A Review of Wildfire Effects on Soils, Hydrologic Processes and Water

LWS 548 Major Project Paper

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I. Executive Summary

Wildfire is a natural process that has happened regularly for millions of years and brings both positive and negative impacts to the forest environment. In recent decades, climate change has become a critical element in increasing the risk and extent of wildfires globally. Changes in climate increase temperature and reduce precipitation, extending the fire season and expanding the burning area. Wildfire affects soil physical properties (e.g. texture, colour, pH, hydrophobicity), chemical properties (e.g. organic matter, macro and micro-nutrients), as well as soil biota (e.g. invertebrates and micro-organisms). Intense wildfires further cause infiltration rate reduction and high surface runoff. Ash and sediments transported with surface runoff contaminate water quality, resulting in damage to the aquatic organisms and drinking water treatment issues. Effects of wildfire on forest soil, hydrologic processes and water are site-specific and complex. The extent of wildfire impacts depends on the intensity and severity of the fire, burning season, pre-fire and post-fire environmental conditions, climate pattern, vegetation types and many other factors. Studies of wildfire effects are diverse, but comprehensive reviews that assemble findings in the three fields are still lacking. Therefore, the purpose of this paper was to review the wildfire effects on forest soil, the hydrologic processes and water quality based on existing literature.

II. Introduction

A. Background Information

The forest is a critical component of ecosystems and plays an essential role in the hydrologic and carbon cycles. As a natural filter, a healthy forest provides an important mechanism to absorb and store greenhouse gases and pollutants from the atmosphere. In the hydrologic cycle, the role of the forest is associated with the interception and evapotranspiration processes. A portion of precipitation is intercepted by leaves, canopies and branches of plants and returns to the atmosphere through evapotranspiration. Forest vegetations prevent heavy rainfall from directly falling on the ground, reducing water runoff and slowing the flow velocity of the water. Plants can also remove excess nutrients and pollutants and protect water quality from getting polluted. Plant roots stabilize soil structure, reducing landslides and soil erosion. (Healthy Forests For Clean Water, 2021).

Forest fire or wildfire is a natural process that has happened regularly for millions of years. However, due to climate change and land-use changes in the past decades, countries such as the United States, Canada, Australia, Chile, and Brazil have experienced more severe and frequent forest fires (Bailey & Yeo, 2019). Countries in Northern Europe that are uncustomed to forest fires also have experienced more frequent fires. From 2011 to 2020, an average of 62,805 wildfires happened per year with an average of 7.5 million acres impacted annually (Wildfire Statistics, 2021). According to the National Interagency Coordination Center (NICC), 58,950 wildfires in 2020 burned 10.1 million acres of forests. In the U.S., California was the top state for wildfires. 10431 number of wildfires in California have burned nearly 4.1 million acres of land, destroyed 10,500 structures and killed 33 people. Five of the top 10 historical largest California wildfires fires occurred in 2020 (Figure 2) (Facts + Statistics: Wildfires, 2021). From the 1980s, the US Environment Protection Association (EPA) has recorded the wildfire frequency and the total area burned annually. Statistics (Figure 3) illustrate that although the number of annual wildfires has decreased slightly over the last 30 years, the full size of land burned annually has risen. These data indicated that in the United States wildfires are becoming more severe and lasting even longer (Wildfire Statistics, 2021).

Rank	State	Number of fires	Rank	State	Number of acres burned
1	California	10,431	1	California	4,092,151
2	Texas	6,713	2	Oregon	1,141,613
3	Arizona	2,524	3	Arizona	978,568
4	Montana	2,433	4	Washington	842,370
5	Florida	2,381	5	Colorado	625,357
6	North Carolina	2,364	6	Montana	369,633
7	Oregon	2,215	7	Wyoming	339,783
8	New Jersey	1,981	8	Utah	329,735
9	Georgia	1,699	9	Idaho	314,352
10	Washington	1,646	10	Nevada	259,275

Figure 1. Top 10 States For Wildfires Ranked By Number Of Fires And By Number Of Acres Burned, 2020 (Facts + Statistics: Wildfires, 2021).

Rank	Fire name (cause)	Date	County	Acres	Structures	Deaths
1	August Complex (Under investigation) (2)	August 2020	Mendocino, Humboldt, Trinity, Tehama, Glenn, Lake, and Colusa	1,032,264	935	1
2	Mendocino Complex (Under investigation)	July 2018	Colusa, Lake, Mendocino and Glenn	459,123	280	1
3	SCU Lightning Complex (Under investigation) (2)	August 2020	Stanislaus, Santa Clara, Alameda, Contra Costa, and San Joaquin	396,624	222	0
4	LNU Lightning Complex (Under investigation) (2)	August 2020	Sonoma, Lake, Napa, Yolo and Solano	363,220	1,491	6
5	Creek Fire (Under investigation) (2)	September 2020	Fresno and Madera	350,331	856	0
6	North Complex (Under investigation) (2)	August 2020	Butte, Plumas and Yuba	318,930	2,352	15
7	Thomas (Power lines)	December 2017	Ventura and Santa Barbara	281,893	1,063	2
8	Cedar (Human related)	October 2003	San Diego	273,246	2,820	15
9	Rush (Lightning)	August 2012	Lassen	271,911 CA/43,666 NV	0	0
10	Rim (Human related)	August 2013	Tuolumne	257,314	112	0

Figure 2. Top 10 largest California Wildfires (Facts + Statistics: Wildfires, 2021).

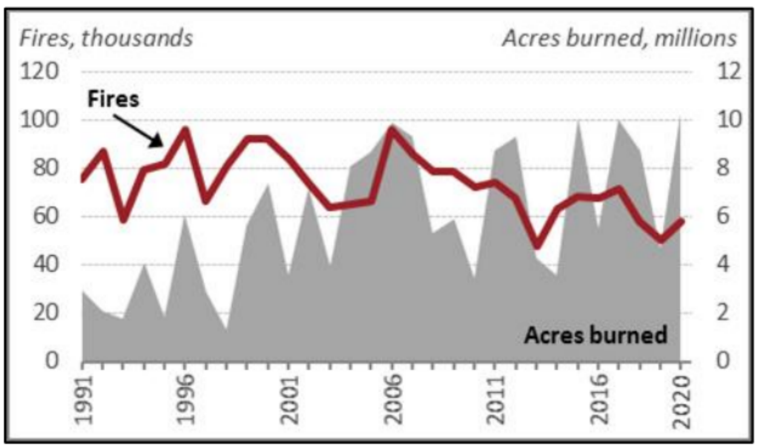

Figure 3. Annual wildfires and Acres Burned from 1991-2020 (Wildfire Statistics, 2021).

Both human activities or natural processes can cause wildfires. In BC, most wildfires are naturally-caused (lightning strikes cause approximately 60% of wildfires per year), whereas 40% of wildfires are human-caused (Wildfire Causes, 2021). However, Balch et al. (2017) showed that humans play a substantial role in altering wildfires and cause more wildfires than before, expanding the spatial and seasonal distribution of wildfire. The fire season of human-caused fires was generally three times longer than the lightning-caused fire and burned areas are seven times larger than those affected by lightning-strike (Balch et al., 2017). High temperature, low soil humidity, strong winds and continuing drought are contributors creating ideal conditions for the fire to spread rapidly and widely (Aoraha, 2020). Wildfires severity can be classified based on the remained vegetations or burned area size. The BC Wildfire Service uses a ranking scale from

1 to 6 to identify wildfires based on a set of visual characteristics (Figure 4). Wildfires rank from low to high severity for ground fire, low, moderate and high vigorous surface fire, crown fire, and finally candling or torching fire (Wildfire Rank, 2021).

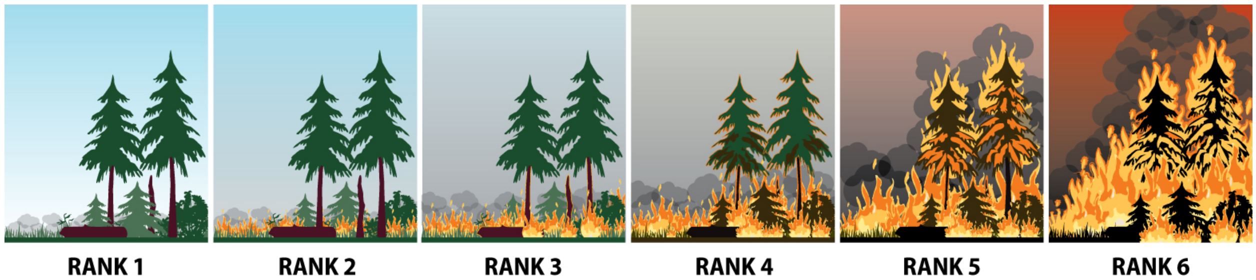

Figure 4. Ranking scale published by BC Wildfire Service. Wildfires behaviour are ranked from 1 to 6 based on a set of visual indicators (Wildfire Rank, 2021).

A forest fire can be both beneficial as well as harmful depending on its severity, frequency and time length. Table 1 below summarized several key positive and negative impacts of wildfire. Fire causes significant damages to the environment as well as losses of human and animal lives. Large quantities of ash and greenhouse gases generated from fire pollute the air and accelerate global warming. But on the other hand, fire kill diseases and harmful insects in the forest that threaten the health of trees. It also helps maintain biodiversity and shape the ecosystem (Vandenbeld et al., 1988). For the soil, severe fires cause significant losses of soil organic matter, deterioration of soil structure and porosity, volatilization of nutrients, soil leaching and soil erosion. The alternation of soil physical and chemical properties caused by fires directly influences soil stability and makes the soil more prone to erosion. There is a period after a wildfire that the forest land is particularly vulnerable to heavy rainfall. Such cases can trigger landslides and create a tremendous amount of soil erosion that impact water quality, and the safety of people and wildlife (Verma & Jayakumar, 2012). Another concern is that the soil water repellent layer generated by wildfire reduces water infiltration into the soils, eliminates the organic horizons and affects the soil water storage capacity (DeGomez, 2011).

Positive impacts	Negative impacts
● Fire kills diseases and insects that damage trees. ● Reducing Unproductive Forest Undergrowth. ● Reduce Combustible Material on the Forest Floor. ● Fire clears heavy brush and litter, leaving room for plants that provide food and habitat for wildlife to regenerate.	● Increases the potential for soil erosion to occur. ● High-intensity fires can cause localized air pollution. ● Animal and plant species can be lost or become in dangered. ● Cause financial loss. ● Releases carbon dioxide and accelerates global warming.

Table 1. Summary table of positive and negative impacts of forest fires.

Vegetation is the main fuel that causes combustion in a forest. Both of the vegetation quantity and type determine fire intensity and the extent of soil properties' changes. Fuel flammability converts throughout the year due to the changes of vegetation chemical and moisture compositions and total biomass. The fire intensity and duration therefore also vary according to vegetation characteristics (Ngole-Jeme, 2019). In general, coniferous trees burn faster and more intensely than deciduous trees because coniferous trees have a large amount of sap in their branches. The sap prompts trees to burn very quickly and supports wildfire expansion (Different tree species impact the spread of wildfire, 2012). Coniferous trees also tend to grow closer together and have low-lying branches than deciduous trees, allowing the fire to spread to large areas and move from the forest floor to the forest canopy effortlessly. Lodgepole pine, Engelmann Spruce, Subalpine fir and Abies balsamea are examples of highly flammable coniferous species (Figure 5.1) (Different tree species impact the spread of wildfire, 2012). However, not all pine trees are easily set on fire. Ponderosa Pine trees are resistant to surface wildfires, because of their particular adaptations, including thick bark, open crown, high foliar moisture content, deep roots, and rapid growing seedlings (Hood et al., 2018). The eucalyptus tree is a particular plant that grows well and burns easily in Australia and areas of California (Figure 5.2). Leaves of the eucalyptus tree contain a volatile, highly combustible oil that can ignite easily and burn quickly. The eucalyptus litter is hard to break down and slow to be decomposed by fungi, which create a dense cover of flammable material on the forest floor and become available burning fuels (Lallanilla, 2013).

Figure 5.1. Highly flammable tree species. From left to right: Engelmann Spruce, Subalpine fir and Eucalyptus tree.

Figure 5.2. Burning eucalyptus trees in Australia.

Climate change has been a critical element in increasing the risk and extent of wildfires globally. Wildfire risks depend on many factors directly or indirectly related to climate change, including temperature, soil moisture, precipitation and the presence of plant fuels. Changes in climate can bring droughts, increase in temperature and irregular precipitation, extending the fire season and expanding the burning area. All these factors promote significant wildfire risks, but the exact effects differ by forest type and location (Wildfires and Climate Change, 2021). Projections show that an average annual temperature of 1 degree C rise in the western United States would significantly increase the median burned area and exceed the maximum yearly size burned in the historical record (Vose et al., 2012). In the southeastern United States, modelling suggests that fire risks and longer fire seasons have increased with ongoing climate change. By 2060, the area destroyed by wildfires ignited by lightning and other natural processes will likely increase by at least 30% compared to 2011 (Vose et al., 2018). In Alaska, data showed that the risk of severe wildfires has increased by 33%–50% due to anthropogenic climate change in the recent decade and is projected to increase fourfold by the end of this century (Wehner et al., 2017). Increases in temperature and changes in precipitation cause snow to melt sooner and soils, forests, and plants become drier. Under these conditions, fuels have higher aridity and flammability, therefore increasing the length of time that wildfires burn (Wehner et al., 2017). Climate change brings irregular high precipitation to some regions, increasing understory vegetation growth and altering vegetation composition. The vegetations later transfer to available burning fuels and act on wildfire behaviour (Fried et al., 2008).

Warm and dry environment conditions also contribute to the expansion of mountain pine beetle and other harmful insects that can weaken or kill trees, indirectly building up fuels availability in a forest (Bentz et al., 2009). The outbreak tendency of mountain pine beetle is sensitive to climatic variation. Current and projected increases in temperature can influence the physiology of insects, reduce their winter mortality and shift their distribution range northward. Stressed host trees coupled with a warm environment and dry soil conditions can result in beetle population outbreak progression across suitable host trees. Current population and distribution expansions have been particularly notable, and the further outbreaks will be exacerbated by increasing temperatures (Vose et al., 2012).

B. Knowledge Gaps

Studies about wildfire effects on forest soil properties are diverse and abundant. Verma & Jayakumar (2012) and Certini (2005) provided good reviews of the impact of wildfire on the physical, chemical, mineralogical and biological properties of soils. They showed that wildfire effects on forest soil properties are diverse. Important physical characteristics of soil that can be altered by wildfire include soil colour, texture, structure, pH, bulk density, and water holding capacity. Chemical properties mainly include soil nutrient dynamics and soil organic matters. Mineralogical changes refer to dehydroxylation and changes of soil phyllosilicate clays. Biological properties changed by wildfire affect invertebrates and micro-organisms living in soil (Verma & Jayakumar, 2012).

Research results on wildfire effects on the hydrologic processes are also diverse, but most papers are case studies that focus on a specific region or a specific type of forest. Imeson et al. (1992) and Inbar et al. (2014) discussed the effects of wildfire and soil repellent layer on soil properties, water infiltration and runoff in the Mediterranean regions and forests. Two case studies conducted in Spain discussed infiltration, runoff and soil loss after local forest fires (Neris et al., 2013 & Rubio et al., 1997). Some other papers discuss wildfire impacts on forest soil in Gunma, Japan, and Northern Rocky Mountain forests (USA) (Sazawa et al., 2018 & Robichaud, 2000). Climate patterns and dominant vegetation species bring up a forest's own soil physical properties, nutrient dynamics, soil parent materials, microbial characteristics and hydrophobic substance concentrations. The effects of wildfire on soil and further impacts on hydrologic processes vary significantly among various types of forests.

Soil quality, water quality and the hydrologic cycle are closely connected and influence each other, while wildfire can bring serve influences to all of them at the same time. By altering soil properties, hydrologic processes related to soil change and the soil erosion process is accelerated. Accompanied by high surface runoff and soil erosion, burned ash and other pollutants are transported into water sources and cause contamination. Although studies and reports relevant to wildfire effects on soil, water quality and hydrology are diverse, comprehensive reviews that assemble these findings are still lacking. A review that contains all scenarios would warn people that the wildfire effects on the forest environment are far more than our general understanding and should be aware of the forest fire.

C. Objectives

The objective of the project was to provide a comprehensive review of wildfire effects on forest soil, the hydrologic cycle and water quality based on existing literature. The specific focus will be on soil properties, water repellent layer issue, water infiltration and soil erosion, water contamination and water treatment issue. The key objectives are to:

1. Provide an overview of the impact of forest fire on the physical, chemical and biological properties of soils.
2. Discuss the soil hydrophobicity and water repellency issue.
3. Make an assessment of wildfire effects on infiltration and surface runoff and erosion susceptibility of forest soils.
4. Review the post-fire contaminants and their effects on water quality and aquatic organisms.
5. Discuss the drinking treatment problems.

III. Methods

A. Literature Review

The main evaluation is based on an extensive review of the available literature.

B. Meta-analysis

A meta-analysis was conducted to summarize what the impacts of wildfire are on soil physical, chemical and biological properties. The summary is based on a wide range of case studies and reviews papers that addressed the issues and effects in different types of forests around the world. The results were summarized in a table format in Appendix I.

C. Framework

There are multiple hydrologic processes that are influenced by forest fires, but this report only focuses on two of them: infiltration and runoff. Data relevant to infiltration and runoff were retrieved from pre-existing literature.

D. Study Areas

The study of wildfire impacts on hydrologic processes focused on two types of forests: Mediterranean forest and coniferous forest. The main climate characteristic of the Mediterranean forest is the two well-defined seasons in a year: winter is raining coinciding with low temperature while summer is hot and almost completely dry (Verheye & de la Rosa, 2009). Temperate coniferous forests are found predominantly in the coastal areas with mild winters, warm summers and heavy rainfall. The soil is usually low in nutrients, light-coloured and acidic (Adamsa et al., 2019).

IV. Results & Discussion

A. Wildfire effects on forest soil issues

1. Soil properties changes

Depending on the fire intensity and the time of combustion, changes in soil properties may be beneficial or deleterious to the entire ecosystem (Verma & Jayakumar, 2012). The wide range of wildfire effects on soil is established on the inherent pre-combustion variability of the burning resources, fire behaviour characteristics, burning season, pre-fire and post-fire environmental conditions and climate pattern. Thermal conductivity of soil also affects the extent of the fire's impact on the soil. Coarse-textured soil and sandy soil would experience more changes after a wildfire, because the high thermal conductivity heat the soil to a greater extent and depth (Ngole-Jeme, 2019). Due to the high discrepancy, this paper only summarized the general features of post-fire soil. A summary table is provided in the appendix (Appendix I).

1.1 Wildfire impacts on soil physical properties

Important physical characteristics of soil affected by wildfire include: soil colour, texture, pH value, bulk density, particle-size distribution, structure stability and water holding capacity. As the high temperature heats the soil matrix, a red hue appears in the burned soils due to the transformation of iron oxides to maghemite and hematite. Ulery and Graham (1993) suggested that maghemite and hematite are highly effective pigmenting agents that can alter soil color to reddish-brown. Since almost all organic C in the surface layer is eliminated when soils were heated over 400 °C, severely burned soil layers contained significantly less organic C than the unburned soils. Therefore, wildfires' burning severity can be detectible by surface patches of reddened soil, organic C level reduction, and maghemite changes compared to surrounding soil (Verma & Jayakumar, 2012). Most studies suggested that fire induces an increase in soil pH. Combustion of organic matter and ash production cause organic acids denaturation and release large quantities of basic cations (calcium (Ca), magnesium (Mg) and potassium (K)). A high soil pH value occurs with great fire intensity and long time duration (Certini, 2005).

Soil particles have high-temperature thresholds and are not easily affected by fire. Studies have suggested that clay is the most sensitive textural fraction, so reddened soil contained significantly less clay than the unburned soil. Clay hydroxylation and clay lattice structures collapse begin when soil temperature exceeds 400 °C and can be completely destroyed at 700–800 °C (Verma & Jayakumar, 2012; Ulery & Graham, 1993). Sand and silt particles are thermally stable because their major component is quartz, which has a extremely high melting point and a high thermal conductivity. Intense fires reduce the amount of organic matter, form sand-size aggregates in the surface soils, collapse soil macropores and alter soil particle-size distribution, resulting in an apparent coarser soil textures (Certini, 2005). Accumulation of sand-sized particles in soils reduces soil sorption capacity and accelerates post-fire contaminant sorption by up to 37.1% (Ngole-Jeme, 2019). Bulk density is the mass of dry soil per unit bulk volume (expressed in g/cm3) and is related to soil porosity. Wildfire increases soil bulk density significantly by collapsing soil aggregates, clogging voids and loss of organic matter. (Verma & Jayakumar, 2012).

1.2 Wildfire impacts on soil chemical properties

Depending on fire severity and duration, moisture content of the surface organic matter (OM), soil moisture and na`ture of the burned materials, the impacts of wildfire on soil organic matter (SOM) vary from total destruction to partially scorched conditions (Verma & Jayakumar, 2012). The major outcomes consist of slight distillation, charring, or complete oxidation. Surface OM and carbon (C) start to be consumed when fire temperature reaches 450°C. Most soil C losses occur when the fire burns for a long time and transfers heat to the mineral soil. Page-Dumroese et al. (2003) pointed out that soil organic matter decomposition rate becomes rapid, and the rate change plays a crucial role in C storage. However, studies also reported that soil OM content might increase due to the deposition of partially burned leaves and charred plant materials from fires (González-Pérez et al., 2004).

Many researchers have examined the relationship between soil nutrients availability and wildfire. Verma & Jayakumar (2012) concluded that "burned soils have lower nitrogen, higher calcium, and nearly unchanged potassium, magnesium, and phosphorus than unburned soils". The immediate outcome after wildfires is soil macronutrients loss through volatilization due to the high temperature. Reports of the effects of fire on the total nitrogen pool are contradictory. Nitrogen volatilization is the dominant mechanism of post-fire soil nitrogen loss. Moderate to high intensity fires convert most soil organic nitrogen into inorganic forms. Ammonium and nitrate are the two inorganic nitrogen available to soil biota. Nitrate formed from ammonium by nitrification but leached out quickly. Ammonium is a direct product of combustion and is held by the negatively charged minerals in soil (Certini, 2005). On the other hand, it is also suggested that fire can affect soil nutrient status by directly adding more nutrient substances and indirectly altering the soil environment through increasing the nitrogen content in the residual material (Verma & Jayakumar, 2012). Wildfire brings fewer impacts on other macronutrients, such as magnesium (Mg) and calcium (Ca), because they have high threshold temperatures and are relatively less sensitive to wildfire. Phosphorus (P) and Potassium (K) could be affected in the high-intensity fire. But Certini's paper indicated that the availability of these nutrients might increase by the combustion of soil organic matter, depending upon the original soil nutrient concentration, vegetation species, soil properties, and pathway of leaching processes (Certini, 2005).

1.3 Wildfire impacts on soil biological properties

Wildfire affects living organisms both directly or indirectly. Soil biological organisms are directly killed by wildfire by exposure to the flames and hot gases or are trapped in environments where heat is high enough to destroy them. Indirect effects usually cause long-term changes to the soil environment and impact the activity of soil organisms (Verma & Jayakumar, 2012). Heat of wildfire brings changes to the soil indirectly affect the survival and re-colonization of soil organisms, such as reduction or alteration of organic substrates and removal of organic residues sources. Furthermore, competition for habitat and food sources, as well as other changes that affect the reestablishment and succession of soil organisms will arise (Certini, 2005). Wildfire leads to significant changes in soil dwelling invertebrates' abundance and species composition. However, compared to soil microorganisms, biomass reduction of soil dwelling invertebrates is less due to invertebrates mobility, enabling them to escape the heat by burrowing deep into the soil (Verma & Jayakumar, 2012).

2. Soil Water Repellency & Hydrophobicity issue

2.1 Fire-Induced Water Repellency

Soil water repellency (WR), also called soil hydrophobicity, is a property that significantly impacts plant growth, surface and ground hydrology and erosion processes, as it reduces the affinity of soils to water. Water repellency is one soil property most affected by combustion. Top mineral soil initially contains hydrophobic substances leached from the organic horizons. Heating at 200–250°C cause vaporization of the hydrophobic substances, pushing the substances to move downwards in response to the soil temperature gradient. The hydrophobic substances condense on soil aggregates and form a uniform coating called the soil-water repellent layer (Figure 6). Fire-induced water repellent layers are generally several inches beneath the soil surface and are commonly 1 inch thick (Certini, 2005 & DeGomez, 2011). The water-repellent layer prohibits water from infiltrating into dry soils and eliminates the soil water storage capacity in formerly rich organic horizons. It accelerates surface runoff and soil erosion during rainy days. Water repellency may also influence seedling survival and following soil recovering establishments (Olorunfemi et al., 2014). Thick hydrophobic layers can persist for more than one year and impact infiltration and plant growth in a long time period. Plant roots, soil microorganisms and post-fire moisture help to break down the repellent layer, but reduced water infiltration will inhibit plant growth and soil biological activities.

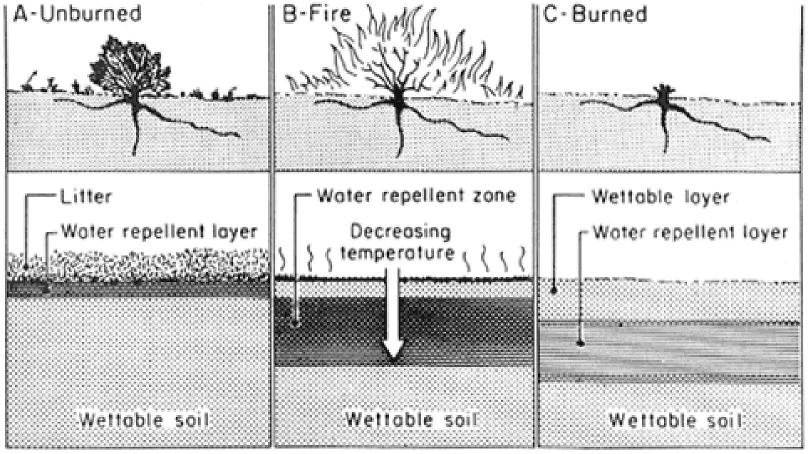

Figure 6. Soil water repellent layer affected by the fire. (A) before the fire: hydrophobic substances accumulate in the surface layer; (B) during fire burns: hydrophobic substances move downward; (C) after fire: water repellent layer stays below the soil surface (DeBano, 1991).

The concentration of hydrophobic substances mainly depends on vegetation species and cover density, and soil characteristics, while the extent of water repellency depends on fire severity, steepness of temperature gradients and soil water content (Verma & Jayakumar, 2012). Based on these factors, the fire effects on water repellency are very site-specific and difficult to predict (Doerr et al., 2000). Soil with low moisture content would have stronger and more extensive water repellency after fire burning(Robichaud et al., 2016). DeBano (1981) discussed in his paper that different vegetations produce different degrees of water repellency. The order of decreasing water repellency-generating plants was phalaris, mallee, heath, and pine. The subsoil on bare areas with decaying roots has a high occurrence of water repellency. Water repellency is also highly found under red pine, hemlock, and mixed hardwood-softwood stand forests (DeBano, 1981). Studies also found that coarse-textured soils exhibit more water repellent and at greater depths than fine-textured soils (Rodríguez-Alleres et al., 2012). Organic matter can prompt water repellency in coarse-textured soils. But conversely, organic matter forms water-stable aggregates in fine-textured soils, which improve soil aggregate stability and water and air movement (DeBano, 1981).

2.2 Management solutions

DeBano (1981) introduced two methods to manage fire-caused water repellency: chemical wetting agents and prescribed fires. Erosion could be reduced by about 40 percent by applying the wetting agent treatment. But since wetting agents are expensive and only effective on small plots, it is difficult to utilize successfully in large areas. He described that prescribed fire could be a more practical water repellency modification method. Prescribed fire is applied during moister conditions, and its intensity and behaviour are well controlled. By consuming fuels that accumulate on the forest floor and burn in the wildfire, water repellency is minimized efficiently. Low intense fire, finer soil texture, wetter soil conditions, and a small quantity of organic matter on the soil surface would allow less water repellent to be produced (DeBano, 1981).

B. Wildfire Effects on soil Infiltration and Runoff

Infiltration plays a crucial role in determining the amount of rainfall flowing into surface runoff or subsurface flows. Fire modifies the soil characteristics and vegetation cover, altering the infiltration process on burned lands (Cerdà & Robichaud, 2009). Nyman et al. (2014) defined that wildfire impacts the infiltration rate by three mechanisms: a) remaining fine ash and soil deposits on the soil surface to enhance water storage capacity and therefore prevent water from infiltrating into the soil; b) altering soil structure and restricting macropore flow, and c) reducing pore-space availability due to water repellent layer generation (Nyman et al., 2014). Like the wildfire effects on soil properties, the degree of infiltration reduction also depends on many factors and varies from site to site. Soil erosion, as a significant consequence, is problematic and should be aware of.

1. Mediterranean forest

Mediterranean arid areas have a high risk of desertification, thus water infiltration capacity is usually high and soil erosion is low. The plant community pattern directly affects soil porosity, which increases water-infiltration capacity and decreases surface runoff. The study of Sardans and Peñuelas (2013) found that the eliminated succession of Mediterranean plant communities after wildfires creates plant patches, which cause long-term soil degradation, water infiltration reduction and finally, desertification (Sardans & Peñuelas, 2013).

Nyman et al. (2014) produced a model that incorporated hydraulic conductivity and water repellency dynamics to determine changes in macropore flow during soil recovery from wildfire. Their study site was in southeast Australia, which experiences a Mediterranean climate. Their experiments showed that the soil profile in burned regions had a substantial water repellency and low infiltration capacity**,** thus restricting water flow through the soil matrix. The major cause of water flow resistance is minimum critical surface tension (CSTmin) remained within the top 10 cm of the soil repellent layer, which generally persisted for several years. The infiltration rate in the burned area remains slow until the wetting front crosses the water repellent layer and move into the underlying soil of the repellent layer (Nyman et al., 2014).

However, another study done by Inbar et al. (2014) in a semiarid Mediterranean region showed opposite results. The IR values were the highest, and the amounts of runoff and soil loss were lowest in the heated soil sample, compared to direct fire and unburned soil treatments (Table 2). The authors examined that heating the soil over 300 °C could enhance the soil-structure stability. High-temperature heating increases the dehydration of 2:1 clay minerals and soil particles' electrical conductivity. These changes promote interactions among the soil particles and prohibit clay dispersion and seal formation, resulting in high infiltration values and low runoff and soil loss in heated soil (Inbar et al., 2014).

Fire treatment	Runoff			Soil loss		
	Consecutive rainstorms			Consecutive rainstorms		
	1st	2nd	3rd	1st	2nd	3rd
	mm			g m^{-2}		
Unburned soil	34.0aA	31.0aB	32.0aAB	580.0aA	646.2aA	585.0aA
Direct fire soil	18.8bC	23.6bB	27.9bA	396.9bC	506.0bB	589.0aA
Heated soil	3.7cC	17.5cB	23.0cA	68.0cC	195.8cB	318.8bA

Table 2. Runoff and soil loss in unburned soil, direct fire soil and heated soils. Letters indicate significant differences (α = 0.05) between fire treatments in each rainstorm and between consecutive rainstorms in each fire treatment, respectively (Inbar et al., 2014).

2. **Coniferous forest**

Robichaud et al. (2016) did a post-wildfire infiltration and erosion study in a montane conifer forest. The unburned soil in the forest contains inherent hydrophobic substances at its surface layer, while the water repellent layer moves downwards 1–2 cm deep in the post-fire condition. Their study indicates that post-fire ground vegetation cover, ash layer on soil surface and soil water repellency affect the soil infiltration capacity. During the year of fire, the burned plots had a high occurrence of soil water repellency, resulting in low infiltration rates. Also, the little ground cover enables wind and water erosion, generating high sediment yields in the surface runoff. But after several years of vegetation recovery and rainwater irrigation, the fire-produced water repellency decreased in extent and severity. The infiltration rates increased and sediment yields decreased subsequently as the repellency diminished (Robichaud et al., 2016).

3. **Soil erosion issues**

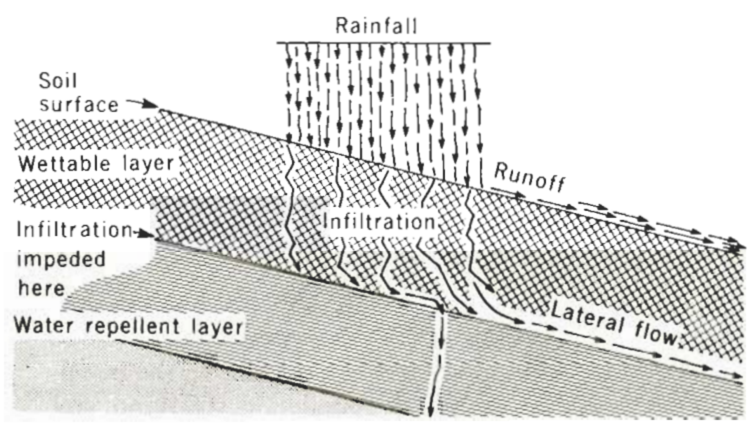

Figure 7. The water repellent layer blocks infiltration and causes surface runoff (DeBano, 1981).

Soil erosion becomes a major outcome of wildfire. Soil hydrophobicity and low soil porosity reduce soil's water infiltration capability, and loss of soil organic matter decreases soil water retention capacity (figure 7). Soil loses the ability to absorb rainfall and snowmelt, to support plants and other life and resistant to erosion. Clay particles in soil are aggregated into sand-sized particles at high temperatures, making the soil texture more coarse. Coarse texture soil has a high permeability, a low water retention ability and high water drainages and becomes more erodible. The combustion of vegetation and litter layer that mitigates the impact of raindrops on soil also contributes to the erosion progress (Certini, 2005). Natural or artificial reintroduction of vegetation is the key method to recover soil organic matter in the burnt areas. The ecological successions of the burned area could lower the recovery time length because of the high net primary productivity. In general, soil hydrology can be recovered if plants recolonize successfully in the burnt area (Certini, 2005).

C. Wildfire Effects on Water issues

1. Contaminants associated with surface runoff

The major water contamination risk resulting from wildfires is post-fire ash and sediment. Ash from wildfire is the particulate residue of burned fuels remaining on the ground. Due to the small vegetation and litter cover, decreased soil stability, and soil erosion enhancement, ash is highly erodible and can be rapidly transferred by wind or rainstorms into water bodies. Mineral materials and charred organic components in ash significantly impact water quality (Bodí et al., 2014). Ash quantity and composition vary depending on fire severity and the biomass and soil organic matter available for burning. Ash production increases significantly with fire severity. Extreme fire severity has the highest ash production, whereas the ash production at high fire severity sites is about half of the extreme fire severity ash production (Figure 8). Higher wildfire severities lead to the completeness of fuel combustion so that the total ash production could be reduced. However, more fuels are affected under higher fire severities, leading to large total ash loads (Santín et al., 2015).

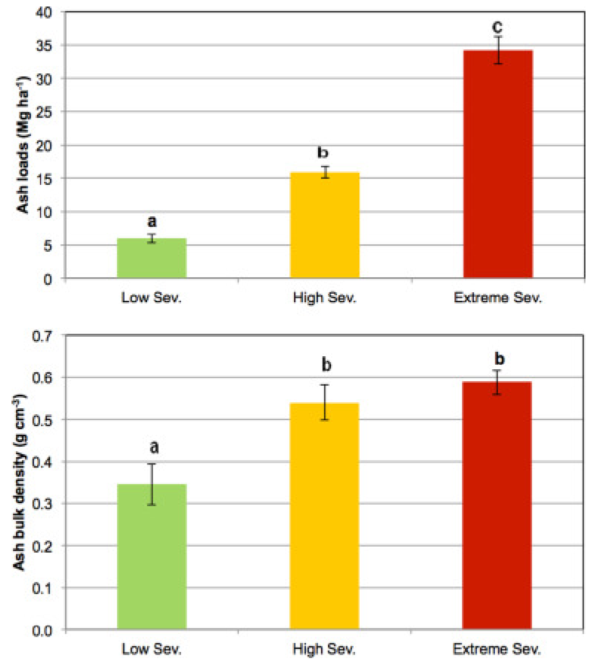

Figure 8. Ash loads (top; Mg ha−1) and Ash bulk density (bottom; g cm−3) for three fire severity testings. Error bars represent the standard error of the mean. Letters indicate significant differences (Santín et al., 2015).

In post-fire conditions, rainfall can be quickly transported by overland flow and accelerate soil erosion. A portion of rainfall carries chemical pollutants infiltrating into the soil through underground flow, causing potential contamination risks to the groundwater. However, the ash layer stays on the top of soil can absorb part of the rainfall due to its high porosity, decreasing the amount of water that reaches the hydrophobic soil. When rainfall exceeds the ash layer's water storage capacity, the ash is eventually transported into water bodies. The total amount of ash after a wildfire is huge and may constitute a large pollution potential during a significant storm event. If a big storm occurs following by a durable dry period, the pollution potential will be exacerbated. In addition to the potential chemical pollutant effects, ash may also increase water turbidity as suspended solids (Santín et al., 2015).

2. Impacts on water quality

Forest fires create permanent and temporary impacts on streams and lakes. Fire acts as an agent of dispersal, where it enhances seed dispersal for some plants. Therefore, in the long term, the vegetation coverage in the area surrounding streams and lakes after the wildfires may become even denser, which indirectly alters the pattern of the local hydrology (Cooper et al., 2013). Forest fires accelerate the melting of snow and glacier, which provides additional water sources to the local freshwater inventory. The melting water increases the volume of streams and lakes, bringing benefits to people and organisms living in those regions suffering from freshwater shortages due to drought.

The negative impacts of forest fires on water quality are twofolds: a) increasing sediment transportation from soil erosion which created turbidity, and b) many toxic contaminants produced during the fire flow into the water. Studies of waters quality after wildfire have reported increases in: turbidity, nutrients, organic carbon, total dissolved solids, chloride, iron, color and taste. The magnitude of water quality influenced by wildfire vary substantially, depending on the severity, intensity, and duration of the fire, burned area proportion, steepness of watershed slopes, and post-fire precipitation intensity and scale (Sham et al., 2013).

Dissolved organic matter (DOM) is the decomposition materials of plants, animals, and soil microorganisms. In most studies, DOM is measured by dissolved organic carbon (DOC), which is from the decomposition of vegetative, microbial, and animal materials. Wildfires break down the materials, release large quantities of DOC into the environment that eventually enter adjacent water bodies through ash deposition and overland runoff (Revchuk & Suffet, 2014). Uzun et al. (2020)'s study showed that the proportion of the watershed burned was significantly related to the downstream water quality. Substantially water turbidity, changes in colour, and high suspended particles are found in water bodies in short term after fire. Concentrations of DOC, total dissolved nitrogen (TDN), dissolved organic nitrogen (DON), and NH4+ are also expected to increase (Uzun et al., 2020). DOM and DOC concentration increases in water may have broad-scale impacts on drinking water quality, aquatic ecosystems health and upland carbon balances, by influencing water acidity, trace metal transportation, light penetration, oxygen exchange and nutrient supply (Evans et al., 2005). DOC could lower the pH value of water both directly (DOC's acid properties) and indirectly (DOC affects other buffer systems regulating pH) (Regan et al., 2017).

DOC includes a larger proportion of high-molecular-weight compounds termed as humic substances, which are formed by microbial activity on plant and animal material. Humic substances consist of colored hydrophilic and acidic complexes, absorb visible light, giving high-DOC concentration water a brown color. High levels of humic substances in water could reduce residual chlorine levels, leading to an increased risk of bacterial productivity and denitrification. Mercury concentration and toxicity increase as DOC increases in drainage lakes because mercury is attached to humic substances (Moore, 1998).

3. Impacts on aquatic organisms

Streams and lakes sustain the local aquatic ecosystem, and change in water conditions negatively impacts the organisms that living in water. As no forests act as a buffer zone, bushfire debris, soil particles and ash enter into the water with rainfall and move downstream kilometres away, impacting the adjacent aquatic life and damaging their feeding and breeding areas. Soil and ash in water cloud the water, reducing light penetration and oxygen exchangeability. Smoke and ash produced by fires can clog fish gills and weaken the filter-feeding animals' breathing ability. These pollutants also contain toxic chemicals, such as copper, zinc, lead and mercury. Ingesting these chemicals could alter the physiology and behaviours of aquatic animals and cause chain reactions through aquatic and terrestrial food webs (Smyth, 2020). The excess organic matter increases the nitrogen and phosphorus levels in waterways and can lead to the growth of algal blooms. Firefighting foam dissolved in water can suffocate fish, while fire retardants contain toxic chemical compounds that are harmful to aquatic organisms (Vartan, 2019).

4. Drinking water treatment issue

Although evidence has shown that short-term water supply benefits from wildfires due to the increased surface runoff induced by the vegetation removal, it should be noticed that wildfires posed great challenges for municipal water treatment in the long term. The filling of water-supply reservoirs is affected since wildfires change the magnitude and timing of surface runoff, which causes the reservoir to reach its operating capacity. Contaminants, sediment and microorganisms that enter into the freshwater supply system after fires can adversely affect the water quality and potentially induce public health issues.

For drinking water, DOC is an important water quality parameter. Elevated levels of DOC and significant turbidity may interfere with the effectiveness of drinking water disinfection processes. In poorly treated post-stormwater, DOC reacts with chlorine to form toxic disinfection by-products (DBP). Trihalomethanes is the major DBP that have long-term effects on human health. Researchers also found the formation of nitrogen compounds and increased nitrogenous DBP (N-DBPs) in high DOC water. Hohner et al. (2019) defined that high toxic N-DBPs would cause a public health concern and water providers should be aware of the formation of N-DBP following wildfire. Partially burned watersheds and moderate-intensity fire can have significant and lasting DBP formation (Hohner et al., 2019). The major mechanism for the removal of humic substances is the coagulation process. Moore (1998) discussed in his report that the coagulation removal process is optimal at water pH 4 to 6. Use of chemical oxidants other than chlorine for removing water organic carbon is effective and can also avoid the formation of DBP (Moore, 1998).

5. Case study: The 2019–2020 Australian bushfire impacts

The 2019–2020 Australian bushfire burned about 18 million hectares of land across the country and impact the aquatic ecosystem and species. A large number of plants were burned during the fire, leaving behind massive scorched plant materials and a huge amount of ash on the ground. Since many forests near the coast were damaged, their ability to filter silt and excess nutrients was also destroyed. The organic matters are rushed by rainwater and flow into rivers, estuaries and lakes. The high concentration of potassium, phosphorus, and nitrogen in those organic materials got washed into the water, supporting algae growth. As a consequence, water's turbidity increases, oxygen level decreases, and total biodiversity decrease. On the other hand, the ash and silt flow into the water body and block sunlight that plants and microorganisms living in water need for photosynthesis. The coastal area is an important habitat place and spawning area for a large range of marine species. Environmental damage on rives, lakes, estuaries and oceans would lead to chain effects throughout the entire ecosystem (Johnson, 2020).

Figure 9. Ash from wildfires is washed up on the beach (Johnson, 2020).

V. Conclusions

Intense wildfires result in loss of soil organic matter, volatilization of nutrients, death of microbes and formation of hydrophobic compounds, causing water repellent intensification, infiltration rate decrease and soil erosion. Post-fire ash and pollutants transport with surface runoff to water, contaminating water quality and generating problems for aquatic organisms' safety and drinking water health. However, climate patterns, vegetation types and cover, fuel combustion extent and many variables influence the post-wildfire soil profile and recovery progress. The effects of wildfire on soil and hydrologic processes are very complex and cannot be concluded absolutely. Thus, in this report, the discussions of wildfire impacts are general reviews of existing works of literature. The main conclusions of this study are summarized in the following table:

Wildfire Impacts on soil	
Physical properties	• Red hue color in the burned soils, due to formation of iron oxides. • Clay particles are less in burned soil. • pH generally increased due to organic acids denaturation and basic cations release. • Bulk density increases by collapsing soil aggregates and clogging voids by the ash.

	● Wildfire collapses soil macropores and alter the particle-size distribution, resulting in coarser textures of soil.
Chemical properties	● OM concentration decreases after the fire, but returns back or even exceeds the pre-fire level due to deposition of litter. ● Nitrogen volatilization during wildfires to nitrate and ammonium. Nitrate leached quickly, while ammonium is held by the soil. Other nutrients loss through volatilization is negligible.
Biological properties	● Both invertebrates and micro-organisms decreases in number. ● Invertebrates decrease less than microorganisms because of their mobility. ● Soil micro-organisms recovery depends on vegetation recolonization.
Soil water repellency	● Heat induces gasification of the hydrophobic substances, pushing the substances to move from soil surface downwards into the soil and condense on soil aggregates to form the soil-water repellent layer. ● The water-repellent layer prohibits water infiltration ability, eliminates the soil water storage capacity and accelerates surface runoff and soil erosion. ● The concentration of hydrophobic substances mainly depends on vegetation species, cover density and soil characteristics. The extent of water repellency depends on fire severity, steepness of temperature gradients and soil water content.
Wildfire Impacts on infiltration and runoff	● Increased hydrophobicity results in decreased infiltration and increased runoff that often results in increased erosion. ● Decreased infiltration and increased surface runoff are found in both the Mediterranean and coniferous forests. ● Studies also suggested that extreme high-temperature heating could enhance soil stability and promote infiltration.
Wildfire Impacts on water	
Contaminants of wildfire	● Post-fire ash and sediment are the main contaminants. They transport to water bodies by wind or water erosion, increasing water pollution and turbidity. ● Ash production increases significantly with fire severity.

Water quality	● Increased sediment transport from soil erosion created turbidity ● Many toxic contaminants are produced during the burning of vegetation. ● DOM and DOC concentration increases may have impacts on freshwater biota, drinking water quality, aquatic ecosystem health and upland carbon balances. ● Humic substances lead to an increased risk of bacterial productivity and denitrification.
Aquatic organisms	● Debris, soil sediments, and ash flow into the water, impacting aquatic lives and damaging feeding and breeding areas. ● Soil and ash reduce light penetration and oxygen exchangeability, clog fish gills and weaken animals' breathing ability. ● Ingesting toxic chemicals of ash could alter the physiology and behaviours of aquatic animals and cause chain reactions in aquatic and terrestrial food webs. ● The excess DOC supports the growth of harmful algal blooms.
Drinking water	● DOC reacts with chlorine to form toxic disinfection by-products (DBP) that have long-term effects on human health. ● The mechanism for the removal of humic substances is the coagulation process. Using chemical oxidants other than chlorine to remove organic carbon is effective and can also avoid the formation of DBP.

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VIII. Appendix

Appendix I. Summary table of wildfire effects on soil physical, chemical and biological properties.

Soil Properties	Wildfire Effects
Physical properties	
Colour	A red hue appears in the burned soils, due to the formation of iron oxides
Texture	Clay particles are less in burned soil
pH	Generally increased due to organic acids denaturation and basic cations released through the combustion process
Bulk density	Increases significantly due to forest fire by collapsing soil aggregates and clogging voids by the ash
Particle-size distribution	Collapse soil macropores and alter the particle-size distribution, resulting in coarser textures of soil
Chemical properties	
Organic matter	Decreases after the fire, but returns back or even exceeds the pre-fire level due to deposition of litter.
Nutrients availability	Nitrogen volatilization during wildfires to nitrate and ammonium. Nitrate leached downwards quickly, while ammonium is adsorbed onto the negatively charged surfaces of minerals and organics and therefore is held by the soil. Other nutrients loss through volatilization is negligible.
Biological properties	
Invertebrates	Decreases, but less than microorganisms because their mobility
Micro-organisms	Decreases; the recovery depends on vegetation recolonization.