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Impact of forest fire on physical, chemical and biological properties of soil: A review

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Abstract

Forest fire is very common to all the ecosystems of the world. It affects both vegetation and soil. It is also helpful in maintaining diversity and stability of ecosystems. Effect of forest fire and prescribed fire on forest soil is very complex. It affects soil organic matter, macro and micro-nutrients, physical properties of soil like texture, colour, pH, Bulk Density as well as soil biota. The impact of fire on forest soil depends on various factors such as intensity of fire, fuel load and soil moisture. Fire is beneficial as well as harmful for the forest soil depending on its severity and fire return interval. In low intensity fires, combustion of litter and soil organic matter increase plant available nutrients, which results in rapid growth of herbaceous plants and a significant increase in plant storage of nutrients. Whereas high intensity fires can result into complete loss of soil organic matter, volatilization of N, P, S, K, death of microbes, etc. Intense forest fire results into formation of some organic compounds with hydrophobic properties, which results into high water repellent soils. Forest fire also causes long term effect on forest soil. The purpose of this paper is to review the effect of forest fire on various properties of soil, which are important in maintaining healthy ecosystem.

Keywords forest soil; wildfires; soil organic carbon; plant available nutrients; soil dwelling invertebrates; soil physical characteristics.

1 Introduction

Evidence of fire is found first in the Carboniferous age 400 million year ago forming fusains or fossilized charcoal in coal deposits (Spinage, 2012). Source of these fires have been both natural and anthropogenic (Kodandapani, 2001). Fire is helping to shape global biome distribution and to maintain the structure and function of fire-prone communities (Thonicke et al., 2001; Sankaran et al., 2005; Bond and Keeley, 2005; Frissell, 1973). Fires are a natural occurrence in tropical forests, and as human development increases, fires may become more frequent. Fire effects on soil may have strong influences on the composition and structure of post-fire forests (Jain, et al., 2008). Fire is used as a management tool to administer a wide range of ecosystem worldwide. Forest fires occur in almost all types of ecosystem. Some of these ecosystems are extremely sensitive to fire, but without subsequent ignition that leads to extensive wildfires, they can recover (Kraus and Goldammer, 2007)

Throughout the last century, great efforts and vast resources have been applied to understanding and managing fire in forest (Knorr et al., 2011). However in tropics recently, demographic and land use changes have made fire a matter of serious concern (Coachrane, 2003; Goldammer, 1990). Many studies have

addressed the influence of such disturbances on soil properties. The role of forest fire on forest soil is very complex and less studied in comparison to its aboveground effect (DeBano et al., 1998). Fire can influence a variety of soil physical and chemical properties of soil including the loss or reduction of structure and soil organic matter, reduced porosity, and increased pH (DeBano, 1990; Certini, 2005). Change in soil properties after fire produces varying responses in the water, vegetation dynamics, and fauna of ecosystems. The wide range of effects is due to the inherent pre-burn variability in these resources, fire behaviour characteristics, season of burning, and pre-fire and post-fire environmental conditions such as timing, amount, and duration of rainfall (Clark, 2001). These changes can also result in various indirect impacts including increased hydrophobicity (water repellency), which results in decreased infiltration and increased runoff that often results in increased erosion (DeBano, 2000). The effects of fire on soils directly depend on fire intensity and the duration of combustion. Depending on the fire severity, these changes in soil properties may be beneficial or deleterious to entire ecosystem (Neary, 1999). The objective of this paper is to summarize the overall possible impact of forest fire on physical, chemical and biological properties of soil from available literature and to find the gap in the studies carried out on forest fire and soil in different ecosystems.

2 Impact of Fire on Physical Properties of Soil

Soil physical properties are those characteristics, processes, or reactions of a soil that are caused by physical forces that can be described by, or expressed in, physical terms or equations (SSSA, 2001). Important physical characteristics in soil that are affected by soil heating include: Soil colour, texture, pH, bulk density, and water holding capacity.

2.1 Soil colour and texture

Many physical properties of soil can be affected by forest fire. The effects are mainly because of burn severity (Ketterings and Bigham, 2000). Soil colour and texture are most noticeable altered in severely burned soil under concentrated fuel in comparison to nearby slightly or moderately burned soil (Ulery and Graham, 1993). At higher temperature reddening of soil matrix occurs. Redder hue appears in the burned soils is apparently because of Fe-oxides transformation and complete removal of organic matter (Ulery and Graham, 1993; Certini, 2005). While in low to moderate fire ground is covered by a layer of black or grey ash (Certini, 2005). Reddening at high temperature (600°C) did not occur until after 45 min of exposure, Munsell hues became yellower as values and chromas decreased with short-term heating at 300 or 600°C (Ketterings and Bigham, 2000). Surface patches of reddened soil indicate the place where soil was severely burned and are detectable by a characteristic increase in magnetization compared to surrounding soil. Hence, the long- term patterning of forest fire intensities over a landscape may be detectable as the spatially heterogeneous accumulation of thermally produced iron oxides in soils (Goforth et al., 2005). In severely burned soil underlying layer is blackened with the thickness of 1-15 cm and lower munsell value (Ulery and Graham, 1993).

The components of soil texture (sand, silt, and clay) have high temperature thresholds and are not usually affected by fire unless they are subjected to high temperatures at the mineral soil surface (A-horizon). The most sensitive textural fraction is clay, which begins changing at soil temperatures of about 400°C when clay hydration and clay lattice structure begin to collapse. At temperatures of 700 to 800°C the complete destruction of internal clay structure can occur (Neary et al., 2008). Ulery and Graham (1993) reported that after fire reddened soil layers had significantly less clay content than unburned soils. Blackened layers and Sand-sized aggregates formed in the surface soils during burning alter the particle-size distribution and resulting in coarser textures due to a greater proportion of sand. 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).

2.2 Soil pH and bulk density

Soil pH is generally increased after forest fire (Tufeccioglu et al., 2010; Aref et al., 2011; Boerner et al., 2009). However significant increase occurs only at higher temperature (450-500⁰C) (Certini, 2005). The presence of ash may increase soil pH due to high pH of ash (Molina et al., 2007; Schafer and Mack, 2010).

Bulk density is the mass of dry soil per unit bulk volume (expressed in g/cm³) and is related to porosity, which is the volume of pores in a soil sample (nonsolid volume) divided by the bulk volume of the sample. Bulk density of forest soils increase significantly as a result of forest fire (Boerner, et al., 2009; Certini, 2005). Bulk density increases because of collapse of aggregates and clogging of voids by the ash and dispersed clay minerals; as a consequence, soil porosity and permeability decreases (Certini, 2005). Bulk density increases with ash depth (Cerdà and Doerr, 2008).

2.3 Water repellency

Soil water repellency (WR) is one of the properties most affected by combustion during a forest fire (Mataix-Solera et al., 2012). The main effect of fire on soil physical properties is to eliminate the storage capacity of water in the organic horizons (several cm). At first, infiltration rates remain high but later these decrease as there is a reduction in porosity (Imeson et al., 1992). High surface temperatures 'burn' off organic materials and create vapours that move downward in response to a temperature gradient and then condense on soil particles causing them to become water repellent (Letey, 2001). Highly variable water repellent soil conditions have been reported after forest fires (Robichaud and Hungerford, 2000; DeBano, 2000; MacDonald and Huffman, 2004). It is strongest at the soil surface in areas burned at high and moderate severity, and declined in strength with decreasing burn severity and increasing depth (MacDonald and Huffman, 2004). Soil water repellency prohibits water from wetting or infiltrating of dry soils (Doerr et al., 2009). Water repellency is caused by presence of organic compound with hydrophobic properties on soil particle surface (Doerr et al., 2009). Water repellency may influence seedling survival and subsequent stand establishment (Reeder and Jurgensen, 1979).

Studies on water repellent soil after fire was started in 60's and enough studies have been done on this topic (DeBano, 2000). Future research on water repellent soil should consider the response of soil water repellency for microbial activity, decomposition rates and plant productivity. Consequently, there is a need for systematic manipulation experiments investigating the effects of dryness and heat on water repellent soil.

3 Impact of Fire on Chemical Properties of Soil

3.1 Impact on organic matter (OM)

There are five principal global C pools. The oceanic pool is the largest, followed by the geologic, pedologic (soil), biotic and the atmospheric pool. Soil organic matter (SOM) represents the third largest terrestrial carbon pool, with a global estimated total of 1526 pgC (Lal, 2004). The most intuitive change soil experience during burning is loss of organic matter (Certini, 2005). The organic horizon is critical component of ecosystem sustainability in that it provides a protective soil cover that mitigates erosion, aids in regulating soil temperature, provides habitat and substrates for soil biota and can be major source of readily mineralizable nutrients (Neary et al., 1999). It plays an important role in soil cation exchange capacity (CEC) and retention of ions (Crasswell and Lefroy, 2001).

The effect of fire on SOM is highly variable from total destruction of SOM to partially scorching depending on fire severity, dryness of the surface OM and fire type (Neary et al., 1999; Gonza'lez-Pe'rez et al., 2004). The effect of fire on SOM is highly dependent on the type and intensity of the fire, among other factors, soil moisture, soil type, and nature of the burned materials. Therefore, the effect on soil processes and their intensity influenced by fire are highly variable and no generalized tendencies can be suggested for most of the fire-induced changes in humus composition (Gonza'lez-Pe'rez et al., 2004). Low-intensity prescribed fire

usually results in little change in soil carbon, but intense prescribed fire or wildfire can result in a huge loss of soil carbon (Johnson, 1992). Whereas increasing the fire frequency results in an increase in carbon in the fine fractions of the soil, and an increase in the $\delta^{13}\text{C}$ value of SOC in all size fractions, while soil texture, on the other hand, controls the magnitude of the increases in both the abundance and $\delta^{13}\text{C}$ value of SOC in all size fractions (Bird et al., 2000). Differences in measured isotope amount ratios of stable carbon isotopes ($^{13}\text{C}/^{12}\text{C}$), commonly called $\delta^{13}\text{C}$ values (Coplen et al., 2006). Charcoal is formed after forest fire in the forest floor. Charcoal can promote rapid loss of forest humus and belowground carbon during the first decade after its formation, because charred plant material causes accelerated breakdown of simple carbohydrates (Wardle et al., 2008). Fernandez et al., (1997) suggested that in low intensity fire, lipids are least affected group whereas 90% of water soluble cellulose, hemicelluloses and lignin are destroyed.

3.2 Impact on nutrient dynamics

This discussion of fire effects on soil nutrients dynamics will focus on the soil chemical changes, losses and availability of macro and micronutrients. These nutrients are most likely to affect site productivity and vegetation dynamics and therefore of most interest to forest managers and ecologists. The nutrient elements in biomass and detritus will have one of three fates following fire. They may be lost to the atmosphere, deposited as ash, or remain in incompletely burned vegetation or detritus (Boerner, 1982). Research suggests that after forest fire soil nutrient decreases but their plant available forms increases (Kutiel and Naveh, 1987). Burned soils have lower nitrogen than unburned soils, higher calcium, and nearly unchanged potassium, magnesium, and phosphorus stocks (Neff et al., 2005).

3.2.1 Macronutrients

The immediate effect of fire on soil macronutrients is its loss through volatilization because of high temperature (Certini, 2005; Neary et al., 1999). During high intensity fire, temperature reaches to 675°C where as in moderate and low intensity fire temperature reaches to 400°C and 250°C respectively (Neary et al., 1999). Nitrogen volatilization during prescribed fire is the dominant mechanism of Nitrogen loss from these systems (Caldwell et al., 2002). At the 500°C , half of the Nitrogen in organic matter can be volatilized (Neary et al., 1999; Knicker, 2007). It has long been controversial in fire ecology whether or not fire significantly alters total soil N pools (Wan et al., 2001). But it is suggested that burning can increase the nitrogen concentration of the residual material. Fire may affect soil nutrient status by direct addition of nutrients and by indirectly altering the soil environment (Marion et al., 1991). Nutrients in small live twigs or dead plant material are probably either lost by volatilization during fire or released in a highly soluble form and deposited on the soil surface. These highly soluble plant nutrients on the soil surface may be used for plant growth or easily lost by erosion (DeBano and Conrad, 1978). This nutrient enhancement is largely restricted to the surface soil (0-5 cm); only soluble N appeared to increase in the subsurface soil (5-10 cm) (Marion et al., 1991). The most significant short-term effects of the wildfire are the increases in the soil solution concentrations and/or leaching of mineral forms of N, S, and P (Murphy et al., 2006).

However, the total amount of nitrogen decreases (Knight, 1996). Magnesium (Mg), calcium (Ca), and Manganese (Mn) are relatively less sensitive in comparison to nitrogen because of high threshold temperature of 1107°C , 1484°C , and 1962°C respectively (DeBano, 1990). Phosphorus (P), Potassium (K) and Sulfur is partially affected in high intensity fire (DeBano and Conrad, 1978).

3.2.2 Micronutrients

The behaviour of micronutrients, such as Fe, Mn, Cu, Zn, B, and Mo, with respect to fire is not well known because specific studies are lacking (Certini, 2005). The influence of fire on micronutrient availability is useful to understand its effect on the post-fire recovery of soils and plants (García-Marco and González-Prieto, 2008). Few studies are suggesting that micronutrients also experience reduction in the amount after forest fire. Marafa

and Chau, (1999) reported reduction in the amount of Mn by 14%, Fe by 12% and Zn by 4% after fire event. García-Marco and González-Prieto (2008) studied short- and medium- term effects of fire on soil micronutrient availability. They reported that prescribed fire cause short-term changes in the soil micronutrient availability, increasing that of Mn and Zn and decreasing that of Fe and Co; they found no effect on Cu availability.

4 Impact of Fire on Biological Properties of Soil

Fire affects biological organisms either directly or indirectly. Direct effects cause short-term changes. In direct effects any particular organism is exposed directly to the flames, glowing combustion, hot gases, or is trapped in the soil and other environments where enough heat is transferred into the organism's immediate surroundings to raise the temperature sufficiently to either kill or severely injure the organism. Indirect effects usually cause long-term changes in the environment that impact the welfare of the biological organisms. These indirect effects can involve competition for habitat, food supply and other more subtle changes that affect the reestablishment and succession of plants and animals.

4.1 Impact on invertebrates

Soil dwelling invertebrates play an important role in litter decomposition, C and nutrient mineralization, soil turnover and soil structure formation (Neary et al., 1999). Generally, the direct effects of fires on soil dwelling invertebrates are less marked than those on micro-organisms, in contrast to plants, may be able to move away from fire. The mobility of invertebrates generally increases with body size, but also for similar- sized organisms, the capacity to burrow through soil differ greatly (Certini, 2005; Wikars and Schimmel, 2001). The fire caused considerable changes in the abundance and species composition of soil dwelling invertebrates through both, instant mortality and habitat alteration acting on the pre-fire community, as well as by a quick colonisation by fire-favoured species. Fire-severity, expressed as the depth of burn, considerably affected the patterns of survival, colonisation and recovery (Wikars and Schimmel, 2001).

It is essential to monitor the recovery of more specific groups of invertebrates. The use of overall species richness and abundance as measures of invertebrate recovery gives misleading results, as these measures here showed little variation, with the major differences being in species composition.

4.2 Impact on micro-organisms

Soil micro-organisms play an important role in nutrient cycling and energy flow, and they are extremely sensitive to environmental changes. Soil micro-organisms have numerous functional roles in forest ecosystems, including serving as sources and sinks of key nutrients and catalysts of nutrient transformations; acting as engineers and maintainers of soil structure; and forming mutualistic relationships with roots that improve plant fitness (Hart et al., 2005). Forest fire can significantly alter microbes that affect large-scale processes such as nutrient cycling (Neary et al., 1999). The immediate effect of fire on soil microorganism is a reduction of their biomass. The intense fire can reduce a significant amount of biomass of microorganism. Infact peak temperature often considerably exceed those required for killing most living being (DeBano et al., 1998).

4.2.1 Impact on soil bacteria

There are insufficient data present on impact of forest fire on soil bacteria few studies conducted on soil bacteria after forest fire suggesting that Bacterial community structure is significantly changed after fire event. Community structure of soil bacteria in post-fire non-climax forest several years after fire can be more heterogeneous compared with that in unburned climax forest (Otsuka et al., 2008). Aerobic heterotrophic bacteria, including the acidophilic and sporulating ones, were stimulated by fire while cyanobacteria, was clearly depressed. In the long term, the positive effect of fire on bacteria was nullified except on the sporulating ones reached the unburned soil values, cyanobacteria also increased. Soil incubation improved the

beneficial and diminished the negative fire effect on the micro biota (Vázquez et al., 1993). Whereas Jaatinen et al. (2004) studied that there is no significant effect of forest fire on methane oxidizing bacteria. They suggested that fire increased CH₄ oxidation rates, but the increased pH after the fire and ash probably do not cause any alterations in methane oxidizing bacteria. Further studies should take into account the long term impact of forest fire on bacterial community and other factors which in turn affect bacterial community.

4.2.2 Impact on Mycorrhiza

Mycorrhizal fungi maintain overall forest health. They play a crucial role in nutrient uptake, extended root life and protection against root pathogens. Stendell et al. (1999) studied that the total ectomycorrhizal biomass in the unburned plots did not differ for any core layer, while in the burnt site, the destruction of the litter organic layer resulted in an eight-fold reduction in total ectomycorrhizal biomass. Mycorrhizal biomass in the two mineral layers was not significantly reduced by the fire. Forest fire can affect arbuscular mycorrhizal (AM) fungi by changing the soil conditions and by directly altering AM proliferation (Rashid et al., 1997). Rashid et al. (1997) suggested that compared with a nearby control area, the burnt site had a similar number of total spores but a lower number of viable AM fungal propagules. To establish the relationships of mycorrhizal activity, time following fire and soil edaphic factors, both the dynamics of succession of vegetation and associated AM fungal populations need to be examined further specially in tropics.

5 Summary and Conclusion

Both prescribed fire and wild fire definitely produce large impact to forests. These fires increase water repellency in forest soil, which results into infiltration and soil erosion. Fires also affect Soil colour, pH, bulk density, texture, etc.

Chemical changes in soil after forest fire are more important. Because changes in nutrient cycle and soil organic matter can change the productivity of ecosystem. The effect of forest fire on SOM varied from complete combustion to increase in amount. The effect of forest fire on nitrogen is also variable. Most of the studies have suggested that increase in the total plant available forms of nitrogen (NH₄⁺) but reduction in the amount of total nitrogen. This reduction in the nitrogen is because of volatilization. Other nutrients are less affected in comparison to nitrogen. High availability of nutrients results into this sudden flush of nitrogen in the soil is followed by a rapid growth of herbaceous plants and a significant increase in plant storage of nitrogen (Kutiel and Naveh, 1987). There are very few studies on effect of forest fires on the micronutrients.

Biological properties of soil are also highly affected. It is because of sensitivity of micro-organisms and invertebrates towards high temperature. Fire decreases the number and species richness of both soil dwelling invertebrates and micro-organisms. But in comparison to micro-organisms, soil dwelling invertebrates are less affected because of high mobility and burrowing habit.

The effect of fire on soil has been studied in various parts of the world. But their effect is not well studied in tropical forest. Consumption of organic soil horizons has only been quantified in a limited number of vegetation types. There is still a need to quantify consumption and soil heating in tropical forest. Soil micro-organisms are complex and how they respond to fire will depend on numerous factors, including fire intensity and severity, site characteristics, and pre-burn community composition. Various vegetation types, which burned with various intensity that are conducted at intervals of 1–10 years may have long-term effects on the abiotic and biotic components of the soil. Understanding of these responses is needed.

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