THE CORRELATION BETWEEN FIRE AND BOREAL FOREST SOIL DEGRADATION: A REVIEW OF THE EFFECTS OF FOREST FIRE ON SOIL PROPERTIES

By

Tiantian Tao

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

April 30th, 2021

THE CORRELATION BETWEEN FIRE AND BOREAL FOREST SOIL DEGRADATION: A REVIEW OF THE EFFECTS OF FOREST FIRE ON SOIL PROPERTIES

By

Tiantian Tao

An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honours Bachelor of Environmental Management

Faculty of Natural Resources Management
Lakehead University

April 30th, 2021

Lense Meyer
Thesis Supervisor

Jian Wang
Second Reader

LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfillment of the requirements for the HBEM degree at Lakehead University in Thunder Bay, I agree that the University will make it freely available for inspection.

This thesis is made available by my authority solely for the purpose of private study and may not be copied or reproduces in whole or in part (except as permitted by the Copyright Laws) without my written authority.

Signature: ______________________________

Date: ______________________________

A CAUTION TO THE READER

This HBEM thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty or of Lakehead University.

MAJOR ADVISOR COMMENTS

ABSTRACT

The boreal forest has a vast area, and its types are distributed in a belt around the polar regions. The soil types of boreal forests are also different due to different vegetation types and climatic conditions in the boreal region. Fire is one of the common disturbances in boreal forests, and it is also one of the methods of boreal forest management. As we all know, fire is one of the causes of soil degradation. Therefore, the main purpose of this article is to explore the correlation between fires and soil degradation in boreal forests by reviewing the effects of forest fires on soil properties. After research, severe fires are one of the causes of forest soil degradation. However, severe fires will cause regional degradation of some soil types in the boreal forests, and the soil degradation of the boreal forests also depends on natural and human factors after the fire.

Key words: Boreal forest, fire, soil degradation boreal forest soil

CONTENTS

TABLES

FIGURES

ACKNOWLEDGEMENTS

I thank my thesis supervisor, Dr. Lense Meyer, and my second reader, Dr. Jian Wang, for their guidance and help with my thesis. And I also thank the authors of all the articles I have cited for their contributions in related fields.

1.0 INTRODUCTION

The boreal forest biome consists of a broad complex of forested and partially-forested ecosystems (Figure 1) (Apps et al. 1993). It is one of the largest biomes in the world, providing important ecosystem services for local and global populations (Gauthier et al. 2015; Thiffault 2019).

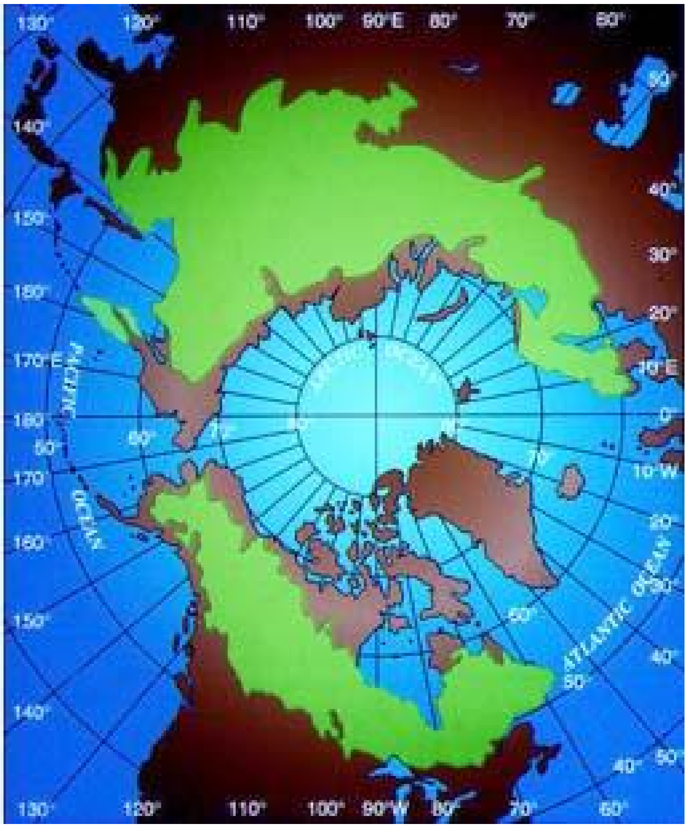

Figure 1. The circumpolar range of the boreal forest (Runesson 2002; Hare and Ritchie 1972).

The boreal biome corresponds to a region with a cold continental and subarctic climate, so its general climatic characteristics are short growing seasons and low average temperatures (Apps et al. 1993; Baldocchi et al. 2000; Thiffault 2019). Moreover, the soil types of boreal forests are diverse and are conditioned by climate, topography, plant physiography and so on, and the soil types that can be found in boreal forests are Podzols, Crysols, Retisols, Gleysols, Histsols and Cambisols (Thiffault 2019). Different climatic conditions, soil types and other factors affect the distribution of vegetation. Therefore, the entire boreal forest vegetation can be divided into latitude zones, and the boreal landscape is divided into treeless tundra, lichen woodlands, closed coniferous forests and mixed coniferous-broadleaf forest, the latter is the main boreal landscape (Thiffault 2019).

As one of the disturbances of boreal forest, forest fire is also considered to be an important factor in determining the composition of vegetation (Ahlgren 1960), which has important advantages in the thinning and regeneration of forests. However, the occurrence of forest fires, may cause huge property losses to forest managers and cause huge pollution and damage to the environment. According to remote sensing image analysis, fire is the most important cause of forest loss in northern forests (Potapov et al. 2008; Hansen et al. 2013). And the severity of the fire, the peak temperature and the duration of the fire will affect many physical, chemical, mineralogical and biological properties of the soil (Certini 2005). Furthermore, the direct impacts of fire on the soil are related to heat, and the indirect impacts are related to the ash-bed effects, degree of vegetation recuperation, post-fire weather patterns, topography and post-fire management (Pereira et al. 2018). The exact impacts of forest fires on the soil are very complex, and depends on the type and texture of the soil, pre-fire conditions, the type and structure of vegetation, the ecosystem, the intensity of the fire, the meteorological conditions during the fire, topography and other factors (Caon et al. 2014; Francos et al. 2018; Pereira et al. 2018). Low-intensity fires can have a beneficial effect on the soil, but high-intensity fires are indeed one of the risks of soil degradation (Nayakekorale 2020).

Soil degradation processes can be divided into soil erosion, alkalinization, salinization, acidification, compaction, fertility decline, and soil pollution (Nayakekorale 2020). Soil erosion, compaction, nutrient deficiency and soil acidification are also the main processes of forest soil degradation (Zhang and Cai 2004). In general, natural forests rarely experience soil fertility decline, and planted forests will cause soil degradation due to tree species characteristics and improper cultivation measures (Zhang and Cai 2004). However, some human activities, such as forest logging and/or frequent prescribed burning, will cause soil erosion or compaction risks to all forests. The frequency of wildfire interference will also be increased by the warming and dry weather caused by human activities, the ability of forests to resist is reduced under the conditions of climate change (Stevens-Rumann et al. 2018), which also increases the risk of forest soil degradation.

In sum, forest fires are one of the common disturbances in boreal forest, and prescribed burning is also a common forest management method. Therefore, the impact of fires on the soil of northern forests is one of the basis for determining how to manage northern forest fires in the future. However, there are few studies on whether forest fires will lead to soil degradation in northern forests. Therefore, the correlation between boreal forest fires and boreal forest soil degradation is a very important research direction. In addition, this research is of great significance for the rational use of fires, the formulation of reasonable management strategies, and the prevention of soil degradation.

1.1 OBJECTIVE

This article reviews some effects of fires on the physical, chemical and biological properties of forest soils to explore the correlation between boreal forest fires and soil degradation.

2.0 METHODS AND MATERIALS

This paper reviews the effects of fire on the physical (soil color, texture and mineralogy, water repellency, structure stability, pH and bulk density), chemical (soil organic matter, soil nutrients), and biological (microorganisms, invertebrates) properties of soils from published studies or reviews. The correlation between fire and boreal forest soil degradation was discussed in the review results.

3.0 ANALYSIS

The most significant impact of forest ecosystem fires is the transfer of heat from the burning biomass to the soil system (DeBano et al. 1998; Neary et al. 1999). This heat transfer is the main mechanism that affects the physical, chemical and biological properties of the soil (Neary et al. 1999). The spatial distribution of soil properties in the soil profile largely determines the magnitude of changes in specific soil properties during a fire, and the specific soil properties also have different sensitivities to heating (DeBano 1991). Specifically, those soil properties on or near the soil surface are more likely to be changed by fire (DeBano 1991). And the temperature required for the destruction of the physical and chemical properties of the soil is much higher than the temperature required for the destruction of the biological properties, and soil microorganisms may be the most sensitive to soil heating (DeBano 1991; Neary et al. 1999). Moreover, soil organic matter (SOM) is located on the topsoil, so SOM can be strongly transformed by fire, which in turn affects the performance of the soil (DeBano 1991; Obalum et al. 2017; Dymov et al. 2017).

3.1 IMPACT OF FIRE ON PHYSICAL PROPERTIES OF FOREST SOIL

3.1.1 Soil Color, Texture and Mineralogy

The color of the soil is largely affected by the type and amount of SOM and iron oxides (Ketterings and Bigham 2000; Schwertmann 1993; Bigham et al. 1978; Schulze et al. 1993; Shields et al. 1968). Ulery and Graham studied the difference in color and texture between burned and unburned soil in 1993. The results of their research (1993) were that the color and texture of severely burned soil are more obvious changes than that of nearby slightly or moderately burned soil. After severe burning, a reddened layer formed at all of the sites, which was redder in hue and had higher chromas and values than the unburned soils, and the blackened layer with lower Munsell values below this reddened layer (Ulery and Graham 1993). Their analysis of this result (1993) was that the redder hues in the burned soils were obviously the result of Fe oxide transformations, while higher values were the result of the almost complete removal of organic matter. The organic carbon content in the blackened layer was also significantly reduced, so the lower Munsell values may be due to the carbonization of residual organic matter (Ulery and Graham 1993). Verma and Jayakumar (2012) also mentioned in their review that the surface patches of reddened soil indicate that the soil was severely burned, and the magnetization was significantly increased compared to the surrounding soil.

The components of soil texture (sand, silt, and clay) are generally not easily affected unless it is directly on the surface of the soil in a very intense fire (Verma and Jayakumar 2012; DeBano 1991). After the mineral structure is decomposed at high temperature, amorphous clay-sized particles can be cemented together by Fe- and Al-hydroxides released during the combustion of SOM, resulting in larger particle sizes (O'Brien et al. 2018; Ketterings et al. 2000). The temperature threshold for degradation of each mineral is different, as shown in Figure 2 (O'Brien et al. 2018). Gibbsite, Goethite, Kaolinite, Chiorite, Halloysite, Illite, Montmorillonite, Vermiculite, and Muscovite have different temperature thresholds. For example, when Kaolinite is heated to between 420 degrees Celsius and 500 degrees Celsius, the structure usually begins to deteriorate (O'Brien et al. 2018; Dixon 1989). Ulery and Graham (1993) summarized some findings and conclusions in their research. The reddened soil layer at all sites had less clay than the unburned soil or the blackened soil layer, the clay content of the latter was not significantly different from each other (Ulery and Graham 1993). And four sites formed sand-like aggregates in the surface soils during the combustion process, which changed the particle size distribution and resulted in coarser textures due to a greater proportion of sand (Ulery and Graham 1993). Burning produced a finer texture at one site due to an increase in the silt fraction, resulting from the decomposition of kaolinized sand grains (Ulery and Graham 1993). And they (1993) also mentioned that the low crystallinity aluminosilicate with a boiling point of 0.5 M KOH increases in the reddened layer at three of the sites, which may help the cementation of the sand-sized gravel aggregates. Verma and Jayakumar (2012) also cited the study by Ulery and Graham (1993) and explained that clay is the most sensitive texture component. When clay hydration and clay lattice structure begin to collapse, it begins to change at a soil temperature of about 400 degrees Celsius (Verma and Jayakumar 2012; O'Brien et al. 2018).

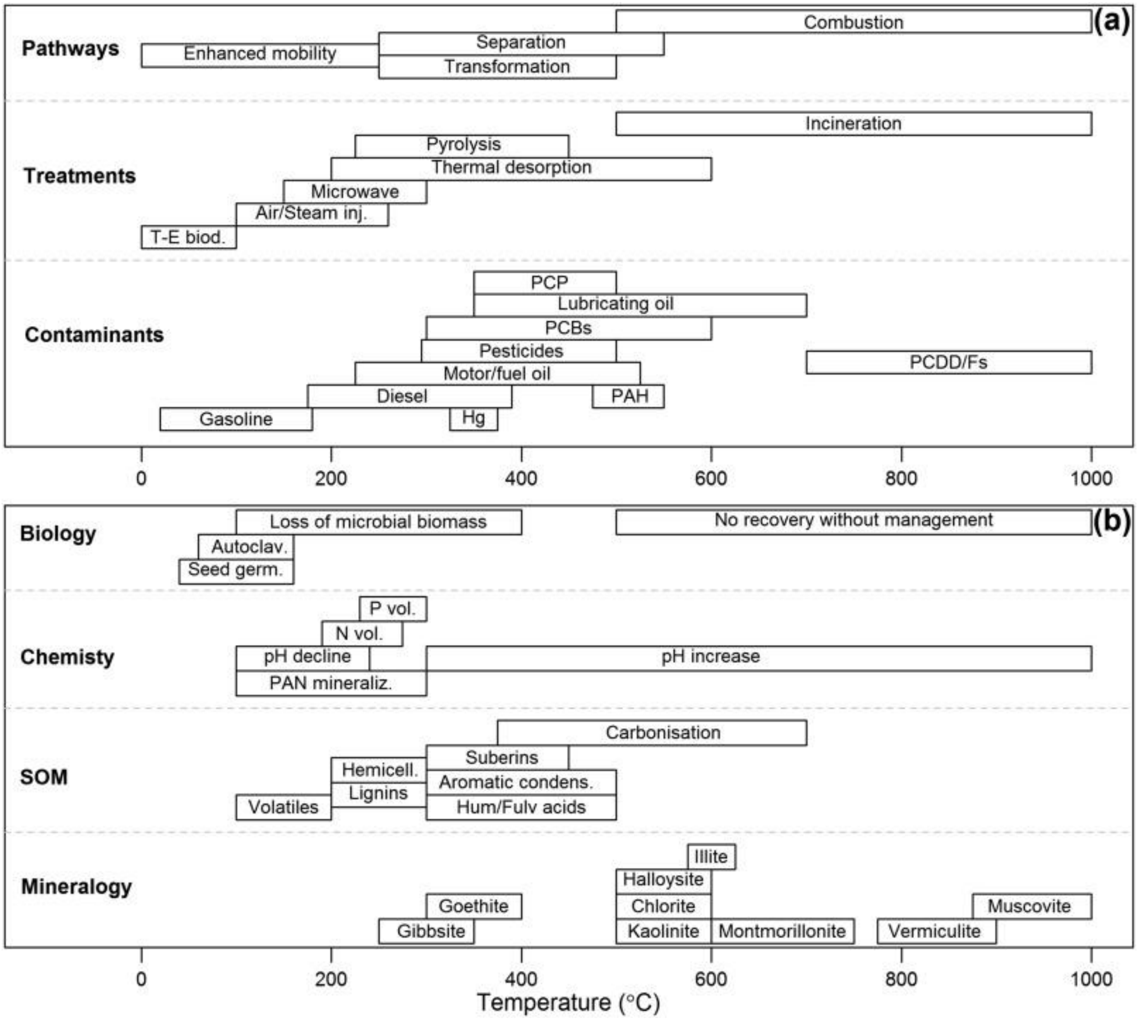

Figure 2. The contaminants, biology, chemistry, SOM, and mineralogy, are affected by the temperature range of the fire (O'Brien et al. 2018).

3.1.2 Water Repellency

An important physical property affected by fire, one that regulates the hydrology of a soil, is water repellency (DeBano 1991; DeBano 1981; Figure 3). In 1981, 1991, and 2000, DeBano in his research and Verma and Jayakumar (2012) in their review also mentioned how fire affects the water repellency of soil. The main effect of fire on the physical properties of soil is to eliminate the water storage capacity in the organic layer (Verma and Jayakumar 2012). Before fire, organic matter accumulates in the litter layer and mineral soil immediately beneath; during fires, the organic matter is volatilized and most of the volatilized organic matter is lost upward in the smoke, but a small amount moves downward along steep temperature gradients in the upper 5 cm of the soil; finally, it condenses on the soil particles to form a water-repellent layer and hinder penetration (DeBano 2000; DeBano 1991; DeBano 1981; Verma and Jayakumar 2012; Letey 2001). MacDonald and Huffman (2004) studied the persistence of soil moisture thresholds of post-fire soil water repellency. In the areas of high and moderate severe burning, the fire-induced soil water repellency is strongest on the soil surface, and as the severity of burning decreases and the depth increases, the intensity decreases (MacDonald and Huffman 2004). Over time, the soil water repellency of the soil gradually weakens. Since combustion, the influence of time on soil water repellency has become more and more significant as the severity of combustion increases, while it becomes less and less important as soil depth increases (MacDonald and Huffman 2004). The soil moisture threshold at which the hydrophobic soil becomes hydrophilic increases significantly with the increase in the severity of combustion (MacDonald and Huffman 2004). Mataix-Solera and Doerr (2004) studied the hydrophobicity of calcareous topsoil under pine forests. The results of their (2004) study proved that fires enhanced the hydrophobicity of pine forest vegetation not only in acidic soils, but also in alkaline soils. However, the spatial frequency and persistence of the hydrophobicity of alkaline soils are lower than those of acidic soils under pine trees (Mataix-Solera and Doerr 2004).

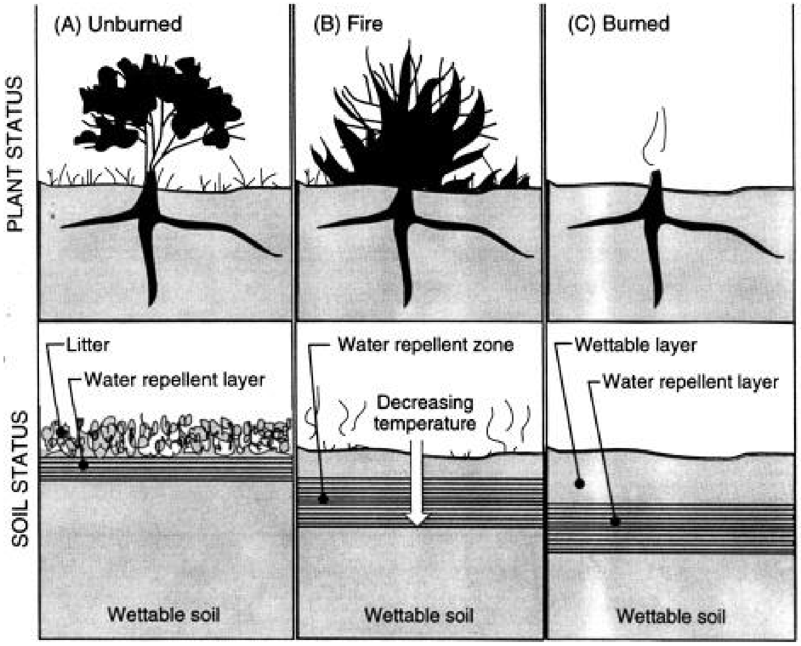

Figure 3. The process of fire affecting soil water repellency (DeBano 2000; DeBano 1991; DeBano 1981).

3.1.3 Structure Stability

One of the most typical consequences of a serious fire is the destruction of the soil structure through the stability of the aggregate (Mataix-Solera et al. 2011). Mataix-Solera et al. (2011) summarized in a review of the effects of fire on soil aggregation and concluded that the response of soil aggregates to fire requires consideration of other soil characteristics (such as soil organic matter, water resistance, texture) and the factors involved (such as fire severity), these factors are comprehensively considered to obtain three different aggregate stability change patterns related to fire severity (Figure 4).

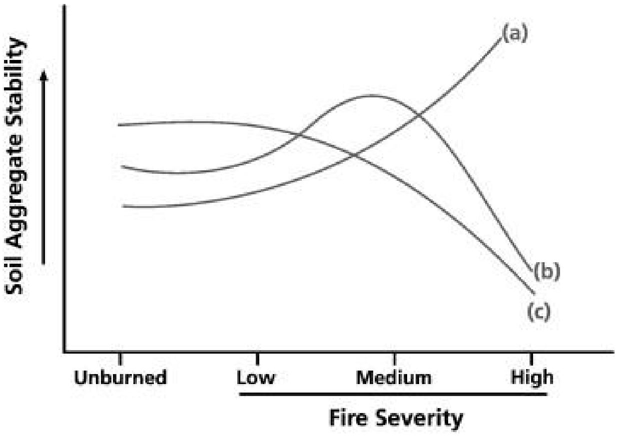

Figure 4. Three different patterns of aggregate stability changes in relation to fire severity (Mataix-Solera et al. 2011).

In Figure 4, a) represents a soil with high clay content, calcium carbonate, Fe and Al oxides as the main cementing substances; b) stands for soil with organic matter as the main binder, the soil has hydrophilic or low hydrophobicity; and c) represents a sandy soil which is highly water-repellent and has organic matter as the principal binding agent (Mataix-Solera et al. 2011). The trend of a) is that the stability of soil aggregates increases as the severity of the fire increases. Mataix-Solera et al. (2011) summarized the trend of b) in that the stability of aggregates initially increased because of the increase in water repellency, and then decreased because the temperature reached a level sufficient to destroy organic matter; regarding the trend of c), Mataix-Solera et al. (2011) concluded that the high organic content and high hydrophobicity of c) soil lead to a high starting point, and the destruction of the main binder leads to a decrease in aggregate stability. However, Mataix-Solera et al. (2011) also believe that the higher stability of the aggregate after a fire does not necessarily mean that the stability of the aggregate is increased due to the fire. In short, the explanation for the increase in aggregate stability with increasing fire intensity is complicated. In addition, Certini (2005) reviewed the two studies of Mataix-Solera and Doerr (2004) and Badía and Martí (2003) and mentioned that low or moderate fires can increase structural stability because a hydrophobic membrane can be formed outside the aggregate, and severe fires will cause the stability to decrease because the organic cements are destroyed. Moreover, in the latter case, the surviving aggregate can exhibit higher stability than the original aggregate due to the formation of cementitious oxides (Certini 2005; Ketterings et al. 2000; Giovannini and Lucchesi 1997).

3.1.4 pH and Bulk Density

At a low temperature of less than 250 degrees Celsius, the pH of the soil remains the same or slightly decreases, but heating above 250 degrees Celsius will cause the SOM to burn and subsequently increase the pH through two mechanisms (O'Brien et al. 2018). One is that the denaturation of organic acids, removing its acidification effect from the soil solution (O'Brien et al. 2018; Pape et al. 2015, Terefe et al. 2008). The other is that higher temperatures and the dehydration of soil colloids will replace hydrogen ions and alkali metal cations, which are abundant in the soil solution after SOM is burned (O'Brien et al. 2018; Sierra et al. 2016; Terefe et al. 2008; Badia and Marti 2003). Therefore, the pH of soils with higher SOM is more affected by fire, but in low SOM or in carbonate-buffered soils, the increase in pH caused by fire is negligible (Certini 2005; O'Brien et al. 2018). This is because calcium carbonate can buffer changes in pH and therefore requires a high temperature before decomposition (O'Brien et al. 2018).

The formula for calculating bulk density is the mass of the oven dry soil in the soil sample divided by the bulk volume of the sample (Verma and Jayakumar 2012). Alcañiz et al. (2018) mentioned in their review that many authors studied the relationship between soil bulk density and open fire and concluded that the destruction of soil aggregates caused by fire is the cause of the increase in bulk density. Certini (2005) concluded in his review that the collapse of the organic mineral aggregates and the sealing due to the plugging of pores by ash or released clay minerals result in an increase in bulk density (Verma and Jayakumar 2012; Giovannini et al. 1988; Durgin and Vogelsang 1984).

3.2 IMPACT OF FIRE ON CHEMICAL PROPERTIES OF FOREST SOIL

3.2.1 SOM

Fire will cause quantitative and qualitative changes to SOM (Mataix-Soler et al. 2011; Zhang and Biswas 2017; Certini 2005). The impact of fire on SOM largely depends on the fire states, soil conditions, climate conditions and other factors (Verma and Jayakumar 2012; Zhang and Biswas 2017; Caon et al. 2014; Nalder and Wein 1999). The scope of the influence of fire on the SOM content may be that the SOM is almost completely destroyed, or the surface SOM content may increase due to external input (González-Pérez et al. 2004; Chandler et al. 1983).

O'Brien et al. (2018) extracted 135 data points from 19 different studies in their review and obtained the data results in Figure 5. When the heating temperature is equal to or lower than 300 degrees Celsius, even if the time increases, the SOM will not be greatly reduced; but when the temperature exceeds 300 degrees Celsius, the temperature increase will greatly reduce the SOM (O'Brien et al. 2018).

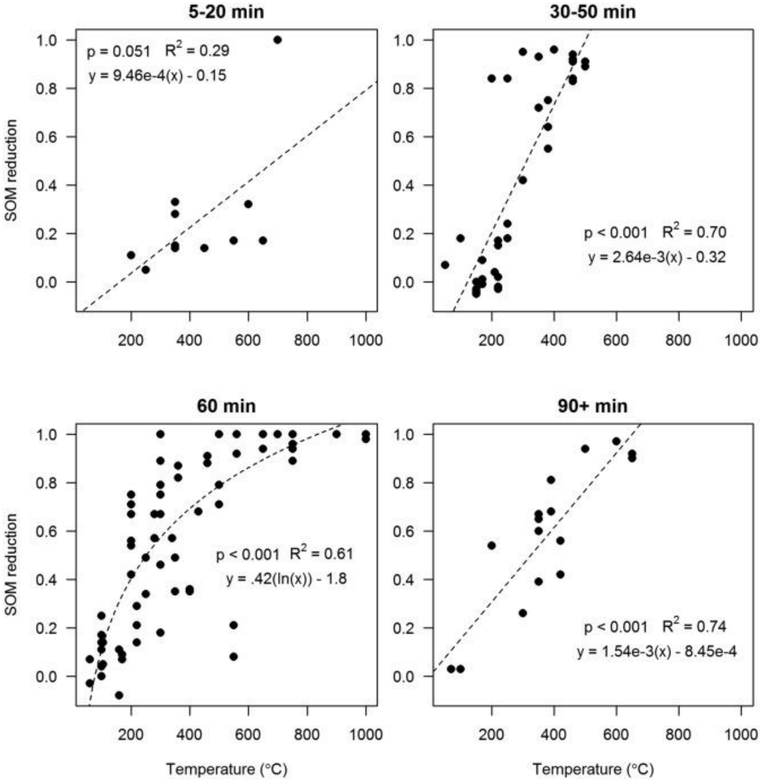

Figure 5. The reduction of soil organic matter (SOM) across a range of temperatures, with each panel corresponding to heating duration (O'Brien et al. 2018).

In addition, Zhang and Biswas (2017) also concluded that the transformation of SOM mainly occurred on the forest floor rather than the mineral soil horizons, and the carbon content after the fire could not be restored to the previous level for a long time. The impact of fire on SOM mainly produces common gaseous carbon such as carbon dioxide, methane, carbon monoxide, and aerosol black carbon. Pyrogenic carbon (black carbon) is also a main by-product of wildfires in northern forests (O'Brien et al. 2018; Soucémarianadin et al. 2015). The occurrence of a fire will significantly increase the emission of these gaseous carbon (O'Brien et al. 2018). Similarly, fires of all severity levels have transformed the composition of SOM from carbohydrates to pyrogenic carbon dominance (Miesel et al. 2015). Moreover, the enhancement of the leading role of aromatic compounds in bulk mineral soils is also the most significant change in SOM research (Miesel et al. 2015; O'Brien et al. 2018).

3.2.2 Soil Nutrients

The fire caused the nutrients stored in the fuel and SOM to be severely heated and caused irreversible changes, but every nutrient has an inherent temperature threshold (DeBano 1991). Therefore, some nutrients with low temperature threshold (for example, N, P, and S) will be easily affected by fire and be volatilized or leached and cause loss (DeBano 1991; Verma and Jayakumar 2012; Certini, 2005; Neary et al., 1999).

Figure 6 is the meta-analysis by Maynard et al. (2014), which compares the burned and unburned areas in boreal zones. In Figure 6, we can observe that the total soil nitrogen (N) has not changed significantly, but the N loss affected by the fire is limited to the forest floor (surface organic layer) and does not extend to the mineral horizons (Maynard et al. 2014; Zhang and Biswas 2017). It is particularly emphasized that this conclusion of Maynard et al. (2014) covers all forest types. In addition, the volatilization rate of N depends on temperature (Zhang and Biswas 2017). At higher temperatures, most of the volatilized N is converted to N_2 (DeBano 1991; Grier 1975); while the N that is not volatilized remains on the site either in uncombusted fuel or as inorganic N (NH_4^+, NO_3^-) in the soil (DeBano 1991).

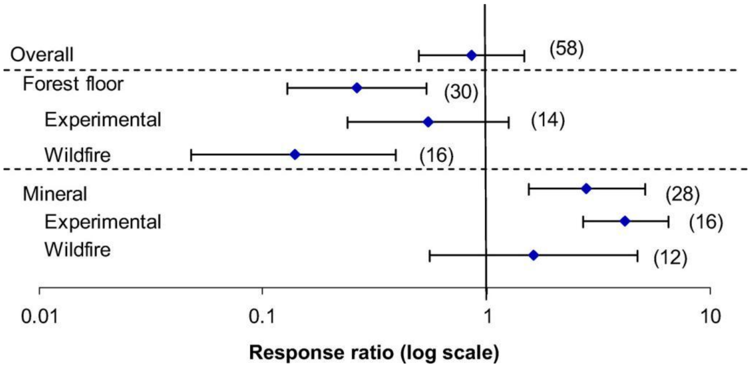

Figure 6. Changes in soil total nitrogen (N) in burned and unburned areas in boreal area (Maynard et al. 2014). [Notes: all points are expressed as response ratios ± 95% confidence intervals (CIs), with the number of studies in parenthesis (Maynard et al. 2014).]

Figures 7 and 8 are also the meta-analysis of Maynard et al. (2014), which reflects the extractable soil phosphorus (P), as well as he response difference of alkali cations (calcium (Ca), magnesium (Mg), potassium (K)) under different vegetation, soil layers and fire types.

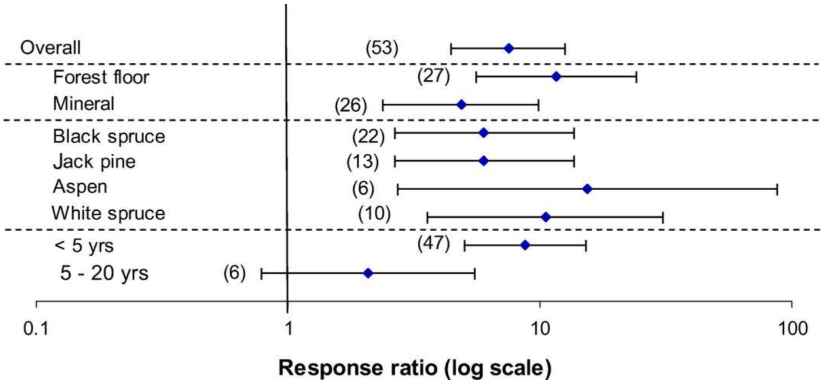

Figure 7. Fire effects on extractable soil phosphorus (P), overall and by soil layer, tree

species, and time since disturbance (Maynard et al. 2014). [Notes: all points are expressed as response ratios ± 95% confidence intervals (CIs), with the number of studies in parenthesis (Maynard et al. 2014).]

In Figure 7, the extractable P was significantly higher in the soil following a fire, and five years after the fire disturbance, the extractable P was found to increase significantly (Maynard et al. 2014). However, Smith (1970) found that a fire occurred after 5 years, the extractable P of L-H horizons will decrease compared with the concentration immediately after combustion, and will continue to decrease on subsequent sampling dates. Smith's (1970) explanation for the decrease in P concentration was probably mainly because they precipitated in acid-insoluble form.

That is, the organic pool of soil P caused by the fire is converted into orthophosphate, which can be absorbed by plants (Certini 2005; Zhang and Biswas 2017; Cade-Menun et al. 2000). In acid soil, orthophosphate combines with aluminum, iron, and manganese oxides through chemical adsorption; and in neutral or alkaline soil, it combines with calcium minerals where it may precipitate as discrete calcium phosphate (Certini 2005). It can be said that P is a very stable element, and the loss caused by it is negligible (Certini 2005; Zhang and Biswas 2017).

In addition to N and P, the availability of other soil nutrients is usually increased through the combustion of SOM, depending on the combined effects of various factors (Certini 2005).

In Figure 8, the exchangeable Ca and Mg were significantly higher in the soil following fires, but the fire had no overall effect on the exchangeable K, and the exchangeable K was higher in the mineral soil layer than in the forest floor. However, Zhang and Biswas (2017) mentioned in their review that other researchers found different results, but they believe that this is a trade-off between the input of combustion products, redistribution along the soil profile, and output due to the loss process.

In general, the exchangeable cations on the forest floor after the fire increased because of the ions released by the burning of ground vegetation and SOM; the increase in exchangeable cations in the mineral soil was due to the redistribution of cations leaching downward (Zhang and Biswas 2017; Maynard et al. 2014).

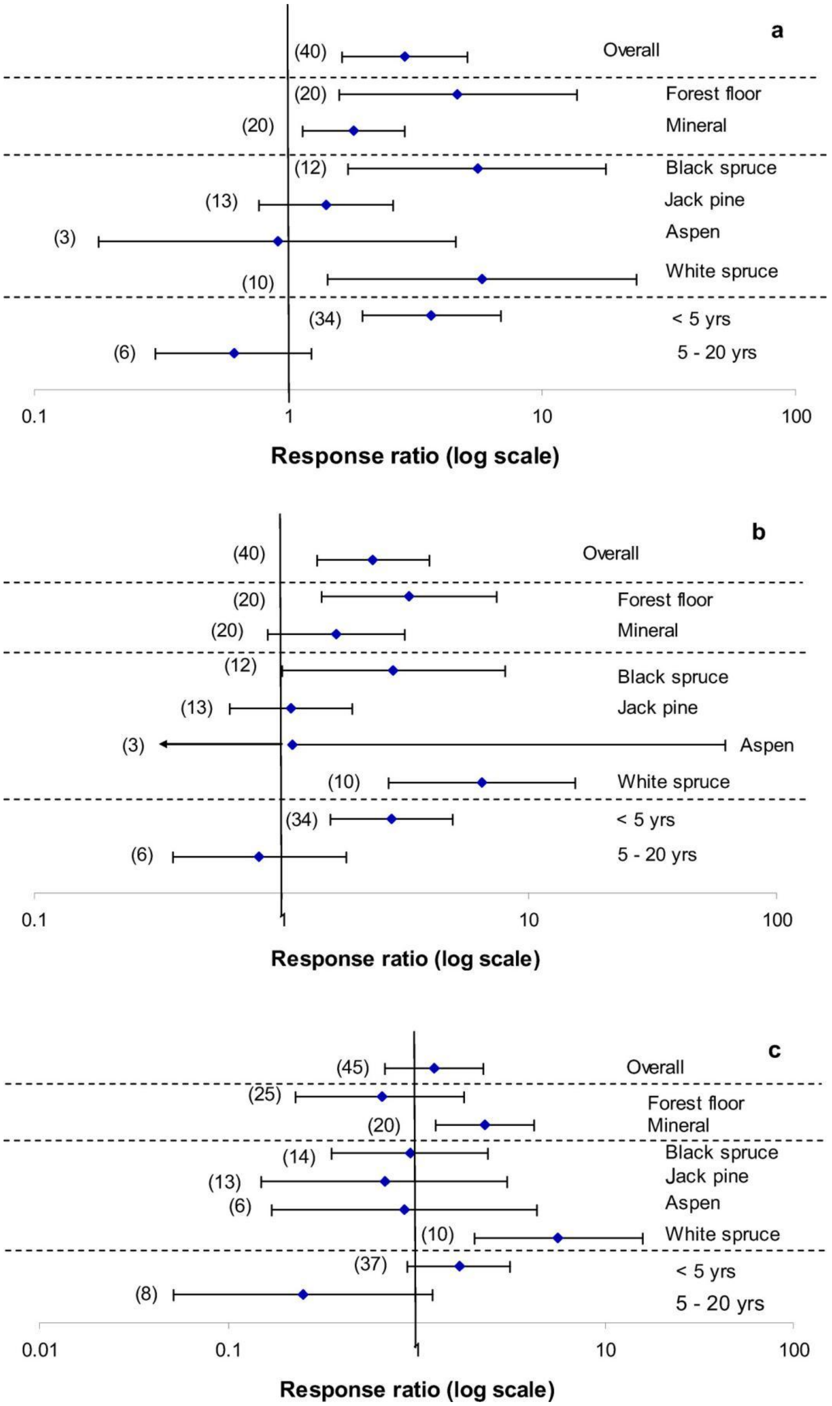

Figure 8. Change in exchangeable (a) calcium, (b) magnesium, and (c) potassium following fire, overall and by soil layer, tree species, and time since disturbance (Maynard et al. 2014). [Notes: all points are expressed as response ratios ± 95% confidence intervals (CIs), with the number of studies in parenthesis (Maynard et al. 2014).]

Moreover, the different adsorption characteristics cause different leaching behaviors of specific cations (Zhang and Biswas 2017; Smith 1970) .

In addition, there are few studies on micronutrients (Fe, Mn, Zn, B, and Mo), but Verma and Jayakumar (2012) concluded in their review that micronutrients will also decrease after a fire.

3.3 IMPACT OF FIRE ON BIOLOGICAL PROPERTIES OF FOREST SOIL

Soil organisms are most sensitive to fire response (Figure 2). Soil heating directly affects organisms by directly killing or changing the reproductive ability of organisms, and can also indirectly affect organisms by changing the soil environment (such as physical and chemical properties) (Verma and Jayakumar 2012; DeBano 1991).

3.3.1 Microorganisms

Fire can directly reduce the biomass and basal respiration of soil microorganisms (Certini 2005). In fact, the peak temperature usually greatly exceeds the temperature required to kill most organisms (Certini 2005; Debano et al. 1998; Verma and Jayakumar 2012). Holden et al. (2016) studied how fire severity affects the response of soil microorganisms to boreal forest fires. Holden et al. (2016) also showed that the soil microbial biomass and basal respiration of burned stands were greatly reduced compared with unburned stands, and the microbial biomass and basal respiration decreased significantly as the fire intensified (Figure 9 and Figure 10).

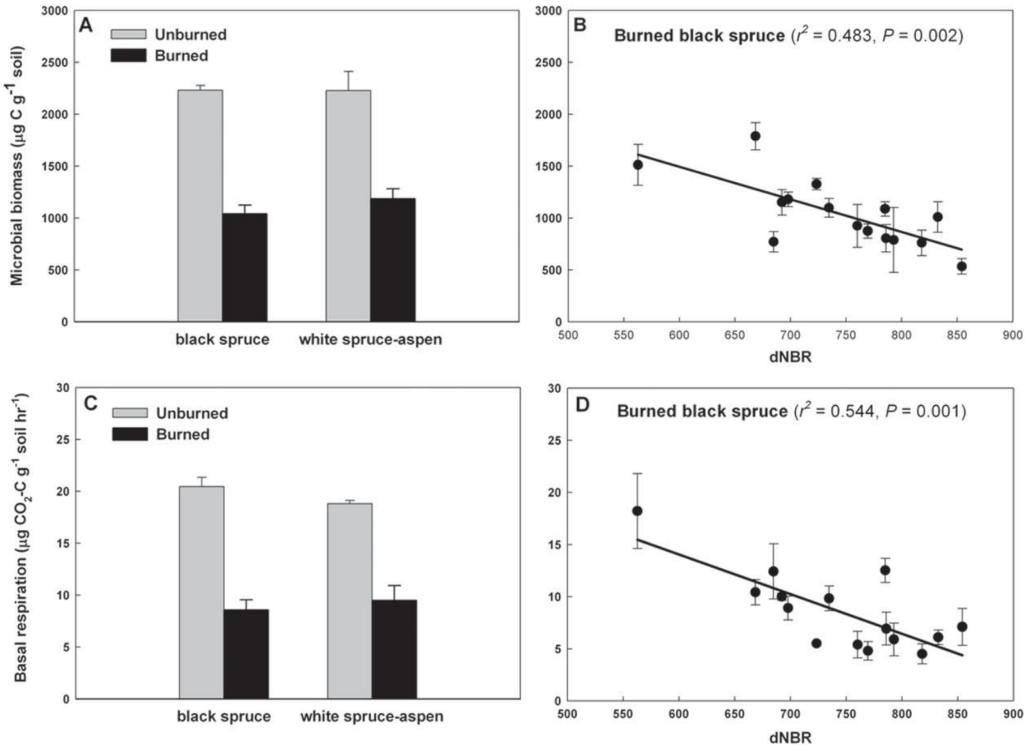

Figure 9. The effect of fire severity on fibric soil microbial biomass and basal respiration (Holden et al. 2016). [Note: Symbols in (B) and (D) represent the mean of 3 soil cores from each burned black spruce stand, and lines are best-fit regressions for burned black spruce stands (n = 15), and the larger the dNBR, the higher the severity of the fire (Holden et al. 2016).]

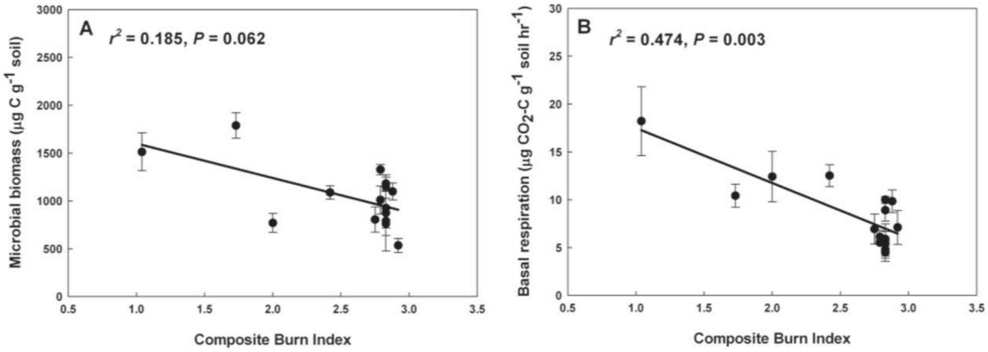

Figure 10. Microbial biomass (A) and basal respiration (B) in burned black spruce stands as a function of the Composite Burn Index (CBI), a visual ground-level assessment of fire severity (Holden et al. 2016).[Note: Black symbols represent the mean of 3 soil cores from each burned black spruce stand (n = 15) and lines are best-fit regressions (Holden et al. 2016.]

As shown in Figure 11, Holden et al. (2016) also found that the fungal phyla and the fungal functional group have different tolerance to fire, and the mycorrhizal group and basidiomycetes have particularly low tolerance to severe fires. In other words, severe forest fires significantly changed the specific combination of mycorrhizal fungi (Holden et al. 2016; Certini 2005; Baar et al. 1999).

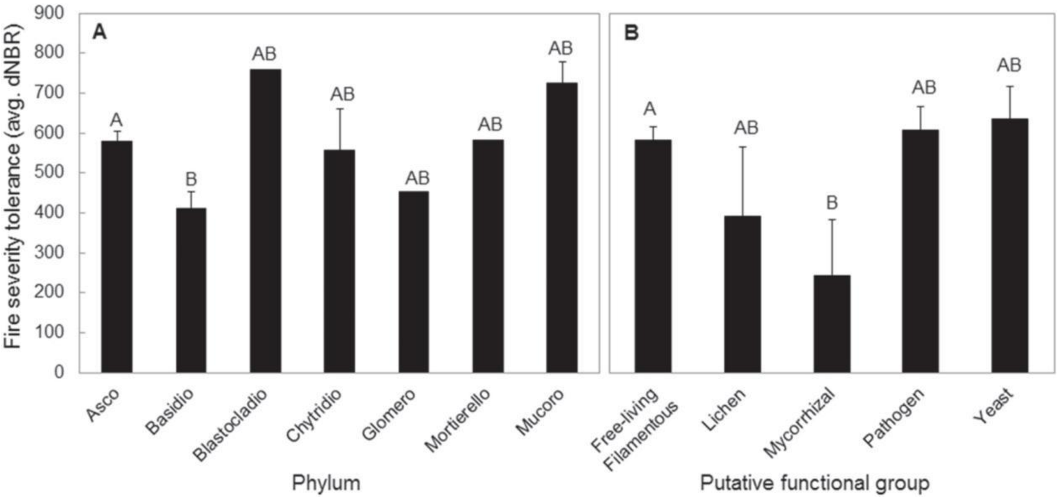

Figure 11. Fire severity tolerance for fungal phyla (A) and fungal functional groups (B) (Holden et al. 2016).

In addition, we can learn from Figure 2(a) that the temperature range required for contaminants is roughly the same as the temperature threshold of the soil biota. In other words, some contaminants produced during the combustion process may also have some indirect adverse effects on the soil biota (Certini 2005). Therefore, fires also can indirectly affect the survival of soil biota by reducing and changing the organic matrix, removing the source of organic residues, and buffering and changing the properties of the soil (Certini 2005; Bissett and Parkinson 1980; Monleon and Cromack 1996).

Combustion also changes the specific composition of the soil microbial community (Certini 2005). This depends on the tolerance of the various components of the soil microbial community to fire.

3.3.2 Invertebrates

The fire adaptability (high mobility, water saving and heat resistance) of invertebrates in fire-affected ecosystems seems to be more species-specific characteristics than fire-specific (Neary et al. 1999).

Wikars and Schimmel studied the effects of fire on soil invertebrates in felled and uncut pine forests in 2001. Their research (2001) showed that the impact of fire on invertebrates living in soil in boreal forests is highly dependent on the depth of combustion in the organic soil, and the death of a single taxa is related to its vertical position in the soil and their ability to move away from the heat. In other words, fire has less impact on invertebrate organisms under normal circumstances. However, in general, the indirect effects of fire, especially the litter mass reduction, can significantly reduce the total quality and quantity of invertebrates (Certini 2005).

4.0 RESULTS AND DISCUSSION

Table 1 is based on the summary of the above review of soil properties affected by fire. In general, low-intensity fires will cause little changes to the physical and chemical properties of the soil but may cause a decrease in the microorganisms in the soil. However, high-intensity fires can cause serious effects. That is, the color of iron-rich soil will become red, the mineral structure will change, the clay content will decrease; the water-resistance of the soil will increase, the pH will increase in non-calcium soil, and the structure of the soil will be destroyed due to the stability of the aggregate. Also, the bulk density will increase, SOM content decreases and its quality changes significantly, nutrients will volatilize and quickly mineralize, the content of microorganisms will decrease and the composition will be changed, and the content of invertebrates will also decrease and their composition will change.

The loss and change of SOM after fire is an important process of the change of the above physical properties. It can be said that the loss of SOM is the most intuitive experience of soil change during the combustion process (Certini 2005; Zhang and Biswas 2017; Verma and Jayakumar 2012). The function of SOM almost always affects the properties and processes of various soils and participates in multiple reactions (for example, SOM can form soil aggregates, build soil structure, absorb and release soil nutrients, retain water, regulate carbon cycle, and support biodiversity) (Obalum et al. 2017; Zhang and Biswas 2017; DeBano 1991). Therefore, in view of the role of SOM in soil accumulation and erosion control, the availability of plant nutrients, and the

Table 1. A review of soil properties affected by fire.

The Effect of Fire on Soil Properties	
Physical Properties	
Soil color, texture and mineralogy	Color, texture, and minerals will not change significantly under low-intensity fires. In a high-intensity fire, the color turns red due to the removal of organic matter and the conversion of iron oxide, and the blackened layer below the reddened layer is due to the carbonization of organic matter. The amount of clay is reduced and there is a finer texture. Changes in the mineral structure.
Water repellency	High and medium-intensity fires will increase the water repellency of acidic and alkaline soil surfaces, but the spatial frequency and persistence of hydrophobicity are different.
Structure stability	The soil structure will be destroyed due to the stability of the aggregate. Different soil types cause different changes.
pH and bulk density	The pH of soils with higher SOM will increase, but in low-SOM or carbonate-buffered soils, the increase in pH caused by the fire is negligible. Bulk density will increase.
Chemical Properties	
SOM	The transformation of SOM mainly occurred on the forest floor. As the temperature increases, the content of SOM decreases, and the quality of SOM changes significantly.
Soil nutrients	Organic N volatilizes or mineralizes. Organic P has different changes in different soil types. Calcium, magnesium, and potassium will increase. The availability of some nutrients will increase, and some nutrients will also be lost.
Biological Properties	
Microorganisms	The microbial biomass and basal respiration will decrease. The composition will also change.
Invertebrates	The reduction of invertebrates is small, and the composition is quite different.

improvement of other forms of soil degradation besides erosion, SOM can be used as the only indicator of soil degradation to assess the risk of soil degradation after fire (Obalum et al. 2017).

SOM is converted into gaseous carbon, pyrogenic carbon or more stable black carbon in case of fire. The volatilization of gaseous carbon will reduce SOM, but pyrogenic carbon or black carbon is not easily decomposed by organisms or non-biologically, so it serves as a long-term soil carbon pool (Zhang and Biswass 2017; Buma et al. 2014). In addition, the greatly reduced microbial biomass and respiration after a high-intensity fire will also lead to the ability of the microbial community to decompose carbon for a long time (Holden et al. 2016; Zhang and Biswass 2017). The reduction in SOM or soil organic carbon stock is soil degradation (Lorenz et al. 2019). Therefore, if the amount of SOM in the forest soil is reduced after a fire and cannot be recovered for a long time due to various reasons, there will be a risk of soil degradation.

SOM combustion period or combustion products will also affect other soil properties at the same time, and some changes in other soil properties will increase the risk of soil degradation. For example, an increase in bulk density after a fire means a decrease in soil water holding capacity, which in turn increases runoff and surface erosion (Certini 2005; Boyer and Miller 1994; Fayos 1997; Martin and Moody 2001). Because fire-induced soil hydrophobicity is used to control fire. The key control factors of post-runoff and erosion rate (MacDonald and Huffman 2004), so the increase of soil water repellency after fire also means that the risk of surface erosion is increased.

Aggregate stability refers to the ability of the soil structure to respond to external mechanical forces (Mataix-Solera et al. 2011). The reduction of aggregate stability means that the soil structure's ability to respond to external mechanical forces is reduced, which also means that there is a risk of soil degradation.

Fires will definitely reduce vegetation coverage, which will also lead to higher soil erosion (Mataix-Solera et al. 2011). Decrease in water permeability and higher soil runoff will also increase the loss of soluble nutrients, and the burning ash is easily blown away by the wind, resulting in a serious decline in nutrients (Zhang and Biswas 2017). The downward leaching of nutrients after a fire can also cause eutrophication problems (Zhang and Biswas 2017).

After a fire, pH will affect the change of ions in the soil. For example, an increase in pH facilitates the solubility of some cations, such as calcium, magnesium, sodium, and potassium, while reducing the solubility of other cations, such as copper and zinc (Pereira et al. 2018; Escudey et al. 2015). A pH above 8 will limit the solubility of phosphorus, but it will easily precipitate with calcium, aluminum and iron (Pereira et al. 2018). These processes will affect the nutrients in the soil, and in some cases, the loss of these nutrients may lead to soil degradation.

The boreal region has a large span and rich soil types. Based on the above results and analysis, corresponding to the matched soil type and vegetation type, we can analyze the correlation of fire disturbance to soil degradation in the northern ecological region. Because fire not only causes soil degradation by affecting the nature of the soil, but natural and human factors after the fire are also the cause of soil degradation (Pereira et al. 2018). Therefore, theoretically speaking, high-intensity fires will cause soil degradation in boreal forests. However, according to the review by Maynard et al. (2014), the fire has no significant impact on the soil erosion of the boreal forest in eastern Canada, but the dry sand landscape ecological zone may increase wind erosion due to the depletion of the thin layer of humus; but elsewhere in the boreal area, the soil erosion caused by these dry sand dunes will be localized. Therefore, we can infer that the possibility of soil degradation in the boreal ecological area after the fire is local, and the soil in more areas will be quickly restored after the adverse impact of the fire.

5.0 CONCLUSION

Low-intensity fires have little impact on forest soils, and even if they have adverse effects, they will be restored in the near future. However, high-intensity fires have an adverse effect on the nature of the soil, which in turn causes the risk of soil degradation under the mutual influence of various factors. There are few studies on boreal forest fires and soil degradation, but we can infer that local areas of boreal soil will degrade after being fired.

Global warming and drought caused by human activities have increased the frequency of wildfires, and frequent wildfires have increased the risk of forest soil degradation. Therefore, future forest management and wildfire prevention and control need to be more cautious to avoid the risk of forest soil degradation.

6.0 LITERATURE CITED

Ahlgren, I. F., and Ahlgren, C. E. 1960. Ecological effects of forest fires. The Botanical Review, 26(4), 483-533.

Alcañiz, M., Outeiro, L., Francos, M., & Úbeda, X. 2018. Effects of prescribed fires on soil properties: A review. Science of the Total Environment, 613, 944-957.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., ... and Vinson, T. S. 1993. Boreal forests and tundra. Water, Air, and Soil Pollution, 70(1-4), 39-53.

Baar, J., Horton, T. R., Kretzer, A. M., and Bruns, T. D. 1999. Mycorrhizal colonization of Pinus muricata from resistant propagules after a stand ‐ replacing wildfire. New Phytologist, 143(2), 409-418.

Badía, D., and Martí, C. 2003. Plant ash and heat intensity effects on chemical and physical properties of two contrasting soils. Arid Land Research and Management, 17(1), 23-41.

Badia, D., and Marti, C. 2008. Fire and rainfall energy effects on soil erosion and runoff generation in semi-arid forested lands. Arid Land Research and Management, 22(2), 93-108.

Baldocchi, D., Kelliher, F. M., Black, T. A., and Jarvis, P. 2000. Climate and vegetation controls on boreal zone energy exchange. Global Change Biology, 6(S1), 69-83.

Bigham, J. M., Golden, D. C., Bowen, L. H., Buol, S. W., and Weed, S. B. 1978. Mössbauer and X-Ray Evidence for the Pedogenic Transformation of Hematite to Goethite. Soil Science Society of America Journal, 42(6), 979-981.

Bissett, J., and Parkinson, D. 1980. Long-term effects of fire on the composition and activity of the soil microflora of a subalpine, coniferous forest. Canadian Journal of Botany, 58(15), 1704-1721.

Boyer, W. D., and Miller, J. H. 1994. Effect of burning and brush treatments on nutrient and soil physical properties in young longleaf pine stands. Forest Ecology and Management, 70(1-3), 311-318.

Buma, B., Poore, R. E., and Wessman, C. A. 2014. Disturbances, their interactions, and cumulative effects on carbon and charcoal stocks in a forested ecosystem. Ecosystems, 17(6), 947-959.

Cade-Menun, B. J., Berch, S. M., Preston, C. M., and Lavkulich, L. M. 2000. Phosphorus forms and related soil chemistry of Podzolic soils on northern Vancouver Island. II. The effects of clear-cutting and burning. Canadian Journal of Forest Research, 30(11), 1726-1741.

Caon, L., Vallejo, V. R., Ritsema, C. J., and Geissen, V. 2014. Effects of wildfire on soil nutrients in Mediterranean ecosystems. Earth-Science Reviews, 139, 47-58.

Certini, G. 2005. Effects of fire on properties of forest soils: a review. Oecologia, 143(1), 1-10.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., and Williams, D. 1983. Forest fire behavior and effects. Fire in Forestry, vol. I.

DeBano, L. F. 1981. Water repellent soils: a state-of-the-art (Vol. 46). US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

DeBano, L. F. 1991. The effect of fire on soil properties. In *Proceedings management and productivity of western-Montane*. Forest Soils (pp. 151-155).

DeBano, L. F. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of hydrology, 231, 195-206.

DeBano, L. F., Neary, D. G., and Ffolliott, P. F. 1998. Fire effects on ecosystems. John Wiley & Sons.

Dixon, J. B. 1989. Kaolin and serpentine group minerals. Minerals in soil environments, 1, 467-525.

Durgin, P. B., and Vogelsang, P. J. 1984. Dispersion of kaolinite by water extracts of Douglas-fir ash. Canadian Journal of Soil Science, 64(3), 439-443.

Dymov, A. A., Gabov, D. N., and Milanovskii, E. Y. 2017. 13 C-NMR, PAHs, WSOC and water repellence of fire-affected soils (Albic Podzols) in lichen pine forests, Russia. Environmental Earth Sciences, 76(7), 275.

Escudey, M., Arancibia-Miranda, N., Pizarro, C., & Antilén, M. 2015. Effect of ash from forest fires on leaching in volcanic soils. Catena, 135, 383-392.

Fayos, C. B. 1997. The roles of texture and structure in the water retention capacity of burnt Mediterranean soils with varying rainfall. Catena, 31(3), 219-236.

Francos, M., Úbeda, X., Pereira, P., and Alcañiz, M. 2018. Long-term impact of wildfire on soils exposed to different fire severities. A case study in Cadiretes Massif (NE Iberian Peninsula). Science of the Total Environment, 615, 664-671.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. Z., & Schepaschenko, D. G. 2015. Boreal forest health and global change. Science, 349(6250), 819-822.

Giovannini, G., and Lucchesi, S. 1997. Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. Soil Science, 162(7), 479-486.

Giovannini, G., Lucchesi, S., and Giachetti, M. 1988. Effect of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Science, 146(4), 255-261.

González-Pérez, J. A., González-Vila, F. J., Almendros, G., & Knicker, H. 2004. The effect of fire on soil organic matter—a review. Environment international, 30(6), 855-870.

Grier, C. C. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Canadian Journal of Forest Research, 5(4), 599-607.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., ... and Kommareddy, A. 2013. High-resolution global maps of 21st-century forest cover change. science, 342(6160), 850-853.

Holden, S. R., Rogers, B. M., Treseder, K. K., and Randerson, J. T. 2016. Fire severity influences the response of soil microbes to a boreal forest fire. Environmental Research Letters, 11(3), 035004.

Hare, F. K., and Ritchie, J. C. 1972. The boreal bioclimates. Geographical Review, 333-365.

Ketterings, Q. M., and Bigham, J. M. 2000. Soil color as an indicator of slash-and-burn fire severity and soil fertility in Sumatra, Indonesia. Soil Science Society of America Journal, 64(5), 1826-1833.

Ketterings, Q. M., Bigham, J. M., and Laperche, V. 2000. Changes in soil mineralogy and texture caused by slash and burn fires in Sumatra, Indonesia. Soil Science Society of America Journal, 64(3), 1108-1117.

Kutiel, P., and Naveh, Z. 1987. The effect of fire on nutrients in a pine forest soil. Plant and Soil, 104(2), 269-274.

Lal, R. 2015. Restoring soil quality to mitigate soil degradation. Sustainability, 7(5), 5875-5895.

Letey, J. 2001. Causes and consequences of fire-induced soil water repellency. *Hydrological Processes*, 15(15), 2867-2875.

Lorenz, K., Lal, R., and Ehlers, K. 2019. Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to U nited N ations' S ustainable D evelopment G oals. Land Degradation & Development, 30(7), 824-838.

MacDonald, L. H., and Huffman, E. L. 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. Soil Science Society of America Journal, 68(5), 1729-1734.

Martin, D. A., and Moody, J. A. 2001. Comparison of soil infiltration rates in burned and unburned mountainous watersheds. Hydrological Processes, 15(15), 2893-2903.

Mataix-Solera, J., and Doerr, S. H. 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in southeastern Spain. Geoderma, 118(1-2), 77-88.

Mataix-Solera, J., Cerdà, A., Arcenegui, V., Jordán, A., and Zavala, L. M. 2011. Fire effects on soil aggregation: a review. Earth-Science Reviews, 109(1-2), 44-60.

Maynard, D. G., Paré, D., Thiffault, E., Lafleur, B., Hogg, K. E., and Kishchuk, B. 2014. How do natural disturbances and human activities affect soils and tree nutrition and growth in the Canadian boreal forest?. Environmental Reviews, 22(2), 161-178.

Miesel, J. R., Hockaday, W. C., Kolka, R. K., and Townsend, P. A. 2015. Soil organic matter composition and quality across fire severity gradients in coniferous and deciduous forests of the southern boreal region. Journal of Geophysical Research: Biogeosciences, 120(6), 1124-1141.

Monleon VJ and Cromack K Jr 1996. Long-term effects of prescribed underburning on litter decomposition and nutrient release in ponderosa pine stands in central Oregon. Forest Ecology and Management, 81(1-3), 143-152.

Nalder, I. A., and Wein, R. W. 1999. Long-term forest floor carbon dynamics after fire in upland boreal forests of western Canada. Global Biogeochemical Cycles, 13(4), 951-968.

Nayakekorale, H. B. 2020. Soil Degradation. In The Soils of Sri Lanka (pp. 103-118). Springer, Cham

Neary, D. G., Klopatek, C. C., DeBano, L. F., & Ffolliott, P. F. 1999. Fire effects on belowground sustainability: a review and synthesis. Forest ecology and management, 122(1-2), 51-71.

O'Brien, P. L., DeSutter, T. M., Casey, F. X., Khan, E., and Wick, A. F. 2018. Thermal remediation alters soil properties–a review. Journal of environmental management, 206, 826-835.

Obalum, S. E., Chibuike, G. U., Peth, S., and Ouyang, Y. 2017. Soil organic matter as sole indicator of soil degradation. Environmental monitoring and assessment, 189(4), 176.

Pape, A., Switzer, C., McCosh, N., and Knapp, C. W. 2015. Impacts of thermal and smouldering remediation on plant growth and soil ecology. Geoderma, 243, 1-9.

Pereira, P., Francos, M., Brevik, E. C., Ubeda, X., and Bogunovic, I. 2018. Post-fire soil management. Current Opinion in Environmental Science & Health, 5, 26-32.

Pereira, P., Ubeda, X., Martin, D., Mataix-Solera, J., and Guerrero, C. 2011. Effects of a low severity prescribed fire on water-soluble elements in ash from a cork oak (Quercus suber) forest located in the northeast of the Iberian Peninsula. Environmental Research, 111(2), 237-247.

Potapov, P., Hansen, M. C., Stehman, S. V., Loveland, T. R., and Pittman, K. 2008. Combining MODIS and Landsat imagery to estimate and map boreal forest cover loss. Remote sensing of environment, 112(9), 3708-3719.

Runesson, U. T. 2002. Borealforest. org. Faculty of Forestry and the Forest Environment, Lakehead University, Thunder Bay, Canada. Available online at: http://www. borealforest. org.

Schulze, D. G., Nagel, J. L., Van Scoyoc, G. E., Henderson, T. L., Baumgardner, M. F., and Stott, D. E. 1993. Significance of organic matter in determining soil colors. Soil color, 31, 71-90.

Schwertmann, U. 1993. Relations between iron oxides, soil color, and soil formation. Soil color, 31, 51-69.

Shields, J. A., Paul, E. A., St. Arnaud, R. J., and Head, W. K. 1968. Spectrophotometry measurement of soil color and its relationship to moisture and organic matter. Canadian Journal of Soil Science, 48(3), 271-280.

Sierra, M. J., Millán, R., López, F. A., Alguacil, F. J., and Cañadas, I. 2016. Sustainable remediation of mercury contaminated soils by thermal desorption. Environmental Science and Pollution Research, 23(5), 4898-4907.

Smith, D. W. 1970. Concentrations of soil nutrients before and after fire. Canadian Journal of Soil Science, 50(1), 17-29.

Soucémarianadin, L. N., Quideau, S. A., Wasylishen, R. E., and Munson, A. D. 2015. Early-season fires in boreal black spruce forests produce pyrogenic carbon with low intrinsic recalcitrance. Ecology, 96(6), 1575-1585.

Stevens-Rumann, C. S., Kemp, K. B., Higuera, P. E., Harvey, B. J., Rother, M. T., Donato, D. C., ... and Veblen, T. T. 2018. Evidence for declining forest resilience to wildfires under climate change. Ecology letters, 21(2), 243-252.

Terefe, T., Mariscal-Sancho, I., Peregrina, F., and Espejo, R. 2008. Influence of heating on various properties of six Mediterranean soils. A laboratory study. Geoderma, 143(3-4), 273-280.

Thiffault, E. 2019. Boreal forests and soils. In Developments in Soil Science (Vol. 36, pp. 59-82). Elsevier.

Ulery, A. L., and Graham, R. C. 1993. Forest fire effects on soil color and texture. Soil Science Society of America Journal, 57(1), 135-140.

Ulery, A. L., Graham, R. C., and Amrhein, C. 1993. Wood-ash composition and soil pH following intense burning. Soil science, 156(5), 358-364.

Verma, S., and Jayakumar, S. 2012. Impact of forest fire on physical, chemical and biological properties of soil: A review. proceedings of the International Academy of Ecology and Environmental Sciences, 2(3), 168.

Wikars, L. O., and Schimmel, J. 2001. Immediate effects of fire-severity on soil invertebrates in cut and uncut pine forests. Forest Ecology and Management, 141(3), 189-200.

Zhang, Q., and Cai, C. 2004. Forest soil degradation research and preventive strategy: a review. *Ecology and Environment*, *13*(4), 677-680.

Zhang, Y., and Biswas, A. 2017. The effects of forest fire on soil organic matter and nutrients in boreal forests of North America: A review. In Adaptive soil management: From theory to practices (pp. 465-476). Springer, Singapore.