Wildfire Impacts on Soil Physical and Chemical Properties - A Short Review of Recent Studies

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Summary

Wildfires are key drivers of changes in soils and the ecosystems. The temperatures reached during a wildfire dictate for the most part the post-fire changes in the soil-system. Additionally, the duration and severity of the wildfire, together with different soil characteristics (e.g. soil organic matter or moisture content) play an important part in the direction and nature of the post-fire changes. Wildfires affect the soil by heating and later trough ash incorporation in topsoil. Wildfire severity determines the degree of vegetation and litter combustion and the soil physical and chemical modifications. Post-fire alterations in soil and its hydrological processes promote erosion in the topsoil layer, which is often associated with quantitative and qualitative changes in soil organic matter. The recovery of soil organic matter is the key for the overall recovery of soil quality after a wildfire. The duration and extremity of the changes of soil properties depend on the severity of the wildfire. Wildfire severity is conditioned by various environmental factors, for example vegetation quantity and type, soil temperature and humidity, wind speed and topography. This paper reviews various studies on the impacts of wildfire on soil chemical and physical properties and sums up the current knowledge on the topic that is increasingly becoming a vital component in recognizing and understanding the mechanisms of adaptation of the global ecosystem to climate change. It is paramount to continue the research of wildfire impacts on soil properties in the attempt to more easily quantify soil degradation processes, predict the ecosystem response to wildfire, and assure the appropriate land management techniques.

Key words

wildfires, soil, fire severity, temporal changes

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Introduction

Wildfires have existed since the onset of terrestrial life on Earth and they affect global ecosystem patterns and processes, such as the carbon cycle and climate (Bowman et al., 2009; Santín and Doerr, 2016). Many changes in ecosystems appear due to wildfires. They cause various fire-adaptive traits in plants and play an important role in forming the Earth's biodiversity (Whelan, 1995; Keeley et al., 2011; McKenzie et al., 2011; Pausas, 2015; Alcañiz et al., 2018). Moreover, humans have been using fire as a land management tool for several thousands of years (Santín and Doerr, 2016). It is generally recognized that weather and climate are one of the most important factors influencing wildfire activity. These factors are continuously differing in space and time and their patterns change as a consequence of human-caused climate change. Taking into account the climate projections, an increased risk of drought and increase occurrence of temperature extremes are to be expected in the future (IPCC, 2013), which will most likely lead to more severe fire weather and an extended wildfire season (Halofsky et al., 2020; Westerling, 2016).

Soils represent one of the most irreplaceable resources on Earth, regulating water purification, emissions of carbon dioxide and other greenhouse gases, and enable nutrient cycling in all terrestrial ecosystems, which makes them fundamental for regulating global climate and sustaining life on earth (FAO and ITPS, 2015).

When discussing wildfire impact on the ecosystem, of which the soil is an integral part, it is essential to define the measure of the ecological effects of wildfire, often referred to as fire severity. Keeley (2009) defined wildfire severity as above and below ground organic matter consumption from fire. Wildfire severity can be determined by the degree of burning of the litter, trunks and leaves, soil coverage by ash and necromass, but also by the colour of the ash, where black ash indicates low and white indicates high severity of fire (Úbeda et al., 2009). Additionally, foliage and trunk combustion above 75% indicates high severity, whereas partial foliage and trunk combustion in addition to less soil coverage by ash and necromass indicate low to medium severity (Pereira et al., 2018a).

It is a known fact that low severity fires are a part of the natural dynamics of most of the Earth's ecosystems (Keeley et al., 2011). Plant communities adapted to low severity wildfires developed the mechanisms for fire-cued germination and serotiny (Richter et al., 2019), the microbial communities of the soil recover faster (Holden et al., 2016; Muñoz-Rojas et al., 2016) and the changes in soil properties are often ephemeral (Moya et al, 2019; Pereira et al., 2015a). The main changes that take place in soils in low-severity wildfires are the decrease of microbial respiration and enzyme activity (Dove et al., 2020), in addition to the increase of soil pH and soil organic matter (SOM) concentration.

High severity wildfire leads to more severe soil degradation, such as volatilization of some of the main soil nutrients, namely carbon, nitrogen, phosphorous and sulphur (Hebel et al., 2009; Neary et al., 1999). Additionally, it can also cause a disturbance in soil aggregate stability (Jordán et al., 2014; 2011), which may lead, depending on the weather conditions, topography, vegetation, soil type and texture, to post-wildfire erosion and runoff (Pereira et al., 2018a). According to Shakesby and Doerr (2006) on hillslope scale, measured erosion could be as high as 414 t ha^{-1} $year^{-1}$.

To understand the processes in soil systems after a wildfire, it is crucial to collect knowledge from short-term and long-term studies. Many studies focus on immediate and short-term impacts of wildfire (Pereira et al., 2017; 2015a; 2015b; 2014b; Jiménez-Pinilla et al. 2016a; Dorta Almenar et al., 2015 etc.). Noticeably fewer studies investigated the long-term evolution of post-fire soil properties (Francos et al. 2018a; Muñoz-Rojas et al., 2016; Rovira et al., 2012; Úbeda et al., 2005).

Generally, it can be asserted that wildfires cause partial or complete combustion of SOM (Jiménez-Pinilla et al., 2016a), degradation of soil structure (Badía-Villas et al., 2014), and nutrient loss through volatilization, erosion, and leaching (Binkley and Fisher, 2013; Shakesby et al., 1993). Such changes are mostly visible in upper few cm of topsoil (Majder-Lopatka et al, 2019; Pereira et al., 2018a). Below 5 cm depth, the soil temperature almost never exceeds 100°C (Úbeda and Outeiro, 2009), redirecting the focus of the studies concerning the effects of fire on soil properties to the few centimetres of the topsoil.

Impact of wildfire on soil chemical properties

One of the major and most abundant constituents of the soil is carbon (C). Carbon is the central building block of living organisms and a key regulator of the global climate. It is also an important element in wildfires, since it accounts for almost 50% of the vegetation dry matter (Schlesinger, 1991) and the 58% of the SOM (Brady and Weil, 1999). Wildfires dramatically affect the nutrient cycling of the soil (Knelman et al., 2015). When the nutrients in SOM are subjected to high temperatures, they begin to volatilize and transform, causing the alterations of SOM. The quantitative and qualitative changes in SOM are the main drivers of post-fire soil erosion and subsequent soil degradation (De la Rosa et al., 2019). Therefore, SOM recovery after a wildfire should be one of the priorities to mitigate land degradation, protect soil quality and the ecosystem.

Qualitative changes in SOM after a wildfire are a complex problem that is challenging in today's research, mostly because SOM is a heterogeneous material consisting of many structures with different functions that are still under study (Finn and Penton, 2020; Zechmeister-Boltenstern et al., 2015). However, it is generally accepted that wildfires cause redistribution of different forms of C in soil, produce water repellent substances, and these changes reflect upon microbial communities and biochemical processes that affect soil quality and fertility (González-Pérez et al., 2004).

The thermo-induced modifications depend on the individual SOM element response to heating. All soil nutrients have their inherent temperature threshold, i.e. the temperature where volatilization occurs. Nitrogen (N) and sulphur (S), the soil nutrients, which most commonly limit terrestrial production (Elser et al., 2007), are the most sensitive to high temperatures, and their threshold is 200°C and 375°C, respectively (DeBano, 1990). Phosphorus (P) and potassium (K) are moderately sensitive, having threshold temperatures of 774°C (Raison et al., 1985). Calcium (Ca) and magnesium (Mg), are considered relatively insensitive, with high threshold temperatures of 1484°C and 1107°C, respectively (DeBano, 1990). At temperatures between 100 and 200°C, minor changes of SOM are detectible, such as condensation of volatile compounds (González-Pérez et al., 2004). More significant changes occur at temperatures between 200 - 300°C, with mineralization and loss of organic gases and aerosols and the re-formation of pyrolytic organic compounds (De la Rosa et al., 2019). High temperatures developed during burning lead to a decrease in functional groups of humic acids, resulting in altered sorptive properties and altered interaction with other soil constituents (González-Pérez et al., 2004).

It is difficult to describe the mechanisms that drive post-wildfire SOM transformation due to the interaction of different processes during and following a wildfire. However, various studies seem to agree there is a balance between degradation and formation of SOM that is dependent on the temperature and duration of the wildfire (Hinojosa et al., 2019; Rhoades et al., 2018; Alexis et al., 2012; Knicker, 2007; González-Pérez et al., 2004).

Immediately after the wildfire, the combustion of SOM leads to a decrease in unstable organic compounds and an increase in aromatic C in soil that is resistant to chemical and thermal decomposition (Knicker et al., 2013). Francos et al. (2018a) conducted a study of the effect of wildfire on total C in soil, and observed its immediate increase in soil after fire, mainly due to the incorporation of coal and ash, and a subsequent (18 years after fire) decline due to post-fire erosion and increased SOM mineralization.

In general, immediately after high-severity wildfires the loss of SOM is to be expected, whereas low-severity fires result in the incorporation of combusted vegetation into the soil, leading to SOM increase (Zhan et al., 2020; Merino et al., 2018). Increases in SOM quantity have been reported in low and medium-severity wildfires, and its return to pre-fire levels could take several years

Table 1. Recent studies of wildfire impact on soil chemical properties

Location	Vegetation	Soil type	Post-fire sampling date	Fire severity	Measured properties	Observed change in the soil	Reference
Portugal	*Pinus halepensis* Mill., *Macrochloa tenacissima* (L) Kunth, *Quercus coccifera* L., *Pistacia lentiscus* L.	Aridisols (Lithic Haplocalcids)	3 years post-fire	low/medium	pH	no change	*Moya et al.(2019)*
					TN		
					SOC		
					Available P	increased	
				medium/high	pH	no change	
					N		
					SOC	increased	
					Available P		
Poland	Mixed coniferous forest	Podzol	1 year post-fire	not discussed	pH	increased	*Majder-Lopatka et al. (2019)*
					TN	decreased	
					SOC		
Spain	*Pinus pinaster* ssp	Typic Haploxerept	18 years post-fire	low	TC	decreased	*Francos et al.(2018a)*
					TN		
					SOM		
					Ca		
					Mg		
					Na		
					K	increased	
		Lithic Haploxerept		high	TC	decreased	
					TN		
					SOM		
					Ca		
					Mg		
					Na		
					K	increased	

Location	Vegetation	Soil type	Post-fire sampling date	Fire severity	Measured properties	Observed change in the soil	Reference
Lithuania	*Leontodon autumnalis* L., *Anthoxanthum odaratum* L.	Albeluvisols	immediately post-fire	low	pH	decreased	*Pereira et al.(2017)*
					EC	increased	
					Ca		
					Mg		
					K		
					Na	no change	
					Al	decreased	
					Mn		
					Fe		
					Zn	no change	
Portugal	*Eucalyptus globulus* L, *Pinus pinaster*	Leptosols	2 weeks post-fire	low	pH	no change	*Otero et al. (2015)*
					SOC	decreased	
					Total Fe	no change	
					Total Al		
					Total Mn	increased	
				high	pH	no change	
					SOC	decreased	
					Total Fe	no change	
					Total Al		
					Total Mn	increased	
Israel	*Pinus halepensis* and *Pinus brutia*	Lithic Xerorthenth	1 month post-fire	low/medium	pH	no change	*Inbar et al.(2014)*
					EC		
					$CaCO_3$		
					CEC	increased	
					SOM		

TN – Total nitrogen; SOC – Soil organic carbon; P – Phosphorous; N – Nitrogen; SOM – Soil organic matter; Ca – Calcium; Mg – Magnesium; Na – Sodium; K – Potassium; EC – Electro conductivity; Al – Aluminum; Mn – Manganese; Fe – Iron; Zn – Zinc; $CaCO_3$ – Calcium carbonate; CEC – Cation exchange capacity

according to some studies (Jiménez-González et al., 2016; Silvana-Longo et al., 2011; Knicker et al., 2006). Decrease of SOM quantity and quality (meaning increased aromatic C content and other refractory soil fractions) has been reported in high severity fires, and its recovery to pre-fire levels, according to recent studies, could take even more than a decade (Francos et al., 2018b; Zavala et al., 2014; Rovira et al., 2012).

Francos et al. (2018a) monitored the long-term effects of a wildfire on TC (total carbon), TN (total nitrogen), SOM, extractable calcium -Ca, magnesium -Mg, sodium -Na and potassium -K in two areas affected by low and high fire severity (Table 1). Their results indicated that SOM was significantly lower in the wildfire affected plots (6.74% and 6.32% in low and high severity fire, respectively) in comparison to the control (9.44%).

Ultimately, SOM and investigated soil nutrients (apart from extractable K) decreased after wildfire of low and high severity and had not recovered after 18 years, which was most likely connected with post-fire erosion and incomplete vegetation recovery according to the authors. Similar results concerning SOM quality and quantity decrease in the long-term post-wildfire period had been reported in studies by Knicker et al. (2013), Alcañiz et al. (2016) and Rovira et al. (2012).

The solubility of soil nutrients, aggregation of mineral particles and the stability of soil microbial community are greatly dependent on soil pH (Finn et al., 2020). In the immediate period after a wildfire soil pH increases due to incorporation of ash into the soil, - media characterized by high electrical conductivity (EC) and concentrations of nutrients (Pereira et al., 2014b; 2015b; Francos et al., 2018b). However, the increase of soil pH was reported as ephemeral, especially in low-severity wildfires.

Wildfires can lead to depletion of soil nutrients in the long-term. Furthermore, fire severity is not the only factor that determines the recovery rate of the soil system. External factors such as weather conditions, topography and soil characteristics can either encourage or discourage soil system recovery. For example, heavy rainfall events following wildfires promote the risk of runoff and soil erosion, effectively interrupting vegetation recovery (Prats et al., 2016). Additionally, soil moisture prevents temperatures from rising above 100°C until all water has evaporated, while soils with higher clay content contain more firmly bound organic C, which is more resistant to thermal decomposition, making these types of soil more impervious to wildfire effects (Santín and Doerr, 2019).

Impact of wildfire on soil physical properties

Changes of soil chemical properties often reflect on its physical properties as well. For example, high Na^+ and K^+ concentrations may induce clay dispersion and decrease aggregate stability (Pereira et al., 2014a; Matosic et al., 2018), conversely to SOM that preserves soil structure acting as a binding agent for soil aggregates (Bogunovic et al., 2019; Jensen et al., 2020).

In terms of soil physical properties, soil texture (ST), aggregate stability (AS), and water repellency (WR) are of specific interest to researchers. Soil texture is generally considered insensitive to high temperatures during wildfires (Badía and Martí, 2019). However, clay particles are generally considered more sensitive to high temperatures than sand and silt fractions (Granged et al., 2011). In this context, it has been reported that the removal of structural hydroxyl ions and collapse of the crystalline structure of clay start at temperatures around 400°C (DeBano et al., 2005), while fusion of clay mineral can occur at temperatures between 600 and 700°C, and complete destruction of clay may occur at 700 - 900°C (Jiménez-Pinilla et al., 2016b). Furthermore, the fusion of clay particles that may occur at high temperatures lead to more stable aggregates, as well as to increased average particle size (Thomaz, 2017; Granged et al., 2011; Giovannini et al., 1988).

These changes in ST, namely clay and sand particles, were investigated in several simulated burning experiments, where soil samples were heated to a desired temperature using muffled furnaces, i.e. under laboratory conditions (Jiménez-Pinilla et al., 2016b; Mataix-Solera et al, 2011; Badía and Martí, 2003). However, similar results were confirmed in field studies (Ketterings et al., 2000; Mataix-Solera et al., 2011).

Aggregate stability is also considered resistant to the increase of temperature, and only in medium to high severity wildfires studies prove that AS decrease exists (Varela et al., 2015), although the increase of AS is also reported (Grover et al., 2020; Thomaz, 2017), depending on whether the SOM is the main binding agent or not (Badía and Martí, 2019). Aggregate stability has an important role in avoiding erosion and degradation (Bogunovic et al., 2020), as well as in the ability of soil to transfer liquids and gases, which are important factors for the ecosystem health (Jiménez-Pinilla et al., 2016b).

Fire-induced WR depends on the combined reaction of soil heating during wildfire and soil properties, namely the amount of hydrophobic organic substances in the soil surface and ST, where sand fraction shows greater WR on the account of its small specific surface (Arcenegui et al., 2019). Water repellent soil can contribute to surface runoff and erosion and WR tends to increase up to 300°C, but is generally destroyed at temperatures exceeding 300°C (DeBano, 2000).

Bulk density (BD) is one of the soil properties linked to soils water sorption ability which in turn affects runoff. Studies show that BD increases during low severity wildfires, due to general decrease of SOM (Moody and Ebel, 2012; Granged et al., 2011; Hubbert et al., 2006). Moreover, BD can be increased after wildfire due to ash incorporation in soil. Ash as a light material clogs the soil pores and increases BD (Pereira et al., 2018b). Additionally, high severity wildfire can increase BD mostly due to collapse of the organo-mineral aggregates during high temperatures (Giovannini et al., 1988). Such changes enhance the forming of surface crust and increase runoff (Mataix-Solera et al., 2011). Table 2 summarizes recent studies of fire impacts on soil physical properties.

Studies of wildfire impacts on physical properties after low-severity wildfires seem to agree that there is no significant change in ST, WR, AS, BD and soil porosity (SP). With increasing severity, the changes start to appear. Almeida Santana et al. (2018) studied the effect of low-severity wildfire on ST, BD and SP. No significant changes were recorded between control and wildfire-affected soil. A study by Varela et al. (2015) investigated the immediate changes in WR and AS after a low and moderate wildfire on acidic soil (Leptic Regosol) in Spain. In low severity wildfire, no significant changes in WR and AS were found, whereas in moderate wildfire both WR and AS decreased as an effect of organic matter combustion. Conversely, Jordán et al. (2014) found that a moderate wildfire did not significantly affect AS due to calcium carbonate as the prevailing binding agent. In addition, both Thomaz (2017) and Martín et al. (2011) found that high temperatures reached during a fire increased AS in cambisols and attributed this change to fusion of clay minerals, which are abundant in this medium to finer textured soils.

There is clearly a relationship between the physical properties of soil and SOM content, AS and WR. However, their temporal evolution and interconnection still needs to be clarified and studied in terms of their temporal changes. The existing studies of post-wildfire changes in soil physical properties focus more on its immediate effect on soil, and less on its temporal dynamic. The relationship between chemical and physical properties of fire-affected soil has yet to be more closely investigated in field conditions, and will surely be a valuable source of information in predicting and managing post-wildfire erosion and runoff.

Table 2. Recent studies of wildfire impact on soil physical properties

Location	Vegetation	Soil type	Fire severity	Measured properties	Observed change in the soil	Reference
Brazil	*Saccharum angustifolium, Aristida laevis, Eryngium pandanifolium,* and *Paspalum* ssp	Typic Hapludalf	low	ST	no change	*Almeida Santana et al. (2018)*
				SP		
				BD		
Spain	*Pinus pinaster*	Leptic Regosols	low	WR	no change	*Varela et al. (2015)*
				AS		
			medium	WR	decreased	
				AS		
Israel	*Pinus halepensis, Pinus brutia*	Lithic Xerorthenth	low/medium	ST	no change	*Inbar et al. (2014)*
				WR		
				AS		
Spain	Grassland (*Poaceae* and *Fabaceae*) and shrublands (*Pistacia lentiscus* and *Chamaerops humilis*)	Calcareous loamy to clayey soils	medium	WR	decreased	*Jordan et al. (2014)*
				AS	no change	
Lithuania	*Leontodon autumnalis* L., *Anthoxanthum odaratum* L	Albeluvisols	low	WR	increased	*Pereira et al.(2014b)*
Spain	*Pinus pinaster*	not discussed	low	WR	no change	*Rodríguez-Alleres et al. (2012)*
			medium/high	WR	decreased	
Spain	*Pinus pinaster*	Leptosols and Humic Cambisol	low	ST	no change	*Martin et al. (2011)*
				AS	decreased	
			high	ST	no change	
				AS	increased (in cambisol)	

ST - Soil texture; WR - Water repellency; AS - Agregate stability; SP - Soil porosity; BD - Bulk density

Conclusion

The impact of fire on soil chemical and physical properties depends on several factors, including the type and severity of wildfire, soil type and vegetation, and the difficulty is to determine the general direction of their change in the long-term post-wildfire period. Generally, combustion causes the mineralization of SOM and litter, which makes the nutrients in soil abundant and available for plant uptake, and water percolating through the ash deposited on the top-layer of soil lead to leaching of large quantities of base cations into the soil that change the soil nutrient status and pH. Low severity fires can lead to increased SOM content, soil C and total extractable cations, whereas high severity fires lead to depletion of SOM, decrease of soil C content and substantial increase of the cations in soil. Studies that monitored post-wildfire temporal changes in soil are scarce, especially in terms of soil physical properties. In general, high-severity wildfires cause long-term decrease of SOM and depletion of soil nutrients. However, the temporal evolution of soil physical properties requires further research.

High temperatures that develop during a wildfire affect only the soil surface. Therefore, the impacts of high severity wildfires could induce changes in its mineral structure and AS. High severity wildfires cause structural degradation, surface siltation, compaction and high overland flow. However, the results of the various studies investigating the impacts of wildfire on soil chemical and physical properties conducted over the years are sometimes conflicting and depend to a great degree on the complex relationship between soil properties that must be taken into account while attempting to reach a comprehensive conclusion. Understanding the mechanisms behind post-wildfire soil processes is of great importance for a successful ecosystem management in the changing climatic conditions.

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