al., 2017; de la Barrera et al., 2018; CONAF, 2020). These Mediterranean-climate regions are fire prone due to hot, dry summers and cool wet winters (Castillo et al., 2020). Furthermore, this area is characterized by an increase of extensive monoculture of exotic, fire prone, forest plantations, which have changed the vegetative landscape in just a few decades, replacing agricultural lands, grasslands, native shrublands and forests (Heilmayr et al., 2016).

In the last three decades, the frequency of major wildfires (≥ 200 ha) in Chile have increase from an annual average of 40 (1991-2000) to 63 (2011-2020) (Figure 2). Moreover, the length of fire season as well as the fire duration increased in the last 30 yr, evidencing that fire regime in central Chile has been altered (González et al., 2018; CONAF, 2020).

The main reasons identified for the higher frequency and severity of wildfire in Chile are: i) climatic variables such as summer drought, winter precipitation, and spring and summer mean temperature that promotes fuel accumulation and flammability (González et al., 2018; McWethy et al., 2018; Urrutia-Jalabert et al., 2018; Gómez-González et al., 2019), ii) increase of the area of fire prone exotic forest plantations (*Pinus* and *Eucalyptus*) and the adoption of intensive forest management practices, which result in the accumulation of a high fuel load (de la Barrera et al., 2018; Gómez-González et al., 2018; McWethy et al., 2018; Bowman et al., 2019), and iii) increase in population density and thus human occupation of the urban-rural interface and human-driven land use change that generates fires and intensify drought (McWethy et al., 2018; Gómez-González et al., 2019; Castillo et al., 2020).

In 2017, 147 major fires (each with an affected surface area ≥ 200 ha), driven by extreme climatic conditions (Bowman et al., 2019), were responsible for burning 546 678 ha (CONAF, 2020), making it by far the worst year of wildfires in the last three decades in Chile (Figure 2).

Figure 1. Köppen-Geiger climate classification (adapted by Sarricolea et al., 2017) and locations of 2017 major wildfires in central Chile.

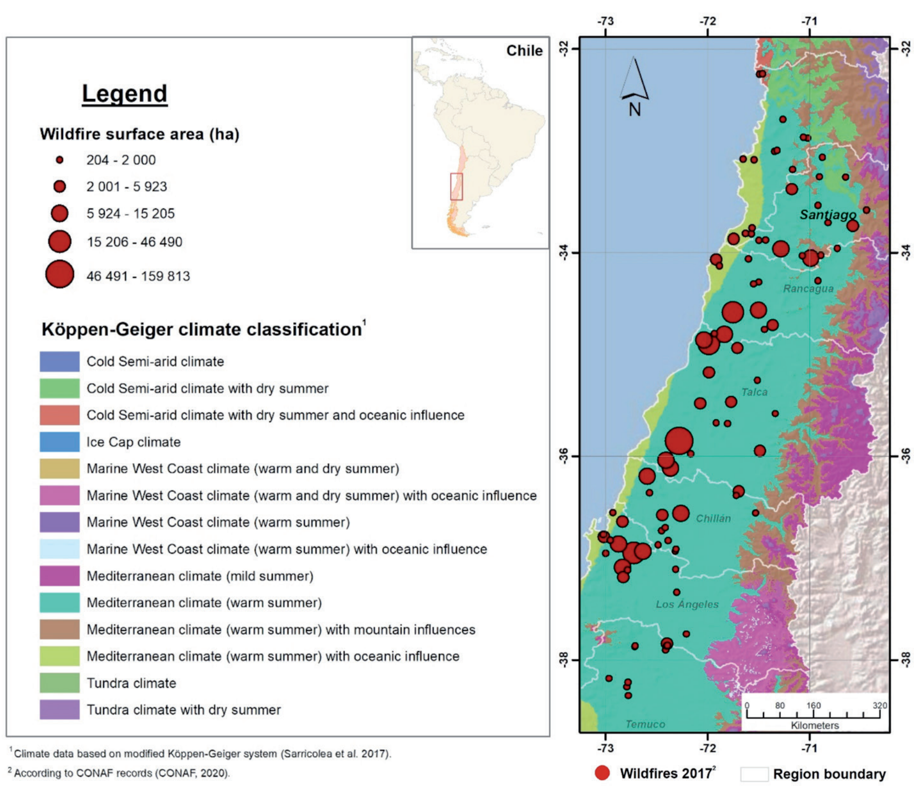
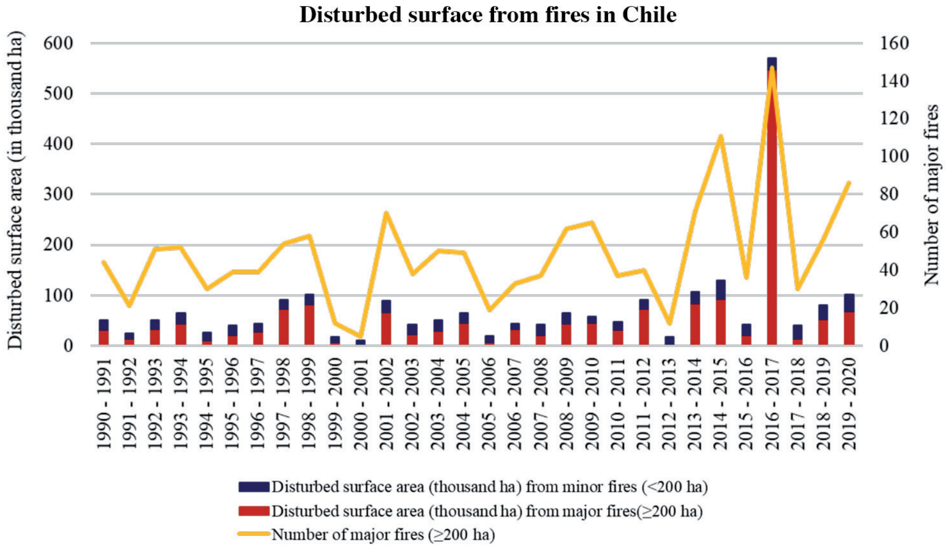


Figure 2. Fire-affected surface area and frequency (number) of major fires (≥ 200 ha) for the last three decades in Chile (CONAF, 2020).



These major-fires burned down forest plantations, native forests, shrublands, agricultural crops and buildings; forest plantations (223 605 ha) whereby the native shrublands (187 906 ha) were the most affected ecosystems (de la Barrera et al., 2018). Likewise, 28 729 ha of agricultural lands between 33°50’ and 38º29’ S lat were affected by these fires (CONAF, 2020).

Wildfires that affect agricultural soils behave differently than prescribed (planned) fires that are used in agriculture that may have neutral or even positive effects (Armas-Herrera et al., 2016). However, high severity fires are not common in agricultural land because of a reduced fuel quantity (Certini, 2005) compared to fire-prone forest lands.

Fire causes an alteration of soil through heating and oxidation, thus generating new sources of physicochemical and biological inputs into the soil system in the form of charcoal, organic distillates, metal oxides and plant litter (Hart et al., 2005; Alcañiz et al., 2018). The capacity of a soil to recover from the fire-induced degradation depends on the type of ecosystem, fire severity (Fernández-García et al., 2019a), fire history, ash properties, topography, postfire weather, plant resilience, and postfire management (Pereira et al., 2018). Mediterranean ecosystems are vulnerable to the increase in fire frequency and severity, with a relative long natural recovery (passive restoration) period of 15-21 yr if not intervened (Moya et al., 2018). Thus, planned interventions such as emergency stabilization treatment are fundamental to prevent soil degradation and recover soil productivity in the short and midterm in agricultural lands.

Postfire emergency stabilization treatments such as mulching and seeding along with organic amendments applications, can be used for decreasing soil degradation (Pereira et al., 2018) and restoring productivity, but the lack of economic incentives for these practices (mulching and organic amendments) may make soil recovery difficult for most of the small landowners. Thus, the aim of this review is to describe the potential impact of wildfires on Mediterranean agricultural soils, and to analyze the inclusion of postfire emergency stabilization techniques into an incentive system with some projections to the case of Chile.

FIRES AND SOIL PROPERTIES

To assess the potential effects of wildfires on soils from Mediterranean-climate agricultural lands, we analyzed 34 studies. All the studies were conducted in Mediterranean-climate region and evaluated (short (≤ 1 yr) and midterm (> 1 yr and ≤ 5 yr) post fire effects of low to moderate severity fires in field conditions (Table 1).

Table 1. Studies that were considered to identify the effects of low to medium severity fires on soil properties in the short and mid-terms in Mediterranean climates.

Authors	Country	Ecosystem	Soil texture	Climate	Type of fire	Type of soil property		
						Biological	Chemical	Physical
Alcañiz et al., 2016	Spain	Forest	Not specified	Csa	Prescribed fire	0	16	0
Faría et al., 2015	Portugal	Forest	Loam	Csb	Wildfire	0	5	0
Fernández-García et al., 2019a	Spain	Forest	Sandy	Csb	Wildfire	11	4	0
Fernández-García et al., 2019b	Spain	Forest	Sandy loam	Csb	Wildfire	11	8	0
Fonseca et al., 2017	Portugal	Shrublands	Loam	Csb	Prescribed fire	9	81	0
Fontúrbel et al., 2012	Spain	Shrublands	Not specified	Csb	Experimental burning	24	12	8
Francos et al., 2018	Spain	Forest	Not specified	Csa	Wildfire	2	6	0
Francos et al., 2019	Spain	Forest	Not specified	Csa	Prescribed fire	4	14	0
Gimeno García et al., 2000	Spain	Shrublands	Sandy loam	Csa	Experimental burning	1	9	0
Goméz-Rey et al., 2013	Spain	Forest	Sandy loam	Csb	Wildfire	0	21	0
Goméz-Rey and González-Prieto, 2014	Spain	Forest	Silty loam	Csb	Wildfire	0	56	0
Granged et al., 2011	Spain	Heathland	Loam	Csa	Experimental burning	4	8	16
Gutknecht et al., 2010	USA	Grassland	Loam	Csa	Wildfire	12	0	0
Hernández et al., 1997	Spain	Matorral	Loam	Csa	Wildfire	14	16	0
Heydari et al., 2016	Iran	Forest	Loam	Csa	Wildfire	2	14	2
Hosseini et al., 2017	Portugal	Forest	Loam	Csb	Wildfire	0	12	0
Hubbert et al., 2006	USA	Chaparral	Loam	Csa	Prescribed fire	0	0	5
Hueso-González et al., 2018	Spain	Shrublands	Sandy loam	Csa	Prescribed fire	2	6	6
Jiménez-González et al., 2016	Spain	Forest	Not specified	Csa	Wildfire	16	32	8
Jiménez-Morillo et al., 2020	Spain	Forest	Sandy	Csa	Wildfire	4	0	0
Jiménez-Pinilla et al., 2016	Spain	Shrublands	Silty loam	Csa	Wildfire	0	0	4
Mataix-Solera and Doerr, 2004	Spain	Forest	Sandy loam	Csa	Wildfire	1	0	2
Mataix-Solera et al., 2013	Spain	Forest	Loam	Csa	Wildfire	5	0	5
Meira-Castro et al., 2014	Portugal	Forest	Clayey	Csb	Prescribed fire	2	2	2
Miesel et al., 2011	USA	Forest	Loam	Csa	Prescribed fire	10	0	0
Moya et al., 2019	Spain	Forest	Sandy clay loam	Csa	Wildfire	18	2	0
Otero et al., 2015	Portugal	Forest	Sandy loam	Csb	Wildfire	1	7	0
Plaza-Álvarez et al., 2018	Spain	Forest	Clayey	Csa	Prescribed fire	6	0	12
Plaza-Álvarez et al., 2019	Spain	Forest	Clayey	Csa	Prescribed fire	6	6	10
Romanyá et al., 2001	Spain	Grassland	Not specified	Csa	Experimental burning	5	3	0
Romeo et al., 2020	Spain	Forest	Clay loam	Csb	Wildfire	6	4	0
Úbeda et al., 2005	Spain	Grassland	Not specified	Csa	Prescribed fire	0	10	0
Varela et al., 2015	Spain	Forest	Sandy loam	Csa	Wildfire	2	0	8
Vega et al., 2013	Spain	Shrublands	Loam	Csa	Wildfire	12	210	0
Total						190	564	88

Csa: Hot summer Mediterranean climate; Csb: warm-summer Mediterranean climate.

Effect of fire on soil properties

Low to moderate severity fire primarily impacts the topsoil. Consequently, the loss of soil organic matter (SOM) rather than alteration of soil minerals, has been the property most related to fire-induced changes in soil physico-chemical properties (Mataix-Solera et al., 2011; Araya et al., 2016).

Soil biological properties are more sensitive than chemical and physical properties to heat, which decreases microbial C through the direct mortality of microorganisms exposed to lethal temperatures (Hart et al., 2005; Muñoz-Rojas et al., 2016) and extracellular enzyme activities by enzyme denaturation (Fultz et al., 2016). Furthermore, changes in chemical and physical properties indirectly alter microbial communities and the decomposing and mineralization processes that they catalyze (Hart et al., 2005).

Occasionally, there is an immediate net increase in available nutrient after a fire, leading to a short-term increase in microbial activity (Caon et al., 2014), but most authors report a decrease of this activity. Furthermore, a meta-analysis of below ground biological community responses to fire concluded that fire reduced the richness, evenness, and diversity of soil microorganisms and mesofauna by up to 99% (Pressler et al., 2019).

Substantial oxidation of SOM begins in the 200-250 °C temperature range (Certini et al., 2011). Although SOM quantity and quality may change with elevated heat (Faría et al., 2015; Jiménez-Morillo et al., 2020), low to moderate severity fires have greater effect over the microbial communities and associated enzyme activities. Not surprisingly then, most studies in Mediterranean-climate region report no effect on SOM quantity (Mataix-Solera et al., 2013; Meira-Castro et al., 2014; Fonseca et al., 2017; Francos et al., 2019; Moya et al., 2019; Plaza-Álvarez et al., 2019) while others showed a significantly decrease on microbial biomass C (Vega et al., 2013; Fernández-García et al., 2019a; 2019b; Moya et al., 2019; Romeo et al., 2020) and the activity of urease, β-glucosidase and acid phosphatase (Miesel et al., 2011; Fernández-García et al., 2019a; 2019b; Moya et al., 2019) (Figure 3).

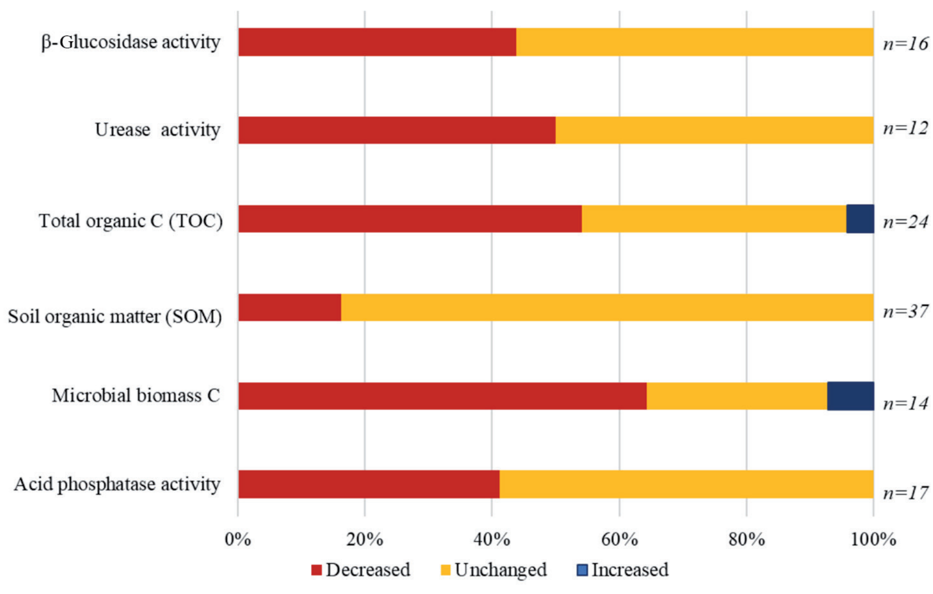
Near 60% of the studies carried out in forest ecosystems report a decrease in enzyme activities in the short and midterm even with low severity fires (Miesel et al., 2011; Fernández-García et al., 2019a; 2019b; Moya et al., 2019), whereas low severity fires in grasslands and matorral report a neutral effect of fire on these properties (Gutknecht et al., 2010; Fontúrbel et al., 2012; Vega et al., 2013).

Soil chemical properties are generally more affected by the peak temperature than the fire residence time (Thomaz, 2017). Some studies report that the most significant changes of soil chemistry occur between 250 and 450 °C (Araya et al., 2016) and are linked to the SOM combustion and its by-products such as ash, pyrogenic organic compounds, increased pH, and transformation of Fe oxyhydroxide into Fe oxides (Caon et al., 2014; Thomaz, 2017). However, most studies on Mediterranean climate report no change in the mid-term of soil pH, electrical conductivity (EC) and cation exchange capacity (CEC) and an increase in available P, and NH_4-N (Figure 4).

Fire usually increases soil pH in the short term because of i) the release of alkaline cations (Ca, Mg, K, Na) that are bound to organic matter (Certini, 2005; Alcañiz et al., 2018), ii) the destruction of organic acids, and iii) the contribution of carbonates and oxides from ash (Granged et al., 2011; Bodí et al., 2012; Zavala et al., 2014; Alcañiz et al., 2016). This increase is ephemeral due to the formation of new humus, leaching of bases and removal of ash by erosion processes (Zavala et al., 2014). Thus, fire has no lasting effect on pH in the midterm.

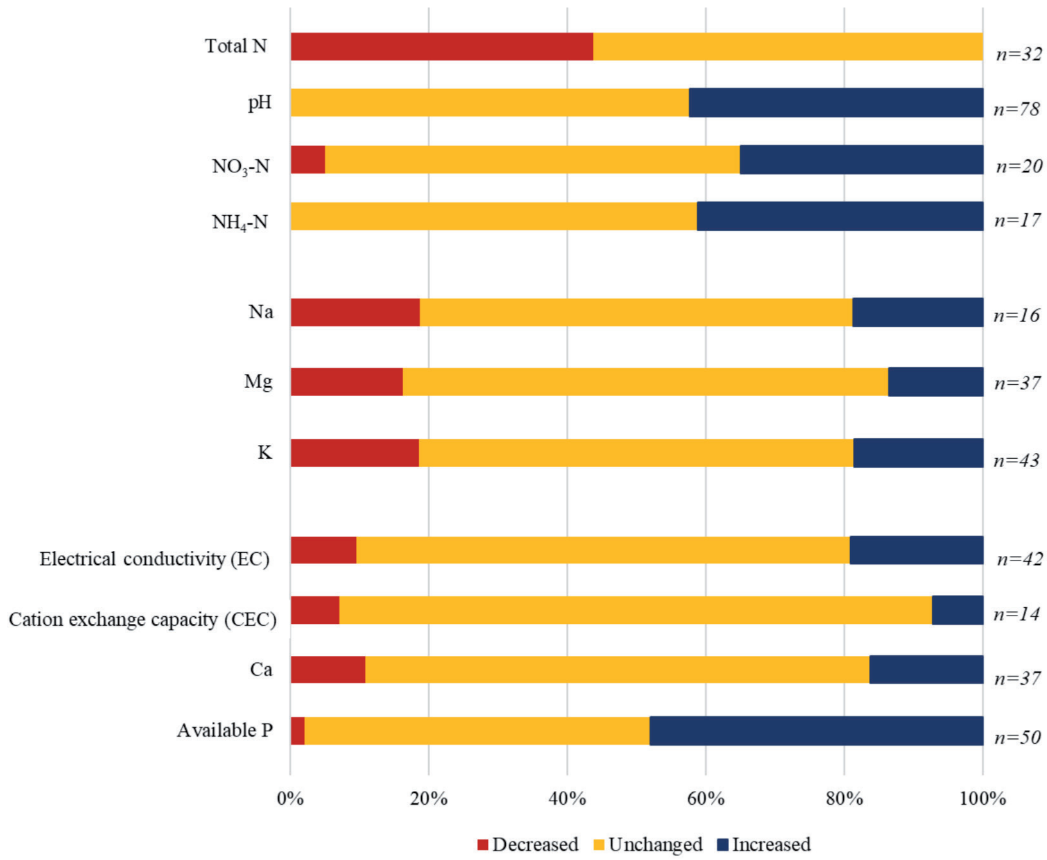
An increase of soil EC is associated to the soluble inorganic ions released during SOM combustion as well as the formation of black carbon and the incorporation of ash into the soil. Conversely, a decrease of CEC after fire is mainly associated with the net loss of SOM (Certini, 2005; Alcañiz et al., 2016; Araya et al., 2016). Some experimental studies have indicated that CEC is altered as far as the fire temperature exceed 300 °C to 350 °C (Thomaz, 2017). However, nonsignificant CEC changes are observed under low-severity fires because of unaffected SOM (Heydari et al., 2016; Fonseca et al., 2017; Plaza-Álvarez et al., 2018; Francos et al., 2019). Significant changes of EC have been reported in the midterm (Hueso-González et al., 2018) but most studies agree in a neutral effect of fire in CE and CEC after 1 yr (Granged et al., 2011; Jiménez-González et al., 2016; Hosseini et al., 2017; Fernández-García et al., 2019b).

Figure 3. Short and mid-term effects of low and moderate severity fire on soil biological properties in Mediterranean climate areas (based on the 34 studies described in Table 1).



n: Number of significant effects reported per soil property.

Figure 4. Short and mid-term effects of low and moderate severity fire on soil chemical properties in Mediterranean climate areas (based on the 34 studies described in Table 1).



n: Number of significant effects reported per soil property.

Nitrogen content is another chemical parameter that experience notable variations in post-fire soils. The total N concentration tends to increase after a fire due to: i) release of the element from dead roots and N-containing organic compounds (Rivas et al., 2012), ii) nitrification enhancement in acid soil, and iii) the addition of partially pyrolyzed materials (Grogan et al., 2000). Similar to pH total N increase is ephemeral, thus most studies report a neutral effect in this property in the midterm.

Generally, positive changes in nutrient availability (P, Mg, K, Ca) occur after a fire; however, the recovery of prefire nutrient concentrations can take approximately 1 yr (Úbeda et al., 2005; Alcañiz et al., 2016), thus, usually there are negligible mid-term effects regarding nutrient availability after a fire (Figure 4).

The main physical changes at low to moderate fire temperatures are an increase of soil water repellency (SWR) and bulk density (BD) and a decrease of aggregate stability (AS) and water holding capacity (WHC). Most studies report an increase of SWR during the first year after following the fire event, and no changes in the midterm (Hubbert et al., 2006; Jiménez-Pinilla et al., 2016; Plaza-Álvarez et al., 2018). Furthermore, SWR is common in long-term unburned Mediterranean calcareous soils (Bodí et al., 2013), thus, fire might not have the same impact as in other types of soil. However, the degree of postfire SWR in the short term depends on fire severity, vegetation type, soil texture, rainy season, soil moisture and land use (Alcañiz et al., 2018).

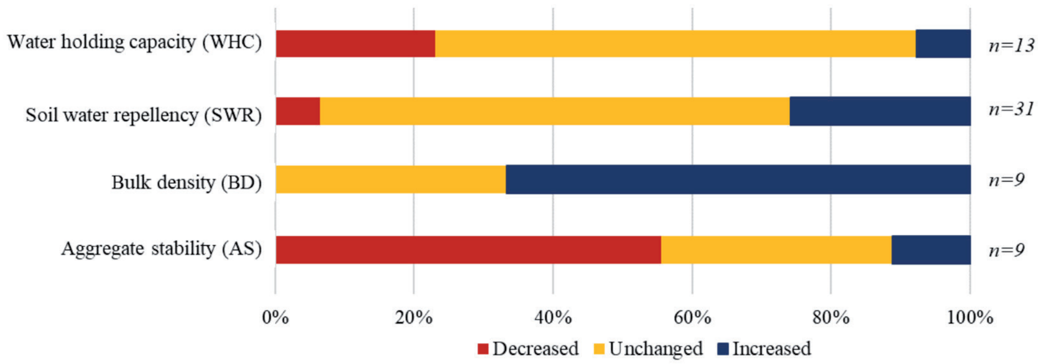
The AS usually decreases after fire in the short and midterm (Granged et al., 2011; Varela et al., 2015), WHC decreases immediately a fire but has no change in the short and midterm (Jiménez-González et al., 2016; Plaza-Álvarez et al., 2018) and BD increases in the short and midterm after a fire (Hubbert et al., 2006; Granged et al., 2011; Heydari et al., 2016) (Figure 5).

Postfire erosion risk

In Mediterranean ecosystems around the world, runoff and sediment yields are around 1-4 orders of magnitude higher on burnt soils compare to unburnt soils, resulting in serious soil degradation (Shakesby, 2011) due to extreme soil erosion rates (Lucas-Borja et al., 2019). After a fire event, a set of factors enhance the postfire risk of erosion: i) the presence of ash that causes the clogging of macropores and surface sealing (Larsen et al., 2009; Bodí et al., 2012), ii) the reduction of AS and increase of SWR and BD which reduces both the rate of infiltration and WHC (Certini, 2005; Jordán et al., 2013; Zavala et al., 2014; Heydari et al., 2016; Weninger et al., 2019), iii) the absence of vegetation cover and superficial litter layer (amount of bare soil exposed) (Bodí et al., 2012; Jordán et al., 2013), iv) the reduction of SOM (Wittenberg et al., 2020), v) the occurrence of intense rainfall immediately after a fire (Pereira et al., 2018), vi) slope, and vii) tillage (Larsen et al., 2009; Vieira et al., 2018) (Figure 6).

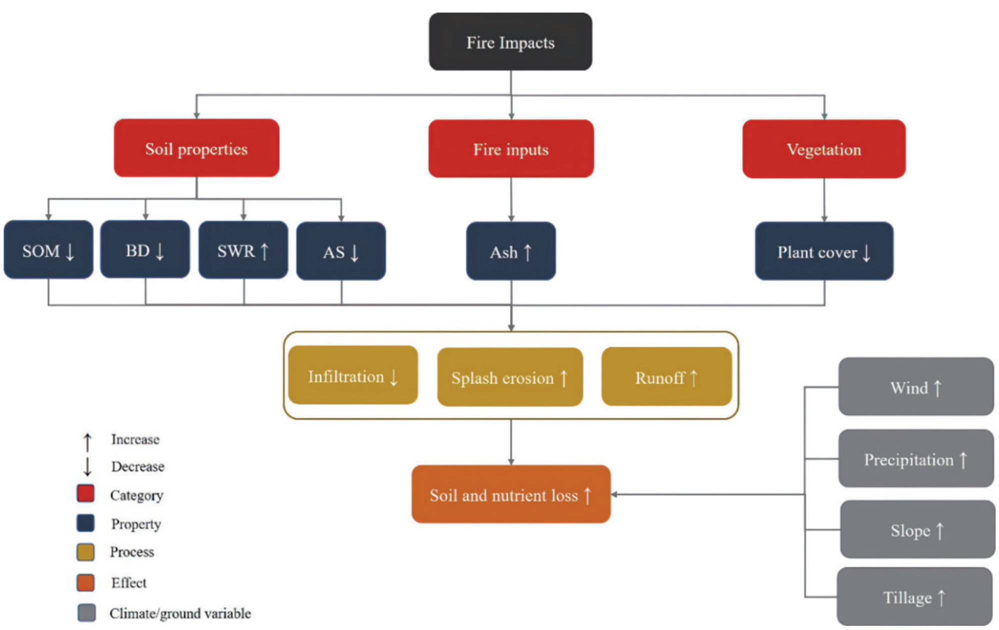
Therefore, postfire interventions are needed to reduce runoff and soil erosion in order to prevent losses of SOM,

Figure 5. Short and mid-term effects of low and moderate severity fire on soil physical properties in Mediterranean climate areas (based on the 34 studies described in Table 1).



n: Number of significant effects reported per soil property.

Figure 6. Changes of soil properties, processes and site variables that increased soil and nutrient losses after a wildfire (adapted from Wittenberg et al., 2020).



SOM: Soil organic matter; BD: bulk density; SWR: soil water repellency; AS: aggregate stability.

nutrients and avoid sediment transport. In addition to addressing the risk of runoff and erosion, the improvement of SOM quantity and quality is fundamental in the process of restoring other physical-chemical and biological soil properties (Varela et al., 2011).

Postfire soil management

In most Mediterranean-climate regions, where wildfires are considered a main soil degradation driver, passive restoration (letting Nature do it) is not a viable strategy for most areas affected, were naturally vegetation recovery takes 5-10 times longer than wetter environments (Caon et al., 2014).

When vegetation cover is completely destroyed by fire, emergency stabilization treatments such as seeding for plant cover and/or mulching must be applied as soon as possible in the burned area to reduce runoff and soil erosion and nutrient losses (Caon et al., 2014; Fernández et al., 2019). Thus, ash deposition and persistence on the soil surface is essential to limiting nutrient losses and fostering vegetation recovery after a fire (Caon et al., 2014).

Plant seeding is a soil stabilization technique to accelerate the reestablishment of a vegetation cover in burnt areas (Fernández-Fernández and González-Prieto, 2020) and is used to reduce erosion and preserve soil nutrient after a fire (Table 2). However, this technique can be ineffective in increasing ground cover or reducing erosion rates and sediment yields, especially during the first critical rain events following a fire (Wagenbrenner et al., 2006; Vega et al., 2014) when it fails to achieve 50%-70% coverage of the ground necessary to mitigate post fire erosion (Robichaud et al., 2013). Furthermore, considering that wildfires in Mediterranean-climate region usually occur during hot dry summers, the establishment of plant seeding after a fire of rainfed agriculture in central Chile might not be viable.

As an alternative, dry mulching (using wheat and rice straw, wood strand and coconut fibers among others) can provide immediate effectiveness in increasing ground cover (Fernández et al., 2011; Wittenberg et al., 2020), reducing runoff speed, increasing water infiltration, and retaining sediments (Fernández-Fernández and González-Prieto, 2020).

Mulching therefore is increasingly employed to reduce postfire runoff and soil and SOM losses (Wagenbrenner et al., 2006; De la Rosa et al., 2019; Lucas-Borja et al., 2019). Although in burned areas with low precipitation, mulching might not decrease the losses of eroded sediment and nutrient (Fernández-Fernández et al., 2016). However, in Mediterranean climate with wet winters (and high precipitation) mulching is highly efficient to reduce erosion and sediment yield (Wagenbrenner et al., 2006; Fernández et al., 2011; Díaz-Raviña et al., 2013; Robichaud et al., 2013; Vega et al., 2014; De la Rosa et al., 2019; Lucas-Borja et al., 2019). In addition to reducing erosion and thus preserving SOM, N, and nutrients after a fire, mulching has others benefits that enable soil restoration after a fire such as increase in soil moisture and recovery of plan cover and preserve activity and diversity of soil microorganism (Fernández et al., 2016; De la Rosa et al., 2019) (Table 2).

To complement postfire emergency stabilization treatments, soil amendment can play a crucial role to recover agricultural soils affected by wildfires. Considering that SOM and microbes can take longer time to recover to pre-fire status compared to chemical and physical properties (Girona-García et al., 2018), applications of organic amendments such as compost have been used after a fire to enhance soil fertility condition by improving physical-chemical and biological soil properties (Varela et al., 2011). But more studies are required to assess the impact of the use of organic

Table 2. Effects of mulching and seeding on soil erosion after a fire.

Mulching effects on soil
• Provide immediate ground cover for exposed soil and protection from raindrop impact and overland flow (Wagenbrenner et al., 2006; Robichaud et al., 2013; Wittenberg et al., 2020) • Increases soil moisture (Fernández et al., 2016) and for coconut fiber mulching also increases soil water retention (Wittenberg et al., 2020) • Preserve N and nutrients increase after a fire (Gómez-Rey et al., 2013; Gómez-Rey and González-Prieto, 2014; Fernández-Fernández and González-Prieto, 2020) • Reduce SOM losses and improved SOM quality of the topsoil (De la Rosa et al., 2019) • Improve the recovery rate of plan cover (Fernández et al., 2016) • Preserve pyrogenic organic matter (De la Rosa et al., 2019) • Preserve biomass and the activity and diversity of soil microorganisms (Fontúrbel et al., 2012)
Seeding effects on soil
• Reduce N losses by erosion (Díaz-Raviña et al., 2013; Gómez-Rey et al., 2013) • Preserve the biomass and the activity and diversity of soil microorganisms (Fontúrbel et al., 2012) • Mitigate the fire triggered negative effects on soil characteristics related with soil fertility and quality (Fernández-Fernández and González-Prieto, 2020)

amendment to restore soil biological properties after a fire.

Fire management and planning tools in Chile

National environmental policies should consider the projected increase of wildfires frequency under expected climate variables, to help reduce the future risk of wildfires (Urrutia-Jalabert et al., 2018). Management options of potentially flammable biomass should be developed and optimized by risk-based modeling approaches and should be mandatory in wildland-urban transition lands (Gómez-González et al., 2018) as well as agricultural land-forest interfaces in order to ensure the long-term sustainability of agricultural land.

In Chile, the Law 20.283 Recovery of Native Forest and Forest Promotion, which has an annual fund of 8 million dollars, was established for the protection, recovery and improvement of native forests, and includes economic incentives for postfire recovery and the prevention and suppression of forest fires. The law provides subsidies for various activities and structures such as soil improvement, rainfall infiltration ditches, and forest thinning and firewalls.

For agricultural lands, the Law 20.412 Agri-environmental Soil Sustainability Incentive System (SIRSD-S) which has an annual budget of 60 million dollars, was established to promote practices that ensure the soils sustainable management in the long term for agricultural and livestock production. The SIRSD-S integrates five subprograms, which include among them plant cover establishment. This subprogram provides financing of 70%-90% of the total costs (depending on farm size) of plant cover establishment for bare soils, which can be used to prevent soil erosion and associated nutrient loss after a fire. But there are no economic incentives for mulching which is the most effective stabilization technique after a fire and could be used in rainfed agriculture which constitutes up to 90% of the total agricultural land that is affected by wildfire in Chile, and where plant cover cannot be easily established after a fire due to long-term droughts during the summer. Inorganic fertilizers are also financed by the sub-program, but organic amendments needed to recover these soils are not included thereby leaving aside degraded agricultural lands affected by wildfires in rainfed agriculture of Central Chile.

CONCLUSIONS

Mediterranean climate regions are prone to wildfires due to hot, dry summers and cool wet winters. Furthermore, considering that wildfire frequency is projected to increase in these regions, fire prevention and suppression efforts must go hand in hand with post fire restoration of these soils. Countries with agricultural lands vulnerable to wildfires such as Chile, should consider economic incentives to restore these soils affected for wildfires and guarantee its sustainable management in the long term.

Fire impacts on soil properties vary among the studies. However, most wildfires enhance the postfire risk of erosion due to the presence of ash, reduction of aggregate stability, and increase of soil water repellency and bulk density. Thus, after a fire the use of emergency stabilization techniques are essential to limit nutrient and soil losses in agricultural lands that need to recover its productivity in the short term.

Much research has been conducted to evaluate wildfire impacts and post fire restoration in forest soils, but there are not studies for agricultural soils affected by wildfires. Further research is needed to define the impacts of wildfire on agricultural soil properties and to evaluate the use of emergency stabilization techniques particularly in rainfed agriculture were the restoration or establishment of plant cover after a fire is not viable. To define the impacts of fire and post fire stabilization techniques will contribute to construct an adequate restoration strategy or guidelines to facilitate the post fire soil restoration in agricultural lands vulnerable to wildfire in the Mediterranean climate regions.

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