International Journal of Plant & Soil Science

Volume 35, Issue 20, Page 8-17, 2023; Article no.IJPSS.105717
ISSN: 2320-7035

Effects of Forest Fire on Soil Properties

Elakiya N. [a++*], Keerthana G. [a++] and Safiya S. [a#]

[a] J. K. K. Munirajah College of Agricultural Science (Affiliated to TNAU), Gobichettipalayam - 638506, Erode, Tamil Nadu, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJPSS/2023/v35i203780

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/105717

Minireview Article

Received: 05/07/2023
Accepted: 10/09/2023
Published: 16/09/2023

ABSTRACT

One of the most harmful challenges to our forest is fire. The impact of forest fires on soil physical properties had an emphasis on texture, bulk density, porosity, aggregate stability, and water content and repellency. Following the fire, the surface soil of the burned region had higher soil pH, total nitrogen, accessible phosphorus, potassium, calcium, and magnesium levels than the unburned area. The low intensity of the fire caused the organic matter in the soil and the litter to burn, increasing the availability of nutrients and -promoting herb regeneration and post-fire community expansion. Higher-intensity fires completely destroy soil organic matter, volatilize nitrogen, phosphorus, and potassium, and kill microorganisms, while Mn, Mg, and other micronutrients are completely burnt at very high temperatures. Some nutrients were more readily available by the burning of soil organic matter (OM), such as N, P, and S, while others were volatilized. Controlled fire did not result in any significant changes to the nutrients or physico-chemical composition of soil and can be utilized as an efficient management technique to reduce the harm caused by wildfires to soil. Remote sensing and GIS technology are the highly advanced tools used to detect forest fires, calculate burned areas, and determination of changes in land use.

[++] *Assistant Professor (SS&AC);*
[#] *B.Sc., (Hons.,) Agriculture Student;*
**Corresponding author: E-mail: elakiya.nandu@gmail.com;*

Keywords: Forest fire; soil; nutrients; water repellency; soil organic matter.

1. INTRODUCTION

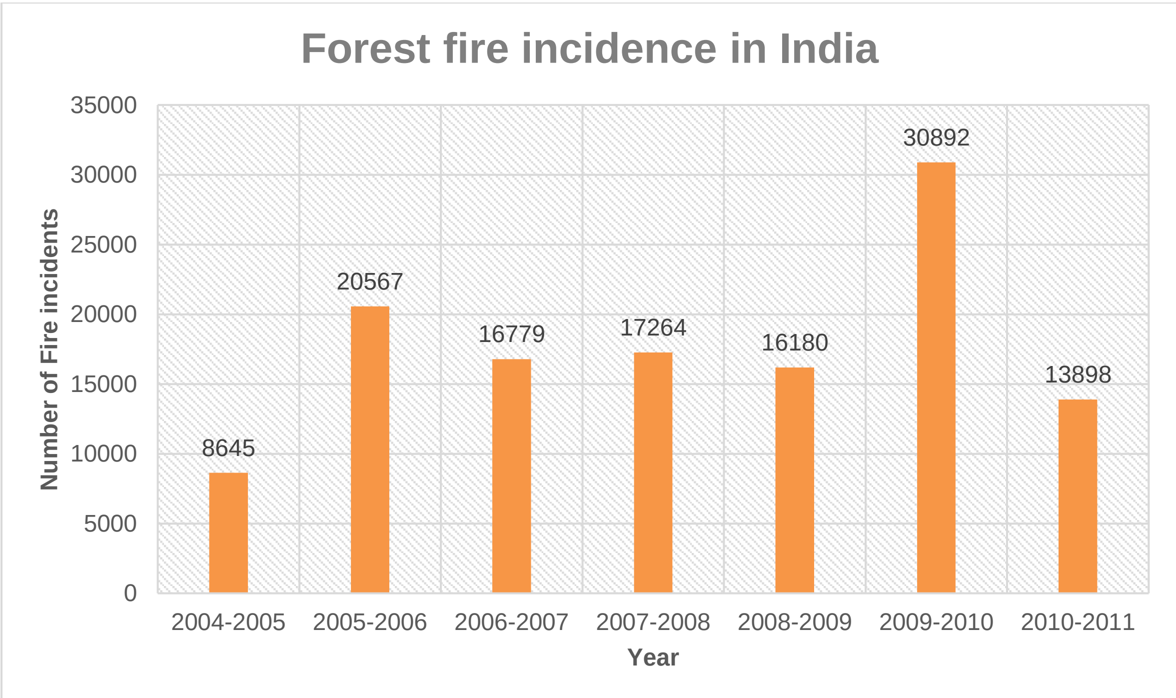
A natural disturbance such as fire can quickly alter –soil's physical, chemical, and biological aspects - in a forest environment [1]. Fires have recently been linked to one of the main soil-forming factors [2]. Forest fires may have an impact on a combination of vegetation cover, structure, composition, density, and productivity - leading to deforestation, population decline, consequences of the forest edge, and exotic animal immigration species [3,4]. A forest fire can change the soil properties including soil texture, soil colour, soil water content, bulk density, CEC, hydraulic conductivity, porosity, pH, EC, macronutrients, micronutrients and microbes which -are the effects of forest fires on soil properties [2].

2. A HISTORICAL PERSPECTIVE OF FOREST FIRE

In India, the trees and other types of vegetation span 80.9 million hectares, or 24.62 per cent of the total land area. According to records from the forest inventory, 35.71% of India's woods have not yet experienced any significant fires, while the remaining 54.45% of forests are subject to occasional fires, 7.49% to moderately frequent fires, and 2.40% to high incidence levels. Madhya Pradesh has the biggest amount of forest cover overall in the nation. Madhya Pradesh, located in central India, is particularly vulnerable to forest fires followed by states like Maharashtra, Chattisgarh, and Odisha [5].

3. FACTORS INFLUENCING FOREST FIRE

Fire is brought into forests by various indigenous populations to help in the collection of non-timber forest products [6] and through incendiarism and accidental fires [7]. Dry deciduous woodland exhibits notable high burnt areas [8]. High resin content in subtropical pine regions and dry conditions in tropical regions, according to Chandra [9] have been important factors in fire propagation in India. The strength of the fire and other factors determine its size, harshness, heating of the soil, season of the burn, length of residency, and time since the last fire. The direct reduction of biomass and carbon stored in seasonally dry tropical forests caused by fire had an impact on biomass and carbon build-up as well [10,11].



(Data collected from FSI., 2012)

Fig. 1. Graphical distribution of year-wise forest fire incidence in India from 2004 to 2011

4. CONSEQUENCES OF FOREST FIRE

Jhariya and Raj [12] claimed that wildfire consequences have an impact on soil productivity. The presence of vital nutrients, such as N, S, P, K, Ca, etc., maintains productivity which fire is capable of altering. The habitat of animals has been impacted by fire, and it could yet be either directly by habitat modification or death [13]. According to Kirkpatrick et al. [14], the longer-term reactions of many bird species are assumed to be predominantly caused by structural changes in vegetation or changes in food availability as a result of fire severity.

5. FIRE EFFECTS ON SOIL PROPERTY

The soil characteristics close to the soil surface were altered by fire because they are exposed to surface heating [15]. The physical, chemical, and biological qualities of soil can be affected by forest fires.

5.1 Fire Effects on Physical Properties of Soil

5.1.1. Soil texture and colour

The relative number of inorganic components in the soil's mineral composition is shown by the texture of the soil, which shows the particle size distribution. Due to the high-temperature thresholds of sand, silt, and clay, the texture is not easily impacted by forest fires [16]. Clay has a lower critical temperature (400-800^{0}C) than sand and other materials, and silt (1414^{0} C) [17]. Consequently, clay particles are more affected in terms of soil texture. At higher temperatures, the soil matrix had turned red from the transformation of iron oxides and the full elimination of organic matter, whereas at lower temperatures, the ground layer was covered with black or grey ash [2].

Clay is the most sensitive textural component, and clay hydration and clay lattice structure start to collapse at soil temperatures of roughly 400^{0} C. The interior clay structure may completely disintegrate at temperatures of 700 to 800 ^{o} C [18]. According to Nardoto and Bustamante [19], fire also had an impact on soil texture, causing variations in sand, silt, and clay between burned and unburned sites at a depth of 0–5 cm. Unburned material increases the amount of sand and silt (21%, and 13%, respectively) at the burned site, however, the clay was reduced from 74% to 66%. According to Pierson et al. [20], the texture of soil stayed the same following a fire clay loam with gravel and silt.

5.1.2 Soil water content

Compared to unburned soil, burned soil has lower soil water content. As a result of the destruction of vegetation by fire, evaporation is accelerated in burned areas during the dry and hot seasons [21]. Soil water repellency (SWR) increases runoff and decreases water infiltration, which leads to increased soil erosion [23]. Soil water content thus declines, which is another factor contributing to lower K salt and infiltration rates and low soil water content in burned soil. Only a minor quantity of the volatilized organic matter goes downward into the soil where it condenses to form a water-repellent layer that prevents infiltration [23].

The modifications may also enhance water repellency, which results in decreased water consumption, among other indirect effects Erosion is frequently made worse by infiltration and increased runoff [1]. Two weeks after the fire, burned soils had less water than unburned soils. Water repellency of the soil affects infiltration and erosion processes in a way that enhances overland flow and decreases water infiltration. It was determined that the low to mild wildfire caused the soil aggregates to break down and the water repellency to increase, this resulted in more runoff [24].

5.1.3 Bulk density

Forest fires have a detrimental effect on soil bulk density, which impacts soil porosity [25, 26, 27]. Because of the collapse of the aggregate and the filling of the voids by the ash, bulk density was slightly raised (less than 1%), causing a reduction in the porosity and permeability of the soil [16]. After a fire, soil aggregation collapses and soil organic matter is destroyed, increasing the bulk density [16]. Heydari et al. [27] reported that an increase in soil bulk density was caused by a drop in organic matter. Since soil porosity and bulk density are inversely related, an increase in bulk density results in a decrease in porosity, further impacting the hydrological properties of the soil [28,29].

5.1.4 Hydraulic conductivity and porosity

Burned soils had lower saturated hydraulic conductivity and porosity than unburned soils. The amount of disruption caused by fire to the surface material typically, organic detritus protecting the underlying mineral soil, is the main determinant of hydraulic conductivity [30]. According to research by Valzano et al. [31], hydraulic conductivity dropped by around 50% in burned soils compared to unburned soils.

In Lapseki soil in Çanakkale, burned sites had higher pH, EC and Available N, P and K content than un-burned soils. Negative effects of forest fire on surface soil carbon contents were observed. Further, in burned soils, the parameters such as Urease, Microbial Biomass Carbon (MBC), Organic Carbon (OC), and Cation Exchange Capacity (CEC) were lower than in un-burned soils. Saturated hydraulic conductivity (Ksat) and porosity values of burned soils were significantly lower than un-burned control. Un-burned soils had higher water content than burned soils.

5.2 Fire Effects on Chemical Properties of Soil

5.2.1 Soil pH and EC

Only at higher temperatures can forest fires considerably raise the soil pH from 5 to 6.3 at depths of 0 to 10 cm and 5.7 to 6.2 at depths of 11 to 20 cm depth [32]. The high pH of the ash may raise the soil pH. An extremely small increase in soil electrical conductivity was seen after one year of controlled fire [33]. Due to the release of inorganic ions from the burned soil organic matter, EC was somewhat higher in burned plots than in unburned plots after the fire [33,34,35]. The presence of base cations in the ash, such as calcium, magnesium, and potassium, causes an elevation in pH and EC [8].

5.2.2 Soil organic matter

The third largest terrestrial carbon store is soil organic matter (SOM), with an estimated amount of 1526 Pg C [37]. According to Nabatte and Nyombi [48], burning reduces the amount of organic matter content which lowered organic matter in burned plots (4.593%, range 2.6-6.1 %) than in unburned plots (5.11%, range 2.8-8.2%). Wildfires can cause a significant loss of soil carbon, low intensity prescribed fire often causes little change in soil carbon [39]. Volatilization of organic carbon and the conversion of organic matter to ash were the main causes of carbon loss from the burned soil [40].

According to studies, the amount of organic matter following a forest fire may rise because of a large amount of dead root biomass [41] or fall due to a lack of aboveground litter fall inputs [42]. Red pine (*P. resinosa*) had more organic materials following burning [43]. Ash covering the top soil layer of the burned parts had raised the organic material content [44. 45].

5.2.3 Cation exchange capacity

Burning lowers soil CEC. In Lapseki soils of Turkey, CEC value of burned soil and un-burned soil was 20.13 and 25.27 cmol kg^{-1}, respectively. The fire should not affect the CEC of mineral soils but may change the CEC of soils rich with organic carbon [40].

Table 1. Mean values of physical, chemical and biological properties of burned and unburned forest soil

Soil parameters	Burnt	Unburnt
EC (mhos cm^{-1})	576.67	189.67
pH (1:2.5 water soil ratio)	5.88	5.41
Organic Nitrogen (%)	0.57	0.44
Microbial Biomass carbon (mg C g $soil^{-1}$)	2	2
Urease activity (mg kg^{-1} 2 h^{-1})	2.28	4.97
Soil organic carbon (%)	714	7.74
Available P (mg kg^{-1})	51.74	18.52
Available K (mg kg^{-1})	194.15	167.05
Cation Exchange Capacity (cmol kg^{-1})	20.13	25.27
Total Porosity (%)	48.52	53.44
Bulk Density (g cm^{3-1})	1.31	1.22
Hydraulic conductivity (cm h^{-1})	5.47	10.5
Soil water content (%)	1.93	4.1

(Huseyin Ekinci, 2006)

5.2.4 Soil Nitrogen

A considerable amount of N is lost during a fire, which has a negative impact on agricultural production. Due to the high temperature, nitrogen is lost through volatilization, and at 500^{0}C, 50% of the nitrogen in OM can be volatilized [17]. However, burning can raise the leftover material's nitrogen concentration. It's likely that nutrients are either volatilized away or released in a highly soluble form and deposited on the soil surface. According to Rundel and Kutiel and Inbar [46,47], N loss can happen during a fire period through volatilization, and after a fire, there may be an increase in biological N fixation due to an increase in the rate of soil mineralization.

A small increase in nitrogen availability was seen across all land uses after a controlled fire that lasted twelve months, at 0-5 cm depth, and the highest percentage increase in available N was observed under burnt pine forest reaching up to 2.84% [48]. Burned soils were found to have greater organic N concentrations than unburned soils. Johnson and Curtis [49] also noted that following a forest fire, the number of N-fixing bacteria rose, which was a direct result of increases in N and C content in the upper soil.

5.2.5 Available Phosphorus, Potassium & Exchangeable Cations

In post-burned soils, phosphate and potassium levels were higher. For plants to absorb, organic phosphorus in the organic matter mineralizes after forest fires to create accessible orthophosphate [50]. Exchangeable cations including Ca^{2+}, Mg^{2+}, K^+ and Na^+ have been shown to increase after forest fires in various studies [51,52]. Plants and leftovers burn, turning to ash in the soil, increasing the P content [53].

Increased exchangeable cation concentrations in soils following a fire, however, may only be temporary and quickly revert to pre-fire levels [25,54,55]. Exchangeable cation losses might result from ash erosion, cation leaching, plant uptake during post-fire succession, and their high vaporization thresholds [56].

5.2.6 Micronutrients

Fe content decreased by 12%, Mn by 14%, and Zn by 4% following a fire [35]. However, the amount of Mn and Zn increased and that of Fe and Co decreased, but no effect on Cu availability. After a fire, the impact of micronutrients like Fe, Cu, Zn, B, and Mo was not well understood [2].

5.3 Fire Effects on Biological Properties of Soil

The heating of soils by wildfires causes variations in soil biological properties (microorganisms, biota activities, and soil invertebrates). Two examples of biological species that could be impacted by fire are invertebrates and bacteria. Fire in the forest significantly alters the microbes that affect the nitrogen cycle. Following fire accidents, the bacterial population increased. The growth of the fungal population in burnt soil was also gradual [57]. Actinomycetes were less abundant in burned soils as a result of the burning of spores. The burnt site has identical spores but a lower viability of Arbuscular Mycorrhizal fungi, which maintain the general health of the forest [58]. Knelman et al. and Moya et al. [59, 60] stated that the microbial biomass count (MBC) in burnt soils had dropped after high-severity wildfires.

The release of chemicals that prevent fungal growth, a decrease in the amount of nutrients available, and the loss of microbial biomass due to fire might be contributing factors to the decline in microbial biomass count (MBC) [34,61]. The impact of fire reduces the biomass of soil microorganisms. Severe fire can greatly reduce the biomass of microorganisms [62]. The microbial community was once dominated by fungi but became dominated by bacteria as a result of fire [60].

Increased pH and the availability of nutrients after a fire may change the microbial communities [63,64]. In addition to altering the microbial ecology, fire affects the enzymatic activity of burned soils. In burnt forest soils, [59,60] showed lower beta-glucosidase activity and linked the loss to the occurrence of fire and the richness in nutrients caused by ash deposits. Reduced acid phosphatase was found by [5, 60] and this could be the result of injury or a fall in microbial biomass activity.

6. POST FIRE MANAGEMENT IN SOIL

Developing early warning strategies for disasters and implementing developmental plans to enhance resilience, rehabilitation, and post-disaster reduction are critical components of disaster risk reduction and management.

Natural disasters are unavoidable, and it is impossible to reverse all of the damage they inflict. However, to a certain extent, the potential risk can be reduced by creating early warning systems for disasters, preparing and putting into action development plans to increase resilience to such catastrophes, and aiding in recovery and post-disaster reduction [65].

Remote sensing and GIS technology prove invaluable in fire risk zonation. Criteria such as fuel load, slope, aspect, altitude, drainage, and proximity to highways and towns are used to identify fire danger zones. Further, ground verification and historical fire data comparison in past years were done. This approach identifies different fire risk levels, enabling prioritized disaster control management [9].

Planting quick-growing tree species is a commonly used strategy in reforestation and afforestation efforts to help hasten the sequestration of carbon from the atmosphere. Active restoration of high-diversity late-successional plant communities caused soil C accrual to accelerate, with C pools accumulating at a rate 2–3 times that observed in natural succession at our site [66]. Management of woody residues within the fire prescription may be a significant N management in a fire setting because some forest soils have the ability to fix nitrogen when wood decays on the surface and in the soil profile [9].

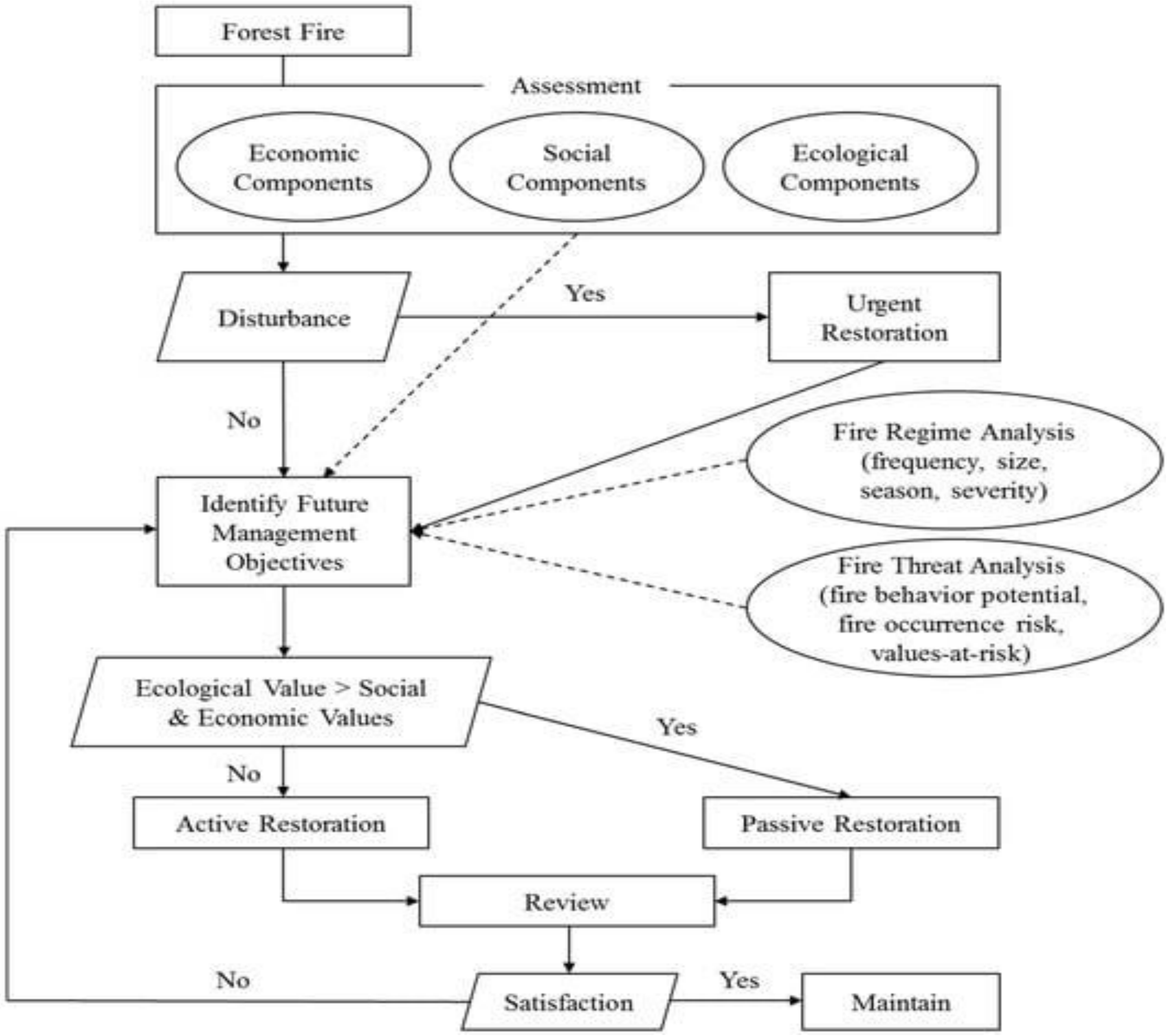
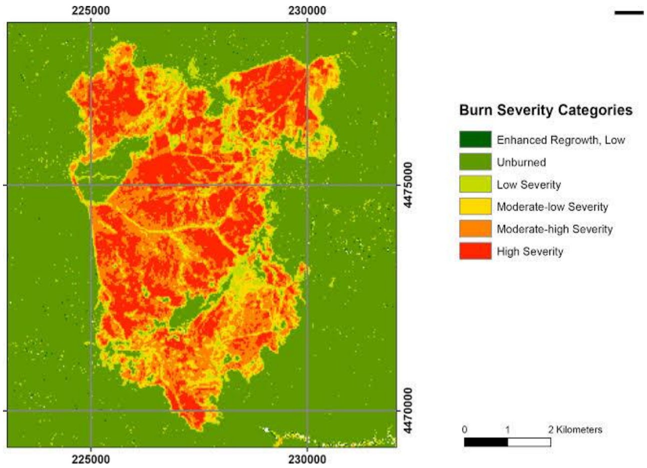
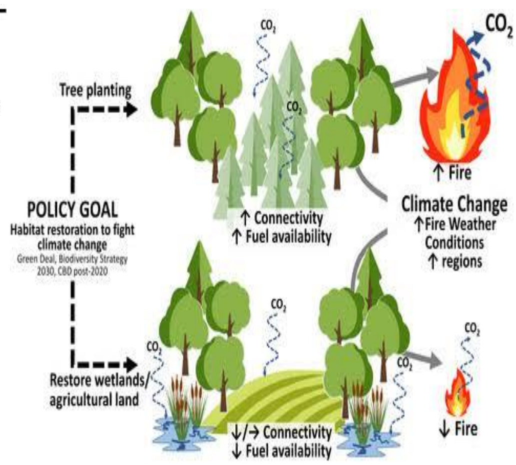


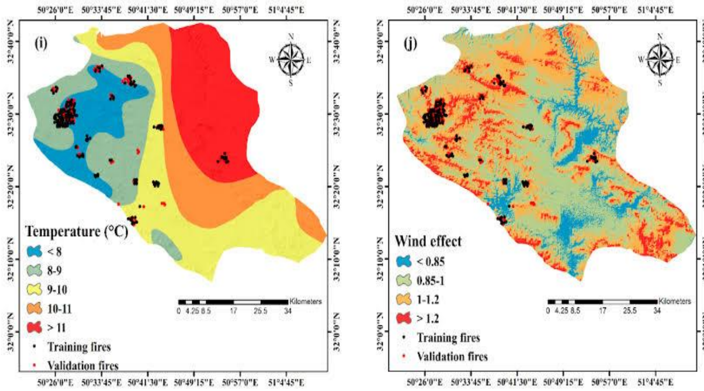
Fig. 2a. Flowchart of the development and execution of a plan to restore burned areas



i. Remote sensing tool to delineate burnt area



ii. Planting Fast growing species



iii. GIS technology

iv. Woody residues for N management

Fig. 2b. Post Fire management in soil

7. CONCLUSION

Forests are undoubtedly and significantly impacted by fire. Fires alter the soil color, pH, bulk density, and texture, which causes erosion and run-off of the soil. Furthermore, forest fires bring adjustments to the nutrient cycles and the organic matter in the soil, which can alter the productivity of the ecosystem. Microorganisms and invertebrates both experience a loss in quantity and species due to fire. In relation to soil erosion, loss of soil and sediment was accelerated by the fire. Maintaining all forest types is crucial from a conservation standpoint since they include a significant amount of plant and wild animals. As a tool for predicting fires, remote sensing, and GIS are highly essential. Hence it is important to understand how fire affects physical, chemical, and biological aspects of forest ecosystems.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Available:https://doi.org/10.1038/s41467-019-08636-w.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/105717