App. Envi. Res. 43(4) (2021): 84-99

Applied Environmental Research

Journal homepage : http://www.tci-thaijo.org/index.php/aer

Fire Drivers Affecting Forest Fire Occurrences in the Tropical Mixed Broad-leaved Forests of Nepal

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Article History
Submitted: 24 November 2020/ Revision received: 4 July 2021/ Accepted: 12 July 2021/ Published online: 16 November 2021

Abstract

Forest fires triggered by various natural and anthropogenic drivers are increasing and threatening forest ecosystems across the globe. In Nepal, the high value Tropical Mixed Broad-leaved Forests are prone to fire caused by both natural and anthropogenic drivers. Thus, understanding fire drivers and their effect is important for the sustainable forest fire management. However, the preceding studies on forest specific fire drivers and their effect are limited. This research has identified the fire drivers and assessed their effect to fire occurrences in the Tropical Mixed Broad-leaved Forests of Nawalparasi District, Nepal. Fire drivers were identified and prioritized by participatory approaches. The fire incidences and burnt areas were obtained from the MODIS fire data (2001–2017). The results revealed altogether 20 drivers including eight natural and 12 anthropogenic. Based on the public perception and magnitude of forest fire, among the natural drivers, temperature, precipitation, forest fuel, aspect, elevation and slope were the major drivers. Likewise, among the anthropogenic drivers, forest distance from roads and settlements showed significant effect. The natural drivers, ambient temperature >30ºC and annual precipitation <2400 mm, revealed significant impacts on forest fire. Likewise, forests situated at lower elevation (<500 m), and southern and eastern aspects were highly vulnerable to fire. Considering anthropogenic drivers, forest lying within 500 m from the roads and settlements were highly vulnerable to fire. Among the forest types, the Hill Sal Forest was more affected. Future strategies should address the major fire drivers, construction of adequate fire lines and conservation ponds for the sustainable forest management.

Keywords: Fire drivers; Fire occurrence; Fire prone; Forest fuel; Forest fire management

Introduction

Forest fire has become one of the important environmental issues across the globe and is increasing over the period of time threatening forest ecosystems [1]. During 1981–2015, forest fire occurrences in the tropical rainforests of South America, Asia, Australia and Africa have been reported to be influenced by the various

https://doi.org/10.35762/AER.2021.43.4.7

fire drivers [2]. In Nepal, over the period of time, the forest fires have been reported to be increasing in the recent years [3]. Moreover, the climate change has also influenced the forest fire occurrence [4]. The forest fire is reported to be caused by both natural and anthropogenic drivers. The natural drivers include elevated atmospheric temperatures, low precipitations and accumulation of forest fuels [5–6]. Among the natural drivers, the climatic drivers are the prime drivers to alter the global fire occurrences [7]. In Nepal, the precipitation and temperature have been reported as the major climatic driver causing forest fire [8–9]. Likewise, forest fuels such as dead and live woody or non-woody biomass is another natural driver of forest fire [10]. Similarly, the topographic drivers like aspect, elevation and slope are also the important drivers for forest fire occurrences [11–12]. In India, the fuel load and early rainfall have been reported to have large influence on fire extent in the seasonally dry tropical forests landscape [13].

Along with the natural factors, anthropogenic factors are also the major drivers of the forest fire which cause 10 times more fire occurrences than the natural factors [14–16]. Around 80% of the world's forest fire is reported to be caused by the anthropogenic activities [17]. The most of the human-induced fires are caused due to carelessness or inattention by wood collectors, campers, hikers, travelers and garbage burners [14–15]. Moreover, anthropogenic factors, particularly settlements have been reported as the major drivers of forest fire [18–19]. Likewise, the forest distance from the road has been reported to be highly responsible factor causing forest fire [20]. Among the forests, the high value tropical rain forests across the globe are vulnerable to fire [21–22]. Nepal is no country of exception to the global phenomena. In Nepal, forest fire is increasing due to both natural and anthropogenic drivers making the high-value tropical forests vulnerable [23–26]. Thus, understanding the fire drivers and their effects to the spatial pattern of fire occurrence under different conditions is important for the sustainable forest fire management. Though there are several studies carried out in Nepal, they are mostly focused on fire risk, the site- specific information regarding the forest fire drivers and magnitude of the forest fire occurrences is limited [27–28]. Thus, this research was carried out with the aim of identifying the major forest fire drivers and assessing degree of their effect on forest fire occurrences in the tropical mixed broad-leaved forests of Nawalparasi Disctrict, Nepal. The findings would be helpful in developing strategies for reducing forest fire events and sustainable management of the forest.

Materials and methods

1) Study area

Nawalparasi District is located in Gandaki and Lumbini Provinces of Nepal with the geographical coordinates between 27°21’–27°47’ North latitude and 83°36’ to 84°35’ East longitude covering an area of 2,156 km^2, i.e. 1.5% area of the country (Figure 1). The district is situated in the mid-part of the east-west stretch of the country and is well known for its historical importance, as it encompasses "Ramgram" the maternal home place of the Buddha [24]. The longest stretch (99 km) of the national highway passes through this district.

Climatically, the district exhibits tropical, subtropical and lower temperate climate. The average maximum monthly temperature varies from 24.40±0.4ºC in January to 37.80±0.4ºC in May and minimum temperature from 8.30±0.4ºC in January to 25.70±0.2ºC in August with defined rainy season from June to September. Similarly, the area reveals the mean maximum annual rainfall 797.40±75.70 mm during July through May with minimum 19.50±5.70 mm during premonsoon, i.e. February to May; and negligible rainfall during post-monsoon period, i.e. October through January. The humidity varies from 58.10± 2.9% in April to 89.60±0.4% in December [29].

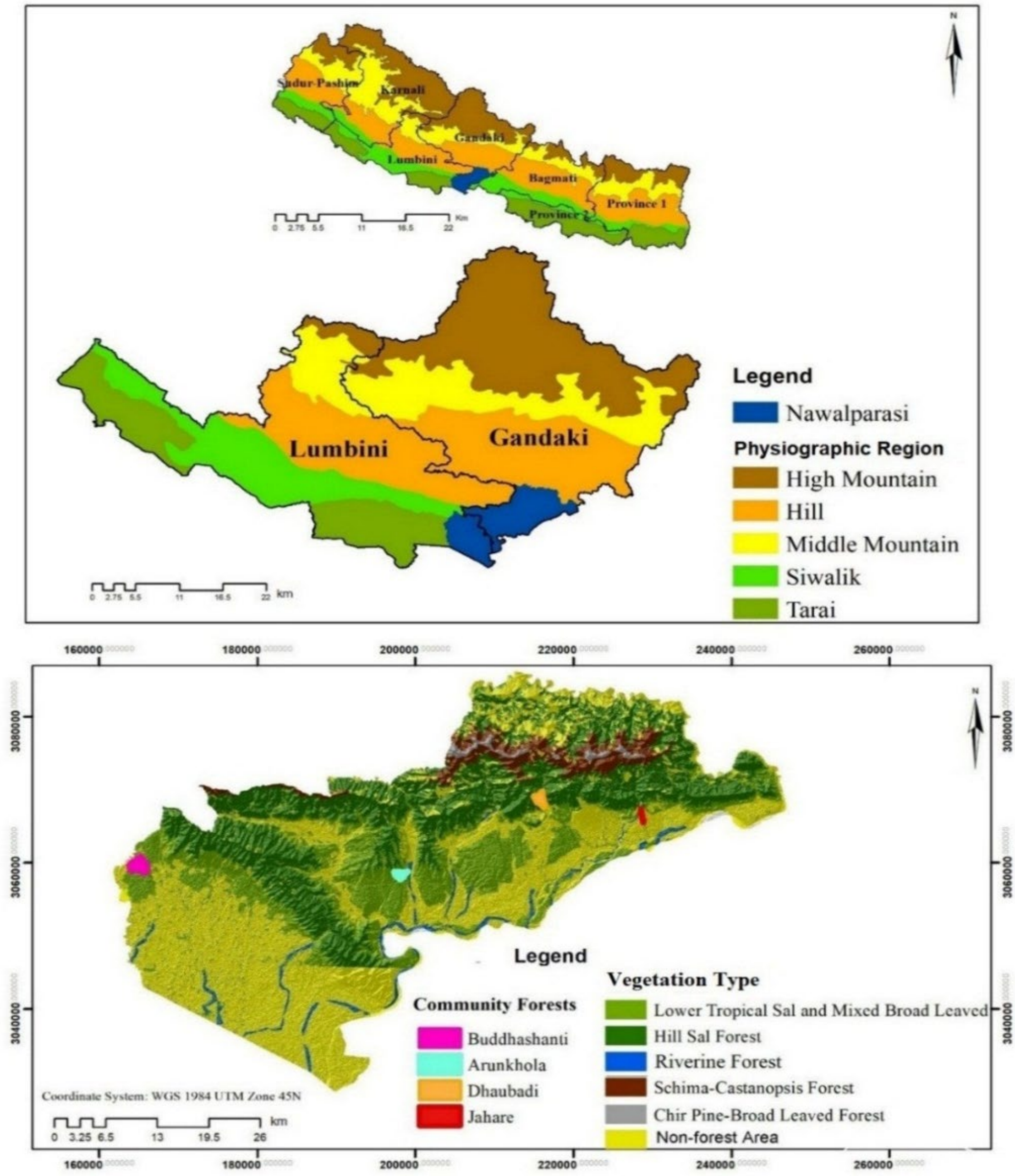

Figure 1 Location of study area showing sampled community forests.

Physiographically, the district constitutes Tarai, Siwalik and Middle-hills having elevation from 91 m to 1,916 m. Tarai region has a flat and fertile land covered with dense tropical and sub-tropical forests. The Siwalik region is a narrow belt of the fragile mountains having about 15–20 km width extending east-west with slope range from 15° to 45° with rugged terrain. The middle-hill is characterized with steep slopes and is nearly uninhabited. Topographically, 58.9% area of the district falls under <15%, 21.8% area under 15% to 30% and 19.2% area under >30% slope covering 61%, 18% and 21% forest areas, respectively. Similarly, by aspect, the east, south, north and west include 28.4%, 27.0%, 22.2% and 19.7% area, respectively). The forest covers 71% in <500 m elevation, 5% between 500–1000 m and 24% >1,000 m elevation (Table 1).

Table 1 Topographic features, forest area cover and forest types in the study area

Topographic features		Total area (km^2)	Forest area (km^2)	Forest types
Aspects	East	613.16	315.63	LTSMBF, HSF
	West	425.19	289.43	LTSMBF, HSF
	North	478.75	297.68	SCF, CBF
	South	582.11	227.69	LTSMBF, HSF
	Flat area	56.75	38.76	LTSMBF, RF
Total		**2,155.96**	**1,169.19**	
	< 15%	1,271.67	711.47	LTSMBF, RF
Slopes	15-30%	470.65	209.86	HSF
	>30%	413.64	247.86	SCF, CBF
Total		**2,155.96**	**1,169.19**	
	<500	1,582.17	830.28	LTSMBF, RF
Elevation (m)	500-1000	127.64	59.83	HSF
	>1000	446.14	279.08	HSF, SCF, CBF
Total		**2,155.95**	**1,169.19**	

Note: LTSMBF: Lower Tropical Sal Mixed Broad-leaved Forest, HSF: Hill Sal Forest, SCF: Schima-Castanopsis Forest, CBF: Chirpine Broad-leaf Forest, RF: Riverine Forest

2) Forest types

There are 35 types of forest in Nepal [30] and Nawalparasi District poses five types viz. Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), Hill Sal Forest (HSF), Riverine Forest (RF), Schima-Castanopsis Forest (SCF) and Chirpine Broad-leaf Forest (CBF) (Figure 1). In the Lower Tropical Sal Mixed Broad-leaved Forest, *Shorea robusta* is the dominant tree species with associated species like *Terminalia alata*, *Lagerstroemia parviflora*, *Syzygium cumini*, *Anogeissus latifolia*, *Buchanania latifolia*. This forest constitutes around 60–80% crown cover. Most of the trees are matured with having high biomass. Likewise, the HSF is also dominated by *Shorea robusta* with having *Terminalia alata*, *T. bellarica*, *Lagerstroemia parviflora*, *Anogeissus latifolius* and *Syzygium cuminia*s the associated species. In the RF, *Dalbergia sissoo* and *Acacia catechu* are the main tree species. In the SCF, *Schima wallichii* and *Castanopsis indica* are the major tree species. Similarly, the CBF includes *Pinus roxburghii* and *Quercus* spp. Among the forest types in the district, the present study has considered the LTSMBF, HSF and RF.

Demographically, the district constitutes 1,28,793 households and 6,43,508 populations with average household size 5.0, the sex ratio 89.4 and population density 298 km^{-2} [31]. In terms of road network, the district constitutes 1,853.49 km accessible roads including 1,060.29 km village road and 1,234.17 km all weather roads [32]. The road density of the district accounts to be 18.53 km per 100 km^2 areas with influencing population 347 per km against the national road density 9.14 km per 100 km^2 areas with influencing population 1,980 per km road [33].

Materials and methods

1) Data collection and analysis

1.1) Forest fire incidences and burnt area

The forest fire incidences and burnt areas from 2001 to 2017 were acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire data of the National Aeronautics and Space Administration (NASA). The shape files of the forest fire points and the date of fire occurrences were downloaded from https://firms.modaps.eosdis.nasa.gov/download/ [34]. The forest burnt area was estimated from the burnt-area product (MCD45A1 collection

5.1) downloaded from ftp://ba1.geog.umd.edu/Collection5/TIFF/Win18/ [34]. The shape-file of the forest types was obtained from the Department of Forests, Government of Nepal [30]. From the shape-file, burnt area was delineated using Arc-GIS (versions 10.1, ESRI). The accuracy of the burnt area was validated by direct field observation through measuring of forest fire burnt area and by comparing with the general accuracy statement of the MOD14 pro-duct performance.

1.2) Fire drivers of forest fire ignition

The forest fire drivers were identified by participatory approaches, i.e. Focus Group Discussion (FGD), Key Informant Interviews (KIIs) and Consultation Meetings. Altogether, 39 individuals and professionals participated in the FGDs and KIIs. The identified forest fire drivers were prioritized by scoring 0 to 4 using Likert 5-point scale method based on the magnitude of fire incidences and severity. The high scored (≥2.4) natural and anthropogenic drivers were selected for further analysis for their effect to forest fire occurrences.

1.3) Natural fire drivers

In order to assess the contribution of climatic drivers, the climate related data, i.e. temperature and rainfall, for the period of 2001 to 2017, were obtained from the Department of Hydrology and Meteorology, Government of Nepal. Likewise, topographic data were obtained from the Survey Department, Government of Nepal. The topographic features, i.e. aspect, slope and elevation were re-classified using the spatial join analysis tool of the ArcGIS (version 10.1). Aspect maps were re-classified into north, south, east and west for analyzing fire incidences. Similarly, for analyzing forest fire occurrences by slope, the slope maps were re-classified into three groups, i.e., <15%, 15–30% and >30% slopes and overlay by forest fire incidences. Likewise, for estimating forest fire occurrences by elevation, the elevation maps were re-classified into three groups, i.e. elevation <500 m, 500–1,000 m and >1,000 m overlay from forest fire incidences.

In order to estimate forest fuel (biomass), the different types of forests were stratified into three strata based on the forest types, namely Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest. From these forest strata, four community-managed forests, namely Budhasanti, Arunkhola, Dhaubadi and Jhahare were selected purposively based on fire vulnerability and topographic representation [24]. The selected community forests are representing each forest type under the Tropical Mixed Broad-leaved Forest in the study area. The vegetation present in each community forest were divided into the three major groups, i.e. tree (>5 cm DBH), sapling (1–5 cm DBH) and leaf-litter, herbs, grasses. Each stratum was considered as a block, and in each block, the sampling plots were allocated proportionately using the Arc-GIS software (version 10.1). The number of the sampling plots was determined based on the optimum allocation method (coefficient of variables) maintaining 1% sample intensity [35]. Total 92 sampling plots were designed for the estimation of biomass as forest fuel. In each sample plot, a circular plot having 12.56 m radius for tree (>5 cm DBH), 5.64 m radius nested plots for sapling (1–5 cm DBH), and 0.56 m radius nested plots for Leaf-litter, Herbs and Grasses (LHG) were established for measuring biomass [36]. The height and diameter at breast height (DBH) of trees and saplings were measured with the help of clinometer and diameter tape, respectively. Similarly, the LHG were destructively collected from the field and brought to the laboratory for estimating biomass. The total above ground biomass as the forest fuels was estimated using standard methods (37–39).

1.4) Biomass estimation

Above ground biomass

The Above Ground Tree (>5 cm DBH) Biomass (AGTB) was estimated according to Eq. 1 [37]. Above Ground Sapling (1–5 cm DBH) Biomass (AGSB) was estimated using Eq. 2 [38]. Similarly, the above ground Leaf-litter, Herbs and Grasses (LHG) biomass was determined by destructive method by collecting samples from the field according to Eq. 3 [39]. Finally, the total above ground biomass (TAGB) was estimated by summing up the AGTB, AGSB and LHG biomass (Eq. 4).

$$AGTB = 0.0509 * p\, D^2 H \quad \text{(Eq. 1)}$$

Where; AGTB = above ground tree biomass (kg), p = wood specific gravity (g cm^{-3}), D = tree diameter at breast height (cm) and H = tree height (m)

In this equation, D (cm) and H (m) values were obtained from the field and species-wise wood specific gravity, p (g cm^{-3}) values were obtained from the government and other sources [38, 40]

$$\text{Log (AGSB)} = a + b \log (D) \quad \text{(Eq. 2)}$$

Where; Log = natural log (dimensionless), AGSB = above-ground sapling biomass (kg), a = intercept of allometric relationship for saplings (dimensionless), b = slope of allometric relationship for saplings (dimensionless) and D = over bark DBH (cm)

The D (cm) over bark value was obtained from the field measurement within the 5.64 m radius circular plots. Species wise 'a' and 'b' values were used from the national allometric biomass [38, 40].

$$LHG = \frac{\text{Wfield}}{\text{A}} \times \frac{\text{Wsubsample dry}}{\text{Wsubsample wet}} \times \frac{1}{1000} \quad \text{(Eq. 3)}$$

Where; LHG = biomass of leaf-litter, herbs and grass (Mg/0.01km^2), W_{field} = weight of the wet LHG within an area A, A = area (km^2) $W_{sub\text{-}sample,\ dry}$ = weight of the oven-dried sub sample LHG (g) and $W_{sub\text{-}sample\ wet}$ = weight of the wet LHG (g) taken to laboratory

$$TAGB = AGTB + AGSB + LHG \quad \text{(Eq. 4)}$$

1.5) Anthropogenic drivers

The data pertaining anthropogenic drivers, i.e. road networks and settlements were obtained from the Survey Department, Government of Nepal [38]. The forest distance from roads and settlements were re-defined and buffered at 500 m, 500–1,000 m and >1,000 m by Arc-GIS process. The forest fire burnt area of each defined buffer zone was estimated by using Arc-GIS (version 10.1).

The statistical significance of each driver affecting forest fire occurrences were assessed using Generalized Linear Model (GLM) with Poisson error structure. The differences in burnt area in different forests were analyzed using ANOVA in the R-software Version 3.3.0 [41].

Results and discussion

1) Forest fire incidences and burnt area

In Nawalparasi District, the forest fire data from 2001 to 2017 revealed that every year, on average, 75 forest fire incidences occur burning 31.52 km^2 area. During the period, forest fire incidences showed a linear increasing trend ($p < 0.05$) with burnt area (Supplementary Material (SM) 1). The higher forest fire incidences were observed in 2004, 2008, 2009, 2010 and 2016. Among the forests, the Hill Sal Forest was found to be more vulnerable to fire demonstrating 57±6.84 annual forest fire incidences burning 23.54±7.02 km^2 area in compared to the Tropical Sal Mixed Broad-leaved Forest with 31±3.74 fire incidences and 10.25 ±3.14 km^2 burnt area, and Riverine Forest with 2±0.9 annual fire incidences and 0.06±0.01 km^2 burnt area (Table 2, SM 1). In Nepal, the previous study has reported around 3720 km^2 forest burnt during the period from 2001 to 2014 [8]. Globally, every year, about 345,000–464,000 km^2 forests have been reported to be burnt during the period from 1990s to 2000s [42]. In China, every year, about 810–1,250

km^2 forest was burnt in the last two decades (1997–2016) [43]. Similarly, in India, annually, around 37,300 km^2 forest has been reported to be affected by fires [44]. During 2004, 2009 and 2010, the highest number of fire incidences was occurred in the Tropical Dry-deciduous Forest in India [45].

2) Forest fire drivers

This study revealed 20 forest fire drivers with eight natural and 12 anthropogenic drivers (Figure 2). The natural drivers include temperature, rainfall, humidity, forest fuel (biomass), aspect, elevation, slope and lightening (Figure 2). The anthropogenic drivers include forest distance from roads and settlements, wildlife poaching, non-timber forest product (NTFP) collection, smoking beehives, fuel-wood collection, campfiring, cigarette butt, grass collection, throwing burning matches, trash fire and vehicular sparks, where distance from roads and settlements were found as the major one (Figure 2).

2.1) Natural fire drivers

The present study revealed that the forest fire occurrences vary with climatic conditions (temperature and rainfall) and topographic features (elevation, slope, aspect). With respect to temperature, the active fire season data from 2001 to 2017 showed higher forest fire occurrences. In 17 years, 1,178 fire incidences occurred burning 517.81 km^2 areas in the temperature regime >30.0 ºC (Table 3). Whereas, in the same period, comparatively low forest fire occurrence (364 incidences and 57.68 km^2 burnt areas) were found in the temperature regime <30.0ºC. This study revealed influence of higher temperature on forest fire occurrences, and was consistent with the preceding studies of Nepal [8–9, 27–28], Iran [20], India [21, 46] and China [22].

Table 2 Forest fire incidences and burnt area during 17 years (2001-2017) by forest types

Forest type	Cumulated forest-fire incidences (No.)	Cumulated burnt area (km^2)	Average forest fire incidences (No./year)	Average burnt area (km^2/year)	Burnt area per incidence (km^2)
Tropical Sal Mixed Broad-leaved Forest	533	174.27	31±3.74	10.25±3.14	0.33
Hill Sal Forest	970	400.23	57±6.84	23.54±7.02	0.41
Riverine Forest	39	0.99	2±0.9	0.06±0.01	0.03
Total	**1,542**	**575.49**	**90**	**33.85**	**0.77**

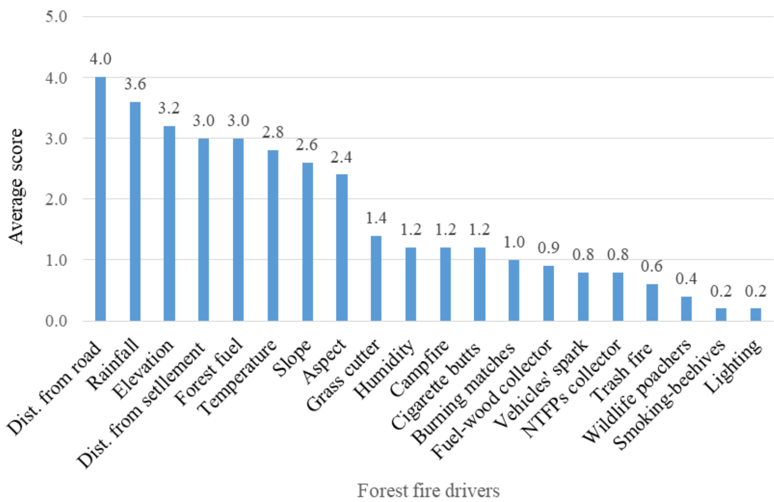

Figure 2 Average score of forest fire drivers in Nawalparasi District.

Table 3 Forest fire occurrences caused by natural drivers from 2001 to 2017

Fire drivers	Total accumulated forest-fire incidences (No.)	Total accumulated burnt area (km^2)	Average forest fire incidences (No./year)	Average burnt area (km^2/year)	Burnt area per incidence (km^2)
Temperature (ºC)					
<30.0	364	57.68	21±10.35	3.39±2.20	0.16
>30.0	1,178	517.81	69±14.39	30.46±9.53	0.44
Rainfall (mm)					
< 2,400	543	281.40	32±13.41	16.55±8.21	0.52
2,400-2,800	504	160.83	30±13.59	9.46±6.23	3.12
> 2,800	405	133.26	24±9.28	7.84±4.74	0.33
Aspect					
East	451	115.27	27±3.01	6.78±1.84	0.25
West	351	144.34	21±2.23	8.49±2.39	0.40
North	259	140.15	15±1.79	8.24±2.31	0.55
South	481	175.73	28±3.74	10.34±2.39	0.37
Slope (º)					
<15	495	184.76	29±4.29	10.87±2.99	0.37
15-30	280	310.98	16±1.88	18.29±5.00	1.14
>30	767	79.75	45±6.33	4.69±1.60	0.10
Elevation (m)					
<500	749	337.11	44±5.63	19.83±6.74	0.45
500-1000	562	184.24	33±4.96	10.84±3.56	0.33
>1000	231	54.14	14±2.97	3.19±1.13	0.23

In terms of rainfall, annual rainfall <2400 mm revealed higher annual fire occurrences, i.e. 543 incidences with 281.40 km^2 burnt area in 17 years accounting 32±13.41 annual incidences with 16.55±8.21 km^2 burnt areas. However, rainfall from 2400 to 2800 mm revealed 504 fire incidences with 160.83 km^2 burnt areas accounting 30±13.59 annual incidences with 9.46±6.23 km^2 burnt area and the rainfall value >2800 mm revealed lowest forest fire occurrences, i.e. 405 incidences with 133.26 km^2 burnt area in the same period accounting 24±9.28 annual incidences with 7.84± 4.74 km^2 burnt area (Table 3). The rainfall and forest fire occurrences revealed negative influence of higher rainfall on forest fire occurrences and was in agreement with the preceding studies carried out in the Nepal [8–9, 27–28], India [21, 47–48], China [22, 49], United States [50] and Iberian Peninsula [51].

2.2) Topographic drivers

The topographic features such as aspects, slope and elevation influence the forest fire occurrences. With respect to aspect, the significantly higher ($p < 0.01$) forest fire (28±3.74 annual incidences with 10.34±2.39 km^2 burnt area) were observed in the southern aspect (Table 3), which might be due to the longer exposure period to solar radiation, longer dry period and accumulation of dry fuels. This finding is similar with the various preceding studies carried out in the Tarai part of Nepal [52] and Klamath-Siskiyou region of Oregon and California [53]. Likewise, in the eastern aspect, 27±3.01 annual forest fire incidences with 6.78±1.84 km^2 burnt area were found. The eastern and northern aspects did not show significant variation in forest fire occurrences. In western aspect, 21± 2.23 annual forest fire incidences with 8.49± 2.39 km^2 burnt area were observed. In northern aspect, relatively less annual forest fire occurrences, i.e. 15±1.79 incidences with 8.24±2.31 km^2 burnt area, were found (Table 3) that may be due to shorter period of exposure to solar radiation, high moisture contents and accumulation of moist vegetation fuel.

With respect to slope, significantly higher ($p < 0.05$) forest fire occurrences were observed in between 15% and 30% with 16±1.88 annual fire incidences and 18.29±5.00 km^2 burnt area in compared to the >30% slope with 4.69±1.60 km^2 annual burnt area and 45±6.33 fire incidences (Table 3, SM 2), which may be due to accumulation of higher amounts of forest fuels in the vertical structure of forest stands as well as due to human interferences. Likewise, the forest with less than 15% slope revealed 29±4.29 annual fire incidences with 10.87±2.99 km^2 burnt areas. The forest with >30% slope showed significantly higher ($p < 0.01$), i.e. 45±6.33 annual forest fire incidences with 4.69±1.60 km^2 burnt area, which may be due to heterogeneity in the terrain structure (SM 3). Higher burnt area in 15–30% slope may be due higher fuel accumulation. Previous studies have also reported the higher burnt area in <30 % slope suggesting forest lying in the lower slope to be highly susceptible to fire [9, 52]. Similarly, in south-eastern region of Australia, forest fire has been reported to be highly influenced by topographic position [11].

With respect to elevation, forest lying in <500 m elevation showed significantly higher ($p < 0.01$) annual fire occurrence (44±5.63 annual incidences) as compared to 500–1000 m and >1000 m elevations (Table 3, SM 4). The higher fire incidences in the lower elevations might be due to the higher coverage of ground-level litter and vegetation. Likewise, 33±4.96 annual forest fire incidences were observed in the 500–1000 m elevation. In >1000 m elevation, least annual forest fire (14±2.97 incidences) were found. In terms of annual burnt area, the elevation <500 m showed significantly higher ($p < 0.05$) burnt area (19.83±6.74 km^2) than the >1000 m elevation with burnt area 3.19±1.13 km^2. This finding is in agreement with the study carried out in Nepal [9, 52] and other countries like Boreal Forest of China [18], India [21], and USA in Gila National Forest of New Mexico and Bitterroot National Forest of the south-western Montana [54].

The present findings pertaining topographic features (elevation, aspect and slope) are similar with the various previous studies from Kangra region of Western Himalaya, India [55], during 1984–2004 periods, the elevation, aspect, slope and ruggedness were reported as the major fire causing topographic factors in Gila Wilderness and surrounding Gila National Forest of New Mexico, USA [54], and in the Santa Catalina Mountains of the south-eastern Arizona [56], and in the Eucalyptus forest and rain-forest of Tasmania, Australia [57].

2.3) Forest fuel

The forest fire incidences and burnt areas vary with the characteristics of forest fuel (biomass) in the forests. Worldwide fire regime has been reported to be influenced by fuel dynamics due to climate change [4]. The present results showed higher annual forest fire occurrences (48±5.90 incidences with 22.64±6.42 km^2 burnt area) in the Hill Sal Forest (HSF) having 158.02 Mg 0.01 km^{-2} biomass (fuel) (Table 4) that may be attributed to the higher amounts of fine fuel on the ground cover (leaf-litter, shrubs, herbs and grasses), trees and climbers making the forest more vulnerable to fire. In the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF) having 284.58 Mg 0.01 km^{-2} biomass, 26±4.00 annual fire incidences with 8.83±2.88 km^2 burnt areas were observed. The lesser forest fire occurrences in the LTSMBF as compared to the HSF may be due to the less fire prone matured trees and lower density of ground vegetation like shrubs, grasses and leaf-litters. Similarly, in the Riverine Forest having 104.41

Mg 0.01 km^{-2} biomasses, least forest fire occurrences (2±0.50 annual fire incidences with 0.05± 0.02 km^2 burnt areas) were observed (Table 4). This Riverine Forest is com-posed of almost even aged tree species with lower vertical vegetation structure. The Hill Sal Forest has found to be highly fire sensitive. This study is in agreement with the various preceding studies carried out in Nepal [9, 52] and Closed Broad-leaved Deciduous Forest and Closed Mixed Broad-leaved Forest in India [46], Boreal Forest of China [58–60], in northeast Iberian Peninsula [61] the southern Rockies of Canada [62] and Quebec's Southern Boreal Forest [63].

2.4) Anthropogenic fire drivers

The anthropogenic drivers are important drivers causing forest fire. Around 80% of the world's forest fire is caused by anthropogenic activities [17]. This study revealed forest distance from roads and settlements are the major anthropogenic drivers for forest fire. The forests lying within 500 m distance from the roads demonstrated higher (69%) annual fire occurrence, i.e. 61±7.27 incidences with 81% (27.30±7.43 km^2) burnt area (Table 5, SM 5). The higher forest fires incidences in the forest lying nearby roads may be due to accumulation of the fine fuel (bushes, shrubs, herbs and grasses) and human activities such as throwing burning matchesticks and cigarette butts by the passenger, grass cutters, campfires, trash fire and exhaust sparks from the passing vehicles. The forest lying between 500 and 1000 m from the roads revealed 21% annual forest fire occurrence, i.e. 20±2.51 fire incidences with 12% (4.18±1.18 km^2) burnt areas. Likewise, the forest lying farther than 1,000 m from the roads revealed 10% annual forest fire occurrence, i.e.10±1.38 fire incidences with 7% (2.37±0.63 km^2) burnt area. The relatively less forest fire occurrences in distant forest may be due to inaccessibility of the place.

In terms of settlements distance, the forest lying within 500 m from the settlements showed higher, i.e. 42% (14.42±4.42 km^2) annual burnt area in 25±3.20 fire incidences. The forest lying between 500 and 1000 m from the settlements showed lowest, i.e. 32% (8.89±2.22 km^2) burnt area in 31± 3.55 fire incidences. Similarly, the forest lying farther than 1000 m distance from the settlements showed 26% (10.55±2.90 km^2) burnt area in 35± 3.90 fire incidences (Table 5, SM 6). The higher burnt areas in the nearby (<500 m) forests from the settlements may be attributed to the relatively high combustible forest fuels like shrubs, herbs, grass and higher human activities like grass cutters, herders, wildlife poachers and NTFPs collectors.

Table 4 Forest fuel and forest fire occurrences (2014–2016) by forest types

Forest types	Forest fuel (Mg/0.01 km^2)	Forest fire (Incidences/year)	Burnt area (km^2/year)
Lower Tropical Sal Mixed Broad-leaved Forest	285	26 ± 4.00	8.83 ± 2.88
Hill Sal Forest	158	48 ± 5.90	22.64 ± 6.42
Riverine Forest	104	2 ± 0. 0.05 ± 0.0250	0.05 ± 0.02

Table 5 Forest fire occurrences caused by anthropogenic drivers during 2001–2017

Anthropogenic drivers	Accumulated forest-fire incidences (No.)	Accumulated burnt area (km^2)	Average forest fire incidences (No./year)	Average burnt area (km^2/year)	Burnt area per incidence (km^2)
Distance from roads					
<500 m	1,044	464.14	61±7.27	27.30±7.43	0.45
500-1000	332	71.05	20±2.51	4.18±1.18	0.21
>1000	166	40.30	10±1.38	2.37±0.63	0.24
Distance from settlemen					
<500 m	421	245.06	25±3.20	14.42±4.42	0.58
500-1000	553	151.10	31±3.55	8.89±2.22	0.29
>1000	568	179.33	35±3.90	10.55±2.90	0.30

These findings are similar with the preceding studies carried out in the Tarai region of Nepal which have attributed human activities to be the reason of increase in forest fire [9, 26, 52]. In the Mid-hills, around 40% of forest fires are reported to be caused by human activities [64]. Similarly, the anthropogenic activities such as recreation (hiking, camping and hunting), settlements, roads and industry were found as the major forest fire drivers across the globe [14]. The human-induced forest fire has increased in the recent years threatening the Tropical Forests across the world [16]. For instance; anthropogenic factors like forest distance from roads and settlements have been reported to be the major drivers for forest fire in north Iran [65], Portugal [66], Canada [67–68], California and Kentucky [69–70], and Southern California [71]. Similarly, significant positive correlation between road densities and forest fire has been reported in Alaskan forest of the Mediterranean Europe [72–73] and the Chinese Boreal Forest [18, 49]. Moreover, the human-induced forest fire has increased in the Boreal landscape forest of Sweden since the last decades [73].

Conclusion

In Nawalparasi District of Nepal, the high value Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest are vulnerable to forest fire mainly due the natural drivers and human-induced drivers. The higher temperature and lower annual precipitation showed increased forest fire occurrences. The forest areas lying in the lower elevation, and facing south and east aspects are more fire vulnerable. Similarly, forests near from the roads and settlements are highly vulnerable to fire. Among the forest types, the Hill Sal Forest is highly vulnerable to fire. Therefore, to protect the high-value tropical forest of Nawalparasi District and other similar forests in the country, the forest management strategies should emphasize addressing the major drivers causing forest fire, and prevention and control strategies for forest fire occurrences in the area. In this connection, provisions of stringent legal tools and effective awareness program will help in controlling the forest fire mediated by anthropogenic activities. In addition, sustainable extraction of accumulated forest fuels before the active fire season, maintaining greenery, construction of adequate fire lines and ponds can help reduce forest fires in the country.

Acknowledgements

The authors are grateful to the Central Department of Environmental Science, Institute of Science and Technology, Tribhuvan University for providing opportunity for carrying the research. The authors sincerely acknowledge the Nepal Academy of Science and Technology for the partial financial support. The authors are also thankful to the Division Forest Office of Nawalparasi District, local communities, fire watcher groups and stakeholders for their generous support and cooperation during the field study. The authors would like to acknowledge Mr. Prakash Sirmal for his contribution in preparing the GIS maps.

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