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Landscape Online
open access peer reviewed

SYNTHESIS

Landscape Online | Volume 99 | 2024 | Article 1128

Submitted: 26 February 2024 | Accepted in revised version: 15 December 2024| Published: 21 December 2024

Mapping and impact of seasonal forest fires on vegetation types, soil dynamics, and tree mortality in the forest ecosystem of Uttarakhand Himalaya

Abstract

This study investigates forest fire dynamics and their implications for management in the Uttarakhand Himalaya region. Utilizing remote sensing analysis, field surveys, and socio-economic assessments, the research aims to understand the spatial and temporal patterns of fires, assess their impact on vegetation, soil properties, and biodiversity, and propose effective management strategies. Results reveal a significant increase in fire frequency and severity, with a 25% rise in fire occurrences observed over the past decade. High-intensity fires caused extensive damage to vegetation, with a 40% reduction in tree density observed in severely affected areas. Soil organic matter loss due to fires averages at 15%, threatening ecosystem health and resilience. However, opportunities for fire management exist, including prescribed burning and community-based prevention programs. Policy recommendations emphasize the importance of integrating ecological and socio-economic perspectives into fire management strategies to promote ecosystem resilience and community adaptation. This study contributes valuable insights for policymakers, forest managers, and local communities to develop science-based fire management policies and practices, ultimately fostering sustainable forest management and fire risk reduction in the Uttarakhand Himalaya region.

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Keywords:
forest fires, fire frequency, vegetation dynamics, soil properties, tree mortality, management strategies, Uttarakhand Himalaya

https://doi.org/10.3097/LO.2024.1128

1 Introduction

Fire has played a pivotal role in evolutionary processes and has been wielded by humans as a transformative tool since ancient times (Bond and Keeley, 2005). Evidence of fire's presence on Earth dates back to the Carboniferous period, approximately 300 million years ago, as indicated by fossilized charcoal found in coal deposits (Spinage, 2012). This period long predates the appearance of humans. Early humans began to use fire much later, around 1.5 million years ago, as suggested by archaeological findings. The use of fire by humans significantly impacted their lifestyle and environment, marking an important evolutionary step.

Forest fires are increasingly recognized as a critical global issue, significantly impacting environments, economies, and public health. While natural ignitions such as lightning still play a role, human activities now drive the majority of global fires. The deliberate use of fire for agriculture, land clearing, and hazard reduction has disrupted natural fire cycles, leading to more frequent and intense fires in many regions. This escalation presents serious challenges for ecosystem resilience and biodiversity conservation. Understanding and addressing the drivers of increased fire activity is essential for mitigating its harmful effects and harnessing any potential benefits.

While lightning remains a primary natural ignition source, human-induced factors increasingly influence fire dynamics, with anthropogenic activities responsible for the majority of global fires (Goldammer and Pyne, 1997). The deliberate use of fire by humans for various purposes such as hunting, agriculture, and hazard reduction has altered natural fire cycles, leading to heightened fire frequencies in many regions (Pyne,1996). This disruption poses challenges for ecosystem resilience and biodiversity conservation, although fire's ecological role encompasses both detrimental and beneficial effects (Rowell and Moore, 2000). Despite efforts to understand and manage forest fires, recent demographic shifts and land-use changes have elevated fire concerns, particularly in tropical regions (Cochrane, 2003). Fire's ecological impacts are multifaceted, influenced by factors including its origin, frequency, vegetation types, and resultant damage extent (Kraus and Goldammer, 2007). Moreover, the relationship between fire, forests, and humans is intricate, with human interventions altering natural fire regimes and landscape dynamics (Pyne,1996). Forest fires also have broader implications, including atmospheric emissions impacting climate and weather systems (Thonicke et al. 2001).

1.1 Need of study

While global research has extensively studied forest fires' impacts, particularly in tropical regions, there remains a significant knowledge gap regarding India's forest ecosystems (Bahuguna and Upadhyay, 2002; Krishna and Reddy, 2012). Limited understanding of forest fire ecology, socioeconomics, and cultural impacts hampers effective forest resource management and climate change mitigation (Saha and Howe, 2003; Kodandapani et al. 2008). Uttarakhand, specifically, has been the subject of several studies exploring various facets of forest fires, including fire history, ecological impacts, and conservation threats (Semwal and Mehta, 1996; Sharma and Rikhari, 1997; Rikhari et al. 1999; Bhandari et al. 2012; Singh et al. 2016; Bargali et al. 2018). These studies provide crucial insights for policymaking and conservation efforts.

Keeping aforementioned aspects in view, the current communication aims to address the

(i) To assess forest fire history, extent of damage and the role of vegetation type in the forest fire in Uttarakhand Himalaya.

(ii) Status of pre-and-post-fire on soil physico-chemical properties in the different vegetation type of Uttarakhand Himalayan region.

and (iii) Post fire tree mortality in different vegetation and topographic region of the Uttarakhand Himalaya.

2 Study area: Uttarakhand Himalaya

Uttarakhand, situated in the Western Himalaya of northern India, encompasses diverse ecosystems and climates. It spans from 28.43°N to 31.27°N and

Figure 1. *Shorea robusta* (Sal) dominant forest at Mansa Devi, Haridwar study site.

Figure 2. *Pinus roxburghii* (Chir-pine) dominant forest at Dhari, Nainital study site.

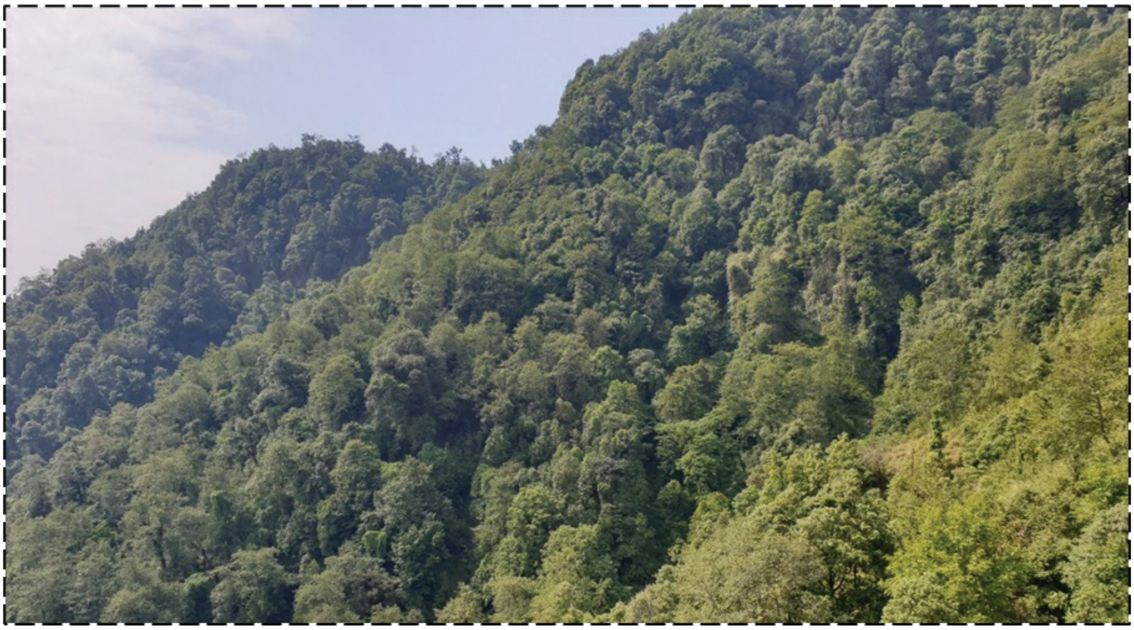

Figure 3. Mixed Forest at Kunjkharak, Nainital study site.

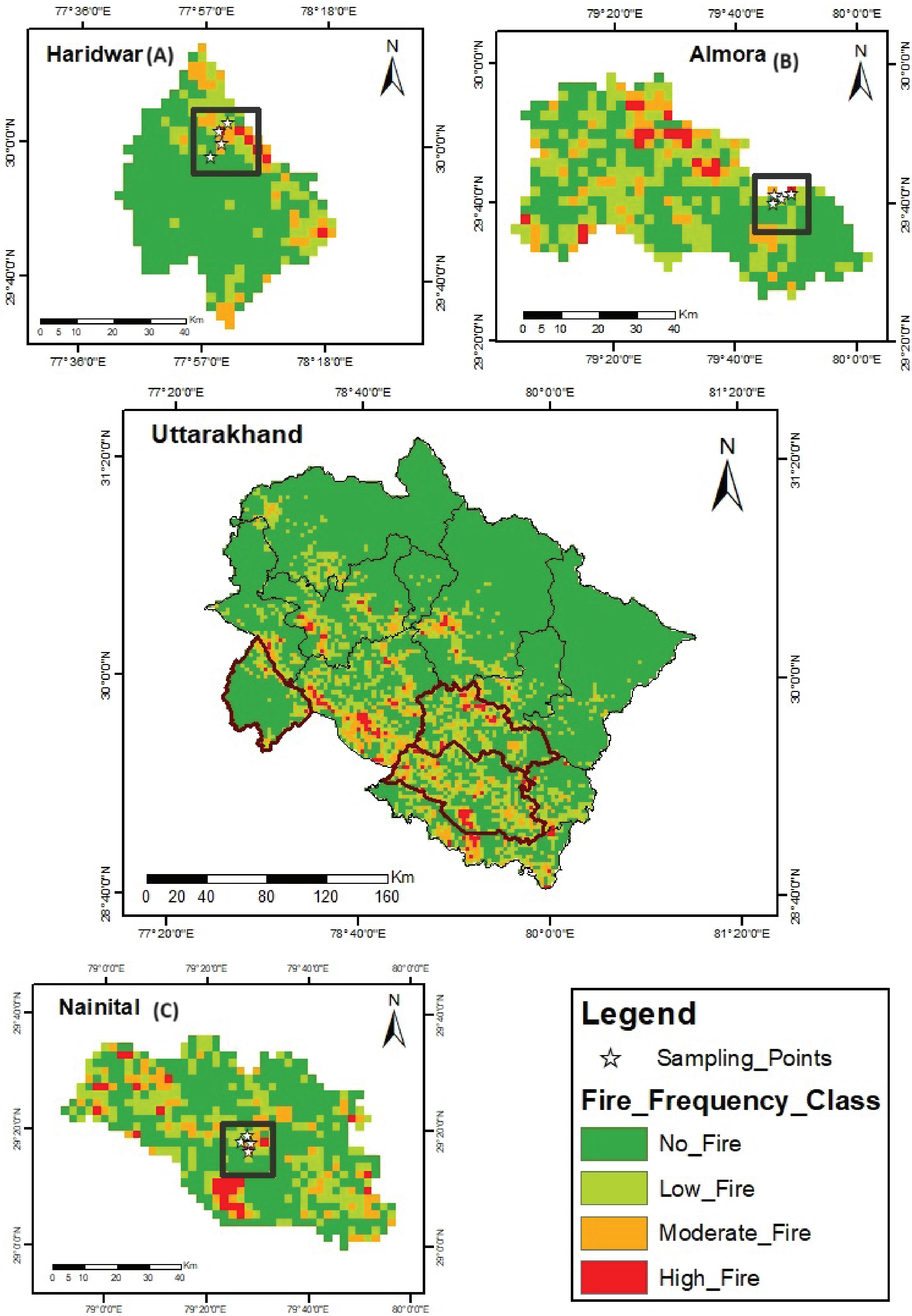

Figure 4. Fire frequency map, sampling points, and selected forest types in the studied sites.

77.34°E to 81.02°E, serving as a transition zone between various geographical regions. The state features a forest cover of 45.6%, including nine distinct forest types. With six national parks, seven wildlife sanctuaries, and four conservation reserves, covering 13.79% of the state's area, Uttarakhand hosts significant biodiversity. However, it faces forest fire challenges, reporting 21,487 incidents from November 2020 to June 2021. These fires, occurring mainly between November and May, stem from natural and human-induced factors like the accumulation of dry foliage. This study examines the impact of fire frequency on tree diversity and regeneration in three fire-prone forests: Sal (Fig.1), Chir-pine (Fig. 2), and mixed forests (Fig. 3). These forests were chosen based on their ecological importance and previous studies have documented their influence on various ecological aspects.

3 Methodological approaches

To fulfill our objectives, we employed a combination of integrated methods including Remote Sensing and GIS, Field Surveys, Historical Records analysis, Interviews/Consultations, and Phytosociology Surveys.

3.1 Remote Sensing and GIS

We analyzed forest fire frequency in Uttarakhand state using Landsat images from 2011 to 2020 and MODIS hotspot data from NASA FIRMS. The data was merged into a single shapefile and classified into four frequency classes using supervised classification. A fishnet was created in ARCMAP, and fire points were spatially joined with raster data to generate the fire frequency map (Fig. 4).

3.2 Field Surveys

A reconnaissance survey was conducted across the study region to select 10 sampling sites spanning an altitudinal gradient of 200-2000m asl. Comprehensive vegetation assessments were conducted pre-and-post-monsoon seasons, encompassing tree, shrub, and herb layers. Sampling included 10m x 10m plots for trees, 5m x 5m plots for shrubs, and 1m x 1m plots for herbs, totaling 100 plots for trees, 200 plots for shrubs, and 300 plots for herbs.

3.3 Historical Records (Forest Department records)

We obtained historical forest fire records from the Uttarakhand Forest Department spanning 2011 to 2020, including data on fire incidences, affected areas, and evaluation of losses.

3.4 Interviews/ consultations

Stakeholder consultations and interviews were conducted to gather information on forest fires, community perceptions, and the loss of provisioning services. Semi-structured questionnaires and focused group discussions were utilized, averaging 15-20 respondents per village.

3.5 Phytosociology survey

Phytosociological assessments were conducted pre-and-post-fire seasons in selected study sites using 10 representative quadrats of 10×10 m size. This includ-

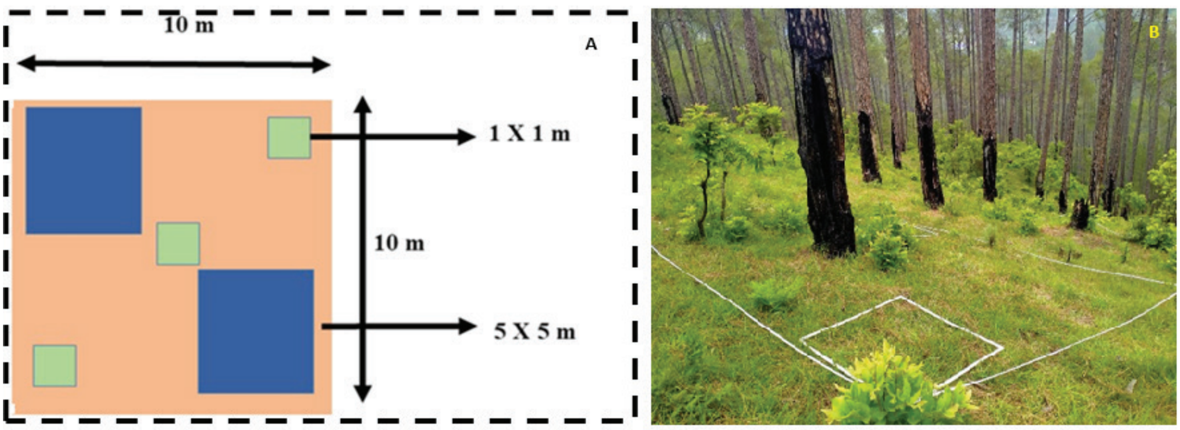

Figure 5. Sampling design (a) Schematic diagram of the study design for assessment of vegetation in the study are (b) Quadrat laid in the field.

ed identifying burnt and damaged trees, fallen logs, and standing dead trees, followed by phytosociological analysis and mortality assessment (Fig. 5)

3.6 Phytosociological analysis

We computed species density, relative density, frequency, relative frequency, relative dominance, and importance value index (IVI). Biodiversity indices like the Simpson, species evenness, and Shannon-Wiener indices were also calculated using standard ecological methods outlined in Mishra (1968) and Muller-Dombois and Ellenberg (1974). Tree species attributes were determined following Sharma et al. (2013).

3.7 Mortality Assessment

We assessed tree mortality caused by fire across species and girth classes. Using simultaneous 95% Bonferroni confidence intervals as per Byers et al. (1984), we identified significant differences in mortality. Regeneration patterns were evaluated by calculating the percentage of saplings and seedlings post-fire.

$$Pie - Z\alpha/2k\sqrt{Pie(1-Pie)/n} < Pie < Pie + Z\alpha/2k\sqrt{Pie(1-Pie)/n}$$

Where, Pie is the observed proportional mortality in each species and $Z\alpha/2k$ is the upper standard normal table value corresponding to a probability tail area of $\alpha/2k$ and n is total number of trees recorded dead. For each species its proportional availability (Pio) in the sample was calculated by dividing its total number (n) from that of total number of all individuals (N) sampled for all species ($Pio = n/\sum N$). Mortality was significantly greater or less than expected when Pio lay outside the 95% confidence limits constructed for proportional mortality (Pie) which was calculated by dividing number of individuals found dead (d) by the total number of dead individuals (D) of all species ($Pie = d/\sum D$).

Proportional mortality (Pie) for each species was calculated as the ratio of the number of dead individuals (d) to the total number of dead individuals (D) across all species. Proportional availability (Pio) of each species was determined as the ratio of its total number of individuals (n) to the total number of individuals (N) sampled for all species. Species showed significant mortality deviations when Pio fell outside the 95% confidence limits of Pie. Regeneration patterns were assessed by calculating the percentage of saplings and seedlings post-fire.

4 Key results

4.1 Fire points under different fire frequency classes

In Uttarakhand from 2011 to 2020, fire incidents were categorized into four frequency classes: no fire, low, moderate, and high. The highest frequency observed was 34, with a consistent decrease in fire points as frequency increased. Incidents varied annually, with notable fluctuations in affected areas and economic losses, reaching a peak in 2016 with 1812 incidents affecting 4433.75 ha and losses of Rs. 4650225, and decreasing to 135 incidents impacting 172.69 ha with losses of Rs. 444135 in 2020 (Fig. 6).

4.2 Spatial pattern of fire

Fire was analysed for their proximity to roads, footpaths and settlements. Fire showed a strong proximity with roads and footpaths but not with settlements. The number of fires was very high near roads and footpaths and started decreasing with increasing distance. The number of fires almost remained same with settlements in 2000 metre distance (Fig. 7a, b, c).

4.3 Soil property variations across various forest types pre-fire (2019-2021) within the top 0-15 cm soil layer

Mixed Forests show highest Soil Moisture Content (SMC) at 18.39%, followed by Sal Forests (12.46%) and Chir-Pine Forests (11.9%). Chir Pine forests have the highest proportion of sand (59.59%), while Sal forests have lower sand concentration (35.55%) and Mixed forests have 57.40% sand. Soil pH is slightly acidic, with the lowest in Chir-Pine Forest (pH 5.88). Mixed Forests exhibit the highest Organic Carbon (OC) at 2.29%, followed by Sal Forests (1.61%) and Chir-Pine Forests (1.58%). Mixed Forests also have the highest Nitrogen (N) content at 0.39%, followed by Chir-Pine (0.26%) and Sal Forests (0.25%).

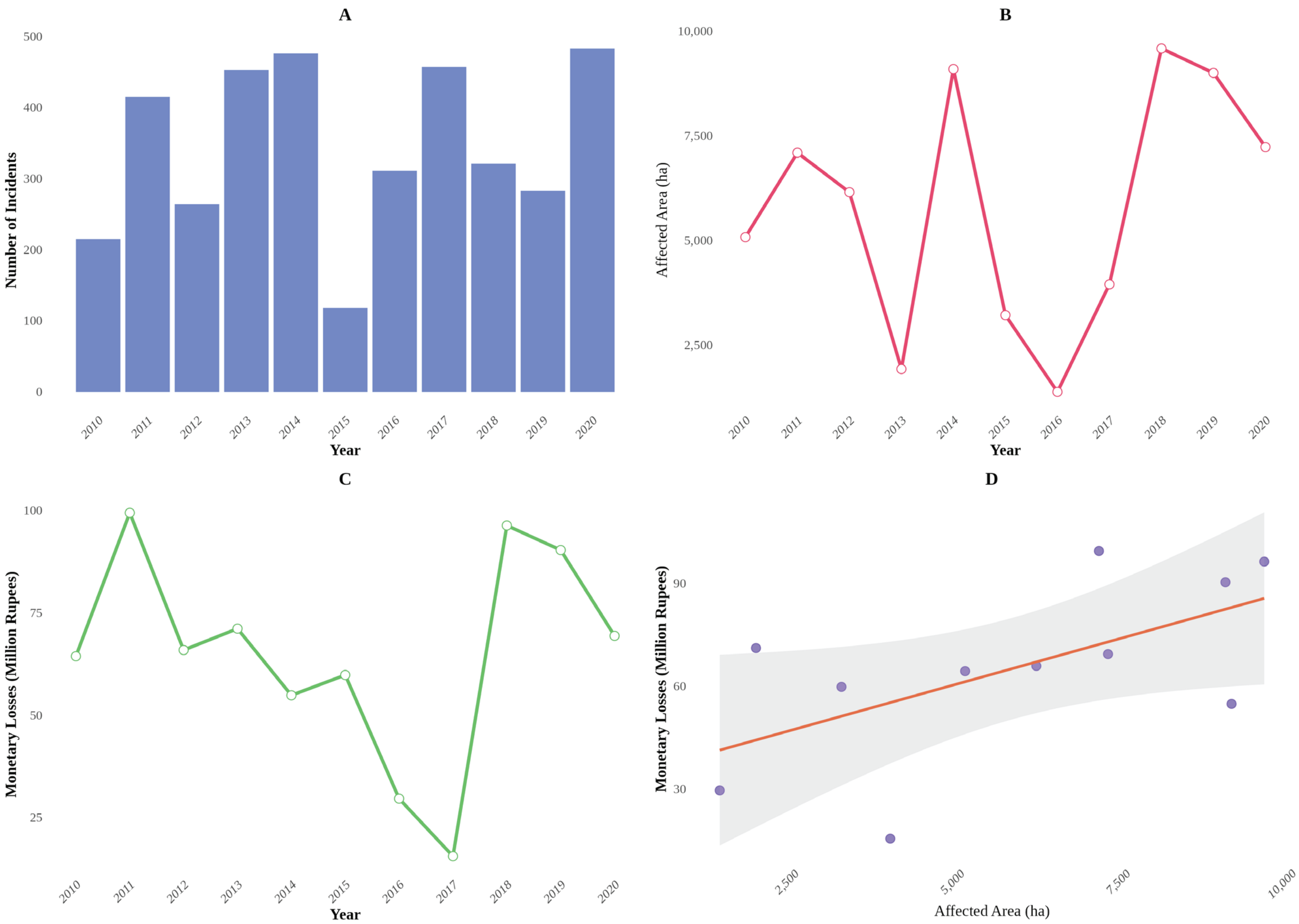

Figure 6. Total number of incidents (no.), total affected area (ha), monetary losses (Rs.) for Uttarakhand (2011-2020). Source: Uttarakhand Forest Department.

Phosphorus (P) values are highest in Mixed Forests (0.20%), followed by Sal Forests (0.13%) and Chir-Pine Forests (0.10%). Potassium (K) values are similar among all three forest types at 0.77% (Fig. 8).

The correlation analysis of soil parameters during pre-fire at 0-15 cm soil depth showed that organic carbon was positively and significantly correlated with SMC (r=0.997), N (r=0.984), P (r=0.957) and K (r=0.023) and the pH was also positively correlated with all the parameters (Fig. 9).

4.4 Soil property variations across various forest types pre-fire (2019-2021) within the top 15-30 cm soil layer

The mixed forest has the highest Soil Moisture Content (SMC) at 18.56%, while Chir-Pine forest has the lowest at 11.54%. Chir-Pine forest consists of 59.23% sand, 26.23% silt, and 4.44% clay. Sal forest recorded lower sand proportion (35.15%) and higher silt (33.72%) and clay (27.60%). Mixed forest's proportions are 57.27% sand, 28.71% silt, and 11.98% clay. Mixed forest has the highest pH (6.17), while Chir-Pine forest has the lowest (5.99). Organic Carbon (OC) is highest in the mixed forest (2.18%), followed by Chir-Pine Forest (1.48%) and Sal forest (1.39%). Nitrogen (N) content is highest in the mixed forest (0.37%), followed by Chir-Pine forest (0.24%) and Sal forest (0.23%). Phosphorus (P) is highest in the mixed forest (0.18%), followed by Sal forest (0.11%) and Chir-Pine forest (0.09%). The mixed and Chir-Pine forests have similar potassium (K) values (0.73% and 0.73%, respectively), while Sal forest has the lowest K value (0.69%). (Fig. 10).

The correlation analysis of soil parameters during pre-fire at 15-30 cm soil depth were depicted in Table 2 and showed that pH was positively significant

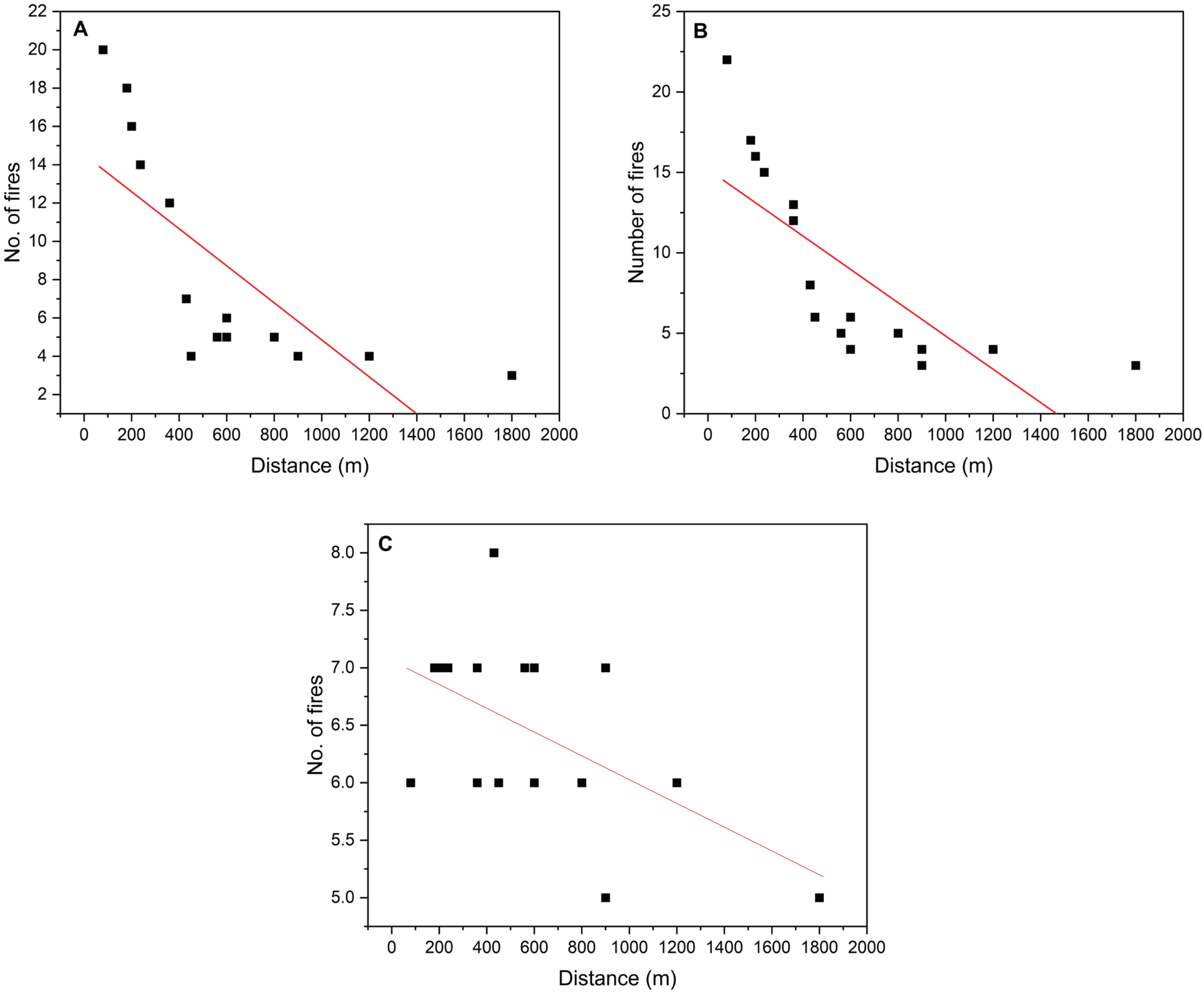

Figure 7. Proximity of fire to A) Road, B) Footpaths, and C) Settlements.

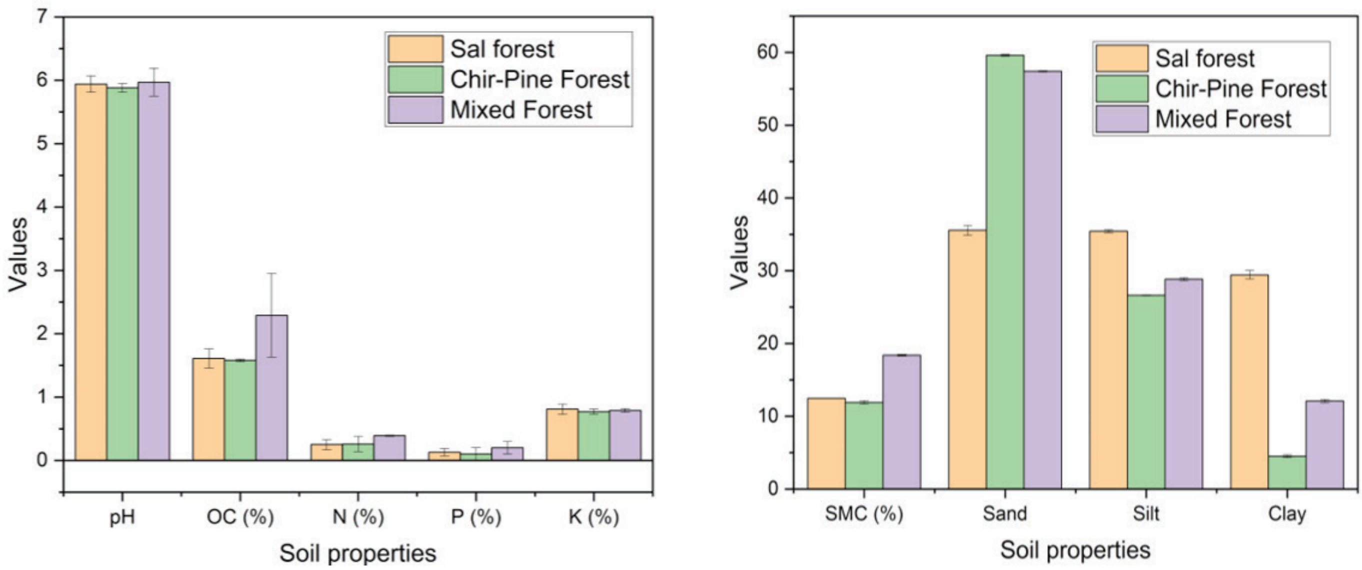

Figure 8. Status of different soil parameters in 0-15 cm depth during pre-fire (2019).

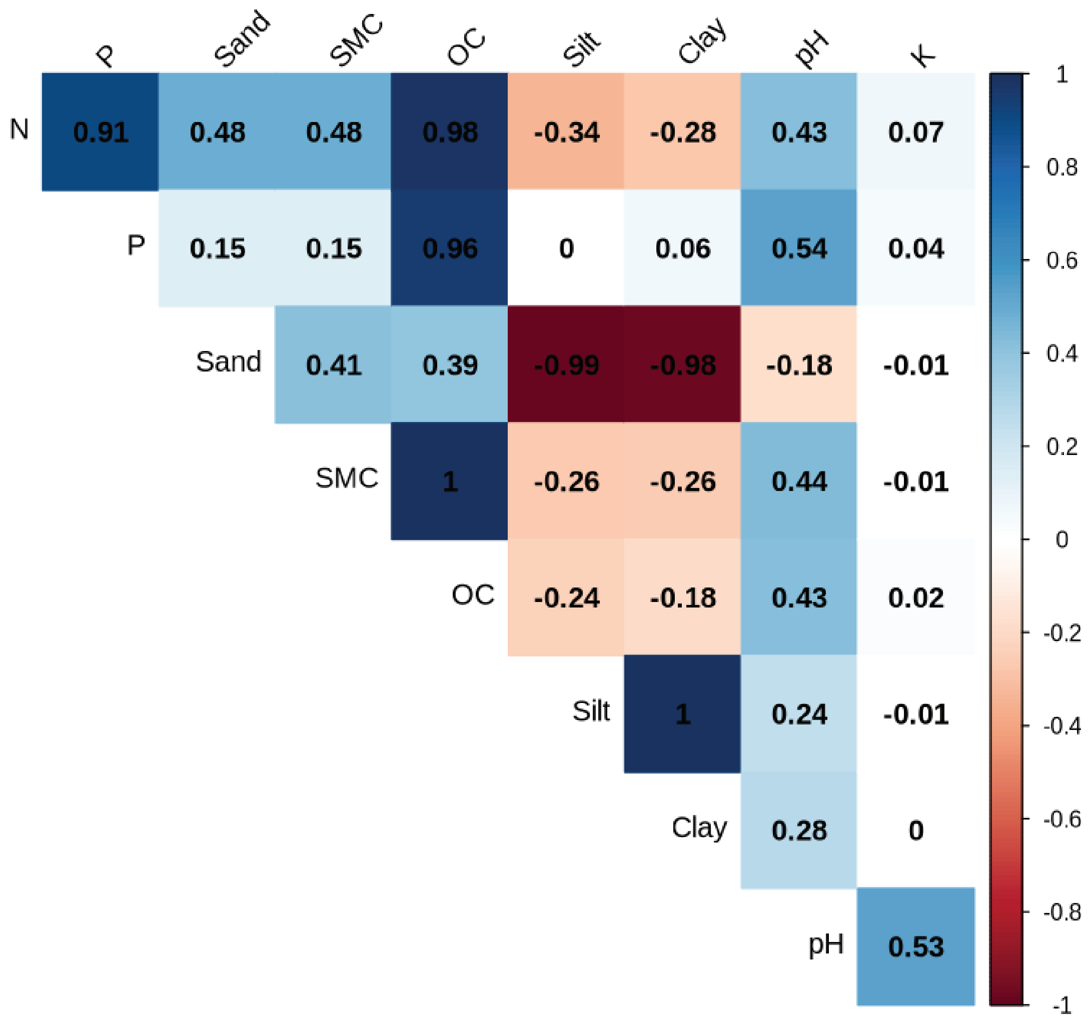

Figure 9. Correlation matrix of soil physico-chemical properties in 0-15 cm depth during pre-fire (2019).

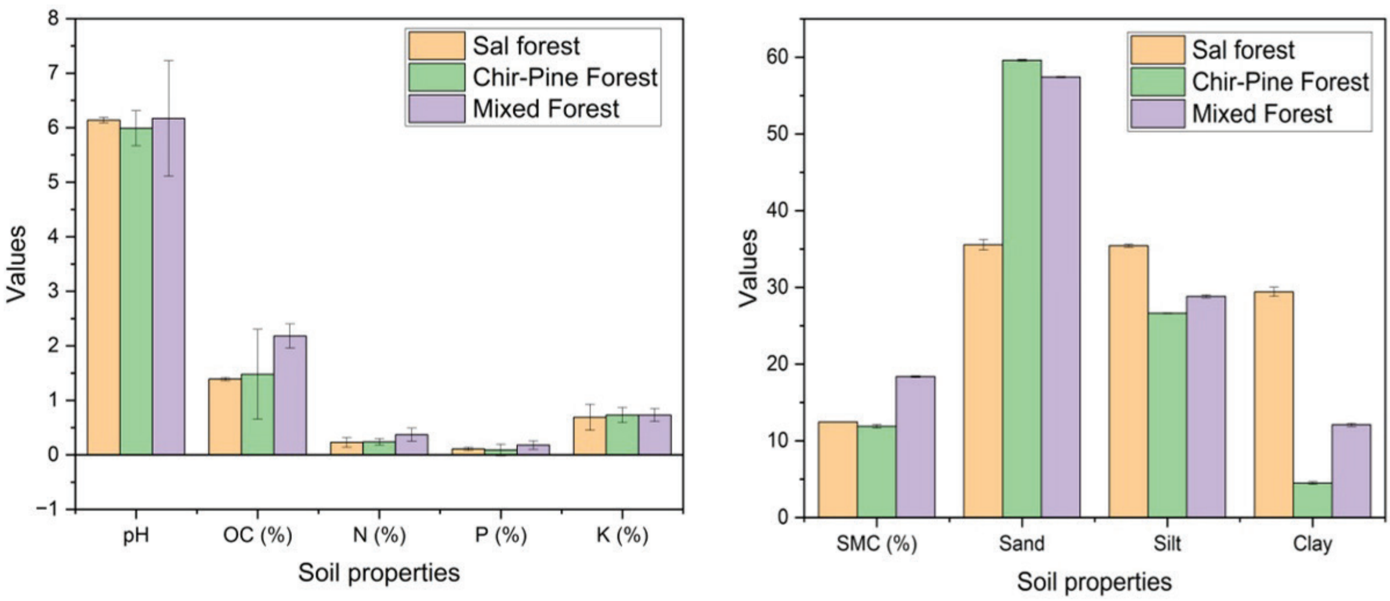

Figure 10. Correlation matrix of soil physico-chemical properties in 15-30 cm depth during pre-fire 2019-2021.

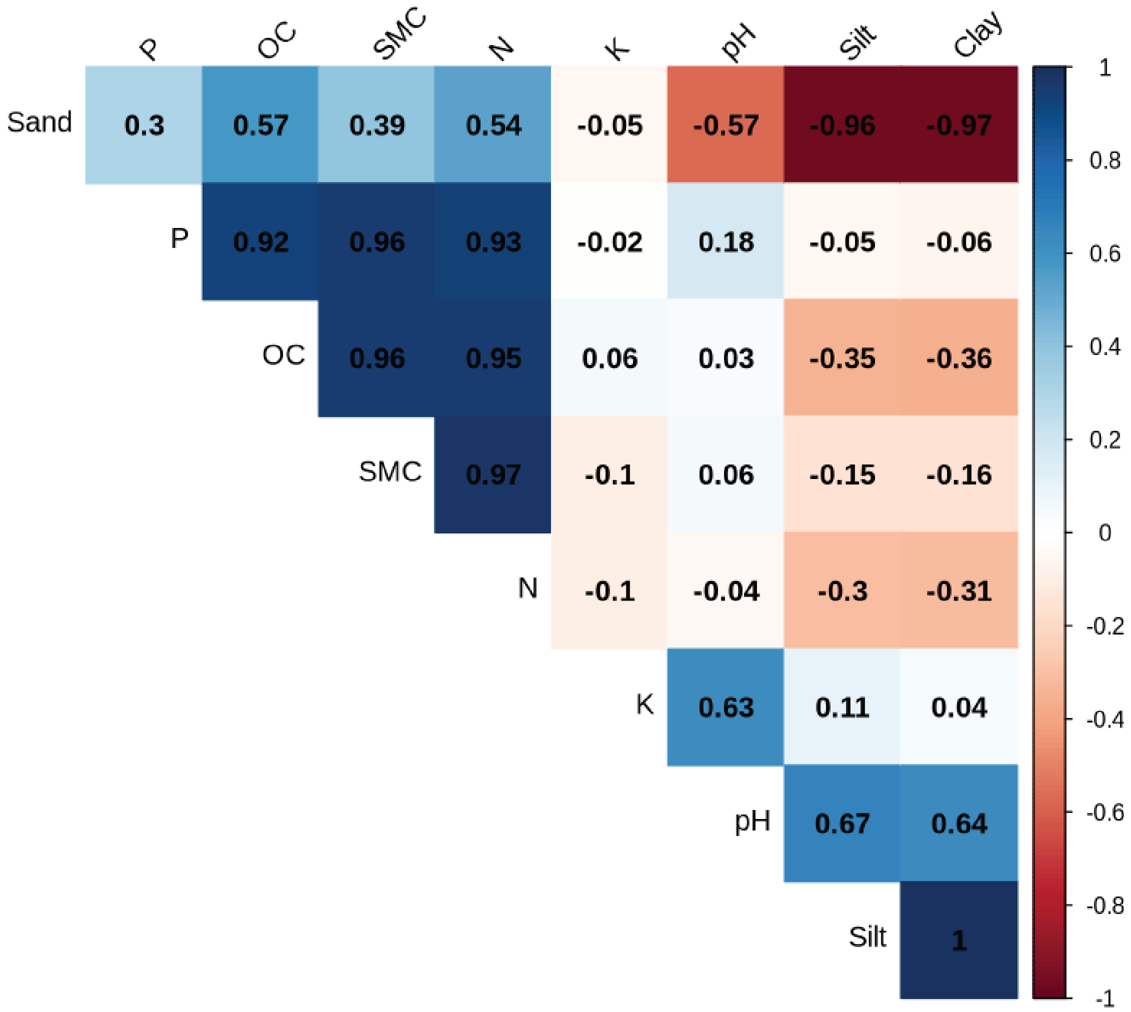

Figure 11. Correlation matrix of soil physico-chemical properties in 15-30 cm depth during pre-fire 2019-2021.

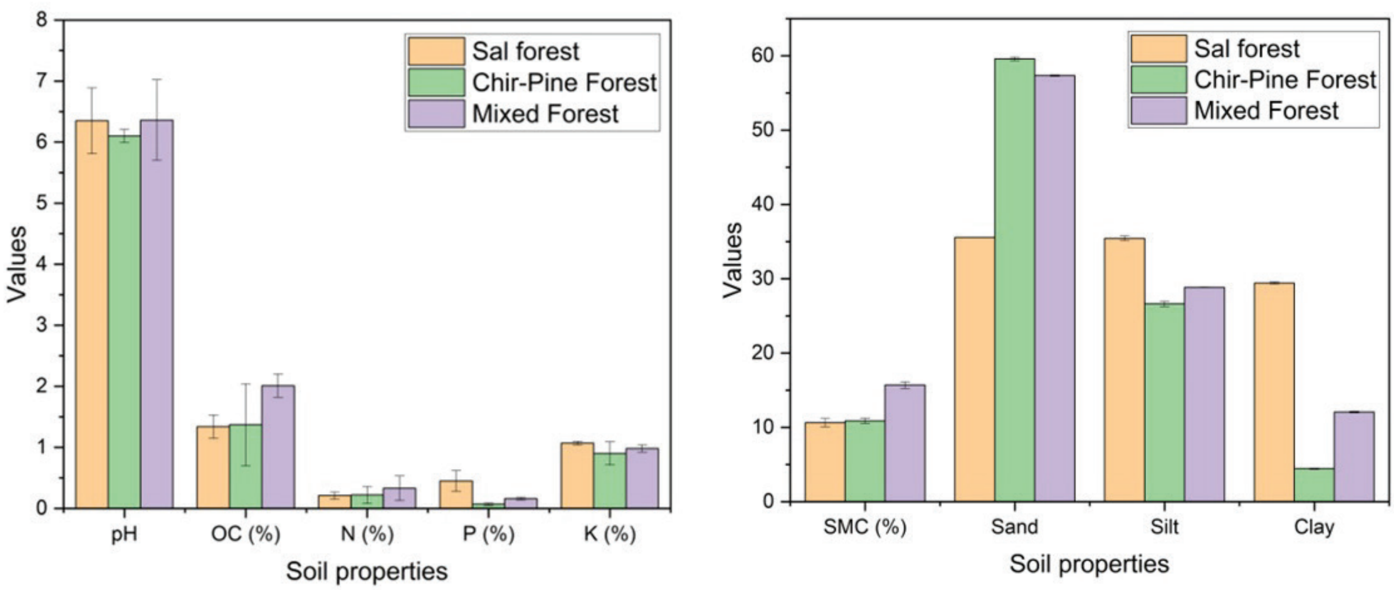

Figure 12. Status of different soil parameters in 0-15 cm depth during post-fire (2019-2021).

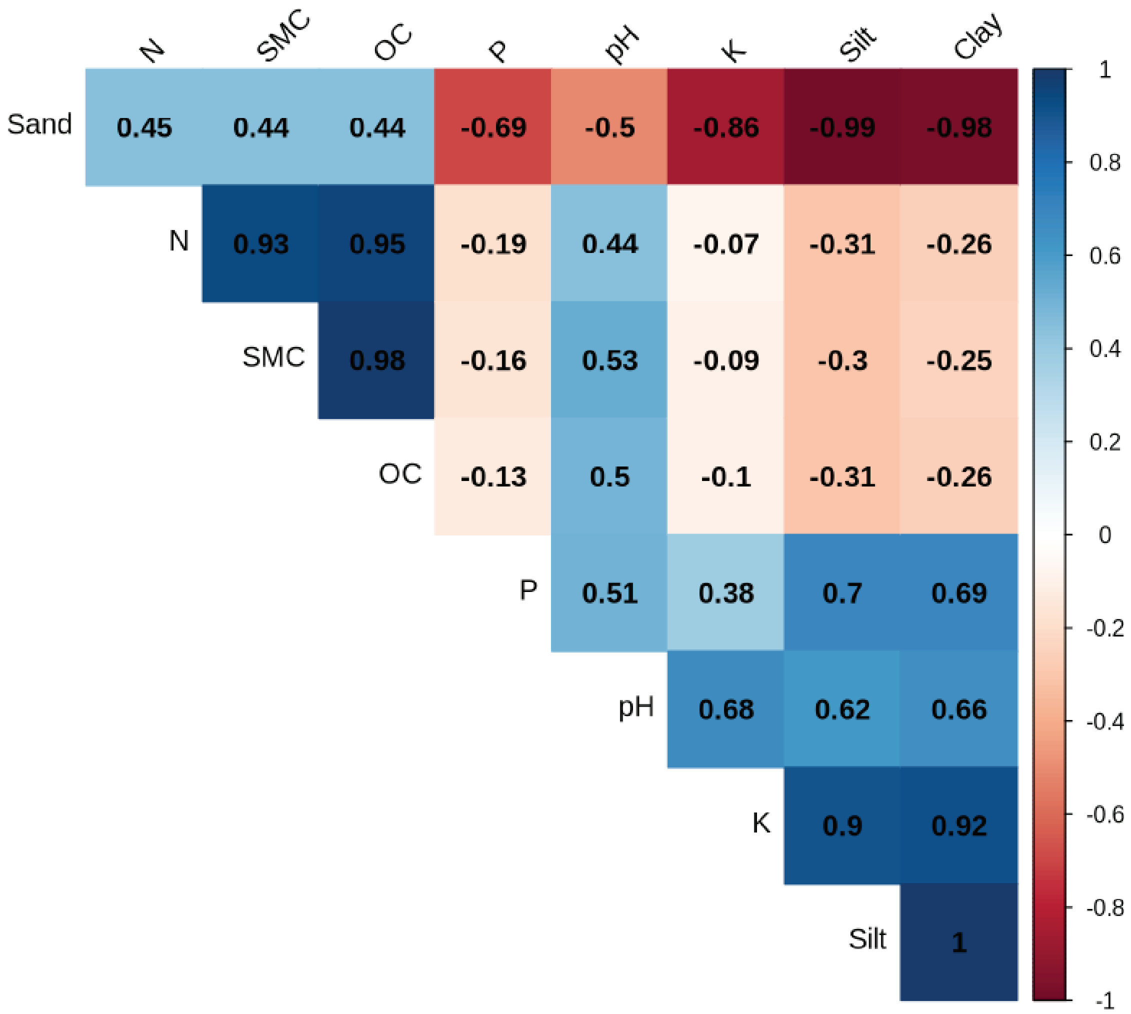

Figure 13. Correlation matrix of soil physico-chemical properties in 0-15 cm depth during post-fire (2019-2021).

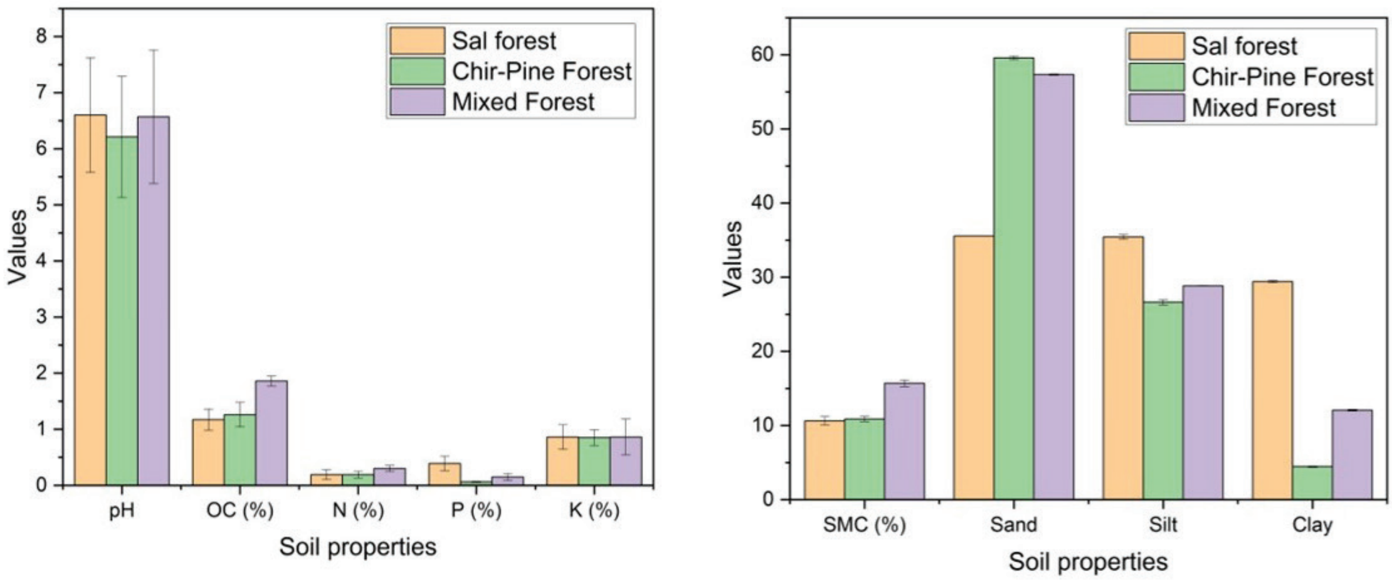

Figure 14. Status of different soil parameters in 15-30 cm depth during post-fire (2019-2021).

with all the parameters except nitrogen (r=-0.045). Moreover, organic carbon was highly significant with N (r=0.950) and P (r=0.920) and moisture content was also positively and highly significant with pH, OC, N and P (Fig. 11).

4.5 Soil property variations across various forest types post-fire (2019-2021) within the top 0-15 cm soil layer

The mixed forest has the highest SMC (15.69%), followed by Chir-Pine forest (10.87%), and Sal forest (10.63%). Soil texture varies significantly in all forest types and the soil texture of Chir pine forest comprises of 59.57% of sand, 26.61% of silt and 4.44% of clay. Sal forest recorded maximum clay content i.e., 29.41% and the remaining sand and silt concentration were 35.55% and 35.43% respectively. The sand, silt and clay proportion of mixed forest were 57.33%, 28.83% and 12.05% respectively. The mixed forest has the highest pH (6.36), followed by the Sal forest (6.35), and Chir-Pine forest (6.10). The Mixed forest has the highest OC content (2.01%), followed by Chir-Pine forest (1.37%), and Sal forest (1.34%). The Mixed forest has the highest N content (0.33%), followed by Chir-Pine forest (0.22%), and Sal forest (0.21%). The Sal forest has the highest P content (0.45%), followed by Mixed forest (0.16%) and Chir-Pine forest (0.07%). The Sal forest has the highest K content (1.07%), followed by the Mixed forest (0.98%), and Chir-Pine forest (0.90%) (Fig. 12).

Table 3 showed the correlation analysis of soil physico-chemical parameters after fire at 0-15 cm soil depth and revealed that pH was positively correlated with OC (r=0.498), N (r=0.44), P (r=0.509) and K (r=0.678). However, SMC, OC and N was negatively correlated with phosphorus and potassium (Fig. 13).

4.6 Soil property variations across various forest types post-fire (2019-2021) within the top 15-30 cm soil layer

Mixed forest had the highest SMC (16.18%), followed by Chir-Pine forest (10.60%), and Sal forest (10.36%). The soil texture of mixed forest comprises of 57.27% of sand, 28.72% of silt and 11.93% of clay. Moreover, Chir pine forest recorded highest concentration of sand (59.23%) and the remaining silt and clay concentrations were 26.23% and 4.38% respectively. In Sal forest maximum silt (33.73%) and clay (27.6%) content was observed during the study. On the other hand, minimum sand concentration (31.43%) was recorded in Sal forest. Sal forest had the highest pH (6.60), followed by Mixed forest (6.57), and Chir-Pine forest (6.21). Mixed forest had the highest OC (1.86%), followed by Chir-Pine forest (1.26%), and Sal forest (1.17%). Mixed forest had the highest N (0.30%) and both Sal forest and Chir-Pine forest have similar values of N (0.19%). Sal forest had the highest P (0.39%), followed by Mixed forest (0.15%), and Chir-Pine forest (0.06%). Sal forest and Mixed forest had similar K content (0.86% and 0.86% respectively), while Chir-Pine forest had less K content (0.85%) Fig. 14).

The correlation analysis of various soil physico-chemical parameters after fire at 15-30 cm soil depth were presented in fig. 14. All the parameters were positively correlated with pH and OC and the SMC was strongly and positively correlated with OC (r=0.914) and N (r=0.927) (Fig. 15).

4.7 Tree mortality in the Sal Forest

In 2019 and 2020, the highest tree density was observed in the Low Fire category, followed by No Fire, Moderate Fire, and High Fire categories. Tree density decreased across all fire frequency categories in 2020 compared to 2019, with the High Fire category showing the greatest decrease (-3.193%). Similarly, sapling and seedling densities followed the same trend, with the Low Fire category having the highest density in both years. The High Fire category experienced the most significant decrease in seedling density (-22.099%) (Table 1).

4.8 Tree mortality in the Pine Forest

In both 2019 and 2020, tree, sapling, and seedling densities peaked in the Low Fire category. Across all categories, there was a decline in density in 2020 compared to 2019, with the most significant decrease in the High Fire category (-3.963% for trees, -17.460% for saplings, -38.095% for seedlings) (Table 1).

4.9 Tree mortality in the Mixed Forest

Tree density decreased in all fire frequency classes from 2019 to 2020, except for “No Fire,” which showed a slight decrease of 0.46%. The largest decrease occurred in "High Fire" (-5.37%), followed by "Moderate Fire" (-2.44%) and "Low Fire" (-1.10%). Similarly, sapling density decreased in all fire frequency classes, with the largest decrease in "High Fire" (-10.11%), followed by "Moderate Fire" (-5.59%). Seedling density also decreased across all classes, with the largest decrease in "Low Fire" (-10.20%), followed by "High Fire" (-14.42%) and "Moderate Fire" (-15.49%) (Table 1).

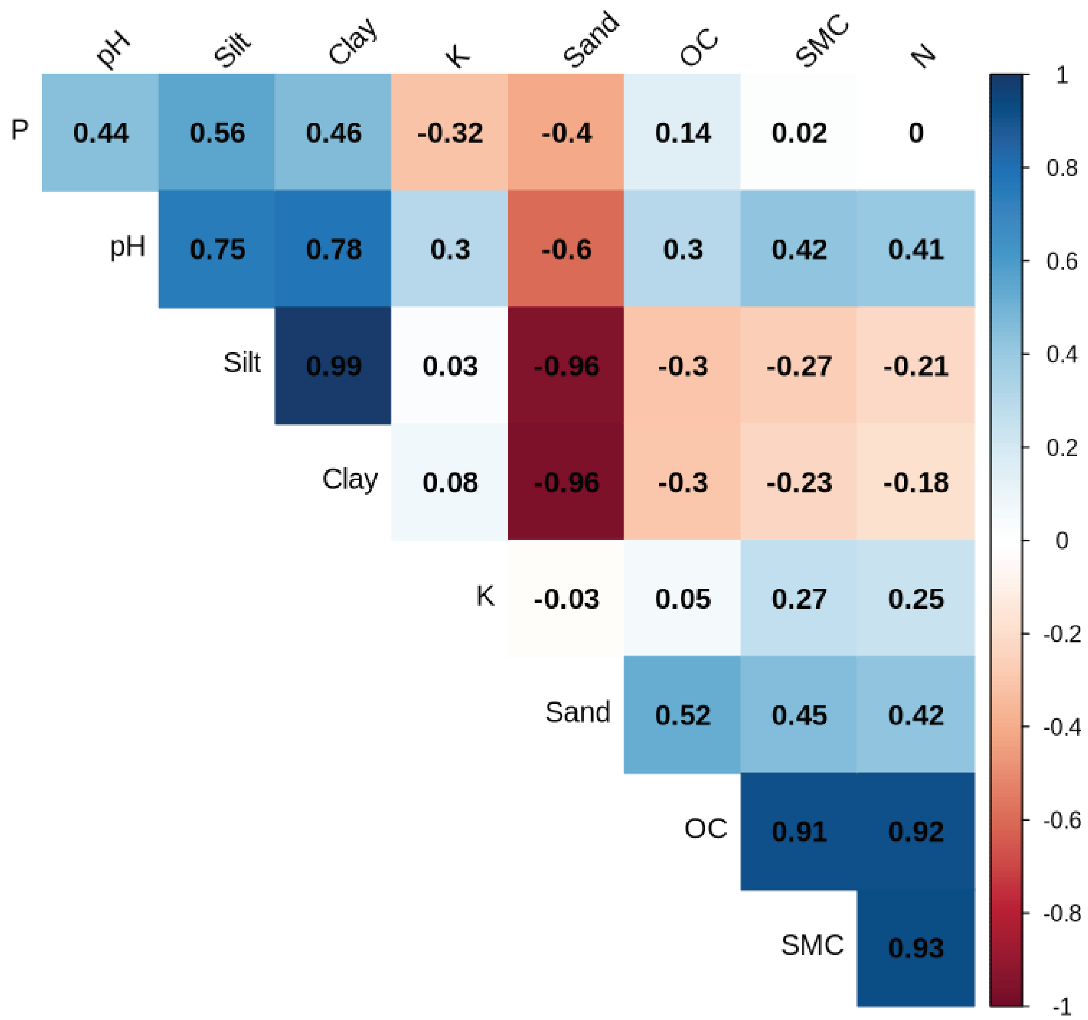

Figure 15. Correlation matrix of soil physico-chemical properties in 0-15 cm depth during post-fire (2019-2021).

Table 1. Tree, saplings, seedlings density under various fire frequency classes during 2019 and 2020.

Forest type (s)	Fire frequency class	Tree Density (Individuals ha−1)		Sapling Density (Individuals ha−1)		Seedling density (Individuals ha−1)	
		2019	2020	2019	2020	2019	2020
Sal Forest	No Fire	626	620	792	780	2230	2120
	Low Fire	664	655	903	880	2560	2330
	Moderate Fire	573	560	599	560	2130	1810
	High Fire	501	485	486	430	1810	1400
Pine Forest	No Fire	782	776	498	480	930	820
	Low Fire	850	837	672	660	1110	990
	Moderate Fire	743	720	458	420	1020	730
	High Fire	656	630	389	320	1050	650
Mixed Forest	No Fire	653	650	842	830	1930	1820
	Low Fire	728	720	913	890	2450	2200
	Moderate Fire	492	480	752	710	2260	1910
	High Fire	354	335	712	640	2150	1830

4.10 Girth class and tree mortality in Sal Forest

In Sal Forest, the overall tree mortality differed significantly between different girth classes in the (Fig. 16). It was maximum (48%) in girth class 0-10cm, which was followed by girth class 11-30cm (35.75%), and 31-60 (10%). The mortality was significantly less than the expected in girth classes ranging between 91 and 150, while no mortality was recorded in >180 cm girth class (Fig. 16; Table 2).

4.11 Girth class and tree mortality in Pine Forest

In Pine Forest also the overall tree mortality differed significantly between different girth classes in the (Fig. 17). It was maximum (76%) in girth class 0-10cm, which was followed by girth class 11-30cm (57%), and 31-60 (10%). The mortality was significantly less than the expected in girth classes ranging between 91 and 150, while less or no mortality was recorded in >180 cm girth class (Fig. 17; Table 3).

4.12 Girth class and tree mortality in Mixed forest

In mixed forest also the overall tree mortality differed significantly between different girth classes in the (Fig. 18). It was maximum (50%) in girth class 11-30cm, which was followed by girth class 0-11cm (32%), and 31-60 (26%). The mortality was signifi-

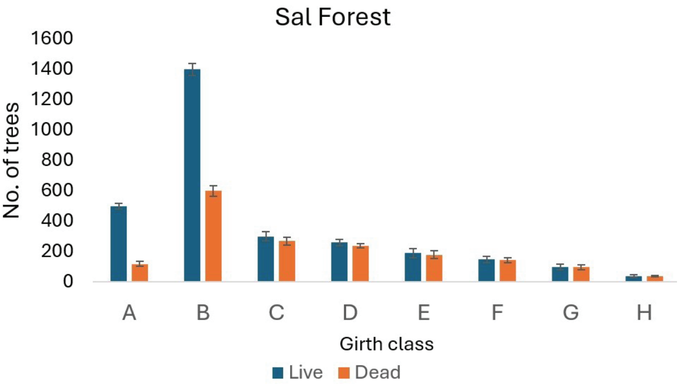

Figure 16. Dead and live trees in Sal Forest and different girth class during 2019 and 2020.

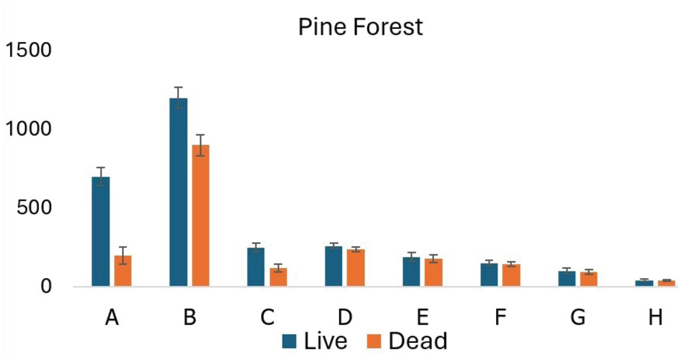

Figure 17. Dead and live trees in Pine Forest and different girth class during 2019 and 2020.

Table 2. Proportion available (Pio), proportion dead (Pie) and 95% Bonferroni confidence limits for different plant species in Sal Forest (0 = Mortality proportional to availability, - = Significantly less mortality. + = Significantly more mortality).

Species	Total	Dead	P_{io}	P_{ie}	% Dead	Relative for P_{ie}	Lower CL	Upper CL	Mortality Rating	Upper CL-P_{io}	Lower CL-P_{io}
Shorea robusta	930	34	0.303	0.248	3.66	1.11	0.209	0.287	Negative	-0.016	-0.094
Aegle marmelos	640	26	0.208	0.190	4.06	0.85	0.147	0.232	0	0.024	-0.061
Butea monosperma	540	18	0.176	0.131	3.33	0.59	0.092	0.171	Negative	-0.005	-0.084
Mallotus philippensis	430	21	0.140	0.153	4.88	0.68	0.106	0.201	0	0.061	-0.034
Syzygium cumini	260	11	0.085	0.080	4.23	0.36	0.034	0.126	0	0.042	-0.051
Cassia fistula	120	6	0.039	0.044	5.00	0.20	-0.007	0.095	0	0.056	-0.046
Ehretia laevis	90	13	0.029	0.095	14.44	0.42	0.010	0.180	0	0.150	-0.019
Schleichera oleosa	60	8	0.020	0.058	13.33	0.26	-0.025	0.141	0	0.122	-0.044

Table 3. Proportion available (Pio), proportion dead (Pie) and 95% Bonferroni confidence limits for different plant species in Pine Forest (0 = Mortality proportional to availability, - = Significantly less mortality. + = Significantly more mortality).

Species	Total	Dead	P_{io}	P_{ie}	% Dead	Relative for P_{ie}	Lower CL	Upper CL	Mortality Rating	Upper CL-P_{io}	Lower CL-P_{io}
Pinus roxburghii	1020	58	0.646	0.586	5.69	3.67	0.546	0.626	Negative	-0.020	-0.099
Lyonia ovalifolia	320	21	0.203	0.212	6.56	1.33	0.153	0.271	0	0.068	-0.049
Myrica esculenta	120	8	0.076	0.081	6.67	0.51	0.017	0.145	0	0.069	-0.059
Pyrus pashia	80	6	0.051	0.061	7.50	0.38	-0.008	0.129	0	0.079	-0.059
Q. leucotrichophora	40	6	0.025	0.061	15.00	0.38	-0.037	0.158	0	0.132	-0.062

Table 4. Proportion available (Pio), proportion dead (Pie) and 95% Bonferroni confidence limits for different plant species in Mixed Forest (0 = Mortality proportional to availability, - = Significantly less mortality. + = Significantly more mortality).

Species	Total	Dead	P_{io}	P_{ie}	% Dead	Relative for P_{ie}	Lower CL	Upper CL	Mortality Rating	Upper CL-P_{io}	Lower CL-P_{io}
Lyonia ovalifolia	440	23	0.373	0.250	5.23	1.95	0.194	0.306	Negative	-0.067	-0.178
Rhododendron arboreum	240	17	0.203	0.185	7.08	1.44	0.117	0.252	0	0.049	-0.086
Q.leucotrichophora	220	19	0.186	0.207	8.64	1.61	0.133	0.280	0	0.093	-0.053
Myrica esculenta	140	14	0.119	0.152	10.00	1.19	0.071	0.234	0	0.115	-0.048
Pinus roxburghii	80	11	0.068	0.120	13.75	0.93	0.022	0.217	0	0.149	-0.046
Viburnum cotinifolium	40	6	0.034	0.065	15.00	0.51	-0.040	0.170	0	0.136	-0.074
Alnus nepalensis	20	2	0.017	0.022	10.00	0.17	-0.066	0.109	0	0.093	-0.083

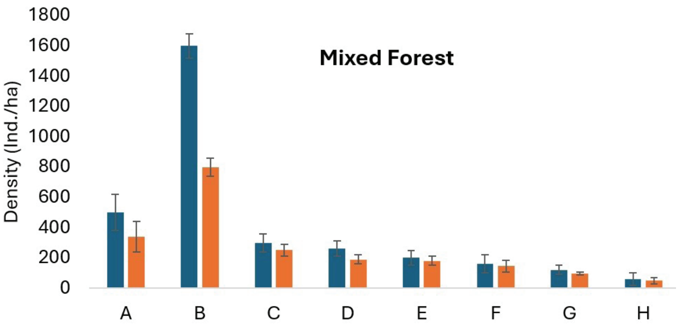

Figure 18. Dead and live trees in Mixed Forest and different girth class during 2019 and 2020.

cantly less than the expected in girth classes ranging between 91 and 150, while no mortality was recorded in >180 cm girth class (Fig. 18; Table 4).

4.13 Pre- and Post-Fire Soil Properties (0-15 cm)

The analysis of soil properties pre-fire (2019-2021) at the 0-15 cm depth showed significant correlations among various parameters. Sand had a highly negative correlation with silt (r=−0.987 P < 0.05 significant) and clay (r=−0.976, P < 0.05 significant), while silt had a highly positive correlation with clay (r=0.998, significant). Soil moisture content (SMC) exhibited weak correlations with other parameters. pH showed weak correlations with other parameters. Organic carbon (OC) had a highly positive correlation with SMC (r=0.997r, P < 0.05) significant) and nitrogen (N) (r=0.984, P < 0.05 significant). Phosphorus (P) showed high positive correlations with OC (r=0.957, P < 0.05 significant) and N (r=0.909, P < 0.05 significant). Potassium (K) had weak correlations with other parameters.

Post-fire data at the 0-15 cm depth revealed similar trends in the correlations between sand, silt, and clay. However, there were notable changes in other parameters. Post-fire pH showed moderate correlations with silt (r=0.618) and clay (r=0.658), which were not present pre-fire. The correlation between OC and SMC remained strong (r=0.982, significant), but the correlation between OC and N decreased slightly (r=0.953, significant). Phosphorus (P) exhibited a significant change in correlation with sand (r=−0.693, moderate) and silt (r=0.699, moderate) post-fire. Potassium (K) showed significant negative correlation with sand (r=−0.857, significant) and positive correlation with silt (r=0.903, significant), changes that were not observed pre-fire.

4.14 Pre- and Post-Fire Soil Properties (15-30 cm)

The analysis of soil properties pre-fire (2019-2021) at the 15-30 cm depth showed significant correlations among various parameters. Sand had a highly negative correlation with silt (r=−0.964, P < 0.05 significant) and clay (r=−0.969, P < 0.05 significant), while silt had a highly positive correlation with clay (r=0.997, P < 0.05 significant). SMC showed weak correlations with other parameters. pH had a moderate positive correlation with silt (r=0.667, P < 0.05 significant) and a negative correlation with sand (r=−0.566). OC was highly positively correlated with SMC (r=0.957, P < 0.05 significant) and N (r=0.950, P < 0.05 significant). P showed high positive correlations with OC (r=0.920, significant) and N (r=0.933, P < 0.05 significant). K had weak correlations with other parameters.

Post-fire data at the 15-30 cm depth revealed similar trends in the correlations between sand, silt, and clay. However, there were notable changes in other parameters. Post-fire pH showed stronger correlations with silt (r=0.747, significant) and clay (r=0.778, P < 0.05 significant), which increased compared to pre-fire correlations. The correlation between OC and SMC remained strong (r=0.914, P < 0.05 significant), but the correlation between OC and N decreased slightly (r=0.915, P < 0.05 significant). P exhibited a significant change, showing a negative correlation with sand (r=−0.401, moderate) and positive correlation with silt (r=0.557, moderate) post-fire. K showed weak correlations with other parameters post-fire, similar to pre-fire observations.

4.15 Comparison of Soil Property Variations Across Various Forest Types Pre- and Post-Fire (0-15 cm and 15-30 cm)

Analyzing the variations in soil properties across different forest types revealed significant changes pre- and post-fire at both soil depths. For the 0-15 cm layer, the correlations between sand, silt, and clay remained consistent, with sand maintaining a negative correlation with silt and clay (pre-fire: r=−0.987 and −0.976; post-fire: −0.987 and r=−0.976). However, post-fire data showed new moderate correlations for pH with silt (r=0.618) and clay (r=0.658), indicating an alteration in soil chemical environment due to fire. The correlation between OC and SMC remained strong post-fire (r=0.982, P < 0.01), but its correlation with N decreased slightly from r=0.984 to r=0.953. Significant changes were observed in the correlations of P and K post-fire. P showed a negative correlation with sand (r=−0.693) and a positive correlation with silt (r=0.699), compared to weak pre-fire correlations. K's post-fire correlations with sand and silt also became significant (r=−0.857 and r=0.903), which were weak pre-fire.

For the 15-30 cm layer, the correlations between sand, silt, and clay remained consistent, with sand maintaining a negative correlation with silt and clay (pre-fire: r=−0.964 and r=−0.969; post-fire: r=−0.960 and r=−0.964). Post-fire data showed an increase in the correlations for pH with silt (from r=0.667 to r=0.747) and clay (from r=0.637 to r=0.778). The correlation between OC and SMC remained strong post-fire (r=0.914), but its correlation with N decreased slightly from r=0.950 to r=0.915. Significant changes were observed in the correlations of P and K post-fire. P showed a negative correlation with sand (r=−0.401) and a positive correlation with silt (r=0.557), compared to weak pre-fire correlations. K's correlations with other parameters remained weak post-fire, similar to pre-fire observations.

5 Discussion

Forest fires in Uttarakhand have varied in frequency over the past century due to human activities and management interventions, including intentional fires for purposes such as grass growth promotion and forest product collection (Kodandapani et al., 2004). The highest affected area was recorded in 2016, while the lowest was in 2020, possibly influenced by the COVID-19 pandemic reducing human activities (Bargali et al., 2022).

The primary reason for the reduction in the number of fire events from 2019 to 2020 is attributed to the COVID-19 restrictions. The pandemic led to a significant decrease in human activities due to lockdowns and social distancing measures, which inadvertently benefited the environment, including a reduction in forest fires.

According to Poulter et al. (2021), the COVID-19 pandemic brought about radical changes in human behavior as workplaces implemented social-distancing guidelines, leading to the postponement or cancellation of many fire management plans. Using active fire data from satellite-based observations, it was found that in the southeastern United States, there was a 21% reduction in fire activity compared to the 2003 to 2019 average. This reduction was even more pronounced for federally managed lands, showing a 41% decrease compared to the past 20 years and a 38% decrease compared to the past decade. While an unusually wet February before the COVID-19 shutdown in mid-March 2020 also contributed to the decline in fire activity, the pandemic's impact on reducing human-caused fires was significant.

Gupta et al. (2020) observed a substantial reduction in forest fire incidences in the Western Himalaya, India, during the COVID-19 lockdown. The study reported an 83.4% decrease in cumulative fire incidences from 24 March to 5 May 2020 compared to the average for the corresponding period from 2006 to 2020. Although the lockdown period experienced higher precipitation, which did not contribute to soil moisture build-up, the lockdown phase saw a notable increase in vegetation health as indicated by higher NDVI and EVI values. This suggests that the reduction in anthropogenic activities during the lockdown played a significant role in decreasing forest fire occurrences.

Different vegetation types exhibit varying susceptibilities to fires, with Chir Pine forests being more vulnerable due to high fuel loads and low rainfall (Bargali et al., 2022). Fire frequency negatively influences tree, sapling, and seedling densities across different forest types, indicating the detrimental impact on forest regeneration.

Soil properties are significantly altered by fire severity, affecting various depths and nutrient levels (Maksimova and Abakumov, 2015; Jhariya and Singh, 2021; Li et al., 2021). Post-fire, there is a decline in soil nutrients, potentially impacting soil fertility and ecological processes (Mittal et al., 2019). Soil pH increases post-fire due to the combustion of organic matter and nutrient-rich ash deposition (Heydari et al., 2017; Li et al., 2021). The severity of the fire influences pH magnitude, with higher values in more severely burned areas (Knicker, 2007). Forest fires lead to biomass and organic layer losses, with nutrient-rich ash deposition increasing soil pH.

The study examined the impact of fire frequency on tree density, sapling density, and seedling density across three forest types: Sal Forest, Pine Forest, and Mixed Forest. Overall, there was a decrease in density across all fire frequency categories in 2020 compared to 2019, indicating the detrimental effect of fires on forest regeneration (Bargali et al., 2022).

The pre- and post-fire comparisons of soil properties indicate significant changes in their correlations due to fire events. The persistence of strong correlations between sand, silt, and clay suggests that the basic soil texture remains relatively unchanged. However, the observed changes in pH, OC, N, P, and K correlations highlight the impact of fire on soil chemistry and nutrient dynamics. These findings suggest that forest fires can alter soil properties in ways that may affect plant growth, soil fertility, and overall ecosystem health. Comparing these results with existing literature supports the observed changes and emphasizes the need for targeted forest management practices to mitigate the adverse effects of fires.

5 Conclusion

Our study underscores the need for a comprehensive understanding of fire dynamics and their multifaceted impacts. By contextualizing our findings within broader trends and exploring the socio-economic implications, we highlight the importance of integrated strategies to manage fire risks and enhance the resilience of both ecosystems and communities. This study demonstrates significant changes in soil property correlations pre- and post-fire, underscoring the impact of fire events on soil composition and nutrient dynamics. These findings highlight the need for effective forest management strategies to ensure soil health and ecosystem resilience in the face of increasing fire occurrences. Future research should focus on long-term monitoring of post-fire soil recovery to inform sustainable forest management practices.

The study conducted in Uttarakhand Himalaya reveals a concerning escalation in forest fire frequency, primarily associated with footpaths/roads rather than settlements, indicating the necessity for enhanced management strategies. Forest fires result in substantial loss of carbon and nitrogen, impacting soil properties and microbial communities. While low-intensity fires can stimulate new growth by reducing fuel loads, high-intensity fires adversely affect soil and impede plant growth. Effective fire management, including prescribed burns and fire breaks, is imperative to mitigate these consequences. Additionally, the findings underscore the adverse impact of fire frequency on tree, sapling, and seedling densities across diverse forest types, stressing the significance of implementing measures to conserve forest ecosystems and facilitate regeneration. Although controlled fires may offer benefits, further research is imperative to comprehend their long-term implications. Overall, proactive fire management is essential for preserving healthy and resilient forest ecosystems.

6.1 Contributions of this thesis

This thesis contributes significantly to the scientific understanding of forest fires and their effects on ecosystems, particularly in the Uttarakhand Himalaya region. Firstly, it advances knowledge of fire regimes by analyzing their spatial and temporal patterns, providing insights into fire spread dynamics crucial for targeted management strategies. Secondly, the thesis investigates the impact of forest fires on soil properties, enhancing understanding of soil-vegetation interactions and ecosystem resilience. Moreover, it examines the effects of fires on flora and fauna, vital for biodiversity conservation and ecosystem management. The thesis also aids in developing effective fire management strategies by highlighting the importance of mitigating fire impacts on forest regeneration. Furthermore, by addressing research gaps in understanding fire regimes in the region, it lays the groundwork for future studies, with practical implications for sustainable forest management.

6.2 Recommendations for planning practice

The findings offer insights for forest management, fire prevention, and ecosystem conservation in the Uttarakhand Himalaya region. Effective fire management plans should prioritize high-risk areas based on fire regimes and landscape features influencing fire spread dynamics. Proactive measures to restore soil health and integrate biodiversity conservation into fire management strategies are recommended. Prescribed burning, community-based approaches, and interdisciplinary collaboration are suggested for holistic fire management. Implementing these recommendations can enhance ecosystem resilience and promote sustainable development.

6.3 Future research directions

Future research could focus on longitudinal studies to assess long-term impacts of shifting fire regimes, interdisciplinary approaches integrating ecological and socio-economic perspectives, and exploring emerging technologies for fire monitoring and management. Evaluating the effectiveness of fire management strategies and identifying synergies with climate change adaptation efforts are also recommended. Addressing these research priorities can advance understanding of fire dynamics and contribute to sustainable fire management practices in the region.

About this work

This work is a synthesis of a cumulative Ph.D. thesis in the Environmental Sciences entitled "***Mapping and Impact of Seasonal Forest Fires on Vegetation Types, Soil Dynamics, and Tree Mortality in Forest Ecosystem of Uttarakhand Himalaya"*** submitted to the Department of Zoology and Environment Science, Gurukula Kangri (Deemed to be University), Haridwar, Uttarakhand, India in 2024. This synthesis is an extract from this thesis, published at the institutional repository of the Gurukula Kangri (Deemed to be University), Haridwar. It comprises results of four published articles and some other working articles:

1. Bargali, H., Kumar, A., & Singh, P. (2022). Plant studies in Uttarakhand, Western Himalaya–A comprehensive review. *Trees, Forests and People*, 8, 100203. https://doi.org/10.1016/j.tfp.2022.100203

2. Bargali, H., Calderon, L. P. P., Sundriyal, R. C., & Bhatt, D. (2022). Impact of forest fire frequency on floristic diversity in the forests of Uttarakhand, western Himalaya. *Trees, Forests and People*, 9, 100300. https://doi.org/10.1016/j.tfp.2022.100300

3. Bargali, H., Bhatt, D., Sundriyal, R., Uniyal, V. P., Pandey, A., & Ranjan, R. Effect of Forest Fire on Tree Diversity and Regeneration in the Forests of Uttarakhand, west Himalaya, India. *Frontiers in Forests and Global Change*, 6, 1198143. https://doi.org/10.3389/ffgc.2023.1198143

4. Bargali, H., Singh, P., & Bhatt, D. (2020). Role of chir pine (*Pinus roxburghii* Sarg.) in the forest fire of Uttarakhand Himalaya. *ENVIS Bulletin Himalayan Ecology*, 28, 82.

Acknowledgements and funding

The authors express their gratitude to the Director of G. B. Pant National Institute of Himalayan Environment (GBPNIHE)for providing institutional support. We acknowledge the Department of Zoology and Environment Science at Gurukula Kangri (Deemed to be University), Haridwar, for their logistic support. The authors thanks to G. C. S. Negi, former Scientist "G" at GBPNIHE, for his valuable suggestions and inputs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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