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Post-fire soil nutrient dynamics in a tropical dry deciduous forest of Western Ghats, India

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Abstract

Background: The effect of forest fire on soil is complex and relatively less understood than its above ground effect. Understanding the effect of fire on forest soils can allow improving management of valuable forest ecosystems as adequate and proper information is very important for efficient management. We have studied the recovery of soil properties after fire, using a chronosequence approach (two, five and fifteen years after fire and control). Soil samples were collected from each plot of four fire patches (B0, B2, B5 & B15) from three different depths viz. 0–10 (Top), 10–20 (Middle), and 20–30 cm (Bottom).

Results: Soil organic carbon was lower than unburned plots after the fire and could not recover to the level of unburned plot (B0) even in 15 years. Total N, available P, and extractable K were lower 2-years and 5-years after the fire but are higher than unburned plot after 15-years. Available nitrogen (NO_3^- and NH_4^+) remain unchanged or higher than B0 in burned patches. Soil pH, Bulk Density, Water Holding Capacity, and Electrical Conductivity was lower initially after the fire. Forest fires have affected soil properties considerably. The response of soil properties varied with years after fire and soil depth.

Conclusion: Forest fires occur very frequently in the study area. Significant quantities of carbon and total nitrogen are lost to the atmosphere by burning of litter, duff, and soil OM. Because nitrogen is one of the most important soil nutrients, the recapture of N lost by volatilization during a fire must receive special attention. Long-term studies are required to better understand the recovery of soil nitrogen.

Keywords: Soil properties, Western Ghats, Tropical dry deciduous Forest, Forest fire, Forest soils

Background

Fire is a significant ecological event that can produce variable effects on forest ecosystem (Whelan 1995; Keane et al. 2002). The role of fire in the forest is to act as an extrinsic disturbance factor (Crutzen and Goldammer 1993). It is a key disturbance that affects succession by selecting and regenerating plants, recycles nutrients, maintains diversity, decreases biomass, controls insects, triggers and regulates plant and animal interactions and most importantly affects biological and biogeochemical processes (Agee 1993; Crutzen and Goldammer 1993; Mutch 1994; Keane et al. 2002; Verma and Jayakumar 2015, 2018). Forest fires can also have global consequences by playing an important role in the global carbon cycle (Thonicke et al. 2001). The effect of forest fire on soils is complex and relatively less understood than its above ground effect (DeBano et al. 1998).

Fire can influence various soil properties, involving the detrimental impact on soil structure and reduction in soil organic matter, reduced porosity and high pH (DeBano 1990; Certini 2005; Verma and Jayakumar 2012). Fire can reduce the number of soil nutrients in a forest by losses from volatilization, smoke, ash transport, leaching, and erosion. These changes can produce several secondary effects like increased hydrophobicity, decreasing infiltration rate and increasing runoff (Inbar et al. 2014; Jiménez-Pinilla et al. 2016). This may result in accelerated soil erosion (DeBano 2000). In the long term, fires may also contribute to the reduced availability

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of nutrients because nutrients released from organic matter and microbial biomass are expected to be removed from the ecosystem by runoff and leaching (Wüthrich et al. 2002; Miesel et al. 2012).

The factors which produce the wide range of responses in soil include pre-burn environment, fire behavior, fire season, and pre-fire and post-fire climatic conditions such as time of year, amount and extent of rainfall (Clark 2001). During burning, plant cover and litter layers are consumed, and the mineral soil is heated, resulting in changes in physical, chemical, mineralogical, and biological soil properties (Fonseca et al. 2017). The combination of combustion and heat transfer produces sharp temperature gradients in the topsoil profile (Certini, 2005).

Organic matter loss is the most spontaneous change that soils experience during a fire (Certini 2005). The organic horizon is an important part of environmental sustainability as it provides a protective soil cover that mitigates soil erosion, helps in regulating soil temperature, provides habitat and substrates for soil biota and is an important source of readily mineralizable nutrients (Neary et al. 1999). The impact of forest fire on soil organic matter (SOM) is extremely variable from complete destruction of SOM to partly scorch, depending on fire severity, aridity of the surface OM and type of fire (Neary et al. 1999; González-Pérez et al. 2004; Fonseca et al. 2017). The impact of forest fire on SOM also depends on soil moisture, soil type, and nature of the burned materials (González-Pérez et al. 2004).

The direct effect of forest fire on soil macronutrients is their loss through volatilization in high temperature, ash entrapment in smoke columns, leaching and erosion (Neary et al. 1999; Certini 2005). Fire may also affect soil nutrient status directly by addition of available nutrients and indirectly by changing the soil environment (Marion et al. 1991). Nutrients present in live twigs and dead plant materials can either be lost by volatilization during a fire or released and deposited on the soil surface in a highly soluble form. These highly soluble forms of nutrients on the soil surface may be used for plant growth or simply lost by erosion (DeBano and Conrad 1978). This nutrient enrichment is mainly limited to the topsoil (0–5 cm) and only soluble N seemed to increase in the sub-surface soil (5–10 cm) (Marion et al. 1991). The most important short-term effects of the forest fire are the upsurge in the soil solution concentrations and leaching of mineral forms of nitrogen, sulfur, and phosphorus (Murphy et al. 2006) however, the total nitrogen decreases (Verma and Jayakumar 2012). Fire can also increase soil nutrient levels, particularly non-volatile elements (K, P, Ca, Mg, etc.) as well as total concentrations after low-intensity fires (Hough 1981; Schoch and Binkley 1986).

The role of forest fire in the nutrient dynamics and global carbon cycle has been comprehensively studied in both natural forests and plantations of boreal and temperate regions, as well as for slash and burn cultivation in tropical regions (Carter and Foster 2004; Meigs et al. 2009). However, effects of forest fire in the tropical forests are not very clear as the effects of fire on tropical forest soils can be extremely variable and there are very limited studies on the impact of forest fire on tropical forest across the world (Verma and Jayakumar 2012, 2018) and almost none in Indian tropical dry deciduous forest. Understanding the effect of fire on forest soils can allow improving management of valuable forest ecosystems as adequate and proper information is very important for efficient management. It is assumed that fire may produce a varied response in total and available plant nutrients after different years of burning. Hence the present study is aimed to understand the changes in soil properties in a fire chronosequence after two, five and fifteen years of a fire event. The main questions are as follows: 1) how fire affects physical and chemical properties of soil in tropical dry deciduous forests and 2) how much time they require to reach the level of the unburned forest?

Materials and methods

Study area

This study was conducted in Mudumalai Tiger Reserve (MTR). MTR is situated at the tri-junction of Tamilnadu, Kerala and Karnataka states on the northeastern slope of Nilgiri part of the Western Ghats descending to Mysore plateau. MTR spreads in an area of 321 km^2, which is a part of Nilgiri Biosphere Reserve (NBR). It is adjoining Wayanad wildlife sanctuary on the northwest, Bandipur tiger reserve on the north, Sigur and Singara reserve forests in the south and east respectively. The MTR is situated between 11^0 32′ & 11^0 43′ N and 76^0 22′ & 76^0 45′ E (Fig. 1). MTR is one of the few reserves in India with a rich flora and fauna and varied terrain. In general, MTR plays a significant role in biodiversity conservation; particularly large mammals with its flora diversity which largely depends on available soil nutrient.

The terrain is undulating with an elevation ranging from about 851 to 1258 m Above Sea Level (ASL) with an average elevation of 1000 m. Broadly two types of soils are recognized in the sanctuary; black sandy loam containing 50% sand and gravel and a red heavy loam soil. Red soil is generally confined in the southern part of the MTR where rainfall is heavier. There are three different seasons recognized with annually two monsoons i.e. south-west and north-east. January to May is a dry summer season; the southwest monsoon starts in May and ends by August whereas the north-east monsoon starts in September and ends by December (Suresh et al.

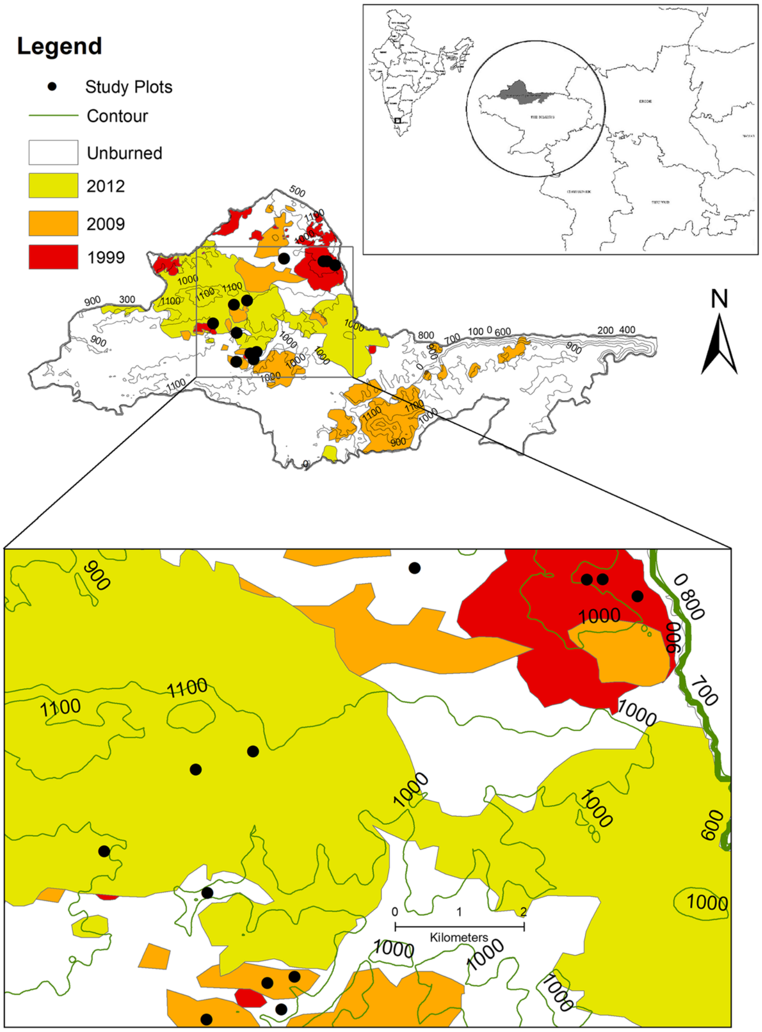

Fig. 1 Location map of the study area

2010). Annual rainfall ranges from about 800 mm in the east to 2600 mm in the west. The average maximum temperature in MTR varied from 25.4 ± 0.5 °C in August to 31.0 ± 0.3 °C in April and average minimum temperature from 13.9 ± 0.5 °C in January to 18.1 ± 0.6 °C in April (Dattaraja et al. 2013).

The vegetation types in MTR are classified into southern tropical dry thorn forest, southern tropical dry deciduous forest, southern tropical moist deciduous forest, southern tropical semi-evergreen forest, moist bamboo brakes and riparian forest (Champion and Seth 1968). Annual dry season fires are common all over MTR. Most of these are surface fires. The fire comes in MTR in the months of January to mid-May. The causes of these fires are poaching, antler collection, grazing, tourism, estates and settlements in and around the reserve (Srivastava et al. 2014). The inflammable material continuously cast down by the deciduous trees offers even an accidental spark the chance of developing into an extensive and devastating fire.

Fire mapping

Toposheets (58 A6 and 58A10) of MTR were collected from the Survey of India at 1:50,000 scales. Burned area maps for the period between 2001 and 2012 were collected from the forest department, Tamil Nadu. Burned area maps for 1999, 2000 and 2013 were prepared using Multi-temporal satellite data of Landsat 5 Thematic Mapper (TM), acquired on 2, February 1999 and 7, April 1999, Landsat 7 Enhanced Thematic Mapper Plus (ETM+) acquired on 28 January 2000, 1 April 2000, 17, April 2000, 3 May 2000, 31 January 2013 and Landsat 8 Operational Land Imager Thermal Infrared Sensors (OLI-TIRS) acquired on 13 April 2013 from United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov/). Supervised classification technique was adopted to prepare fire maps

Table 1 Description of study sites and fire classes

Class Code	Fire Class	Year of occurrence	Number of Plots	Basal area (SD) (m^2 ha^{-1})	Stem density (SD) (ha^{-1})
B0	Unburned	Never Burned in Past 15 Year	3	36.81 (2.19)	407 (41.63)
B2	Two year old	2012	3	24.88 (3.25)	370 (52.91)
B5	Five year old	2009	3	29.70 (7.21)	463 (32.15)
B15	Fifteen year old	1999	3	25.49 (5.85)	570 (6.46)

based on the shortwave infrared composite image (band combination 7–4-1 in RGB for Landsat ETM+) to delineate the burned area. Maximum likelihood (ML) classification method was used for the supervised classification. The ML algorithm is a parametric classifier that presupposes that the training data values for each class in each spectral band are normally distributed (Jensen 2005). The ML classification is achieved by allocating pixels to their most likely class of membership (Atkinson and Lewis 2000). Representative training sites were extracted before the classification through visually selecting pixels representing burned and unburned surfaces using ERDAS Imagine 2011 software. Burned area maps for every year were converted into raster data and combined using map algebra to prepare fire frequency maps using spatial analyst module in ArcGIS 10 software.

From the fire frequency map, unburned pixels and burned once between 1999 and 2013 were selected. The unburned pixels were grouped into Unburned (B0), pixels that burned only once in 2012, 2009 and in 1999 were designed as 2-y-old burn (B2), 5-y-old burn (B5) and 15-y-old burn (B15).

Study design and data collection

The study was carried out only in the deciduous forest in MTR. Four classes (B0-Unburned, B2-Burned two years ago, B5-Burned five years ago and B15-Burned fifteen years ago) were prepared to study the impact of forest fire. The soil was black sandy loam in all patches. All the patches were at the elevation of 900–1100 m ASL and slope was gentle. For each class, three 0.1 ha square plots were laid randomly and there were no significant environmental differences within these plots. Soil samples were collected from all burned and unburned classes (Table 1). Five samples were collected from each plot from three different depths viz. 0–10 (Top), 10–20 (Middle), and 20–30 cm (Bottom). Samples were collected between September 2013 and January 2014. Soil samples were immediately transported to the lab to analyze for total nitrogen and available nitrogen. Remaining soil samples were air-dried and mixed to get composite samples. Air-dried soil was sieved through 2 mm sieve.

Soil analysis

Soil pH and EC were analyzed in aqueous soil extract (1:2, Soil: Water). Soil organic carbon content was determined by dichromate oxidation method described by Walkley and Black (1934). Water holding capacity was determined by water saturation method. Total nitrogen was analyzed by the Kjeldahl method. Nitrate (NO_3^-) content in the soil was determined by the method of Cataldo et al. (1975) using a spectrophotometer. Ammonium (NH_4^+) content in soil was also estimated by using Nessler's reagent (K2HgI4 + NaOH) method as described by Weatherburn (1967).

Table 2 Result of the two-factor ANOVA (Fire class and soil depth) for the soil properties

Soil Properties	Variables	*F* ratio	*p*-value
pH	Fire class	13.129	**< 0.001**
	Depth	3.712	**0.039**
	Fire x Depth	4.372	**0.004**
EC	Fire class	25.989	**< 0.001**
	Depth	2.851	0.077
	Fire x Depth	0.342	0.908
Bulk density	Fire class	3.898	**0.021**
	Depth	4.518	**0.022**
	Fire x Depth	1.044	0.422
Organic carbon	Fire class	5.994	**0.003**
	Depth	6.736	**0.005**
	Fire x Depth	1.478	0.228
Total nitrogen	Fire class	24.181	**< 0.001**
	Depth	4.994	**0.015**
	Fire x Depth	2.036	0.100
NO_3^-N	Fire class	0.155	0.925
	Depth	1.832	0.182
	Fire x Depth	6.520	**< 0.001**
NH_4^-N	Fire class	3.759	**0.024**
	Depth	20.869	**< 0.001**
	Fire x Depth	1.126	0.377
Available P	Fire class	45.477	**< 0.001**
	Depth	5.175	**0.014**
	Fire x Depth	3.277	**0.017**
Extractable K	Fire class	86.571	**< 0.001**
	Depth	17.190	**< 0.001**
	Fire x Depth	3.455	**0.013**

Significant effects (at α = 0.05) are shown in bold type

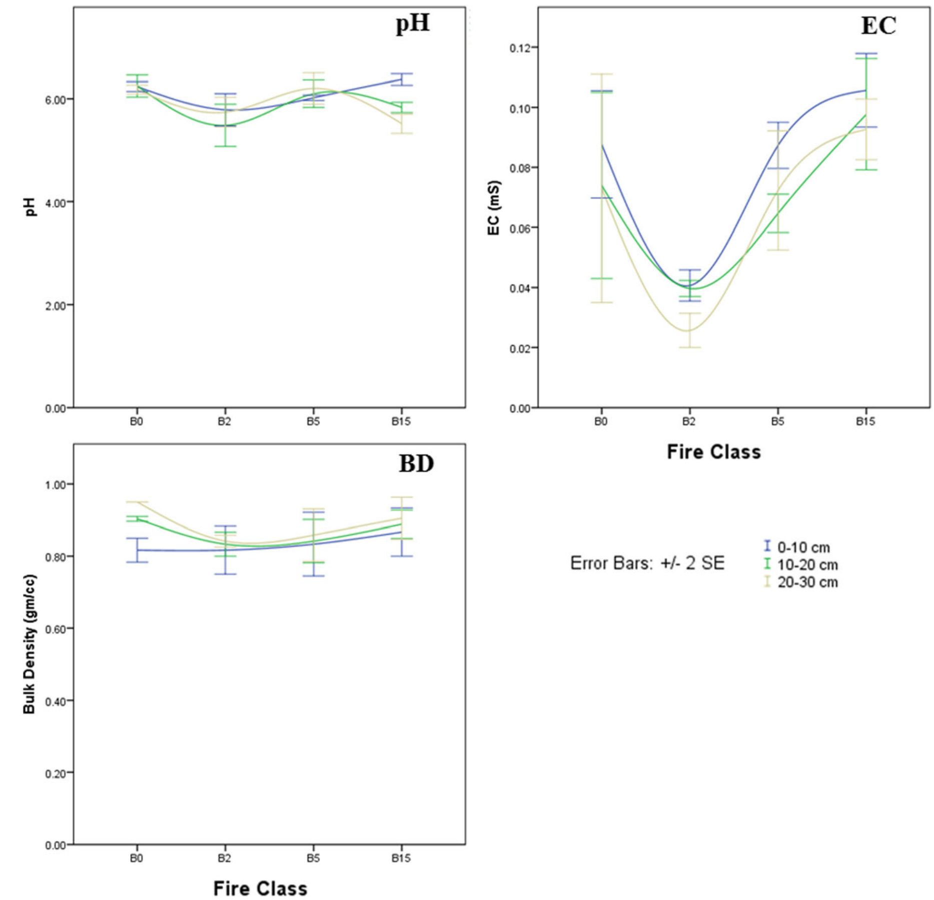

Fig. 2 Mean (±SE) pH, Electrical Conductivity and Bulk Density

Absorbance (optical density) in each case was recorded using UV-visible spectrophotometer) at the wavelength of 410 and 420 and the λ_{max} values in the UV-Visible spectrum indicate the presence of nitrate and ammonium, respectively. Available phosphorus was determined by Bray extraction method (Bray and Kurtz 1945) using a spectrophotometer. Extractable potassium was determined by ammonium acetate extraction method using flame photometer.

Statistical analysis

Data were analyzed by a two-way analysis of variance (ANOVA) at which soil depth and fire chronosequence were selected as factors (Table 2). We tested both factor effects (soil depth and fire) and their potential interaction. The explained variance was partitioned using the type III sum of squares. Statistical analysis was done by SPSS 20 (IBM Corp., Armonk, NY, USA).

Results

Soil pH was 5.79 ± 0.27 in B2 which is lower than other burned classes including B0 in the top layer (0–10 cm). Soil pH was higher than Unburned in B15. A similar pattern was observed in the middle and bottom layers (Fig. 2). Soil pH showed significant variation across the depth and fire classes. Electrical conductivity was also lower two years after the fire in all layers. EC was higher than B0 in B5 and B15 classes in the top and bottom layers and in the middle layer, it was higher in B15 (Fig. 2).

Water holding capacity of soil was lower in B2 (48.26 ± 2.9%) in top layer compared to B0 (54.83 ± 3.09%). In B5 (51.62 ± 3.83%) and in B15 (54.19 ± 5.73%) it reached to the level of B0. In middle and bottom layers only B2 was lower than B0 and in none of the layer they are significantly different (Additional file 1). Bulk density did not change after fire in top layer but was lower after fire in the bottom layer (Fig. 2).

Organic carbon was significantly different in across the depth classes and fire classes. In all three layers, organic carbon was higher in B0 than burn classes. In the middle layer, organic carbon was recorded 1.33 ± 0.16% in B0 and 0.94 ± 0.04% in B2 (Fig. 3).

Total N was significantly low in B2 compared to B0 in the top and middle layer and recorded higher in B5 and B15 compare to B2. It was higher than B0 fifteen years after fire (from 0.11 ± 0.01% in B0 to 0.12 ± 0.01% in

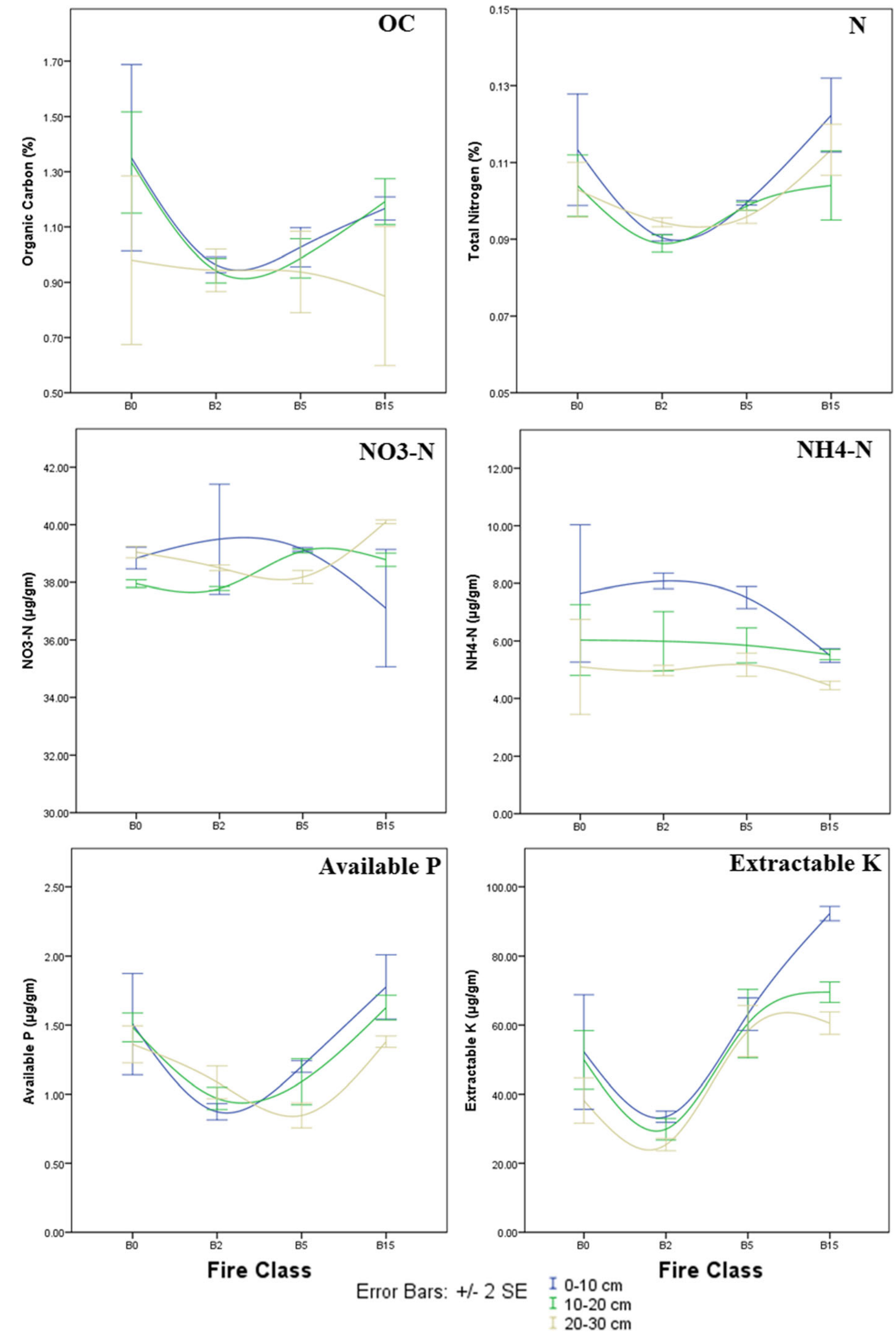

Fig. 3 Mean (±SE) Organic Carbon, Total nitrogen, NO_3^-N, NH_4^-N, Available Phosphorus and Extractable Potassium in different fire classes

B15) in the top layer. Changes in bottom layer were similar to the top layer and middle layer though not significantly different from unburned (Fig. 3).

Available forms of nitrogen (NO_3^- and NH_4^+) did not change much after a fire. In the top layer, both NO_3^- and NH_4^+ were slightly higher after fire (in B2) and slightly lower in B5 and B15 compared to B0 (Fig. 3). Whereas in mid-layer NO_3^- was lower in B2 but higher in B5 and B15. In the bottom layer, it was higher than B0 in SB15. In middle and bottom layers NH_4^+ was lower than B0 in burn classes.

In top layer available phosphorus was recorded 1.51 ± 0.32 µg/gm in B0, 0.87 ± 0.05 µg/gm in B2 and 1.78 ± 0.20 µg/gm in B15. In the middle layer and bottom layer also available phosphorus was lower in B2 but was higher than B0 in B15. Change in concentration of extractable potassium was very significant. In all soil depth, it was lower in B2 but was very significantly high in B15 (Fig. 3).

Discussion

Forest fires have affected soil properties considerably. The response of soil properties varied with years after the fire and soil depth. While the soils in our study are acidic in nature, the fire has reduced the soil pH. Results observed in this study agrees with data reported by Badía and Martí (2003) and Terefe et al. (2008). Terefe et al. (2008) have suggested that pH decrease initially with increasing temperature up to 200 °C but started increasing with temperature rise to 500 °C. These outcomes possibly reflect a collective effect of desiccation and heating, which favors proton-reducing oxidation reactions (Sertsu and Sánchez 1978).

EC was lower in two-year-old burn but recorded higher in B5 and B15. The explanation for the reduction of EC in all the soil samples could be the collapse of the clay minerals, the formation of base oxides and the generation of coarse sand size particles, which can enclose base oxides. Water holding capacity of soil has shown a decreasing trend after a fire. Soil water holding capacity is one of the properties most affected by combustion during a forest fire. The main effect of fire on soil physical properties is to eliminate the storage capacity of water in the organic horizons (several cms). Infiltration rates remain high at first but later decrease as there is a decrease in porosity (Imeson et al. 1992). High surface temperatures burn off organic materials and create vapors that travel downward in response to a temperature gradient and then condense on soil particles making them water repellent (Letey 2001). Bulk density was also slightly lower in middle and bottom layers but slightly higher in top layer after the fire. Bulk density increases due to the collapse of aggregates and clogging of voids by the ash and dispersed clay minerals that result in reduced soil porosity and permeability (Certini 2005).

Fire seems to decrease Organic carbon as a consequence of the pyrolysis of organic materials by heat (Orioli and Curvetto 1978; Almendros et al. 1990). The impact of fire on soil organic matter includes volatilization, charring, and oxidation (Giovannini et al. 1988). Substantial loss of organic matter occurs at 200–460 °C (Giovannini et al. 1988).

Total N was significantly low after the fire compared to control. Generally, a noteworthy decrease in total N happens after fire in all studied fire classes, which is also suggested by Neff et al. (2005). Forest floor layers are a major reservoir of soil N and their removal during forest fires can cause substantial decreases in it (Driscoll et al. 1999).

Available forms of nitrogen (NO_3^- and NH_4^+) did not change much after a fire. It is suggested that the increase of available nitrogen, particularly NH_4^+, is generally short-lived and quick immobilization could reduce it after 6 months (Adams and Attiwill 1986).

Available P was lower than control in B2 but higher in B15. Losses of phosphorus by volatilization or leaching are small. Burning changes the organic pool of soil P to orthophosphate (Cade-Menun et al. 2000); the sole form of available P. Fire may be mineralizing organically bound P thus reducing extractable P. Changes in concentration of extractable potassium were very significant. It decreased initially but increased fifteen years after fire.

Conclusion

Forest fires occur very frequently in MTR. Soil properties showed varied response after the fire. Soil organic carbon, nitrogen, available P and extractable K was lower 2-years after the fire but started recovering 5-years after the fire. Whereas available forms of nitrogen were higher in 2-year old burn patch and lower in 15-year old burn patches. Significant quantities of carbon and total nitrogen are lost to the atmosphere by burning of litter, duff, and soil OM. Because nitrogen is one of the most important soil nutrients, the recapture of N lost by volatilization during a fire must receive special attention. Long-term studies are required to better understand the recovery of soil nitrogen. Availability of few plant nutrients increases after fire though some other nutrients are volatilized during combustion. Fire plays a significant role in the dynamics of forest ecosystems across the world. However, careful planning is necessary to assure that forests are not adversely affected by fire-related changes in soils.

Additional file

Additional file 1: Mean (±SE) Water Holding Capacity (WHC) in different fire classes. (TIF 37 kb)

Abbreviations

^{0}C: Degree Celsius; ASL: Above Sea Level; EC: Electrical Conductivity; ETM: Enhanced Thematic Mapper; Ha: Hectare; K: Potassium; ML: Maximum Likelihood; mm: Millimetre; MTR: Mudumalai Tiger Reserve; N: Nitrogen; NBR: Nilgiri Biosphere Reserve; OLI-TIRS: Operational Land Imager Thermal Infrared Sensors; OM: Organic Matter; P: Phosphorus; SD: Standard Deviation; SOM: Soil Organic Matter; TM: Thematic Mapper; USGS: United States Geological Survey; WHC: Water Holding Capacity

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Authors' contributions
SJ and SV planned the work and did analysis and manuscript preparation. SV and DS Prepared Fire Maps. SV conducted field work. DS, AJ and SV did soil analysis. All authors read and approved the final manuscript.

Ethical approval and consent to participate
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Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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