RESEARCH ARTICLE

Post-fire nutrient availability in the sub-tropical forest ecosystem of the Koubru Hills, Manipur [version 1; peer review: 1 not approved]

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Abstract

Forest fires are known to significantly alter soil nutrient availability. The study investigated the post-fire nutrient availability in the sub-tropical forest ecosystem of Koubru Hills, Manipur (North-East India). The forested ecosystem was disturbed by forest wildfire in January 2010. To study the fire effect, collection of burned and unburned soil samples from three soil depths (0-5, 5-10 and 10-15 cm) was started approximately three months after the fire event and continued at monthly intervals for a period of one year. The collected soil samples were analyzed for soil organic carbon (SOC), NH_4^+ -N, Bray-extractable phosphorus, available potassium and micronutrients such as Fe, Cu, Mn and Zn. Results of the ANOVA test showed significant reduction in the SOC, NH_4^+ -N and available K contents of the surface (0-5 cm) and sub-surface (5-10 and 10-15 cm) soil layers of the burned area. However, significant increases in the Bray-extractable phosphorus were observed in all the three soil depths studied. With respect to the effect of forest fire on soil micronutrient availability, results are contradictory. The available Fe depleted in all the three soil depths, whilst the available Cu declined in the 0-5 cm but increased in the 10-15 cm soil layer. The available Cu content of the 5-10 cm soil layer did not vary between the burned and unburned areas. While no significant effect of fire was observed on the available Mn contents of the 0-5 and 10-15 cm soil layers, there was a significant post-fire decrease in the Mn availability of the 5-10 cm soil layer of the burned area compared with the unburned area. Forest fire also resulted in a significant loss of the available Zn from the 0-5 and 5-10 cm soil layers of the burned area but in the 10-15 cm soil layer, no significant variation was observed between the burned and unburned areas.

Keywords

nutrient availability, soil, sub-tropical, ecosystem, fire

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Introduction

Forest fires form part of ecosystem disturbances and those provoked by human activities are a paramount environmental problem and a serious threat to biodiversity¹. Pickett and White² defined ecosystem disturbances as “any relatively discrete event(s) in time and space that disrupts the structure of populations, communities, and ecosystems and causes(s) change in resource availability or the physical environment”. Fire as natural or anthropogenic disturbance can cause short- or long-term changes in ecosystem dynamics^{3,4}.

The effect of forest fire on forest soil is very complicated and less studied in comparison to its aboveground effect⁵. Fire effects on soil can vary greatly among different ecosystems depending on the severity (a combination of fire line intensity and duration) according to Keeley⁶ and frequency of fires. While low severity-fires do not substantially affect soils, high severity-fires can affect a wide range of soil properties, one of which is nutrient availability⁷. The concentrations, forms, and depth distribution of soil nutrients can be dramatically altered after fire disturbance⁸. The productivity of burned soils can be impacted, in some cases, in an irreversible way resulting from fire-induced changes on soil properties⁹. Post-fire nutrient losses can be accelerated through volatilization, leaching and erosion⁷.

Most studies on fire-associated alterations in soil nutrients have been focused on evaluating changes in available macro-nutrients^{10–12}. Very few studies have evaluated post-fire effects on soil micronutrients. This paper presents information regarding the post-fire availability of nutrients which include both macro- and micro-nutrients of the burned and unburned areas in the sub-tropical forest ecosystem of Koubru Hills, Manipur (NE India). The role of fire in this region is poorly understood, therefore, the aim of this study was to investigate changes in some of the soil nutrients following forest wildfire using conventional soil analytical tools. Results from the present study would provide insight into potential fire effects on soil nutrients at this site and also give some direction for sorely needed future research.

Materials and methods

Site description

This research was conducted between March 2010 and April 2011 in the sub-tropical forest ecosystem of the Koubru Hills, Manipur (NE India). The site under study lies at 24°55'N latitude and 93°48'E longitude. Average elevation of the site is approximately 1294 m above mean sea level. Mean annual precipitation is about 3.99 mm with the wet season between June and August. Average annual relative humidity is 75.99%. Average annual air temperature is 21.14°C. The data are based on long term records from the Indian Council of Agricultural Research (ICAR) located nearby the study site. The soil is sandy loam in texture. Vegetation at the site is dominated by *Cinnamomum zeylanicum* and some unidentified species belonging to the genus *Litsaea*.

In mid January 2010, a forest wildfire occurred in the study site which had been undisturbed by fire for more than 100 years. The fire removed almost all the understory vegetation and soil surface litter.

Soil sampling and sample analysis

Soil sampling at monthly intervals started in April 2010 and ended in March 2011. Sampling was carried out approximately three months after the occurrence of the forest wildfire. Two representative plots (with an area of 6000 m² per plot), one each in the burned and the adjacent unburned areas, were taken. Each plot was equally divided into fifteen sub-plots (with an area of 20×20 m² per sub-plot). From amongst the fifteen sub-plots, ten sub-plots were randomly selected following the random number table method of Fisher and Yates¹³. Soils were sampled from three depths (0–5, 5–10 and 10–15 cm) in each of the randomly selected ten sub-plots of both burned and adjacent unburned areas using 5 cm × 5 cm soil cores. Soils collected from the similar depths in each of the ten sub-plots of the burned area were pooled into one composite sample (for instance, soils collected from the 0–5 cm soil depth of the burned area were pooled into one composite sample representing the 0–5 cm soil depth of the burned area). The same was repeated for soils sampled from three depths in each of the ten sub-plots of the unburned area. Thus, each composite soil sample representing a specific depth of either the burned or unburned area was composed of ten pooled sub-samples collected from the randomly selected ten sub-plots. The collected soil samples were air-dried, crushed and passed through a 2 mm mesh soil sieve (Shiva Scientific Instruments, India) for nutrient analysis.

Soil organic carbon (SOC) contents were analyzed using H₂SO₄–K₂Cr₂O₇ oxidation method¹⁴ with five replications. Ammonical nitrogen was determined by the alkaline permanganate method using an AlpKem autoanalyser (Kjeltec system 1026 Distilling unit, Sweden) with three replications. Bray-extractable phosphorus (2.85 g soil in 0.03 N NH₄F plus 0.025 N HCl) was analyzed using spectrophotometer 169 (Systronics, India) with three replications. Available potassium was extracted by 0.1 M ammonium acetate solution adjusted to pH 7 at a 1:5 soil solution ratio and determined by flame photometer 128 (Systronics, India) with three replications. The plant-available fractions of micronutrients (Fe, Cu, Mn and Zn) were determined by using 0.05 M DTPA (Diethylene Triamine Pentaacetic Acid) plus 0.01 M CaCl₂ plus 0.1 M Triethanolamine, adjusted to pH 7.30 at a 1:2 soil solution ratio¹⁵. The concentrations of the elements were assessed using atomic absorption spectrophotometry (Aanalyst 200, PerkinElmer, USA).

Statistical analysis

A two way ANOVA test was performed to test the effects of forest fire (burned and unburned) and sampling month (time) on the soil nutrients studied at three different soil depths (0–5, 5–10 and 10–15 cm). A one way ANOVA test was performed to detect the differences in soil nutrient concentrations between the burned and unburned areas at a specific sampling month. P≤0.05 was considered to be significant. The data analysis was carried out using Microsoft Excel 2007.

Results

Soil organic carbon

The SOC contents of the surface layer (0–5 cm) ranged from 2.10 to 2.18% in the unburned area while in the burned area they ranged from 1.94 to 2.02% (Table 1). In the sub-surface layers (5–10 and

Table 1. The maximum and minimum soil nutrient concentrations of the burned and unburned areas at three soil depths (0–5, 5–10 and 10–15 cm).

SOIL NUTRIENTS	0–5 cm				5–10 cm				10–15 cm			
	UNBURNED		BURNED		UNBURNED		BURNED		UNBURNED		BURNED	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
SOC (%)	2.18	2.10	2.02	1.94	2.04	1.97	1.74	1.62	1.89	1.76	1.58	1.49
NH ₄ ⁺ -N (kg/ha)	592.10	543.47	389.57	349.12	519.99	475.86	325.38	294.15	443.47	396.27	292.25	265.25
Available P (kg/ha)	25.73	21.36	26.69	24.98	21.42	18.77	26.24	23.72	21.82	19.10	26.30	23.99
Available K (kg/ha)	852.76	697.07	623.62	484.62	579.19	482.84	368.40	306.07	457.27	369.77	288.29	241.78
Available Fe (mg/kg)	98.37	87.22	84.42	73.54	83.36	77.44	72.52	64.52	78.41	68.87	67.93	58.88
Available Cu (mg/kg)	0.79	0.51	0.40	0.20	0.39	0.08	0.31	0.12	0.16	0.06	0.39	0.23
Available Mn (mg/kg)	79.58	61.28	74.16	60.44	61.51	45.11	48.36	39.39	48.31	35.00	41.12	34.38
Available Zn (mg/kg)	4.17	2.18	2.22	1.41	2.46	1.59	2.12	1.21	2.17	1.17	2.01	1.05

10–15 cm) the SOC contents of the unburned area were observed to vary from 1.97 to 2.04% and from 1.76 to 1.89%, respectively (Table 1). In contrast, the SOC contents of the sub-surface layers in the burned area ranged from 1.62 to 1.74% and from 1.49 to 1.58%, respectively (Table 1).

A two way ANOVA test showed that fire reduced the SOC of the surface layer (0–5 cm) varying significantly ($P=0.00005$) between the burned and unburned areas (Unburned > Burned, Figure 1A, Table 2) while it did not vary significantly over the sampling months ($P=0.480$). The SOC of the 5–10 cm soil layer was also significantly affected ($P<0.001$) by fire (Unburned > Burned, Figure 1B, Table 2) while there were no significant variation ($P=0.090$) among the sampling months. The SOC also varied significantly ($P<0.001$) between the burned and unburned areas in the 10–15 cm soil layer (Unburned > Burned, Figure 1C, Table 2) while it did not vary significantly ($P=0.324$) among the sampling months.

Ammonium nitrogen

Soil NH₄⁺-N contents in the surface layer (0–5 cm) ranged from 543.47 to 592.10 kg/ha in the unburned area while in the burned area, they ranged from 349.12 to 389.57 kg/ha (Table 1). In the sub-surface layers (5–10 and 10–15 cm) of the unburned area, soil NH₄⁺-N contents ranged from 475.86 to 519.99 kg/ha and from 396.27 to 443.47 kg/ha, respectively while in the burned area, they ranged from 294.15 to 325.38 kg/ha and from 265.25 to 292.25 kg/ha, respectively (Table 1).

A two way ANOVA test indicated that fire caused a significant reduction ($P<0.001$) of soil NH₄⁺-N in the surface (0–5 cm) layer (Unburned > Burned, Figure 2A, Table 2) while sampling date did not significantly ($P=0.141$) affect the soil NH₄⁺-N. NH₄⁺-N of the 5–10 cm soil layer was also significantly lower ($P<0.001$) in the burned area compared to the adjacent unburned area (Unburned >

Burned, Figure 2B, Table 2) while it showed no significant variation ($P=0.073$) over the sampling months. Fire also affected the NH₄⁺-N content of the 10–15 cm soil layer (Unburned > Burned, Figure 2C, Table 2) varying significantly ($P<0.001$) between the burned and unburned areas while no significant effect ($P=0.322$) of sampling month was observed.

Bray-extractable (available) phosphorus

The available P of the 0–5, 5–10 and 10–15 cm soil layers in the unburned area varied from 21.36 to 25.73 kg/ha, 18.77 to 21.42 kg/ha and from 19.10 to 21.82 kg/ha, respectively (Table 1). In contrast, the available P of the burned area in the three different soil layers ranged from 24.98 to 26.69 kg/ha, 23.72 to 26.24 kg/ha and from 23.99 to 26.30 kg/ha, respectively (Table 1).

A two way ANOVA test showed that fire resulted in a significant rise ($P=0.022$) of the available P in the upper 5 cm of the burned area (Unburned < Burned, Figure 3A, Table 2) while it did not vary significantly ($P=0.131$) over the sampling months. In the 5–10 cm soil layer, fire also significantly increased ($P<0.001$) the available P, the concentration being higher in the burned area than the adjacent unburned area (Unburned < Burned, Figure 3B, Table 2) while sampling month had no significant effect ($P=0.231$) on the available P. The available P of the 10–15 cm soil layer also showed significant variation ($P<0.001$) between the burned and unburned areas (Unburned < Burned, Figure 3C, Table 2) while no significant variation ($P=0.850$) was observed over the sampling months.

Available potassium

The available potassium contents in the surface soil layer (0–5 cm) of the unburned and burned areas ranged from 697.07 to 852.76 kg/ha and from 484.62 to 623.62 kg/ha, respectively (Table 1). In the sub-surface soil layers (5–10 and 10–15 cm) of the unburned area the available potassium contents respectively ranged from 482.84

Figure 1. Soil organic carbon % at 0–5 (**A**), 5–10 (**B**) and 10–15 cm (**C**) soil layers. Significant differences ($P < 0.001$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=5$).

Figure 2. $\text{NH}_4^+\text{-N}$ (kg/ha) at 0–5 (A), 5–10 (B) and 10–15 cm (C) soil layers. Significant differences ($P < 0.001$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=3$).

Figure 3. Available phosphorus (kg/ha) at 0–5 (**A**), 5–10 (**B**) and 10–15 cm (**C**) soil layers. Significant differences ($P < 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=3$).

Table 2. Results of F tests based on two way ANOVA for SOC, $\text{NH}_4^+\text{-N}$, Bray-extractable P, available K and DTPA-extractable (available) micronutrients (Fe, Cu, Mn & Zn) at the 0–5, 5–10 and 10–15 cm soil layers. Fire effect (F) and sampling month effect (E); *, ** and *** statistically significant at $P < 0.05$, 0.01, 0.001 respectively.

Soil nutrients	0–5 cm		5–10 cm		10–15 cm	
	F	E	F	E	F	E
SOC	40.83***	1.03	189.0***	2.31	73.22***	1.32
$\text{NH}_4^+\text{-N}$	281.07***	1.94	408.09***	2.47	151.99***	1.32
Available P	6.97*	2.01	44.52***	1.57	25.37***	0.52
Available K	103.85***	8.64***	150.86***	4.46*	70.79***	2.25
Available Fe	16.61**	1.18	27.78***	1.01	18.01**	2.07
Available Cu	33.98***	1.04	0.05	0.24	18.15**	0.76
Available Mn	1.09	5.00**	15.72**	5.36**	3.55	4.34*
Available Zn	12.97**	2.32	7.38	8.40***	1.68	16.80***

to 579.19 kg/ha and from 369.77 to 457.27 kg/ha while they ranged from 306.07 to 368.40 kg/ha in the 5–10 and from 241.78 to 288.29 kg/ha in the 10–15 cm sub-surface soil layers of the burned area (Table 1).

A two way ANOVA test showed a significant fire induced loss ($P < 0.001$) of the available potassium from the 0–5 cm soil layer of the burned area (Unburned > Burned, Figure 4A, Table 2) and there was also significant variation among the sampling months ($P < 0.0006$). Fire also caused a significant reduction ($P < 0.001$) of the available potassium in the 5–10 cm soil layer (Unburned > Burned, Figure 4B, Table 2) and it varied significantly among the sampling months ($P = 0.010$). A significant difference ($P < 0.001$) in the potassium availability between the burned and unburned areas was also observed in the 10–15 cm soil layer (Unburned > Burned, Figure 4C, Table 2) while there was no significant variation ($P = 0.096$) among the sampling months.

DTPA-extractable (available) micronutrients (Fe, Cu, Mn and Zn)

The DTPA-extractable Fe of the unburned area ranged from 87.22 to 98.37 mg/kg in the 0–5, 77.44 to 83.36 mg/kg in the 5–10 and 68.87 to 78.41 mg/kg in the 10–15 cm soil layers while in the burned area, it ranged from 73.54 to 84.42 mg/kg, 64.52 to 72.52 mg/kg and from 58.88 to 67.93 mg/kg in the 0–5, 5–10 and 10–15 cm soil layers, respectively (Table 1). Thus, the unburned area had a higher Fe availability compared to the burned area in all the three soil layers.

A two way ANOVA test indicated a significant effect ($P = 0.001$) of fire on the DTPA-extractable Fe which showed a decrease in the surface 0–5 cm soil layer of the burned area (Unburned > Burned, Figure 5A, Table 2) while no significant effect ($P = 0.393$) of sampling month was observed. In the subsurface layer (5–10 cm), the DTPA-extractable Fe showed a significant variation ($P < 0.001$) between the burned and unburned areas (Unburned > Burned, Figure 5B, Table 2) while no significant difference ($P = 0.490$) was found among the sampling months. The 10–15 cm soil layer also showed a significant ($P = 0.001$) fire-induced loss of the DTPA-extractable

Fe which was found to be lower in the burned area than the adjacent unburned area (Unburned > Burned, Figure 5C, Table 2) while there was no significant difference ($P = 0.121$) among the sampling months as confirmed by the two way ANOVA test.

The DTPA-extractable Cu contents of the 0–5 cm soil layer ranged from 0.51 to 0.79 mg/kg in the unburned area while in the burned area, they ranged from 0.20 to 0.40 mg/kg (Table 1). The DTPA-extractable Cu contents of the sub-surface layers (5–10 and 10–15 cm) respectively ranged from 0.08 to 0.39 mg/kg and from 0.06 to 0.16 mg/kg in the unburned area while in the burned area they ranged from 0.12 to 0.3 mg/kg and from 0.23 to 0.39 mg/kg, respectively (Table 1).

As confirmed by the two way ANOVA test, fire caused a significant decline ($P < 0.001$) of the DTPA-extractable Cu contents in the 0–5 cm soil layer (Unburned > Burned, Figure 6A, Table 2) but there was a significant post-fire increase ($P = 0.001$) in the 10–15 cm soil layer. The 5–10 cm soil layer showed no significant variation ($P = 0.820$) between the burned and unburned areas with respect to the post-fire Cu availability. No significant variation was observed among the sampling months in the DTPA-extractable Cu contents of the 0–5 ($P = 0.470$), 5–10 ($P = 0.984$) and 10–15 cm ($P = 0.668$) soil layers.

In the unburned area, the DTPA-extractable Mn of the 0–5, 5–10 and 10–15 cm soil layers varied from 61.28 to 79.58 mg/kg, 45.11 to 61.51 mg/kg and from 35.00 to 48.3 mg/kg, respectively (Table 1). In contrast, the DTPA-extractable Mn of the three different soil layers respectively ranged from 60.44 to 74.16 mg/kg, 39.39 to 48.36 mg/kg and from 34.38 to 41.12 mg/kg (Table 1).

A two way ANOVA test indicated that fire had no significant effect on the DTPA-extractable Mn contents of the 0–5 ($P = 0.318$) and 10–15 cm ($P = 0.085$) soil layers. However, a significant post-fire decrease ($P = 0.002$) in the Mn availability was noticed in the 5–10 cm soil layer (Unburned > Burned, Figure 7B, Table 2). The DTPA-extractable Mn also varied significantly among the sampling months in the 0–5 ($P = 0.006$), 5–10 ($P = 0.004$) and 10–15 cm ($P = 0.011$) soil layers.

Figure 4. Available potassium (kg/ha) at 0–5 (**A**), 5–10 (**B**) and 10–15 cm (**C**) soil layers. Significant differences ($P \leq 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=3$).

Figure 5. Available iron (mg/kg) at 0-5 (**A**), 5-10 (**B**) and 10-15 cm (**C**) soil layers. Significant differences ($P < 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=4$).

Figure 6. Available copper (mg/kg) at 0-5 (**A**), 5-10 (**B**) and 10-15 cm (**C**) soil layers. Significant differences ($P < 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=4$).

Figure 7. Available manganese (mg/kg) at 0-5 (**A**), 5-10 (**B**) and 10-15 cm (**C**) soil layers. Significant differences ($P < 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=4$).

In the surface layer (0–5 cm), the DTPA-extractable Zn of the unburned area ranged from 2.18 to 4.17 mg/kg while in the burned area, it ranged from 1.41 to 2.22 mg/kg (Table 1). The DTPA-extractable Zn contents of the sub-surface layers (5–10 and 10–15 cm) in the unburned area respectively ranged from 1.59 to 2.46 mg/kg and from 1.17 to 2.17 mg/kg while in the burned area, they ranged from 1.21 to 2.12 mg/kg and from 1.05 to 2.01 mg/kg, respectively (Table 1).

The results of the two way ANOVA test showed that fire reduced the DTPA-extractable Zn contents of the 0–5 cm soil layer varying significantly ($P=0.004$) between the burned and unburned areas (Unburned > Burned, Figure 8A, Table 2) while it did not show significant variation ($P=0.08$) among the sampling months. A significant decline ($P=0.020$) was also observed in the 5–10 cm soil layer (Unburned > Burned, Figure 8B, Table 2). The DTPA-extractable Zn of the 5–10 cm soil layer also varied significantly ($P<0.001$) among the sampling months. The 10–15 cm soil layer showed no significant variation ($P=0.220$) in terms of the Zn availability between the burned and unburned areas. However, it showed significant variation ($P<0.001$) among the sampling months.

Post forest fire soil nutrient levels in burned and unburned areas of the Kouburu Hills, Manipur

8 Data Files

<http://dx.doi.org/10.6084/m9.figshare.903706>

Discussion

Soil organic carbon

SOC contents decreased in all the three soil layers of the burned area as confirmed by the two way ANOVA test and the decrease persisted throughout the sampling period. The persistence of this condition throughout the study reflects the high severity of the forest fire and the fact that we found a significant decrease of SOC in the 5–10 and 10–15 cm soil layers is further evidence of the high severity of the forest fire. The fire-induced reduction in SOC in this study is consistent with the results from studies conducted elsewhere^{16–20}. However, contrasting results have also been obtained by other researchers^{21–23} who reported increased SOC after fire disturbance. The decrease in SOC content of the burned area may be attributed to the volatilization of organic carbon and conversion of organic matter to ash^{24,25}. In a laboratory experiment, Terefe *et al.*²⁶ observed a significant reduction in SOC content from A horizons after heating at 200 and 300°C with the complete loss of SOC at 500°C.

NH₄⁺-N and available potassium

As confirmed by the two way ANOVA test, forest wildfire resulted in a significant loss of NH₄⁺-N and available K from the burned area. Most studies^{17,27–29} show an initial increase in inorganic forms of nitrogen such as NH₄⁺-N after fire followed by a decline with time. In the present study, however, we found a decrease in NH₄⁺-N concentration of the burned area and the decrease persisted until the study ended. This finding agreed with the results obtained by Shaoqing *et al.*³⁰ and Longo *et al.*¹⁹. The burned area also had lower available potassium than the adjacent unburned area. Yinghua *et al.*³¹ reported short-term increase in available potassium after fire

which then declined and was lower than the unburned area at later sampling times. The decrease in NH₄⁺-N and available potassium of the burned area may be attributed to the individual or combined effect of several factors such as volatilization, slow mineralization rate, increased uptake by newly sprouted vegetation³², dry ravel erosion³³, surface run-off and leaching. In addition to the above mentioned factors, the loss of NH₄⁺-N from the burned area may also be due to the nitrification of NH₄⁺ to NO₃⁻ as heat-sensitive nitrifying bacteria recolonized the area^{34,35}. Among all nutrients vital for plant growth, N is the most sensitive to volatilization. Half of the N in organic matter can be volatilized at 500°C^{35,36}. The volatilization temperature of K is 760°C. Because the forest fire consumed the entire understory vegetation and the litter layer, it is possible that the temperature was sufficiently high during the fire to volatilize significant quantities of NH₄⁺-N and available potassium. The rate of nutrient mineralization may have been slowed down probably due to fire-induced reduction in soil decomposer organisms which include microbes and invertebrates. High severity-fires sterilize the soil or delay the recovery of soil microbes and consequently reduce their activity^{37,38}. The litter loss and microclimatic changes resulting from fire can indirectly decrease the total mass and species numbers of soil and litter dwelling invertebrates^{39,40}. Choromanska and DeLuca⁴¹ reported that N mineralization decreased after fire and did not recover after nine months of the study period.

Soil that has been protected from erosional processes for decades by vegetation or litter cover is particularly vulnerable when the cover is removed⁴². When the vegetation and litter layer is destroyed by fire, the soil is susceptible to dry ravel^{43,44}, which can be defined as the movement of particles by rolling, sliding and bouncing down slope under the influence of gravity^{45–47} and to water erosion during the first major rain event^{48,49}. Following fire, surface run-off and erosion can be increased by several orders of magnitude^{50,51}, mainly during the first months when the soil is bare, if intense rainfall events are frequent^{52–54}.

Available (Bray-extractable) phosphorus

In this study, the available P was higher in the burned area than the adjacent unburned area in all the three soil layers and the increase was significant as proved by the two way ANOVA test. This finding is in agreement with the findings of several other workers who have reported increased post-fire available P levels^{55–59}. Though post-fire increase in the available P level is a common trend in most research findings, decreases have also been noted^{19,60}. The significant post-fire increase in the available P may be attributed to a number of factors such as fire-induced conversion of organic forms of soil phosphorus to inorganic forms, lack of orthophosphate leaching and lack of plants that utilize this nutrient in the study site. P loss through volatilization generally does not take place⁶¹. However, burning converts the soil organic P to orthophosphate^{62,63}, the sole form of soil P available to biota. The time in which the positive effect on P bioavailability runs short is highly variable depending on numerous factors. Romanya *et al.*⁶⁴ found increased post-fire soil concentrations of available P (NaHCO₃-extractable) and labile P (NH₄F HCl-extractable) even at seven months after clear felling and slash burning, in a *Eucalyptus* forest. In a *Picea* dominated forest, Macadam⁶⁵ found that the available P in the upper 30 cm mineral soil had increased by up to 50%, nine months after slash burning,

Figure 8. Available zinc (mg/kg) at 0–5 (**A**), 5–10 (**B**) and 10–15 cm (**C**) soil layers. Significant differences ($P < 0.05$) between unburned and burned areas on specific sampling months are indicated by different letters above histogram bars. Data show mean $\pm$ SE ($n=4$).

and this increase persisted, although somewhat diminished, twenty months after the fire event. In this research, sampling at monthly intervals started approximately three months after the fire event and continued for a period of one year, so it may have been within the fire-associated P enrichment period.

Available (DTPA-extractable) micronutrients (Fe, Cu, Mn and Zn)

The available Fe levels depleted in all the three soil layers (0–5, 5–10 and 10–15 cm) of the burned area and the depletion was significant as confirmed by the two way ANOVA test. Some recent studies have also reported a decline in the Fe availability of burned soils^{18,29,66–68}. The fire induced depletion of the available Fe in the burned area could be associated with losses (by convection in smoke columns, transport by wind, erosion and leaching) and/or conversion to insoluble oxidized forms in soils as have been reported for several other nutrients^{25,69}.

Contradictory results were obtained in terms of fire-induced effects on the soil available Cu contents of the three soil layers studied. While the available Cu content of the 0–5 cm soil layer declined significantly, it showed no noticeable variation between the burned and unburned areas in the 5–10 cm soil layer. The 10–15 cm soil layer showed an increase in the Cu availability after the fire event, the available Cu being higher in the burned area than the adjacent unburned area. Other authors^{68,70} have also observed fire-induced increases in the soil available Cu. The fire induced-loss of the available Cu from the 0–5 cm soil layer of the burned area may be due to the singular or combination effects of several factors such as erosion, leaching, transport by wind, *etc.* Solute losses increased during the first rain events following fire according to one study⁷¹. Thus, it is possible that during rains some amounts of the available Cu in the ash resulting from fire leached into the deeper soil layers causing higher Cu availability in the 10–15 cm soil layer.

As confirmed by the two way ANOVA test, fire had no significant effect on the available Mn contents of the 0–5 and 10–15 cm soil layers, although Gomez-Rey *et al.*²⁹ reported higher post-fire Mn availability in the 0–5 cm soil layer, attributed to Mn supplied by ashes from the burned vegetation. In contrast to the lack of difference in terms of the Mn availability between the burned and unburned areas in the 0–5 and 10–15 cm soil layers, the 5–10 cm soil layer showed a significant post-fire decrease in the available Mn compared with the unburned areas. Research findings from several studies have been mixed in terms of post-fire Mn availability. Brye⁷² observed a significant decline in the soil available Mn (extracted with Mehlich 3) as a consequence of 12 years of annual burning on a tall-grass prairie. However, other authors^{66,68,73} have reported a significant increase in the soil available Mn after fire.

With respect to the post-fire Zn availability, we found that the available Zn decreased in the 0–5 and 5–10 cm soil layers showing significant variations between the burned and unburned areas as indicated by the two way ANOVA tests. No fire effect was seen in the 10–15 cm soil layer as regards the available Zn which did not differ between the burned and unburned areas. The post-fire decline

in the available Zn of the 0–5 and 5–10 cm soil layers is consistent with the observation of Marafa and Chau⁷⁴ who have also reported a post-fire reduction in the amount of Zn. Other researchers have obtained contradictory results. For example, Garcia-Marco and Gonzalez Prieto⁶⁶ observed an initial rise in the available Zn after fire disturbance followed by a decline one year after the fire. However, Close *et al.*⁶⁸ and Stankov Jovanovic *et al.*⁶⁹ have reported enhanced Zn availability in burned soils due to the release of Zn by ashes from burned vegetation. The available Zn depletion in the 0–5 and 5–10 cm soil layers of the burned area may be attributed to leaching and erosional losses as this element could be quickly leached⁷⁵ or lost in eroded sediments²⁹.

Conclusion

The SOC was significantly reduced following fire in all the three soil layers (0–5, 5–10 and 10–15 cm) and the significant reduction of the SOC even in the sub-surface layers (5–10 and 10–15 cm) is an indication of the high severity of the forest wildfire. The forest wildfire also had a significant effect on the available macronutrient concentrations, decreasing $\text{NH}_4^+\text{-N}$ and available K and increasing that of available P in all the three soil layers. Contradictory results were obtained with respect to the soil micronutrient availability. While the available Fe declined in all the three soil layers, the available Cu declined only in the 0–5 cm soil layer. However, in the 10–15 cm soil layer, the available Cu showed an increase, the concentration being higher in the burned area compared to the unburned area. The available Cu contents of the 5–10 cm soil layer did not vary significantly between the burned and unburned areas. The Mn availability declined in the 5–10 cm soil layer but no fire-induced effect was found on the available Mn contents of the 0–5 and 10–15 cm soil layers. Fire significantly reduced the available Zn contents of the 0–5 and 5–10 cm soil layers. The available Zn content of the 10–15 cm soil layer did not show significant variation between the burned and unburned areas. Thus, the forest wildfire resulted in a significant loss of most soil nutrients at this site. Taking into account the post-fire decline of most soil nutrients in one or all of the three soil layers studied, it can be concluded that forest wildfire had detrimental impacts on soil nutrients at this site and the ecologically most significant effect was the loss of N and K from the burned soil.

Data availability

Figshare. Post forest fire soil nutrient levels in burned and unburned areas of the Koubu Hills, Manipur, <http://dx.doi.org/10.6084/m9.figshare.903706>⁷⁶

Author contributions

TBS conceived the study, suggested expertise in soil science and contributed to the preparation of the manuscript. AS carried out the research, interpreted the data and prepared the first draft of the manuscript. Both authors critically revised the draft manuscript and have agreed to the final content of the version to be published.

Competing interests

No competing interests were disclosed.

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Supplementary materials

Supplementary Table 1. The individual P values (both significant and non-significant) determined by the one way ANOVA test for all the soil nutrients studied at 0–5 cm soil depths in each sampling month. The significant P values are followed by the letters (ab) on the right.

Months	SOC %	NH ₄ ⁺ -N	Available P	Available K	Available Fe	Available Cu	Available Mn	Available Zn
APRIL	0.013732ab	0.00000115ab	0.092399	0.000488ab	0.024384ab	0.0000408ab	0.01729ab	0.000438ab
MAY	0.0000436ab	0.00000025ab	0.788271	0.0000327ab	0.00000562ab	0.013035ab	0.005514ab	0.00768ab
JUNE	0.000298ab	0.0000014ab	0.003423ab	0.00036ab	0.031598ab	0.0000341ab	0.114677	0.00692ab
JULY	0.000395ab	0.00000053ab	0.794072	0.001494ab	0.643206	0.000121ab	0.059718	0.214843
AUG	0.014326ab	0.00000152ab	0.024494ab	0.00105ab	0.000201ab	0.00000008ab	0.243871	0.006771ab
SEPT	0.000863ab	0.0000011ab	0.011319ab	0.000102ab	0.001058ab	0.00000717ab	0.001556ab	0.000325ab
OCT	0.000972ab	0.00000272ab	0.033226ab	0.0000868ab	0.000357ab	0.014517ab	0.002495ab	0.000144ab
NOV	0.033615ab	0.00000281ab	0.027905ab	0.00000602ab	0.000322ab	0.00000114ab	0.0005ab	1
DEC	0.000518ab	0.0000013ab	1	0.0000596ab	0.051249	0.031933ab	0.000194ab	0.00000004ab
JAN	0.006283ab	0.00000487ab	0.144604	0.001808ab	0.013683ab	0.00000004ab	0.003687ab	0.0000157ab
FEB	0.005026ab	0.0000412ab	0.40357	0.0000306ab	0.280835	0.00000016ab	0.24263	0.00000323ab
MARCH	0.000102ab	0.00000367ab	0.411553	0.000126ab	0.345353	0.0000001ab	0.0000107ab	0.00000033ab

Supplementary Table 2. The individual P values (both significant and non-significant) determined by the one way ANOVA test for all the soil nutrients studied at 5–10 cm soil depths in each sampling month. The significant P values are followed by the letters (ab) on the right.

Months	SOC %	NH ₄ ⁺ -N	Available P	Available K	Available Fe	Available Cu	Available Mn	Available Zn
APRIL	0.0000668ab	0.00000646ab	0.001899ab	0.000556ab	0.000462ab	0.008833ab	0.0000248ab	0.09716
MAY	0.0000001ab	0.00000019ab	0.002151ab	0.000418ab	0.000846ab	0.00000119ab	0.00000001ab	0.000363ab
JUNE	0.00000401ab	0.00000065ab	0.009753ab	0.0000491ab	0.007329ab	0.003581ab	0.0000273ab	0.113956
JULY	0.00000187ab	0.00000209ab	0.10013	0.000231ab	0.0000721ab	0.000608ab	0.000925ab	0.000433ab
AUG	0.00000066ab	0.0000194ab	0.00312ab	0.000937ab	0.0000302ab	0.000108ab	0.0000412ab	0.000161ab
SEPT	0.0000584ab	0.00000082ab	0.015419ab	0.000561ab	0.04445ab	0.00000059ab	0.0000775ab	0.03002ab
OCT	0.00000279ab	0.0000083ab	0.002957ab	0.00000804ab	0.010212ab	0.0000984ab	0.000168ab	0.445416
NOV	0.00000083ab	0.00000426ab	0.002128ab	0.0000177ab	0.018233ab	0.00000043ab	0.001414ab	0.398956
DEC	0.0000233ab	0.0000033ab	0.071242	0.000434ab	0.754006	0.00000425ab	0.887478	0.000595ab
JAN	0.00000961ab	0.00000112ab	0.911763	0.00061ab	0.0000144ab	0.0000008ab	0.330956	0.022487ab
FEB	0.0000296ab	0.00000233ab	0.32646	0.000356ab	0.422327	0.00000001ab	0.001609ab	0.001269ab
MARCH	0.00000301ab	0.00000169ab	0.839951	0.0000777ab	0.011502ab	0.00000003ab	0.01477ab	1

Supplementary Table 3. The individual P values (both significant and non-significant) determined by the one way ANOVA test for all the soil nutrients studied at 10–15 cm soil depths in each sampling month. The significant P values are followed by the letters (ab) on the right.

Months	SOC %	NH ₄ ⁺ -N	Available P	Available K	Available Fe	Available Cu	Available Mn	Available Zn
APRIL	0.00000108ab	0.00000581ab	0.004729ab	0.059703ab	0.00012ab	0.00000053ab	0.058366	0.000401ab
MAY	0.00000021ab	0.00000249ab	0.036467ab	0.008756ab	0.012965ab	0.00000016ab	0.0000159ab	0.001884ab
JUNE	0.012776ab	0.00000176ab	0.146323	0.010478ab	0.388751	0.00011ab	0.0000002ab	0.670412
JULY	0.020453ab	0.00000173ab	0.100267	0.000127ab	0.226362	0.030766ab	0.002672ab	0.112669
AUG	0.00000326ab	0.00000336ab	0.001433ab	0.0000612ab	0.046472ab	0.002253ab	0.000118ab	0.467994
SEPT	0.00000086ab	0.00000688ab	0.001989ab	0.0000153ab	0.03155ab	0.000379ab	0.00132ab	0.0000651ab
OCT	0.0000421ab	0.00000645ab	0.00128ab	0.000469ab	0.000522ab	0.0000123ab	0.0000891ab	0.199622
NOV	0.000233ab	0.000394ab	0.002893ab	0.000152ab	0.001832ab	0.906289	0.000154ab	0.50188
DEC	0.00000268ab	0.0000273ab	0.536106	0.001558ab	0.003051ab	0.00000943ab	0.122436	0.016703ab
JAN	0.000001ab	0.0000366ab	0.217319	0.0000711ab	0.008413ab	0.0000444ab	0.582289	0.536963
FEB	0.000227ab	0.0000316ab	0.2242323	0.0000375ab	0.476041	0.00000005ab	0.291113	0.570456
MARCH	0.00000031ab	0.00000499ab	0.429647	0.002118ab	0.306916	0.00000173ab	0.000455ab	0.207031

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Version 1

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The authors addressed post-fire nutrient availability in a subtropical forest. They found that the forest wildfire resulted in a significant loss of most soil nutrients. Throughout the whole manuscript, however, the authors mainly described the results rather than mechanisms. In fact, there was lack of direct evidence to explain their findings. They pointed out that very few studies have evaluated post-fire effects on soil micro-nutrients, but did not show why they did this work. "very few" may mean that this work is not important, or it has been very clear. Hence, the major concerns are related to the novelty and the mechanism explanations.

Others:

1. I am a little curious that the abstract mainly described the results without conclusion.
2. In the "site description", 3.99 mm for mean annual precipitation?
3. Table 1, please show the sampling time, and better to unify the unit (e.g. N and P).
4. The authors mentioned element contents (such as SOC), the term "content" means stock. So it is better to show the responses of total soil nutrient stocks to fire for the whole soil layers.
5. Repeated-measure ANOVA can be used to examine the overall fire effects on soil nutrient dynamics over the study period.

Is the work clearly and accurately presented and does it cite the current literature?

No

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

No

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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