Dynamics of soil organic carbon reservoir and microbial biomass carbon under controlled fire in the northwestern Himalaya

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Fluctuations in soil organic carbon (SOC) and microbial biomass carbon (MBC) following controlled fire were examined for one year under four land-use systems, viz. chir pine forest (*Pinus roxburghii*), grassland, scrubland and non-fire site in chir pine (control) in Solan district, Himachal Pradesh, India. The experiment consisted of five replications in a factorial randomized block design. A controlled fire was set in March 2018, and soil samples were taken before and after burning at three soil depths, viz. 0–5, 5–10 and 10–15 cm. Fire impact was rated in terms of SOC and MBC, which were found to be the lowest in the month immediately following the fire (April 2018) but started increasing in subsequent months and reached the highest at the end of the experiment, i.e. 12 months after fire; however, the remained slightly below pre-fire levels. Post-fire, SOC content was found to be the highest under unburnt chir pine site (11.9 g kg^{-1}) and the lowest (11.0 g kg^{-1}) under burnt chir pine forest. The highest per cent reduction in SOC content (1.63) post-fire was found in the surface layer (0–5 cm depth) compared to the other two depths. The unburnt chir pine forest recorded the highest MBC (181.04 μg g^{-1} soil), while the lowest (138.83 μg g^{-1} soil) was recorded in the scrubland. The highest MBC (167.77 μg g^{-1} soil) was recorded at 5–10 cm and the lowest (162.18 μg g^{-1} soil) at 10–15 cm soil depth. Unlike wildfires, post-fire negative effects of controlled burning on SOC and MBC were for a shorter period and thus, the soil recovered rapidly. Despite corresponding to a short monitoring time, these findings may add to a better understanding of the potential of controlled fire as a management tool for preventing wildfires.

Keywords: Controlled fire, land-use systems, microbial biomass carbon, soil organic carbon, wildfires.

WILDFIRES are now becoming a serious environmental threat in many parts of the world, including India, due to rising temperatures causing climate change, a universal concern, resulting in adverse environmental conditions, loss of biodiversity, etc.[1,2]. Evidence of a forest fire 400 million years ago in the Carboniferous age resulting in fossilized coal deposits has been found[3,4]. The forest ecosystem has approximately 50% of the total terrestrial carbon pool, with two-thirds of this found in forest soils[5]. Globally, the emission of greenhouse gases (GHGs) increased from 38,679 to 46,141 million tonnes (mt) of CO_2 equivalent over the period 2005–16 (ref. 6). Alterations in forest land cover have caused a net input of 0.91015 g C year^{-1} to the atmosphere, which is the result of a net loss of 1.61015 g C year^{-1} at low latitudes and a net gain of 0.71015 g C per year^{-1} at high latitudes[7]. Forest degradation and biomass burning might be one of the major reasons for the increasing emission of GHGs into the atmosphere and the planet's pity health according to reports of the Intergovernmental Panel on Climate Change[8]. Stand-replacing wildfires and organic soil drainage in deforested areas contribute to 1.1% of the gross emission of GHGs globally[9]. The global carbon C emissions from fires have been estimated to be 3.53 Pg per year[10].

India is the world's third highest emitter of GHGs[11]. The country witnessed the most devastating forest fires during the 1995 summer in the hills of Uttarakhand and Himachal Pradesh of the northwestern Himalaya[12]. Out of the total forest cover in India, approximately 2.41%, 7.49% and 54.40% are exposed to highly frequent fires, moderately incidence fires and occasional fires respectively, according to the Forest Survey of India (FSI)[13]. The studies have revealed repeated annual fires in nearly about 94% of the forest area in Meghalaya, 93% in Arunachal Pradesh, 87% in Nagaland, 76% in Madhya Pradesh and Odisha, 69% in Himachal Pradesh, 67% in Bihar, 58% in Uttar Pradesh, 51% in Assam and Gujarat, 46% in Jammu & Kashmir, 45% in Karnataka and 33% in West Bengal[4,12]. In the last few decades, the frequency of forest fires in India has increased due to weather and the subsequent drought conditions[14]. It has been estimated that a total of 37,059 active forest-fire events occurred in the country during 2018, indicating a 1.5 times increase in forest fires when compared to 2012 (ref. 13). Forest fires caused a total economic loss of INR 4.95 billion in 2018 alone in India.

There are five principal global C pools. The third largest terrestrial C pool is pedologic, i.e. soil organic carbon (SOC), with a global estimated total of 1526 Pg C (ref. 12). The long-term effects of fires on C exchange between

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the ecosystem and atmosphere is complex, depending on the accumulation and release of C in soils and plants after the fire[15]. Several studies have reported that SOC increases significantly after a fire[16–18]. However, some studies have reported the negative effect of fires on SOC[19,20].

Microbes are primarily responsible for nutrient cycling and sustaining soil fertility; thus, they serve as soil health indicators. Microbial biomass carbon (MBC) indicates the microbial status of the soil; hence, it contributes to the biological properties of the soil[21–23]. Fire indirectly affects soil microbes by causing alterations in physico-chemical properties of soils, which further influence the behaviour and nutrition requirements of microbes[24]. Microbial biomass is a sensitive biomarker of soil health that can be used to assess the effects of forest fire on the soil[25]. Wildfires result in a severe reduction in microbial biomass[26,27] by developing conditions of unavailability of soil C and nutrients for microbes after the fire[28,29].

Chir pine forests (*Pinus roxburghii*) occurring in the Western Himalaya and Shiwaliks ranges at an altitude of 450–1800 m amsl, rarely up to 2300 m amsl[9] are particularly more prone to fires during summer as they shed resin-containing needles, making these forests highly inflammable by providing ample source of fuel to wildfires[30]. Chir pine trees are large, have a diameter of up to 2 m, and can reach 30–50 m in height[31]. In chir pine forests, the total C stock (tree and soil C) varies from 65.6 to 99.5 Mg ha^{-1} (ref. 30). The frequency of fires in these forests is high and generally repeats every year. Climate change prediction models revealed that these 'mega-wildfires' would be more frequent and intense in the coming decades[32].

Depending on how we define fire, it can be either a destructive force or a management tool for preventing mega-fires. Recently, the use of controlled fires (prescribed fires) has been gaining popularity as a tool to reduce the occurrence and impact of wildfires by decreasing fuel availability. Prescribed fire is a systematic, planned use of fire under predetermined weather, fuel and topographic parameters to achieve clearly defined objectives[33]. Some researchers reported a decrease or small (non-significant) alterations in SOC and MBC following controlled fire[34–37]. However, the impact of prescribed fire on soil properties is still a matter of debate.

In the northwestern Himalayas, particularly in Himachal Pradesh, more than half of the forest area is subjected to recurrent annual fires. Around 1200 to 2500 forest fires have been reported during 2016–17, affecting thousands of hectares area. The annual economic loss to the state during this period ranged from INR 1.7–3.5 crore, mainly due to wildfires of chir pine forests, according to reports of the Himachal Pradesh Forest Department. Therefore, controlled fires are generally induced to prevent wildfires in chir pine forests by State Forest Department. In shrubland and grassland prescribed burning is also carried out with the objective to prevent shrub encroachment and fuel load, which otherwise may also result in wildfires in adjoining forest. However, information on the effect of controlled fires on soil properties, mainly SOC and MBC of these land uses, is still lacking. In order to fill this knowledge gap, the present study was carried out. To the best of our knowledge, there have been no such assessments especially in Himachal Pradesh. The main objectives of this study were to determine (i) the comparative effect of controlled fire in terms of SOC and MBC under different ecosystems and (ii) to understand whether controlled fire can be used as an effective management tool to prevent wildfires. We hypothesize that controlled fire might result in short-term alterations in SOC and MBC, and can be used as an effective management tool to control wildfires.

Materials and methods

Study site

The study was carried out during 2018–19 in Solan district, Himachal Pradesh. The experimental sites comprised of chir pine plantations, grasslands, scrublands and control (unburnt chir pine area adjoining the same burnt chir pine plantations) under the Department of Silviculture and Agroforestry, Dr YS Parmar University of Horticulture and Forestry, Nauni. The study region is located at 30°52′N lat and 77°11′E long, at an elevation of 1260 m amsl. The research site, which falls under the sub-temperate, sub-humid agro-climatic zone-II, receives an average annual rainfall of about 1115 mm (about three-fourths of it is received during mid-June to mid-September). The first significant rainfall event after the controlled fire occurred in June (190.0 mm). Winter rainfall is scanty (received during January and February). May and June are the hottest, while December and January are the coldest. Geologically, the area is a part of the outer Himalayas. The soil is derived from Inferakasol, which comprises calcareous shales and dolomitic limestone with bands of intermittent shales[38]. The soil under tree/grass vegetation is particularly shallow with a poorly developed loamy texture. According to the Soil Taxonomy of United States Department of Agriculture (USDA), soils of the experimental site fall in the order Inceptisol and sub-group Eutrochrept. Table 1 gives the agrometeorological data of the study area (March 2018–March 2019).

Experimental design and controlled fire specifications

Four representative sites depicting three different ecosystems, viz. burnt chir pine forest, grassland, scrubland and a non-fire chir pine site (control), were selected. The experiment consists of five replications in a factorial randomized block design. In March 2018, prescribed burning was carried out according to the prescription parameters established for chir pine forest, grassland and scrubland of a study site by qualified firefighters under the supervision of officials of the Himachal Pradesh Forest Department. The maximum temperature was 24.3°C, and no rainfall occurred for 15 days prior to the prescribed burning. Mean evaporation was 59.5 mm with a wind speed <10 km h^{-1} during the month of prescribed fire. Fire spread was 0.52 ha h^{-1} with a maximum flame height of 1.2 m and 1.7 m in length. Table 2 gives the initial soil properties (0–5 cm, 5–10 cm and 10–15 cm soil depth).

Soil sampling and analysis

After the prescribed fire, prior to soil sampling in the burnt plots, ash and the remaining organic layers were removed from the soil floor. For depth reference, a ruler was put into the soil, and mineral layers were carefully scrapped from the topsoil using a steel spatula at 0–5, 5–10 and 10–15 cm soil depth from a square delimited plot size of 50 m × 50 m for each land use at monthly intervals for one year (March 2018–March 2019). Each sampling square was about 5 m apart from the neighbouring square. Soil samples were also taken from unburnt chir pine forest (control) in a similar manner. Pre-fire soil samples were collected for each burnt land use. All soil samples were collected in plastic bags to avoid desiccation and stored in a refrigerator at 4°C at the earliest to maintain fresh conditions. There were totally 720 samples from all the land uses. SOC was determined by the rapid titration method of Walkley and Black[39]. MBC was determined by soil fumigation–extraction method[40] and estimated using the following formula

$$\text{MBC } (\mu g\ g^{-1} \text{ soil}) = OC_F - OC_{UF}/K,$$

where OC_F is the total amount of EC (extractable C) in the fumigated soil; OC_{UF} the total amount of EC in the unfumigated soil and K (constant factor) = 0.45.

Table 1. Agro-meteorological data of the study area (March 2018–March 2019)

Month and year	Temperature (°C) Maximum	Temperature (°C) Minimum	Rainfall (mm)	Evaporation (mm)
March 2018	24.3	8.8	17.4	59.5
April 2018	27.1	12.6	39.6	81.5
May 2018	30.7	16.1	54.9	120.6
June 2018	29.7	18.9	190.0	114.8
July 2018	26.7	20.2	340.2	65.1
August 2018	27.6	20.0	216.6	76.3
September 2018	26.5	16.9	224.3	55.4
October 2018	25.1	9.1	2.6	56.2
November 2018	21.7	6.5	24.8	45.5
December 2018	18.1	1.6	21.6	37.7
January 2019	15.7	2.0	73.0	31.7
February 2019	16.3	4.4	103.1	24.5
March 2019	20.3	6.6	54.6	36.8

Source: Meteorological Observatory of the Department of Environmental Science, Dr YS Parmar University of Horticulture and Forestry, Solan.

Statistical analysis

The data generated on SOC and MBC were analysed using two-way analysis of variance (ANOVA) under factorial randomized block design at a 5% level of significance, according to the method of Panse and Sukhatme[41]. The data recorded were processed using MS-Excel, OPSTAT and SPSS 16.0 package.

Results and discussion

SOC

After the prescribed fire, the temporal variation patterns of SOC were similar under all land uses for all three depths. The mean highest SOC (12.9 g kg^{-1}) was observed in March 2019, i.e. after 12 months of fire which produced non-significant differences (12.8, 12.7, 12.7 g kg^{-1}) with SOC observed in December 2018, January 2019 and February 2019, while the lowest SOC (10.8 g kg^{-1}) was observed in April 2018, i.e. one month post-fire under all the burnt land uses. At 0–5 cm soil depth (Figure 1), in the burnt forest, the highest SOC was observed in March 2019 (12.1 g kg^{-1}), whereas the lowest in April 2018 (10.8 g kg^{-1}). A similar trend was observed for grassland and scrubland soil. When different land uses were compared, the highest SOC (13.0 g kg^{-1}) was observed under grassland, which was found at par (12.9 g kg^{-1}) with unburnt chir pine, and the lowest (11.6 g kg^{-1}) under burnt chir pine forest.

Table 2. Initial values of soil properties under various land uses at different depths

Properties and land uses	Depths (cm) 0–5 cm	5–10 cm	10–15 cm
Soil pH			
Chir pine forest	5.8	5.7	5.9
Grassland	6.2	6.1	6.3
Scrubland	6.3	6.2	6.5
Unburnt chir pine	5.7	5.8	8.9
Soil electrical conductivity (dSm^{-1})			
Chir pine forest	0.48	0.46	0.45
Grassland	0.54	0.52	0.51
Scrubland	0.52	0.51	0.50
Unburnt chir pine	0.48	0.46	0.45
Soil organic carbon (g kg^{-1})			
Chir pine forest	12.3	11.6	11.4
Grassland	13.8	12.2	11.9
Scrubland	13.1	12.1	11.7
Unburnt chir pine	12.3	11.6	11.4
Microbial biomass carbon (μg g^{-1} soil)			
Chir pine forest	177.23	174.18	171.46
Grassland	155.78	151.42	146.31
Scrubland	152.34	149.61	145.68
Unburnt chir pine	177.23	174.18	171.46

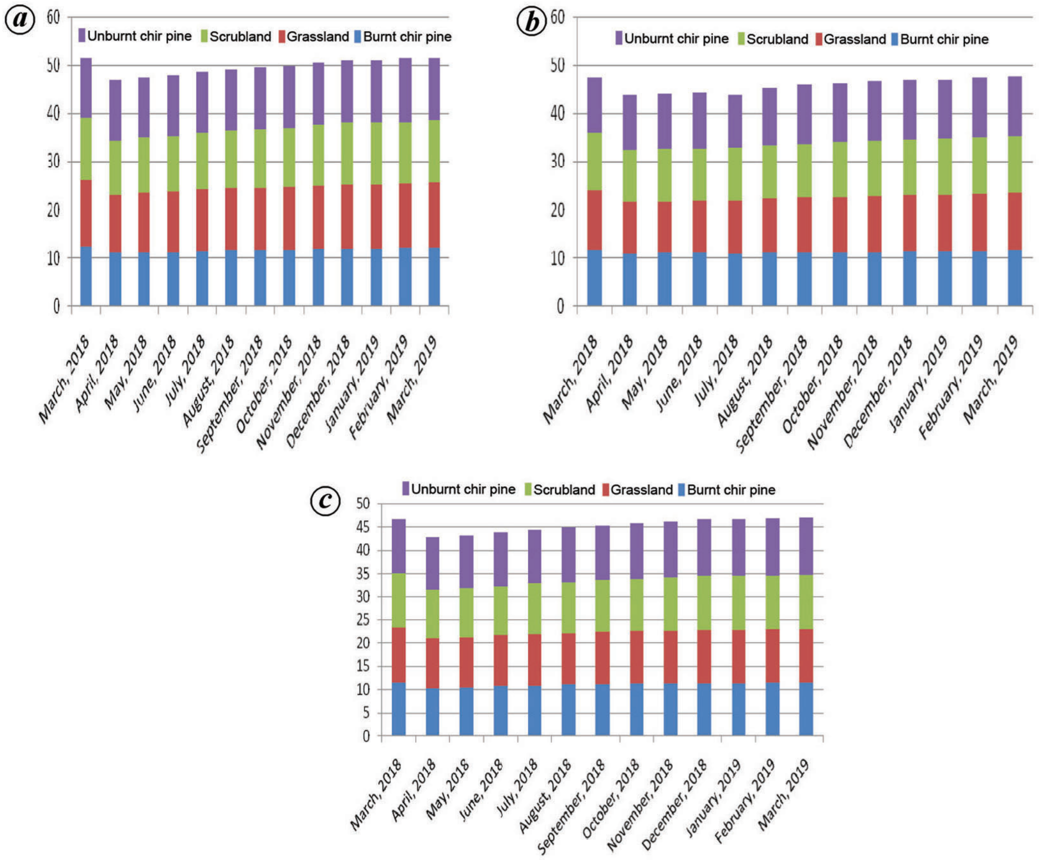

Figure 1. Soil organic carbon at soil depth of (***a***) 0–5 cm, (***b***) 5–10 cm and (***c***) 10–15 cm soil.

When different land uses were compared for 5–10 cm depth (Figure 1 *b*), the highest SOC was observed under control, i.e. unburnt chir pine site with an average of 12.1 g kg^{-1} and the lowest (11.1 g kg^{-1}) in fire exposed chir pine forest.

SOC at 10–15 cm soil depth varied from 10.7 g kg^{-1} in April 2018 to 11.8 g kg^{-1} in March 2019 (Figure 1 *c*). In burnt grassland and scrubland, the highest SOC (11.7 g kg^{-1}) was observed in March 2019 and the lowest in April 2018, with an average of 10.7 g kg^{-1} in grassland and 10.5 g kg^{-1} in scrubland. When different land uses were compared for all three depths, the highest SOC was observed under the unburnt chir pine site (11.9 g kg^{-1}), which was found to be significantly higher than all other land uses. When different soil depths were compared, the highest decline in SOC (1.63%) was observed for the surface layer (0–5 cm depth) compared to the other two depths (0.86% and 0.72% in 5–10 and 10–15 cm depth respectively).

SOC decreased during the initial few months after the fire, but in the subsequent months, it increased rapidly. However, SOC content stayed slightly below pre-fire levels one year post-fire, which might be due to the assimilation of charcoal, unburnt leftovers, as well as post-fire N-fixers adding considerably to SOC in the advancing months post-fire. Our results corroborate the findings of other studies[16,19,42,43]. In contrast, some researchers reported that SOC content increased post-prescribed fire, as the soil was not exposed to high temperatures, which could cause oxidation of soil organic matter[35,44–48]. High SOC in the surface layer of grassland soil might be due to the large fraction of organic matter added belowground by the rapid regeneration of grasses caused by ash in the soil post-fire, resulting in higher root density and, thus more SOC.

Significantly higher SOC was observed under control compared to burnt land uses at all three depths. This might be due to the non-exposure of organic residues to high temperatures caused by the fire. Our results corroborate the findings of other studies as well[20,49]. Though SOC decreased with an increase in soil depth as the amount of organic residues incorporated in the subsurface layers was less compared to surface layers, the per cent decline observed in SOC was more in the surface layers than in the subsurface layers. This might be due to the exposure of topsoil to higher temperatures caused by prescribed fire compared to the other two soil depths[50,51].

MBC

MBC is directly related to the distribution of SOC. It varies significantly with land uses as well as with advancing

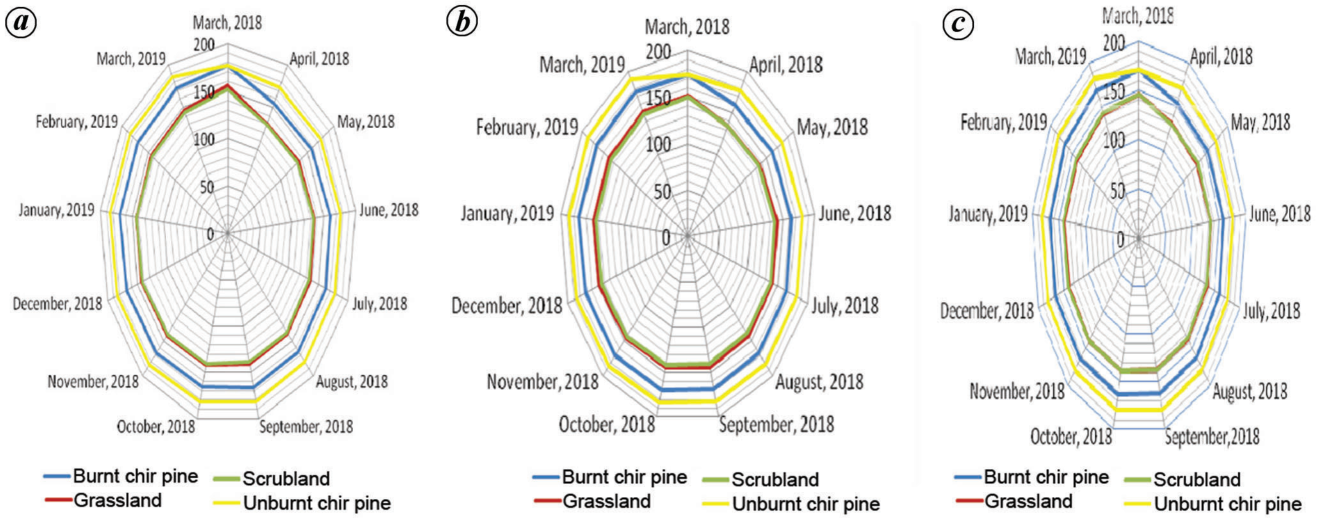

Figure 2. Microbial biomass carbon at the soil depth of (***a***) 0–5 cm, (***b***) 5–10 cm and (***c***) 10–15 cm.

months post-fire. At 0–5 cm soil depth (Figure 2 *a*), MBC varied from an average of 147.86 $\mu g\ g^{-1}$ soil in April 2018 (month immediately succeeding the fire) to 162.86 $\mu g\ g^{-1}$ soil in March 2019. The findings in forest land use followed a similar temporal pattern as that of SOC, with the lowest MBC (155.50 $\mu g\ g^{-1}$ soil) in April 2018, which significantly increased from June 2018 onwards (with the onset of monsoon) and reached a maximum (172.92 $\mu g\ g^{-1}$ soil) in March 2019. When different land uses were compared, the highest MBC (181.04 $\mu g\ g^{-1}$ soil) was observed under unburnt chir pine forest (control), whereas the lowest (138.83 $\mu g\ g^{-1}$ soil) was under scrubland. This might be due to the non-exposure of unburnt chir pine site to sudden rise in soil temperature caused by the prescribed fire in burnt land uses.

At 5–10 cm depth (Figure 2 *b*), monthly dynamics of MBC varied from 150.84 $\mu g\ g^{-1}$ soil in April 2018 to 166.73 $\mu g\ g^{-1}$ soil in March 2019. When different land uses were compared, a similar pattern was observed as in the case of 0–5 cm soil depth. At 10–15 cm soil depth (Figure 2 *c*), in terms of temporal variations, MBC ranged from an average of 146.94 $\mu g\ g^{-1}$ soil in April 2018 to 159.55 $\mu g\ g^{-1}$ soil in March 2019. The highest value was found statistically at par with those (157.87 $\mu g\ g^{-1}$ soil) in February 2019. When different land uses were compared for 10–15 cm soil depth, the highest MBC (178.47 $\mu g\ g^{-1}$ soil) was observed under an unburnt chir pine site, whereas the lowest (137.32 $\mu g\ g^{-1}$ soil) was in the grassland post-fire.

When different depths were compared, the highest soil MBC (167.77 $\mu g\ g^{-1}$ of soil) was observed at 5–10 cm soil depth compared to 0–5 cm depth (165.09 $\mu g\ g^{-1}$ of soil) and 10–15 cm (162.18 $\mu g\ g^{-1}$ of soil) soil depth. When comparing different land uses for all three depths, the highest MBC (181.04 $\mu g\ g^{-1}$ of soil) was observed under an unburnt chir pine forest, which was substantially higher than the other three land uses.

From the analysis of data, we can interpret that the soil MBC declined significantly after the experimental fire for the first few months in all the burnt plots compared to their pre-fire values. The C substrate loss during fire and release of chemicals might inhibit microbial growth[49,52–59]. We also observed that MBC recovered rapidly as time progressed post-fire, more significantly with the onset of the monsoon season. The findings of Ahlgren and Ahlgren[60] also support our results. Although soil MBC significantly increased after rainfall, it remained slightly below pre-fire levels till the end of the study period. Our results also endorse the findings of Pietikainen and Fritze[61]. Higher MBC in subsurface layers compared to surface layers might be because of more favourable temperatures due to less effect of the prescribed fire on these layers. In addition, the highest MBC recorded under control might be due to the non-exposure to sudden temperature alterations induced by the prescribed fire. This is in line with the findings of Mabuhay *et al.*[58]. On the contrary, higher MBC in the burnt sites of a dry deciduous forest compared to control due to increased root turnover and root exudates providing extra resources for the microbes was reported by Singh *et al.*[62].

Conclusion

From the results of this study, it can be concluded that unburnt chir pine forest, i.e. control (non-fire site in chir pine forest) shows the highest SOC and MBC among all the land uses, and the fire effects are mainly limited to surface layers (0–5 cm) alone. SOC and MBC declined in the initial few months following a controlled fire in all the burnt land uses. Thereafter they started to recover, more significantly with the onset of rainfall and reached a maximum at the end of the study period showing only slight variations from the initial levels. Controlled fire-induced negative alterations in SOC and MBC only initially for a short period of time. Thereafter the soil recovered rapidly to pre-fire conditions. Thus, controlled fire can be used as an effective management tool in preventing wildfires in fire-prone ecosystems, as it causes fuel reduction without adversely affecting SOC and MBC.

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