Mina et al. Fire Ecology (2023) 19:14
https://doi.org/10.1186/s42408-023-00177-4

Fire Ecology

Association for Fire Ecology

FIELD NOTE

Open Access

Forest fires and climate attributes interact in central Himalayas: an overview and assessment

Usha Mina*, A. P. Dimri and Sandhya Farswan

Abstract

Background In Uttarakhand, a state in northern India, forest fire events increased from 922 in 2002 to 41,600 in 2019, influencing forest structure and function. In the literature, it has been reported that, globally, climate change influences the intensity and expansion of forest fire events. However, with regard to Uttarakhand, studies on the relationship between climate and forest fire events were very limited. In this study, a brief review of Uttarakahand state forests, forest fire types, forest biomass carbon stock, and factors influencing forest fires was carried out, followed by assessment of the relationships between forest fires and climate attributes.

Results This study indicated that there was a positive and significant correlation between the number of forest fires and temperature (maximum, average, and diurnal range; $0.05 \geq P \leq 0.001$); whereas, there was a negative and non-significant correlation of forest fire with relative humidity, and a non-significant correlation of forest fire with minimum temperature and wind. The Ångstrom index and Fuel Moisture Index were found to be good indices to indicate the prevalence of favorable climatic conditions for forest fire. The results of the study indicated a vulnerability of forest floor biomass carbon to forest fire.

Conclusion Temperature was a regulating factor in altering the forest fire potential in the district. Forest fire caused the loss of carbon sequestered in forest biomass carbon stock. In the future, due to climate change, a greater number of forest fire events may occur and disturb the carbon cycle.

Keywords Carbon stock, Central Himalayas, Climate, Forest biomass, Forest fire

*Correspondence:
Usha Mina
ushamina@mail.jnu.ac.in
School of Environmental Sciences, Jawaharlal Nehru University, G5Q9+R4M, Delhi 110067 New Delhi, India

Resumen

Antecedentes En Utarakhand, un estado en el norte de la India, los eventos de incendios forestales se incrementaron de 922 en 2002 a 41.600 en 2019, influenciando la estructura y el funcionamiento del bosque. En la literatura, ha sido reportado que, globalmente, el cambio climático influencia la intensidad y expansión de los incendios forestales. Sin embargo, y relacionado con Uttarakhand, los estudios sobre las relaciones entre clima y eventos de incendios forestales son muy limitados. En este estudio, una breve revisión de los bosques del estado de Uttarakhand, los tipos de incendios forestales, el stock de carbono en la biomasa de esos bosques, y factores que influencian los incendios forestales fueron llevados a cabo, seguidos por la determinación de las relaciones entre los incendios forestales y las características del clima.

Resultados El estudio indicó que hubo una correlación positiva y significativa entre el número de incendios y la temperatura (máxima, promedio, y rango diario de variación; $0.05 \geq P \leq 0.001$); mientras que esta correlación fue negativa y no significativa entre incendios forestales con la humedad relativa, y una correlación no significativa con temperaturas mínimas y viento. El Índice de Ångstrom y Índice de Humedad del Combustible fueron buenos para indicar la prevalencia de condiciones climáticas favorables para los incendios forestales. Los resultados del estudio indican la vulnerabilidad del carbono contenido en la biomasa del suelo forestal al efecto de los incendios forestales.

Conclusiones La temperatura fue un factor regulador en la alteración del potencial de los incendios forestales en el distrito. Los incendios forestales causaron la pérdida del carbono secuestrado y almacenado en la biomasa forestal. En el futuro, y debido al cambio climático, un mayor número de eventos de incendios forestales puede ocurrir, y disturbar el ciclo de carbono en esos bosques.

Introduction

Approximately 90% of the world's plantation forest is in South Asian countries, including India (FAO 2010). According to FAO (2010), India has 1% of the global primary forest (native, natural, and undisturbed forest ecosystem without any anthropogenic activities). Globally, anthropogenic activities (such as agriculture, urbanization, and industrialization) to meet the demand of increasing populations are disturbing and reducing the pristine nature of primary as well as of secondary forest ecosystems (Parashar and Biswas 2003; Cobb and Metz 2017).

Along with other factors, forest fire is one of the major challenges for forest ecosystems. Across the globe, there has been an increase in frequency and intensity of wildfire (Robinne et al. 2018). Every year, forest fire events affect ~1% of all forested area in the world. It is also a fact that the regeneration process of some forest ecosystems completely depend on fire (SCBD 2001; Forbes et al. 2011). Forest fires not only influence the climate of the region (Keith et al. 2009), the region's climate also regulates the pattern, magnitude, and intensity of forest fires (Skvarenina et al. 2003). Increased frequency of forest fire events across the globe in recent decades has generated interest in the scientific community to explore the climate–fire relationship (Abatzoglou and Kolden 2013). Studies on climate–fire relationships that were carried out on different landscapes were grouped into two regimes. One was a fuel-limited regime, which is associated with higher fuel abundance resulting from increased moisture availability that leads to heightened wildfire activity the following year through increased fuel connectivity and the ability of the landscape to carry fire. The other was a flammability-limited regime, which is associated with concurrent moisture deficits that increase the availability of fuels to carry fire in forested landscape (Abatzoglou and Kolden 2013). Both regimes highlight the importance of climatic conditions in preconditioning of fuels in the months to years before the onset of fire season.

The objectives of this study were to provide a brief integrated assessment of forest fires, climate, and forest biomass carbon stock; to describe the relationship between forest fires and fire-related indices; and to provide an estimate of forest biomass carbon stock losses from fire during the predominant fire season (April to June) for the Dehradun district of Uttarakhand, as represents the greater Indian central Himalayan region.

Indian forests and forest fires

The Food and Agriculture Organization and the United Nation Framework Convention of Climate Change define dense, moderately dense, and open forest types on the basis of canopy cover and tree height (Table 1). In India, total forest cover is ~76.4 million ha (22% of India's total area and 2% of global forested area, which includes 1% of global primary forest) and is composed of 18 forest types (FSI 2019). Based on dominant vegetation, forests are broadly placed in five major categories: (1) tropical evergreen forest, (2) tropical deciduous forest, (3) tropical

Table 1 Criteria that Food and Agriculture Organization (FAO) and the United Nation Framework Convention of Climate Change (UNFCCC) use to categorize forest type. These categories were used in our review of climate attributes and their affects on forest fire between 2002 and 2019 in the Dehradun district, in the state of Uttarakhand, India

Agency	Forest type	Canopy cover (%)	Shared attributes (minimum values or ranges)
FAO	Dense	> 70	Tree height: ≥5 m Forested area: ≥0.5 ha Crown cover: ≥10%
	Moderately dense	40 to 70	
	Open	10 to 40	
UNF-CCC	Dense	> 70	Tree height: 2 to 5 m Forested area: 0.01 to 1.0 ha Crown cover: 10 to 30%
	Moderately dense	40 to 70	
	Open	10 to 40	

thorn forest, (4) montane forest, and (5) swamp forest (FSI 2015). The forest types in India have variable fire proneness. Kumar et al. (2019) used GIS analysis of forest fire points (detected in 5 × 5 km grids annually) over 13 years to categorize forests' fire proneness into the following classes:

(1) Extremely fire prone forest area: average frequency of forest fire detected in ≥ 4 grids per year (i.e., ≥ 52 detected forest fire points).
(2) Highly fire prone forest area: average frequency of forest fire detected in ≥ 2 and < 4 grids per year (≥ 26 and < 52 detected forest fire points).
(3) Fire prone forest area: average frequency of forest fire detected in ≥ 1 and < 2 grids per year (≥ 13 and < 26 detected forest fire points).
(4) Moderately fire prone forest area: average frequency of forest fire detected in ≥ 0.5 and < 1 grids per year (≥ 6 and < 13 detected forest fire points).
(5) Less fire prone forest area: average frequency of forest fire detected in < 0.5 grids per year.

Nearly 4% of India's forest cover is extremely fire prone; 6% is highly fire prone, and 36% is prone to frequent forest fires; these fires have ecological and economic consequences (FSI 2019). Approximately 65% of the deciduous forests of India are prone to forest fire, causing a loss of ~ 104 million US dollars annually (Ashutosh et al. 2019). Nearly 534,160.79 US dollars (44 million Indian rupees) is spent annually to patrol and suppress forest fires. Under the Intended Nationally Determined Contributions (INDC) plan, India is committed to increasing its forest cover to 33% of its geographical area by 2030, which will support an additional ~ 2.5 to 3 billion tonnes of carbon stock (Dogra et al. 2018).

In India, 192 active forest fires were reported during May 2019 (FSI 2019): Uttarakhand reported the most with 91, followed by Chhattisgarh with 36, and Madhya Pradesh with 17. India Meteorological Department (IMD) cited a sudden rise in temperature and a prevailing

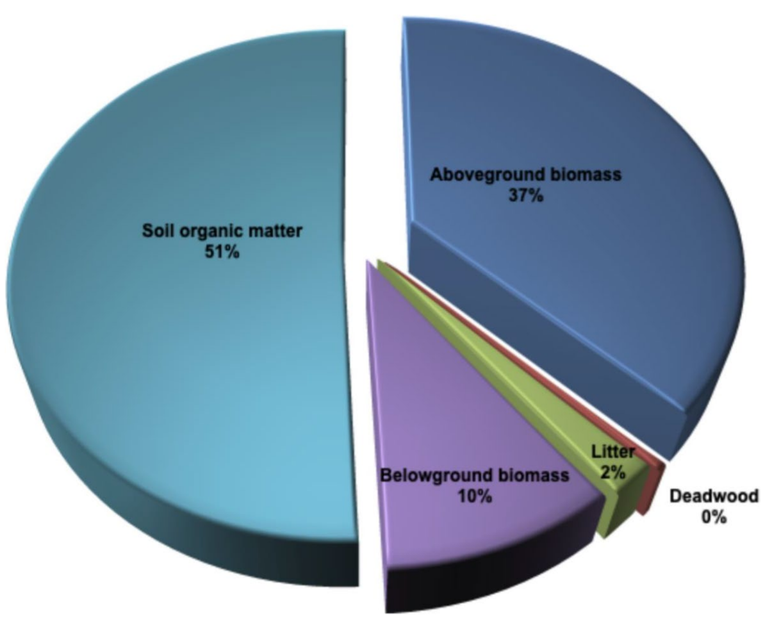

Fig. 1 Sequestered carbon stock distribution reported (FSI 2017) in different pools of Uttarakhand's forest ecosystem. These data were used in our review of climate attributes and their affects on forest fire between 2002 and 2019 in the Dehradun district, in the state of Uttarakhand, India

rainfall deficit during the preceding week in Uttarakhand to explain the prevalence of these fires. The May 2019 forest fires that occurred in Uttarakhand affected, on average, 644 ha each, with total loss of ~ 1 278,343.90 US dollars (~ 10.53 crore Indian rupees) (Kukreti 2019). Increasing frequency of forest fires may hinder achieving INDC plan goals.

Forest fire and forest carbon stock

World-wide, forests store 638 Gt of carbon (C), of which 238 Gt is terrestrial vegetation biomass carbon (i.e., 80% of terrestrial vegetation biomass carbon in the world) (FAO 2006; Wani et al. 2012). Over the past 25 years, a decline of about 11 Gt of global forest biomass carbon stock had been reported (FAO 2015). The reported rate of decline in carbon stock in world forest biomass during 2005 to 2010 was 0.5 Gt year^{-1} (FAO 2015). Total carbon stock in forests of India was estimated at 7044 million tonnes. Between 2011 and 2013, it was reported that forest carbon stock of India increased by 103 million tonnes (FSI 2015).

Forest ecosystem carbon pools are derived from living aboveground biomass (AGB), belowground biomass (BGB), dead organic matter as deadwood, and litter and soil as soil organic matter (SOM) (FSI 2017; Fig. 1). However, forest fires causes 98.11 Tg year^{-1} of total carbon dioxide (CO_2) emission, mostly contributed by tropical dry deciduous type forest fires (50%) and tropical moist deciduous type forest fires (39.3%) (Reddy et al. 2017).

Uttarakhand: forests and fire incidents

In terms of forest density (Table 1), forest cover in Uttarakhand is classified as follows: very dense (4762 km^2), moderately dense (14,167 km^2), and open or least dense (5567 km^2) (Uttarakhand Forest Department 2015). Cumulative forest cover for Uttarakhand made up approximately 45% of its total geographic area (Table 2). In 2017, the maximum and minimum forest cover were reported from the Nainital district (71.7% cover) and Udhamsingh Nagar district (17.2% cover), respectively. Major forest types of Uttarakhand include tropical moist deciduous, tropical dry deciduous, sub-tropical pine, Himalayan moist temperate, Himalayan dry temperate, subalpine, and alpine (FSI 2005). Overall, 2.4 billion US dollars per year of ecosystem services have been provided by Uttarakhand forest (Singh 2014).

Uttarakhand State Forest Department recorded forest fires in all districts during April to June since 2002 (Table 3). The forest fire season in the state is longer than that of Himalayan and non-Himalayan states, and exhibits its peaks in late April and late May or early June. The record indicated an increase in total number of forest fires, from 922 in 2002 to 41,600 in 2019 (Table 3). These fires caused loss of valuable timber resources, endangered species, and caused extensive damage to forest ecology as well as to the landscape of the area (Gupta et al. 2018). When comparing forest fires by district during 2002 to 2019, data revealed that the fewest fire occurrences were observed in 2011 for most districts, while the greatest number of fires occurred in 2019 (Table 3). However, in 2017, the greatest number of forest fires (411) were

Table 2 Change in forest cover from 2002 through 2017, per district, in the state of Uttarakhand, India, during our review of climate attributes and their affects on forest fire between 2002 and 2019

District	Geographic area		2001 forest cover		2011 forest cover		2017 forest cover	
	km^2	% of state	km^2	% of district	km^2	% of district	km^2	% of district
Almora	3144	5.88	1495	47.55	1577	50.16	1718	54.64
Bageshwar	2241	4.19	1297	57.87	1381	61.62	1261	56.27
Chamoli	8030	15.01	2583	32.16	2695	33.56	2709	33.73
Champawat	1766	3.30	1125	63.70	1181	66.87	1224	69.30
Dehradun	3088	5.77	1486	48.12	1607	52.04	1605	51.97
Garhwal	5329	9.96	3142	58.96	3289	61.72	3394	63.68
Haridwar	2360	4.41	612	25.93	619	26.23	588	24.91
Nainital	4251	7.95	3108	73.11	3090	72.69	3048	71.70
Pithoragarh	7090	13.26	2033	28.67	2094	29.53	2078	29.30
Rudraprayag	1984	3.70	1153	58.11	1125	56.70	1141	57.51
Tehri Garhwal	3642	6.80	2064	56.67	2147	58.95	2065	56.70
Udhamsingh	2542	4.75	769	30.25	546	21.48	436	17.15
Uttarkashi	8016	14.99	3071	38.31	3145	39.23	3028	37.77
Totals	53,483		23,938		24,496		24,295	

Table 3 Number of forest fires per year, from 2002 to 2019, during the fire season (April through June) in each district of the state of Uttarakhand, India, during our review of climate attributes and their affects on forest fire between 2002 and 2019. Total fire incidents per year, and average number of incidents per district (± standard deviation; SD) are also given

District	Number of forest fires per year in April through June																		Average ± SD
	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002	
Almora	6214	379	167	1125	105	441	64	1412	33	345	624	264	51	29	243	292	468	86	685.7 ± 1 385.3
Bageshwar	4130	319	12	361	17	207	22	836	72	214	272	208	7	0	169	116	247	33	402.3 ± 924.7
Chamoli	2451	237	59	650	78	464	32	985	38	121	842	255	149	14	186	218	221	9	389.4 ± 572.3
Champawat	4328	136	8	581	127	212	7	463	32	127	188	732	12	108	161	96	251	54	423.5 ± 967.1
Dehradun	845	186	63	723	165	71	41	382	22	781	463	133	267	94	349	161	367	69	287.9 ± 255.3
Haridwar	881	24	46	366	41	83	12	117	2	239	164	118	178	42	79	43	48	16	138.8 ± 201.3
Nainital	7747	264	411	2296	687	356	200	1437	107	975	821	1471	114	399	1195	701	986	215	1 132.3 ± 1 700.7
Pauri Garhwal	3359	1433	192	2474	267	549	200	1578	16	1008	1420	1854	304	107	1046	1060	710	254	990.6 ± 884.9
Pithoragarh	1083	42	11	127	8	118	8	85	33	91	53	157	8	5	152	41	163	10	121.9 ± 239.5
Rudraprayag	39	2	0	20	1	15	3	46	0	8	32	16	2	0	1	27	4	0	12.0 ± 14.5
Tehri Garhwal	8555	1248	49	1469	272	637	124	1692	36	275	1729	409	398	166	286	668	626	91	1 040.6 ± 1 902.1
Udhamsingh Nagar	851	87	138	206	63	53	36	99	112	114	123	86	83	101	99	43	125	35	136.3 ± 178
Uttarkashi	1117	357	9	205	15	296	8	286	67	210	745	15	41	31	37	191	73	50	208.5 ± 284.5
Total incidents	41,600	4714	1165	10,603	1846	3502	757	9418	570	4508	7476	5718	1614	1096	4003	3657	4289	922	5 957.7 ± 9 102.2

reported in the Nainital district, and the fewest number of forest fires (0) were reported in the Rudraprayag district (Table 3). In 2019, the greatest number of forest fires was 8555 in Tehri Garhwal district, and the fewest number of of forest fires was 39 in Rudraprayag district.

Uttarakhand forest fire driving forces

Almost 95% of Indian forest fires are caused by humans, whether accidental or intentional. Most common ignition sources of forest fire in India are grazers, sparks from vehicles, hiking or picnicking activities, shifting cultivation, and burning litter (pine needles) for a flush of fresh grasses. Anthropogenic causes of Uttarakhand forest fires are associated with land use dynamics, particularly near roads and human settlements (Pourtaghi et al. 2016). Intentional fires are associated with revitalizing grazing land and biomass in chir pine (*Pinus roxburghii* Sarg.) forested areas (Bhandari et al. 2012). During the summer season, heavy leaf-fall accumulation and the deposition of thick layers of litter on the forest floor are burned by locals. The nutrients released from the burned leaves promote growth of edible fungi. In local markets of Dehradun and surrounding areas, demand for the edible fungus *Astraeus hygrometricus* (Pers.) Morgan is high, which encourages the use of fire in the forests of Uttarakhand (Verma et al. 2019).

The most significant and fundamental reason that forests are susceptible to catching fire is that they contain dry vegetation biomass. High atmospheric temperatures and dryness (low humidity) due to high incoming solar radiation over southern and western aspects create favorable conditions for forest fires (Luna et al. 2018). In deciduous forests of Uttarakhand, fire occurrence is 25% of the total fire events because its undergrowth is humid, which can prevent fire. However, in coniferous forests, fire events make up 75% of the total, in part because of the high resin content in tree trunks and the availability of dry leaves for fuel (Negi and Dhyani 2012). Mountain forest vegetation is dominated by trees that contain high resin content (Miller 2022). Resin is a secondary metabolic product in the form of a clear, viscous, and sticky liquid consisting of terpenoids, hydrocarbons, and other compounds that contribute to elevated flammability (Ormeno et al. 2009). Vegetation of tropical dry deciduous forest and tropical wet evergreen forest are the most susceptible to forest fire events (Fig. 2). Moderately dense forest and open forest vegetation types in India have suffered from the highest number of forest fires since 2004 (Fig. 2). The prolonged dry season promotes leaf fall of almost all old leaves and, on accumulation, form a carpet of needles on the forest floor that provides large surface-to-volume ratios and low surface fuel bulk densities that readily support surface fire.

The monitoring of forest fires in Uttarakhand has indicated that chir pine forests are most susceptible to forest fires, followed by dry deciduous scrub forest. This may be due to high availability of surface fuel in the form of dry needles, high temperature, and high char content (Suresh Babu et al. 2016). Chir pine forests also exhibited variation in number of forest fire incidents due to variation in solar light availability on southern and western aspects in their elevation zones. In the mountains, steep slopes combined with strong winds can expand fire spatially, causing damage to oak (*Quercus* L. spp.) forest crowns and rhododendrons (*Rhododendron* L .spp.) (Gupta et al. 2018). Other causes of forest fire in Uttarakhand are related to a shift in traditional land management practices. Migration of locals to cities in search of better livelihoods has resulted in forests that are less used for grazing; less used for the collection of grasses, animal bedding, and dry wood; and controlled burning to clear forest litter is less frequently practiced. Accumulated fuel loads create potential for more severe and destructive forest fires in those areas (Dogra et al. 2018; Reddy et al. 2017) confirmed that, in India, the temperature rise was the main cause of the highest intensity and expansion of forest fire events during 2009, 2010, and 2012.

Forest fire-related indices

Long-term and short-term forest fire related indices not only help with management of forest fires, but they also estimate the contribution of climate in affecting the intensity and growth of forest fires. Long-term indices are based on vegetative, topographic, and anthropogenic indicators. Short-term indices are based on indicators that change suddenly and influence ignition and spreading of forest fires (e.g., air temperature, relative humidity, wind speed, and rainfall).

In the literature, it has been reported that short-term indices are more strongly related to forest fire events than long-term metrics and indices (Riley et al. 2013).

Baijnath-Rodino et al. (2020) reviewed 24 fire indices used worldwide. These indices were computed using six attributes: fuel, weather, topography, fuel moisture, meteorology, and fire behavior. In their review, it was reported that the most documented and globally adopted fire indices were the National Fire Danger Rating System's Burning Index and the Canadian Forest Fire Danger Rating System's Fire Weather Index (FWI). The FWI indicates potential fire intensity due to fuel aridity and fire weather, irrespective of land cover and biomass. The FWI's sensitivities to temperature, precipitation, humidity, and wind speed (Flannigan et al. 2016) and its empirical relationship to burned area across broad regions of the globe has already been established (Abatzoglou and Kolden 2013).

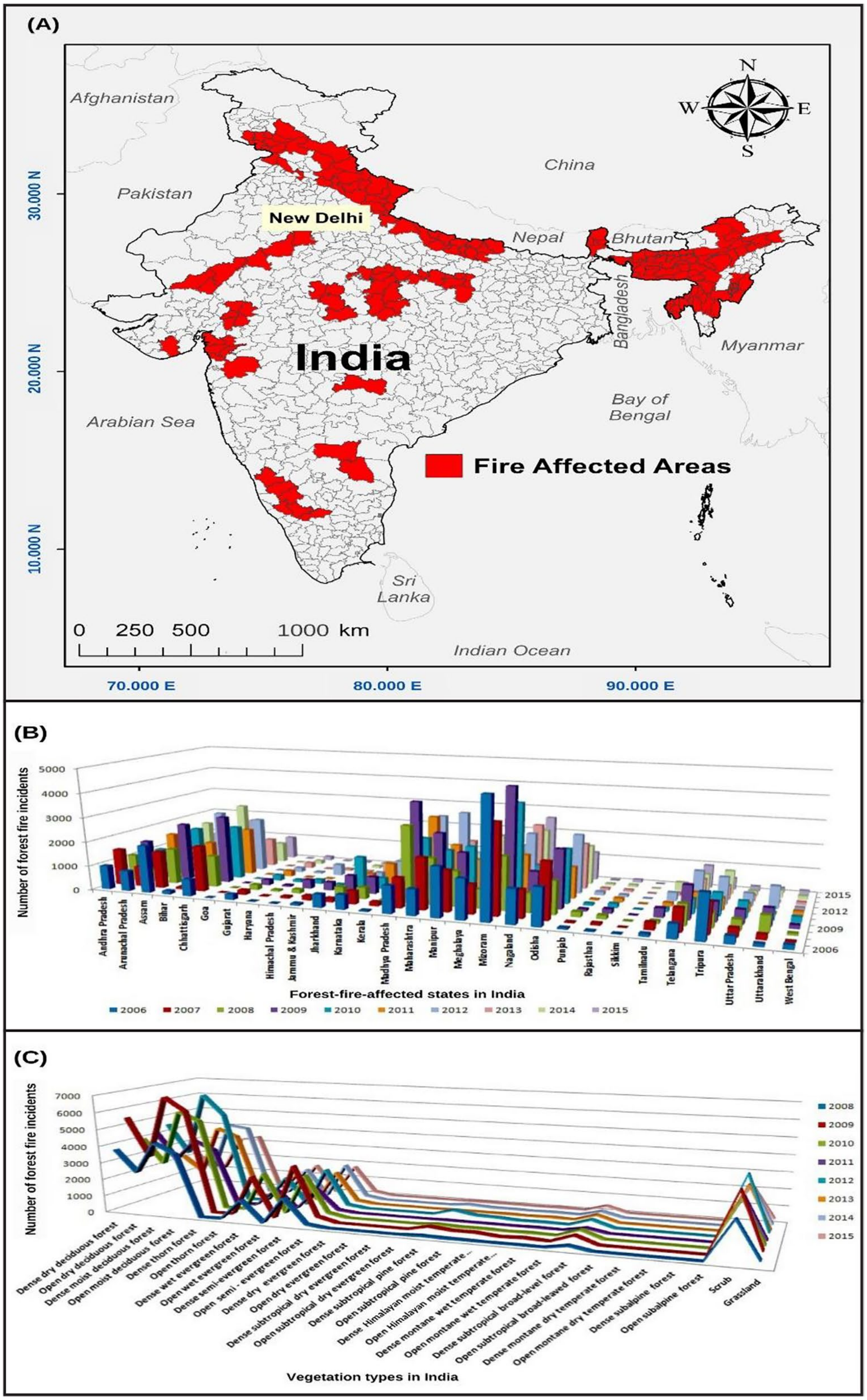

Fig. 2 Data adapted from Reddy et al. 2017 that illustrates **A** India's most forest-fire-affected states; **B** the observed number of forest fire incidents in these states between 2006 and 2015; and **C** the observed number of forest fire incidents in different vegetation types in India between 2008 and 2015. These data contributed to our review of climate attributes and their affects on forest fire between 2002 and 2019 in the Dehradun district, in the state of Uttarakhand, India

Similarly, Mavrakis et al. (2013) compared the Nesterov and Ångstrom indices with respect to the role of climatic attributes in the outbreak of large forest fires in Greece during summer 2007, which caused heavy human casualty. The study confirmed that favorable climatic conditions prevailed at the time of forest fire outbreak, and continued to contribute to the difficulty of controlling the fire. The study concluded that the Ångstrom index is a very good predictor of forest fire potential.

Uttarakhand forest carbon stock

Uttarakhand contains 4.02% (284.664 million tonnes) of the total forest carbon stock of India (FSI 2017). Every year, about 5.9 million tonnes of carbon is added to the forest through tree growth. The total standing aboveground biomass of forest woody vegetation is one of the major carbon pools. Aboveground biomass is composed of all woody stems, branches, leaves of living trees, creepers, climbers, and epiphytes, as well as herbaceous undergrowth. Total forest floor biomass carbon stock (AGB + deadwood + litter) was estimated as carbon stock. In Uttarakhand forest, carbon is predominately stored in soil organic matter and aboveground biomass, with smaller amounts found in belowground biomass, litter, and deadwood (Fig. 1).

Between 2002 and 2008 in Uttarakhand, estimated burned forested area was ~ 3289.09 km^2 of the total state forested area (MEFCCGI 2018). Of the total forest cover of Uttarakhand, the burned forest area was 0.02% and 0.05% in 2015 and 2019, respectively (FSI 2017). Approximately 32.2 and 53.2 thousand tonnes of forest biomass carbon stock may have been lost in 2015 and 2017, respectively (Table 4; Additional file 1). For other years, it cannot be estimated due to lack of literature and secondary data on forest burned area with regard to total area.

During forest fires in May and June 2016, around 3774.14 km^2 (15.28%) of total forest cover of Uttarakhand was completely burned, and the worst affected districts were Tehri Garhwal, Pauri Garhwal, and Nainital districts (Gupta et al. 2018). Ministry of Environment, Forest and Climate Change, Government of India (2018) reported the monetary losses due to forest fire events in Uttarakhand from 2007 to 2016 (Additional file 2).

Temperature increase is one of the alarming attributes of climate change that affects vegetation cover, soil, and carbon-pool stability in forest ecosystems (Kasischke and Stocks 2012). Forest carbon-pool size is also changing relative to climate changes, more so in vegetation compared to the soil (Gonsamo et al. 2017). Numerous approaches have been developed to measure the change in carbon pools in vegetation and soil. However, studies on the effect of forest fire on changes in forest carbon stock were very limited (Kasischke and Stocks 2012).

In this study, an integrated assessment of forest fires, climate, and forest biomass carbon stock of the Dehradun district of Uttarakhand was carried out (Fig. 3). Long-term climate data (2002 to 2019) was used to define relationships between forest fires and forest fire indices, and forest biomass carbon stock loss was estimated.

Methods

Study site

We selected the Dehradun district in Uttarakhand (latitude between 29.96° and 31.03° N, and longitude between 77.56° and 78.3° E), covering 3088 km^2 (5.7% of the entire state), for exploring the relationship between forest fire

Table 4 Forest surface fuel biomass (t ha^{-1}) and carbon vulnerable to fire (t) in the predominantly dry-mixed-type forests in the six divisions of Dehradun district, state of Uttarakhand, India, in 2018. Dominant forest type is dry-mixed. Total area (ha), forested area (ha, %), and burned area (ha, %) for each division is given. Data were collected during our review of climate attributes and their affects on forest fire between 2002 and 2019. Details on the average surface fuel biomass are available in Additional file 1.

Division	Total area (ha)	Forested area[a] (ha)	Total burned area[b] (ha)	Average surface fuel biomass (t ha^{-1})[c]	Biomass carbon vulnerable to fire (t)
Chakrata Forest Division	12,2208.0	43,967.9 (35%)	2032 (4.6%)	5.07	~ 10,302.24
Dehradun Forest Division	86,761.0	50,481.9(58%)	1471 (2.9%)	5.07	~ 7457.97
Kalsi Soil Conservation Division	43,534.9	23,321.3 (53%)	506 (2.1%)	5.07	~ 2565.42
Mussoorie Forest Division	80,336.9	39,082.9 (49%)	3133 (8.0%)	5.07	~ 15,884.31
Tons Forest Division	76,141.5	62,208.9 (81%)	2245 (3.6%)	5.07	~ 11,382.15
Rajaji National Park Division	82,042.0	82,042.0 (100%)	19,252 (23%)	5.07	~ 97,607.64
Totals	491,024.3	304,225.4 (61.9%)	28,639 (9.4%)	30.42	~ 145,199.73

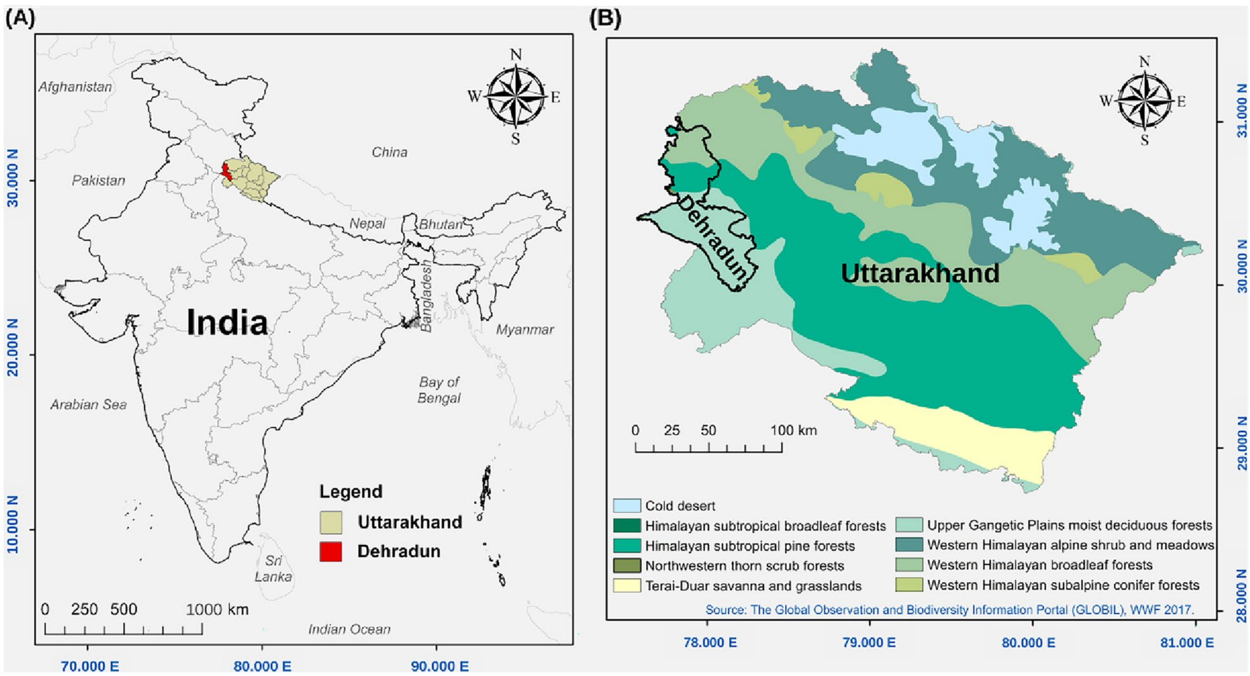

Fig. 3 Maps depicting the area of focus for our review of climate attributes and their affects on forest fire between 2002 and 2019 in the Dehradun district, in the state of Uttarakhand, India: **A** map of India with Uttarakhand state and its Dehradun district located in the central Himalayan region highlighted, and **B** map of Uttarakhand state depicting forest ecological regions and the Dehradun district boundary

incidents, climate, and forest biomass carbon stock. The district is bordered by the Himalayas in the north, the Rajaji Range of the Shivalik Hills in the south, the river Ganges in the east, and the Yamuna River in the west. 52% (1605 km^2) of the district is covered by forest.

Average annual rainfall in Dehradun is ~220 cm, and the elevation ranges from 400 to 1600 m above mean sea level. Forest vegetation is dominated by sal (*Shorea robusta* C.F. Gaertn.) and dense mixed forest (Rawat 2003). In 2017, Dehradun district reported a 4% increase in forest cover since 2001 (Table 2).

Thakur and Singh (2014) mapped potential forest fires zones using parameters such as number of leaves deposited on the forest floor as fuel and their moisture content for Dehradun district forest area, and estimated that 3.13% of forest area fell under very high fire potential zone, while 50.25% area was in high fire potential zone.

Forest fires in Dehradun district during 2002 to 2019

Forest fire events in the Dehradun district, Uttarakhand, that occurred during the fire season (April through June) from 2002 to 2019 were downloaded from Forest Fire Alert System 3.0 (FAST 3.0; FSI 2019; Fig. 4). FAST 3.0 tracks large forest fire events, based on Near Real Time fire point data obtained from the satellite sensors SNPP-VIIRS (Suomi National Polar-Orbiting Partnership-Visible Infrared Imaging Radiometer Suite; resolution of 375 m × 375 m) and MODIS (Moderate Resolution Imaging Spectroradiometer; resolution of 1 km × 1 km), processed by the National Remote Sensing Centre in Hyderabad, Telangana, India. The frequency of the data generated by the sensors was six times per day (24 h) at the time of this study. Any fire hotpots detected by satellite (i.e., MODIS or SNPP- VIIRS sensor) that was located in the forest area of India was regarded as a forest fire incident. Criteria for any large forest fire event was that it should be active for at least 12 h with at least three proximate VIIRS pixels (i.e., a minimum fire-covered area of 42 ha). GPS locations for all forest fire events in the study site were exported as shapefiles and superimposed above the spatial layers of Dehradun district boundaries in ArcGIS (ESRI, Redlands, California, USA) software. The fire season (April to June) point layers for each year (2002 through 2019) were finalized as layout maps, which were later extracted and compiled for the analysis.

Climate attributes

In this study, India Meteorology Department climate data from 2002 to 2019 were used to analyze the climatology of the district. The climate data variables used for the analysis were monthly averages for temperature (°C; minimum, maximum, average), relative humidity (%), and wind speed (km h^{-1}) for the fire season in Dehradun district (Additional file 3).

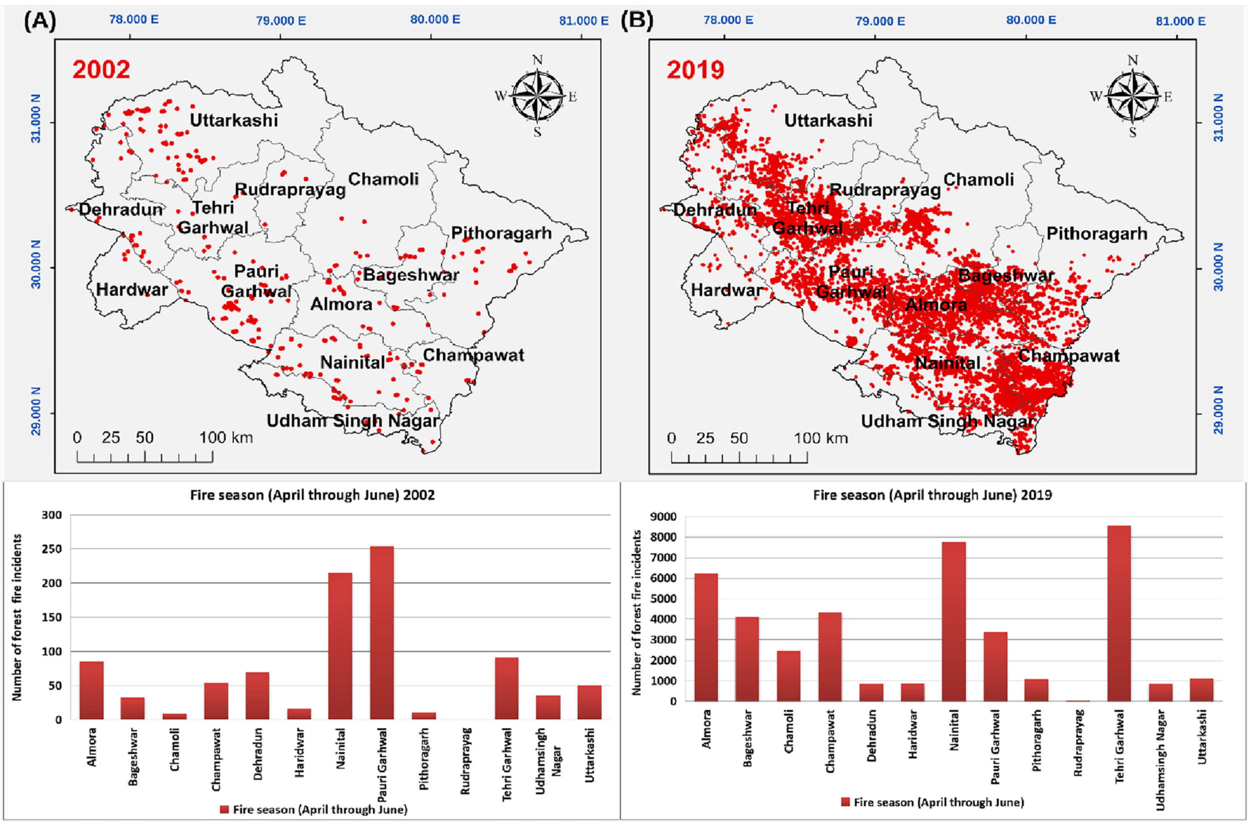

Fig. 4 A comparison of fire incident data from the beginning (2002) and the end (2019) of the period of our review of climate attributes and their affects on forest fire in the Dehradun district, in the state of Uttarakhand, India. Map of fire incidents (red dots) during fire season (April through June) in Uttarakhand for **A** year 2002 and **B** year 2019. Graph of the number of fire incidents during fire season (April through June) observed for per Uttarakhand district in **C** year 2002 and **D** year 2019

Table 5 Kendall's tau (τ) test and correlation of climate variables (diurnal temperature range, DTR; relative humidity, RH; minimum temperature, Tmin; maximum temperature, Tmax; average temperature, Tav; and wind speed, WS) to the forest fire incidents reviewed in our study of climate attributes and their affects on forest fire between 2002 and 2019, in the Dehradun district, state of Uttarakhand, India. *Z*-statistics and *P*-values are also given. ** = $P \leq 0.001$, highly significant correlation; * = $P \leq 0.05$, significant correlation; ns = non significant correlation

Climate variable	Kendall's tau (τ)	*Z*-statistic	*P*-value	Concordant pairs	Discordant pairs
DTR (°C)	0.5033	2.9166	0.003*	115	38
RH (%)	− 0.1438	− 0.8333	0.40^{ns}	65	87
Tmin (°C)	0.1503	0.8712	0.38^{ns}	88	65
Tmax (°C)	0.5229	3.0302	0.002*	116	36
Tav (°C)	0.6601	3.8256	0.001**	119	34
WS (km h^{-1})	0.1699	0.9848	0.32^{ns}	89	63

Diurnal temperature range was computed by subtracting the minimum temperature from the maximum temperature for each day. Monthly averages of climate attributes and forest fire events for the study site were subjected to Kendall's tau (τ) correlation test (Kendall 1938; Table 5) to identify the type and significant relationship ($P \leq 0.05$) between climate attributes and forest fire incidents.

$$\tau = \frac{\sum A - \sum B}{\sum A + \sum B} \quad (1)$$

$$\sum A + \sum B = \frac{n(n-1)}{2} \quad (2)$$

$$Z = \frac{3 * \tau * \sqrt{n(n-1)}}{\sqrt{2(2n+5)}} \quad (3)$$

where A = concordant pairs, B = discordant pairs, n = number of observations, and Z = Z-statistic. Kendall's tau (τ) value ranges between −1 and 1, where 0 and 1 indicate no relation and perfect positive relation, respectively.

Forest fire indices

In this study, Ångstrom index (I) and Fuel Moisture Index (FMI) were computed using monthly average values of climate data (Luna et al. 2018).

Ångström index (I)

The Ångström index is computed on the basis of relative humidity and temperature attributes as:

$$I = \frac{R}{20} + \frac{(27 - T)}{10} \quad (4)$$

It indicates the danger of forest fire on the basis of ambient temperature (T in °C) and relative humidity (R in %). The index value ranges from 0 to 4. If the index value is low (0), then fire potential is higher, while values above 4 represent no fire potential. The Ångstrom index is an indication of air dryness, which indicates favorable or non-favorable conditions for forest fires (Skvarenina et al. 2003). Probability of forest fires has been categorized according to derived index values.

Fuel Moisture Index (FMI)

The amount of moisture present in fuels is a key regulating factor of forest fire danger potential and behavior in different forest types (Sharples et al. 2009). Fuel Moisture Index (FMI) estimates fuel moisture content on the basis of air temperature (°C) and relative humidity (%). Its value ranges from 0 to 30; the smaller the index value, the higher the danger of forest fire.

$$FMI = 9.67 - 0.27(T - R) \quad (5)$$

In this study, we used a modified FMI (FMI_{mod}) developed by Pook and Gill (1993) to estimate the moisture content in fuels under dry conditions. The modified FMI makes better use of fuel moisture content by incorporating the effect of available moisture content in top soil (ms; in % volume).

$$FMI_{mod} = 9.67 - 0.27(T - R) + 0.69ms \quad (6)$$

Impact of Dehradun district forest fires on forest biomass carbon stock

In Uttarakhand, forest fire type is mainly surface fire (Dogra et al. 2018). The sum of the carbon pools on the forest floor is equivalent to forest biomass carbon stock. Based on this, an assumption was made that surface forest fires mostly consume a portion of aboveground biomass (AGB), which consists of dry leaves, twigs, dry litter, and dry herbaceous grasses. Hence, AGB represents the forest floor carbon pool that is vulnerable to fire; however, the total forest carbon stock that is vulnerable to fire includes AGB, deadwood, and litter. Aboveground biomass stored in branches and boles is not usually consumed during surface fires.

In our study of Dehradun district forests, secondary data for surface forest fire fuel content (i.e., dry weight of leaves, twigs, grass and herbaceous grasses) in different forest types (mixed sal, sal, dry mixed, mixed, and moist mixed; Rawat 2003) was collected from the literature (Additional file 1). There was a lack of data on percent of area burned in different forest types other than the dry mixed forest type. Loss of forest biomass carbon stock due to surface fire was estimated for dry mixed forest type of the Dehradun district (Table 6). In the Shivalik Hills, Dehradun district forest average forest floor fuel loading varied between 350 and 460 g m^{-2} (Additional file 1). The average forest floor fuel loading units, g m^{-2}, were converted into t ha^{-1}, then an average of all forest-type fuel loads was estimated and multiplied with the average area of forest type to find the available forest floor load (g) for forest fire fuels. Loss of forest biomass carbon stock in the Dehradun district's surface forest fire incidents during the fire season was calculated by multiplying the average forest floor fuel load by forest burned area per year (Table 6; Additional file 1).

Results and discussion

Dehradun district: forest fires

In 2017, a 0.07% decline in forest cover of Dehradun district was observed as compared to 2011; whereas, in 2011, there was a 9.12% increase in forest cover as compared to 2001 (Table 2). On comparing forest fires during 2002 to 2019, year-to-year variability was observed in the number of forest fire incidents (Table 3; Fig. 5). Total number of forest fires during 2002 to 2019 was 5182 for the period, with a maximum of 845 fires and a minimum of 22 forest fires reported in 2019 and 2011, respectively. Monthly analysis of forest fires indicated that the most fires occurred during early April and late May or early June. Our results were similar to those of Gupta et al.

Table 6 Ångstrom index and Fuel Moisture Index values for Dehradun district, state of Uttarakhand, India, for each year of our review of climate attributes and their affects on forest fire, between 2002 and 2019. Empty cells indicate months in which data was not collected

Year	Ångstrom index value per month												Fuel Moisture Index value per month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	5.6	4.7	3.8	2.9	2.6	3.6	4.1	4.5	4.8	4.0	4.6	5.3	28.6	24.6	21.2	17.3	16.8	22.0	24.6	26.2	27.2	22.5	24.5	27.5
2003	5.8	5.2	3.9	2.5	2.1	3.2	4.6	4.8	4.4	3.8	4.4	5.5	29.2	26.9	21.1	15.7	14.0	20.3	27.0	28.1	25.4	21.2	23.4	28.0
2004	5.7	4.6	2.9	2.6	2.1	3.5	4.1	4.6	4.1	4.4	4.8	5.3	29.2	24.2	16.8	16.2	14.4	21.1	24.4	26.8	24.3	24.2	25.5	27.3
2005	5.3	5.1	3.8	2.5	2.2	2.2	4.6	4.7	4.5	4.3	4.3	4.8	27.1	26.5	21.1	15.4	14.4	15.4	27.1	27.4	26.2	24.5	22.7	24.7
2006	5.1	3.9	3.8	2.5	3.1	3.6	4.8	4.4	5.0	4.0	4.5	5.1	26.2	21.2	20.9	15.7	19.1	21.8	28.5	25.8	28.7	22.8	24.4	26.3
2007	5.0	5.0	4.3	2.8	3.1	3.4	4.3	4.7	5.2	4.4	4.6	6.0	25.2	25.9	23.2	17.5	19.3	21.0	25.7	27.7	29.9	24.9	24.8	30.9
2008	5.3	4.8	3.1	2.8	2.7	4.1	4.7	4.7	4.3	4.3	4.7	5.3	26.6	24.6	17.8	17.1	16.8	24.5	27.6	27.6	24.9	24.1	25.2	27.7
2009	5.0	4.4	3.3	2.2	3.0	2.2	4.0	4.4	5.3	4.7	5.1	5.0	26.0	23.0	18.7	13.9	18.9	14.9	24.3	25.9	30.8	25.8	27.0	25.8
2010	6.0	4.7	3.3	2.0	2.3	2.3	4.3	4.6	4.7	4.2	4.6	5.1	30.9	24.9	19.0	13.4	15.8	15.8	25.6	26.8	26.8	23.6	25.0	26.0
2011	5.6	4.7	4.2	2.8	2.6	4.1	4.3	4.8	4.5	4.1	4.9	5.2	25.7	24.4	17.8	17.7	24.1	25.7	28.0	25.9	22.5	25.1	25.3	26.5
2012	5.5	4.8	3.6	3.0	1.9	1.9	4.2	4.6	4.2	4.0	4.8	5.2	27.9	25.1	20.1	17.7	13.3	13.6	24.9	26.6	24.7	22.8	25.4	26.5
2013	5.5	5.5	5.3	4.1	2.6	2.0	4.0	4.6	4.4	4.3	4.8	4.6	27.6	27.6	22.8	15.9	13.8	24.1	27.1	25.9	25.1	26.9	24.4	28.3
2014	5.4	5.2	4.7	2.9	2.4	2.8	4.3	4.2	4.2	4.5	4.4	5.4	27.8	26.6	25.6	16.9	15.3	18.4	25.3	24.9	24.4	25.5	23.7	27.6
2015	5.6	4.8	4.5	4.0	2.8	3.2	4.7	4.4	4.1	4.1	5.0	5.2	28.7	25.1	24.4	22.3	18.2	20.2	27.6	26.0	24.4	23.5	27.0	26.9
2016	5.1	4.5	3.9	3.0	2.6	3.7	4.8	4.5	4.5	4.3	4.9	5.2	26.0	23.5	21.5	18.2	17.1	22.7	28.3	26.7	26.4	24.4	26.0	27.0
2017	5.4	4.9	4.0	3.5	2.9	3.5	4.3	4.5	5.1	4.1	4.9	5.3	27.7	26.2	22.0	20.9	18.5	21.4	25.4	26.3	29.9	23.5	25.9	27.7
2018	7.1	4.7	3.6	2.8	2.4	3.6	4.3	4.7	4.4	4.3	5.0	5.4	36.8	24.9	20.1	17.2	15.5	22.2	25.7	27.3	25.8	24.2	26.9	27.5
2019	5.6	5.3	4.4	3.2	2.6	3.0	4.9	4.5					28.6	27.5	23.8	19.2	16.9	19.2	28.7	26.8				

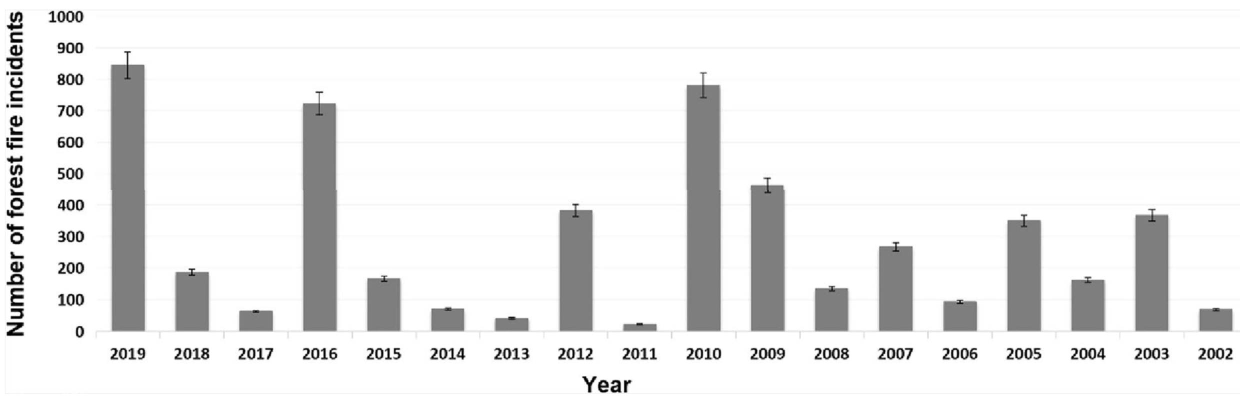

Fig. 5 Total number of forest fire incidents recorded in Dehradun district, state of Uttarakhand, India, during fire seasons (April through June) during our review of climate attributes and their affects on forest fire between 2002 and 2019. Errors bars depict standard deviation

(2018), who reported the same period as the critical period for forest fires in the Uttarakhand region.

Forest fire incidents at all locations were directly or indirectly governed by multiple natural and anthropogenic factors. Suitable and unsuitable climate conditions (Wotton 2009) were among multiple factors affecting forest fire incidents in the Dehradun district. In the literature, it has been reported that heat waves, temperature increases, and reduced rainfall are the major contributors to 2016 Dehradun forest fires (Negi and Kumar 2016). In 2016, fires started as early as February and continued through June because of the low rainfall (only 16.2 mm) received in the preceding winter, which reduced soil moisture and led to drying of the forest floor biomass and buildup of suitable forest fire fuel loads (Negi and Kumar 2016). High temperature and low precipitation affect forest ecosystem processes. It has been reported that Uttarakhand received 28% less precipitation in 2015, a warm year (Sharma and Pant 2017). These attributes—high temperature, low precipitation, low soil moisture—coincided with leaf fall and their drying period of the major tree species of the Himalayan forest. Followed by a dry summer, these attributes played a critical role in developing forest fire potential for the region.

Monsoon season in the Dehradun district is from mid or late June through mid September. In India, field studies addressing the relationship between the monsoon season and forest fires are very limited and needed to fill the knowledge gap.

Climate attributes and forest fires

In forest fires, fuel consumption is dependent on fuel loading and wind speed. Forest fire intensity is dependent on wind speed, moisture content of fuel, vegetation height, and vegetation cover.

In our study, the relationship between climate attributes during 2002 to 2019 and number of forest fires events were analyzed. Kendall's tau (τ) correlation coefficient for number of forest fires and the climate attributes maximum temperature, minimum temperature, average temperature, diurnal temperature range, relative humidity, and wind speed were +0.52, +0.15, +0.55, +0.50, −0.14, and +0.16, respectively (Table 5; Fig. 6). The association of diurnal temperature range and average temperature with fire incidents was highly significant ($P \leq 0.001$), whereas the association of maximum temperature with fire incidents was significant ($P \leq 0.05$) (Table 5). The results indicated that correlations were found between number of forest fires and minimum temperature, wind speed, and relative humidity; however, they were statistically non-significant ($P \leq 0.05$). This may be due to our use of monthly climate data summaries. In future research, the relationships between number of forest fires and climate attributes using daily or hourly data should be explored.

The prevalence of elevated temperatures facilitates rapid drying of biomass, which support its easy and rapid burning (Prasad et al. 2008). Air temperature has a direct influence on forest fire behavior by promoting the heat requirements for ignition. Temperature rise can affect or alter some forest species' growing stages in their life cycles (Kramer et al. 2000).

The climatology of the Dehradun district indicates prevalently calm winds from April to June, in the range of 0.61 to 3.80 km h^{-1}. During peak fire season of our study, the range of wind speed was 1.09 to 3.74 km h^{-1}. This indicated that, in the Dehradun disctrict, wind is not a regulating factor for spread of forest fire. Sharma et al. (2012) also reported the prevalence of calm winds during summer months, in the range of 1.8 to 5.4 km h^{-1}. However, Saglam et al. (2008) reported that wind speed plays a crucial role in spreading and enhancing the intensity of forest fires in the Mediterranean regions by

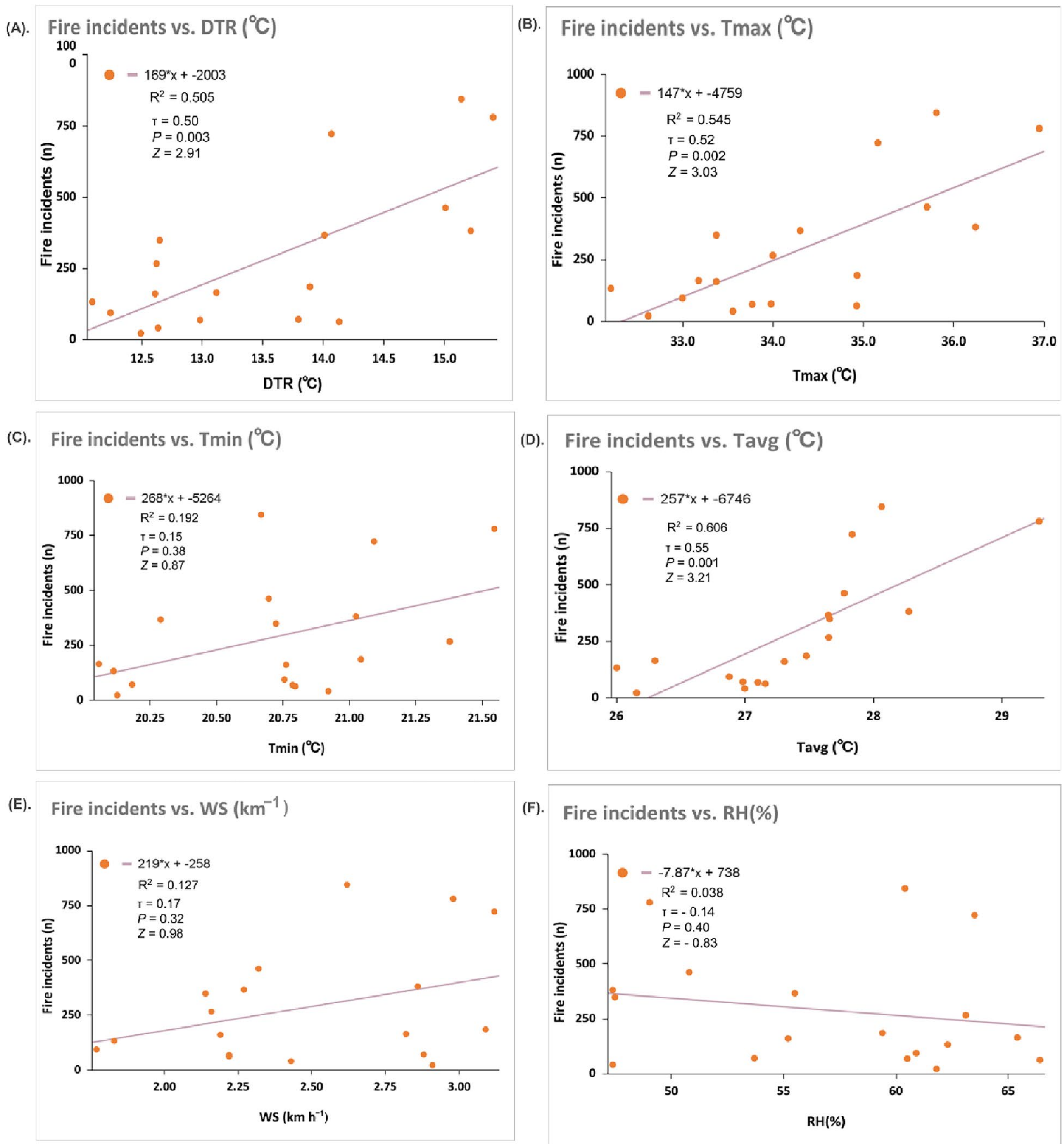

Fig. 6 Graphs depicting Kendall's tau (τ) values, correlation regression equations ($y=mx+c$; where m is the slope of the line relating y to x, and c is the y intercept of that line; pink line), R^2 values (coefficients of determination); *P*-values (≤ 0.05), and *Z*-statistics (± 1.96) between forest fire incidents (orange dots) and climate attributes for Dehradun district, state of Uttarakhand, India, during fire seasons (April through June) during our review of climate attributes and their affects on forest fire between 2002 and 2019: **A** correlation plot of number of fire incidents and diurnal temperature range (DTR; °C); **B** correlation plot of number of fire incidents and maximum temperature (Tmax;°C); **C** correlation plot of number of fire incidents and maximum temperature (Tmin; °C); **D** correlation plot of number of fire incidents and average temperature (Tavg; °C); **E** correlation plot of number of fire incidents and wind speed (WS; km h^{-1}); and **F** correlation plot of number of fire incidents and relative humidity (RH; %)

maintaining oxygen supply and tilting the flames towards unburned fuels. Our results indicated that average wind speeds were calm, but gusty periods associated with fire spread may not be revealed by the average monthly climatology. Wind will push flames, sparks, and firebrands into new fuel. By pushing the flames closer to the fuel in front of the fire, the fuel is preheated more quickly from increased radiant heat. More fuel becomes available for combustion since it is dryer, and can reach ignition temperature more quickly.

The 30-30-30 rule of thumb—ambient air temperature at ≥ 30 °C, relative humidity at $\leq 30\%$, and open wind speed at ≥ 30 km h^{-1}—has been used around the world as an indicator of extreme fire behavior potential (Steffens 2016). For the fire season in the Dehradun district during our study, it was observed that the ambient air temperature maximum was 36.9 °C, relative humidity was $\leq 41.5\%$, and open wind speed was ≥ 1.09 km h^{-1}. This indicates that climate-attribute thresholds, with regard to forest fire behavior, vary by ecoregion. Temperature and relative humidity were the key regulators of forest fires in the Dehradun district during our study period.

In this study, correlation between relative humidity and number of forest fires was negative. This is similar to findings by Prasad et al. (2008) and Saglam et al. (2008) that, under low atmospheric relative humidity, moisture in fuels is readily evaporated, enhancing burn potential.

Diurnal temperature range (DTR) influences a forest's biophysical state (Easterling et al. 1997). In our study, DTR was 12.1 to 15.4 °C. The correlation between annual DTR and forest fire events was negative as well as positive. The DTRs for years 2019, 2016, and 2010, having 845, 723, and 781 forest fires, respectively, were 15.1, 14.1, and 15.4 °C, respectively. The DTRs for years 2013, 2011, and 2006, having 41, 22, and 94 forest fires, respectively, were 12.6, 12.1, and 12.2 °C, respectively. However, there were exceptions: years with lower DTR and higher forest fires such as 2008 (DTR = 12.1 °C; number of forest fires = 133), 2007, 2005, and 2004 (DTR = 12.6 °C; number of forest fires = 267, 349, and 161, respectively). The increase in DTR for the Dehradun region during 2019, 2016, and 2010 was due to increasing maximum temperature and almost no change in minimum temperatures. Minimum temperature in forest ecosystems is enhanced by moisture loss from biomass at night. No change in minimum temperatures in the Dehradun region indicates that there was a dry fuel load on the forest floor during fire season. Higher DTR is an indicator of drier air and lower relative humidity. The Kendall tau correlation between DTR and forest fire events was positive and significant at $P \leq 0.05$ (Table 4). Further studies using hourly and daily climate data are needed to explore the relationship between DTR and forest fires.

Forest fire-related indices

Ångström index (I) value range observed during forest fire season (April to June) from 2002 to 2019 was 1.86 to 4.13 (Table 6). The estimated I values for all three months of the forest fire seasons, from 2002 to 2019, indicated that climatic attributes were favorable for forest fire incidents, with the exception of the years 2019, 2017, 2015, and 2013. In 2019, a maximum number of forest fires (845) were reported, despite the fact that only two of the three fire-season months, May and June, experienced climate conditions favorable for forest fire incidents. In 2017, a low number (63) of forest fire incidents were reported, which may have been due to the fact that only one of the fire-season months, May, experienced climate conditions conducive to forest fire. In years 2005, 2010, 2012, and 2014, I values were > 3 for all 3 months of the fire season, and reported fire incidents were 349, 781, 382, and 71, respectively, which indicated a prevalence of favorable climate for forest fire incidents. The results of our study were similar to the observations of Chandler et al. (1983) and Arpaci et al. (2013), who reported that the Ångström index captured region-specific prevalent weather conditions and was a good indicator for monitoring forest fire incidents. However, the reasons for the observed low number of forest fires in 2014, despite a low index value, indicating favorable climate conditions for forest fire, need to be explored further.

The Fuel Moisture Index (FMI) value range observed for twelve months (January to December) during 2002 to 2019 was 13.3 (minimum; May 2012) to 37 (maximum; January 2018) (Table 6). Low FMI values indicate that fuel is dry and forest fire potential is high, and vice versa. However, the FMI range for the fire season (April to June) during 2002 to 2019 was 13.3 (minimum; May 2012) to 26 (maximum; June 2011) (Table 6). Low FMI values during May indicated availability of dry fuel on forest floor for forest fire.

I and FMI indices indicated that, during fire season, forest fire potential was enhanced by prevailing climatic conditions.

Forest fires and forest biomass carbon stock

Forest fires reported in the Dehradun district during 2002 to 2019 consumed forest biomass accumulated as surface fuel, consequently affecting forest biomass carbon stock. Reports on the extent of the impact of forest fires on forest biomass carbon stock are limited. In the literature, surface fuel accumulation for different forest types has been reported (Additional file 1; Table 4). Fuel for surface fire is assumed to be composed of dry leaves, twigs, and grasses. In the Dehradun district, forest cover is distributed into six divisions. Rajaji National Park and Chakrata divisions have the most (100% of the forest) and least (35% of the forest) forest cover, respectively (Table 4). The maximum and minimum total burned forest area and forest biomass carbon stock loss are in Rajaji National Park (23% and 97 thousand tonnes) and the Kalsi Soil Conservation Division (2.1% and 2 thousand tonnes), respectively. The estimated loss of forest surface biomass carbon stock due to fire in the district's mixed sal forest (burned area of 8.05%) was 2.2 $\times 10^5$ tonnes.

The difference in biomass carbon stock loss among the different forests may be due to number of fires and availability of fuel type, as well as to climate. In the literature, the impact of these attributes on biomass carbon stock loss for different regions has been reported (FSI 2019). Forest-fire-induced loss of forest biomass carbon stock is high, depriving the soil of nutrients. Our results also indicated that, in the future, carbon stock loss may increase, with increase in percentage of burned area as well as with frequency of forest fire. To minimize loss, the interlinkages between forest fire incident, fuel type and its availability, and climatology need to be explored.

Conclusion

This study indicated that forest fire incidents in districts of Uttarakhand are variably increasing. Forest fire intensity and spread in the Dehradun district and its various forest divisions is variable. Dehradun district forest fire incidents exhibited positive and highly significant correlation with average temperature, maximum temperature, and DTR climate attributes, and highlight the fact that climate plays a crucial role in altering forest fire potential. Correlations between number of forest fires and a few climate attributes such as minimum temperature, wind speed, and relative humidity were positive and not significant ($P \leq 0.05$). These results may be due to use of monthly climate data summaries. In the future, the relationships between number of forest fires and climate attributes should be analyzed by using daily or hourly weather data.

The relationship between Ångstrom index and Fuel Moisture Index values and forest fire incidents indicated that both are good indicators to capture the vulnerability of Dehradun forest to forest fire.

This study also showed that forest fires are causing a loss of carbon sequestered in forest biomass carbon stock. In the absence of forest fire, the lost forest biomass carbon would have been been incorporated into the soil via carbon cycling processes to be made available to plants to support forest productivity.

For management of forest fires, region-specific knowledge of fire-season relationships with climate attributes, fuel type and its suitability, fire related indices, and forest biomass carbon stock needs to be strengthened. The state department of agriculture of Uttarakhand constructed water retaining tanks and check dams (1.46 million cubic liters of water storage) from 2007 to 2017 to recharge springs and maintain moisture content on the forests floor to reduce the number of forest fires. However, the effect has been insignificant (although it may have affected the size of fire), as the number of forest fires are still increasing, indicating that climate is playing a greater role in forest fires. Many gaps exist in our knowledge about forest fires, despite our use of remote sensing-based regular monitoring of burned forest area and carbon emissions. More extensive ground studies are needed to estimate actual carbon stock loss due to forest fire.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00177-4.

Additional file 1. Graph of surface fuel density (dry weight of leaves, twigs, and grasses; Rawat 2003) and carbon loss due to forest fire in Dehradun district forests (Gupta et al. 2018) during our review of climate attributes and their affects on forest fire between 2002 and 2019 in the state of Uttarakahnd, India. Average surface fuel density (includes dry weight of leaves, twigs, and grasses) in different forest types of Dehradun district is used to compute average surface fuel load (g m-2). Average surface fuel load is multiplied by average area of mixed sal forest type to compute average surface fuel load (t). Average surface fuel load is multiplied by forest burned area to compute forest biomass carbon stock loss (t). Empty cells indicate that data was not available.

Additional file 2. Graph of economic losses and loss per hectare in Indian rupees and US dollars for the state of Uttarakhand, India, due to forest fire incidents between 2007 and 2016 (MEFCCGI 2018), during our review of climate attributes and their affects on forest fire between 2002 and 2019. One Indian lakh rupee is equivalent to 0.1 million rupees.

Additional file 3. Monthly average value of climate attributes of Dehradun district during our review of climate attributes and their affects on forest fire between 2002 and 2019 in the state of Uttarakahnd, India. Tavg = average temperature; Tmax = maximum temperature; Tmin = minimum temperature; WS = wind speed; and RH = relative humidity. Data for peak fire season (April through June) are in bold text.

Acknowledgements
We acknowledge the reviewers who provided comments to improve the manuscript.

Authors' contributions
UM conceptualized and wrote the manuscript. APD analyzed the data and edited the manuscript. SF extracted, compiled, and analyzed the data, and wrote the manuscript. All authors read and approved the final manuscript.

Funding
Not applicable.

Availability of data and materials
All data that supports the findings of this study are available in the main text and supplementary material files.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 25 July 2021 Accepted: 2 March 2023
Published online: 14 March 2023

References

Abatzoglou, J. T., and C. A. Kolden. 2013. Relationships between climate and macroscale area burned in the western United States. *International Journal of Wildland Fire* 22 (7): 1003–1020. https://doi.org/10.1071/WF13019.

Arpaci, A., C. S. Eastaugh, and H. Vacik. 2013. Selecting the best performing fire weather indices for austrian ecoregions. *Theoretical and Applied Climatology* 114 (3): 393–406. https://doi.org/10.1007/s00704-013-0839-7.

Ashutosh, S., S. Kumar, A. Choudhary, T. Biswas, and S. Ghosh. 2019. Identification of fire prone forest areas based on GIS analysis of archived forest fire points detected in the last thirteen years. Technical Information Series volume 1 number 1. Dehradun: Forest Survey of India, Ministry of Environment, Forest & Climate Change, Government of India.

Baijnath-Rodino, J. A., E. Foufoula-Georgiou, and T. Banerjee. 2020. Reviewing the "hottest" fire indices worldwide. *ESS Open Archive* 1–43. https://doi.org/10.1002/essoar.10503854.1.

Bhandari, B.. S.., J.. P.. Mehta, and R.. L.. Semwal. 2012. Forest fire in Uttarakhand Himalaya: an overview. In *Glimpses of forestry research in the Indian Himalayan region*, ed. G..C..S.. Negi and P..P.. Dhyani. Almora: Pant Institute of Himalayan Environment and Development; and Dehradun India: Bishen Singh Mahendra Pal Singh.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. *Fire in forestry. Volume 1. Forest fire behavior and effects. Volume 2. Forest fire management and organization*. New York: Wiley.

Cobb, R. C., and M. R. Metz. 2017. Tree diseases as a cause and consequence of interacting forest disturbances. *Forests* 8: 1–13. https://doi.org/10.3390/f8050147.

Dogra, P., A. M. Mitchell, U. Narain, C. Sall, and R. Smith, and S.Suresh. 2018. *Strengthening forest fire management in India*. Washington, D.C.: The World Bank. https://doi.org/10.1596/30013.

Easterling, D. R., B. Horton, P. D. Jones, T. C. Peterson, T. R. Karl, D. E. Parker, M. J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, and C. K. Folland. 1997. Maximum and minimum temperature trends for the globe. *Science* 277 (5324): 364–367. https://doi.org/10.1126/science.277.5324.364.

FAO [Food and Agriculture Organization of the United Nations]. 2006. *Global forest resources assessment 2005: progress towards sustainable forest management.* FAO forestry paper 147. Rome: Food and Agriculture Organization of the United Nations. Available online at http://www.env-edu.gr/Documents/Global%20Forest%20Resources%20Assessment%202005.pdf.

FAO [Food and Agriculture Organization of the United Nations]. 2010. *Global forest resources assessment 2010: main report.* FAO forestry paper 163. Rome: Food and Agriculture Organization of the United Nations. Available online at https://www.fao.org/3/i1757e/i1757e.pdf.

FAO [Food and Agriculture Organization of the United Nations]. 2015. *Global forest resources assessment 2015, desk reference.* Rome: Food and Agriculture Organization of the United Nations. Available online at https://www.fao.org/3/i4808e/i4808e.pdf.

Flannigan, M. D., B. M. Wotton, G. A. Marshall, W. J. de Groot, J. Johnston, N. Jurko, and A. S. Cantin. 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. *Climatic Change* 134 (1–2): 59–71. https://doi.org/10.1007/s10584-015-1521-0.

Forbes, K., J. Broadhead, G.B. Bischetti, F. Brardinoni, A.L. Dykes, D. Gray, F. Imaizumi, S.L. Kuriakose, N. Osman, D.N. Petley, A. Stokes, and B. Verbist. 2011. Forests and landslides: the role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia. In *RAP publication 2011/19*. Bangkok: Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific.

FSI [Forest Survey of India]. 2005. *India state of forest report 2005.* Dehradun: Forest Survey of India, Ministry of Environment and Forests. Available online at https://fsi.nic.in/forest-report-2005.

FSI [Forest Survey of India]. 2015. Important characteristics of different forest type groups. Chapter 6. Pages 86–107. In *India state of forest report 2015.* Dehradun: Forest Survey of India, Ministry of Environment and Forests. Available online at https://fsi.nic.in/isfr-2015/isfr-2015-important-characteristics-of-indian-forest-types.pdf.

FSI [Forest Survey of India]. 2017. *India state of forest report 2017.* Dehradun: Forest Survey of India, Ministry of Environment and Forests. Available online at https://fsi.nic.in/forest-report-2017.

FSI [Forest Survey of India]. 2019. *India state of forest report 2019.* Dehradun: Forest Survey of India, Ministry of Environment and Forests. Available online at https://fsi.nic.in/isfr2019/isfr-fsi-vol2.pdf.

Gonsamo, A., J. M. Chen, S. J. Colombo, M. T. Ter-Mikaelian, and J. Chen. 2017. Global change induced biomass growth offsets carbon released via increased forest fire and respiration of the central canadian boreal forest. *Journal of Geophysical Research Biogeosciences* 122 (5): 1275–1293. https://doi.org/10.1002/2016JG003627.

Gupta, S., A. Roy, D. Bhavsar, R. Kala, S. Singh, and A. S. Kumar. 2018. Forest fire burnt area assessment in the biodiversity rich regions using geospatial technology: Uttarakhand forest fire event 2016. *Journal of the Indian Society of Remote Sensing* 46: 945–955. https://doi.org/10.1007/s12524-018-0757-3.

Kasischke, E. S., and B. J. Stocks, eds. 2012. *Fire, climate change, and carbon cycling in the boreal forest. Ecological studies. Volume 138*. New York: Springer -Verlag.

Keith, H.., B.. G.. Mackey, and D.. B.. Lindenmayer. 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proceedings of the National Academy of Sciences* 106 (28): 11635–11640. https://doi.org/10.1073/pnas.0901970106.

Kendall, M. G. 1938. A new measure of rank correlation. *Biometrika* 30: 81–93. https://doi.org/10.1093/biomet/30.1-2.81.

Kramer, K., I. Leinonen, and D. Loustau. 2000. The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology* 44: 67–75. https://doi.org/10.1007/s004840000066.

Kukreti, I. 2019. Regional Fire Management Resource Center - South East Asia (RFMRC-SEA). Six-fold increase in forest fires as temperatures rise in many states. https://rfmrc-sea.org/six-fold-increase-in-forest-fires-as-temperatures-rise-in-many-states/ Accessed 25 Jan 2023.

Kumar, S.., C.. Chaudhary, T.. Biswas, S.. Ghosh, and S.. Ashutosh. 2019. *Identification of fire prone forest areas based on GIS analysis of archived forest fire points detected in the last thirteen years. Technical information series volume 1 number 1*. Dehradun: Forest Survey of India, Ministry of Environment, Forest and Climate Change, Government of India.

Mavrakis, A., A. Agelakis, and G. Theoharatos. 2013. Forest fire indices in Greece during the forest fire events of summer 2007. In: *Advances in Meteorology, Climatology and Atmospheric Physics*, pages 223–229, edited by C. Helmis and P. Nastos. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-29172-2_32.

MEFCCGI [Ministry of Environment, Forest and Climate Change, Government of India]. 2018. *Strengthening forest fire management in India*. Washington D.C.: World Bank. https://doi.org/10.1596/30013.

Miller, D. 2022. Sciencing. The difference between tree sap & tree resin. Available online at https://sciencing.com/difference-between-tree-sap-tree-resin-12296179.html.

Negi, G.C.S., and P.P. Dhyani. 2012. *Glimpses of forestry research in the indian himalayan region*. Almora: Pant Institute of Himalayan Environment and Development.

Negi, M. S., and A. Kumar. 2016. Assessment of increasing threat of forest fires in Uttarakhand, using remote sensing and GIS techniques. *Global Journal of Advanced Research* 3 (6): 457–468.

Ormeno, E., B. Cespedes, I. A. Sanchez, A. Velasco-García, J. M. Moreno, C. Fernandez, and V. Baldy. 2009. The relationship between terpenes and flammability of leaf litter. *Forest Ecology and Management* 257 (2): 471–482. https://doi.org/10.1016/j.foreco.2008.09.019.

Parashar, A., and S. Biswas. 2003. The impact of forest fire on forest biodiversity in the Indian Himalayas (Uttaranchal). Paper submitted to the Forests, Source of Life conference, XII World Forestry Congress. Food and Agriculture Organization of the United Nations, 21 to 28 September 2003, Quebec City, Canada. Avaiable online at https://www.fao.org/3/XII/0358-B1.htm.

Pook, E. W., and A. M. Gill. 1993. Variation of live and dead fine fuel moisture in *Pinus radiata* plantations of the australian capital territory. *International Journal of Wildland Fire* 3 (3): 155–168. https://doi.org/10.1071/WF9930155.
Pourtaghi, Z. S., H. R. Pourghasemi, R. Aretano,, and T. Semeraro. 2016. Investigation of general indicators influencing on forest fire and its susceptibility modeling using different data mining techniques. *Ecological Indicators* 64: 72–84. https://doi.org/10.1016/j.ecolind.2015.12.030.
Prasad, V. K., K. V. S. Badarinath, and A. Eaturu. 2008. Biophysical and anthropogenic controls of forest fires in the Deccan Plateau, India. *Journal of Environmental Management* 86 (1): 1–13. https://doi.org/10.1016/j.jenvman.2006.11.017.
Rawat, G. S. 2003. Fire risk asessment for fire control management in Chilla Forest Range of Rajaji National Park Uttaranchal (India). Thesis, International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands. https://www.iirs.gov.in/iirs/sites/default/files/StudentThesis/gsr_thesis.pdf.
Reddy, C. S., V. V. L. P. Alekhya, K. R. L. Saranya, K. Athira, C. S. Jha, P. G. Diwakar, and V. K. Dadhwal. 2017. Monitoring of fire incidences in vegetation types and protected areas of India: implications on carbon emissions. *Journal of Earth System Science* 126: 11. https://doi.org/10.1007/s12040-016-0791-x.
Riley, K. L., A. E. Klene, I. Grenfell, and F. A. Heinsch. 2013. The relationship of large fire occurrence with drought and fire danger indices in the western USA, 1984–2008: the role of temporal scale. *International Journal of Wildland Fire* 22 (7): 894–909. https://doi.org/10.1071/WF12149.
Robinne, F.N., K.D. Bladon, C. Miller, M.A. Parisien, J. Mathieu, and M.D. Flannigan. 2018. A spatial evaluation of global wildfire-water risks to human and natural systems. *Science of the Total Environment* 610 (611): 1193–1206. https://doi.org/10.1016/j.scitotenv.2017.08.112.
Saglam, B., E. Bilgili, Ö. Küçük, and B. D. Durmaz. 2008. Fire behavior in Mediterranean shrub species (Maquis). *African Journal of Biotechnology* 7 (22): 4122–4129.
Savita, R., V. Luna, D. Dhawan, Kumar, and A. Chaudhary. 2018. Impact of ban on green felling in chirpine forests of Uttarakhand. *Indian Forester* 144 (8): 699–710.
SCBD [Secretariat of the Convention on Biological Diversity]. 2001. *Impacts of human-caused fires on biodiversity and ecosystem functioning, and their causes in tropical, temperate and boreal forest biomes. CBD Technical Series no. 5* Montréal, Québec, Canada: Secretariat of the Convention on Biological Diversity. Available online at: https://www.cbd.int/doc/publications/cbd-ts-05.pdf.
Sharma, A., O. P. Singh, and M. M. Saklani. 2012. Climate of Dehra Dun. Dehra Dun: India Meteorological Department, Government of India, Ministry of Earth Sciencs. https://mausam.imd.gov.in/dehradun/mcdata/DEHRADUN_CLIMATE.pdf.
Sharma, S., and H. Pant. 2017. Vulnerability of indian central himalayan forests to fire in a warming climate and a participatory preparedness approach based on modern tools. *Current Science* 112 (10): 2100–2105. https://doi.org/10.18520/cs/v112/i10/2100-2105.
Sharples, J. J., R. H. D. McRae, R. O. Weber, and A. M. Gill. 2009. A simple method for assessing fuel moisture content and fire danger rating. Pages 275–281 In *Interfacing Modelling and Simulation with Mathematical and Computational Sciences–proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation*, ed. R.S. Anderssen, R.D. Braddock, and L.T.H. Newham. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, 13–17 July 2009, Cairns, Australia.
Singh, S.. P.. 2014. Attributes of Himalayan forest ecosystems: they are not temperate forests. *Proceedings of the Indian National Science Academy* 80: 221–233. https://doi.org/10.16943/ptinsa/2014/v80i2/55103.
Skvarenina, J., J. Mindas, J. Holecy, and J. Tucek. 2003. Analysis of the natural and meteorological conditions during two largest forest fire events in the Slovak Paradise National Park. *Journal of Meteorology* 7: 167–171.
Steffens, R. 2016. When fire burns, are we prepared? *Wildfire* 25 (3): 8. https://www.iawfonline.org/wp-content/uploads/2018/02/25.3-May-June-2016-Wildfire-Web.pdf.
Suresh Babu, K. V., A. Roy, and P. R. Prasad. 2016. Forest fire risk modeling in Uttarakhand Himalaya using TERRA satellite datasets. *European Journal of remote Sensing* 49 (1): 381–395. https://doi.org/10.5721/EuJRS20164921.
Thakur, A. K., and D. Singh. 2014. Forest Fire Risk Zonation using geospatial techniques and analytic hierarchy process in Dehradun district, Uttarakhand, India. *Universal Journal of Environmental Research and Technology* 4 (2): 82–89.
Uttarakhand Forest Department. 2015. *Uttarakhand Forest Statistics 2014–2015*. Dehradun: Uttarakhand Forest Department. Available online at http://www.uafdc.in/Acts&Rules/Forest_Statistical_2014-15.pdf.
Verma, R. K., V. Pandro, S. N. Mishra, D. Raj, and A. J. K. Asaiya. 2019. Sal forest: a source of wild edible mushrooms for livelihood support to tribal people of Dindori District, Madhya Pradesh, India. *International Journal of Current Microbiology and Applied Sciences* 8 (1): 563–575. https://doi.org/10.20546/ijcmas.2019.801.063.
Wani, A., P. K. Joshi, O. Singh, and R. Pandey. 2012. Carbon sequestration potential of indian forestry land use systems—a review. *Nature and Science* 10: 78–85.
Wotton, B. M. 2009. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental and Ecological Statistics* 16: 107–131. https://doi.org/10.1007/s10651-007-0084-2.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.