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

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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. 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
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 District, 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 km², 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 pre-monsoon, 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].
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 subtropical 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 (km²) | Forest area (km²) | 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 cumini* as 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 km² [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 km² areas with influencing population 347 per km against the national road density 9.14 km per 100 km² 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 ArcGIS (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. 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) Bio-
mass (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).

\[ \text{AGTB} = 0.0509 \times p D^2 H \] (Eq. 1)

Where; \( \text{AGTB} = \) 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]

\[ \log(\text{AGSB}) = a + b \log(D) \] (Eq. 2)

Where; \( \log = \) natural log (dimensionless), \( \text{AGSB} = \) 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].

\[ \text{LHG} = \frac{W_{\text{field}}}{A} \times \frac{W_{\text{subsample dry}}}{W_{\text{subsample wet}}} \times \frac{1}{1000} \] (Eq. 3)

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

\[ \text{TAGB} = \text{AGTB} + \text{AGSB} + \text{LHG} \] (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
km² forest was burnt in the last two decades (1997–2016) [43]. Similarly, in India, annually, around 37,300 km² 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 km² 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 km² 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 (km²) | Average forest fire incidences (No./year) | Average burnt area (km²/year) | Burnt area per incidence (km²) |
|------------------------------|----------------------------------------|----------------------------|------------------------------------------|-------------------------------|-------------------------------|
| 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 (km²) | Average forest fire incidences (No./year) | Average burnt area (km²/year) | Burnt area per incidence (km²) |
|--------------|-----------------------------------------------|----------------------------------|-----------------------------------------|-------------------------------|-------------------------------|
| 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 km² burnt area in 17 years accounting 32±13.41 annual incidences with 16.55±8.21 km² burnt areas. However, rainfall from 2400 to 2800 mm revealed 504 fire incidences with 160.83 km² burnt areas accounting 30±13.59 annual incidences with 9.46±6.23 km² burnt area and the rainfall value >2800 mm revealed lowest forest fire occurrences, i.e. 405 incidences with 133.26 km² burnt area in the same period accounting 24±9.28 annual incidences with 7.84±4.74 km² 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 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 km² 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 km² burnt area were observed. In northern

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 km² 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 km² 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 km² burnt area were observed. In northern
aspect, relatively less annual forest fire occurrences, i.e. 15±1.79 incidences with 8.24±2.31 km² 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 km² burnt area in compared to the >30% slope with 4.69±1.60 km² 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 km² 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 km² 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].

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 and Bitterroot National Forest of the south-western Montana [54].

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 km² 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 km² 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 composed 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 matchsticks 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 ± 0.05                      | 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 settlements |                                          |                                     |                                         |                                      |                                     |
| <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.

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References

[1] Moreira, F., Viedam, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., ..., Bilgili, E. Landscape-wildfire interactions in South Europe: Implications for landscape to management to minimize the hazards. Journal of Environmental Management, 2011, 92, 2389–2402.

[2] Juárez-Orozco, S.M., Siebe, C., Fernández, D. Causes and effects of forest fires in tropical rainforests: A bibliometric approach. Tropical Conservation Science, 2017, 10, 1–14.

[3] Ministry of Environment. National Adaptation Programme of Action to Climate Change. Ministry of Environment (MoE),
Government of Nepal (GoN), Kathmandu, Nepal, 2010.

[4] Intergovernmental Panel on Climate Change. Climate Change Synthesis Report 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, 2014, 151.

[5] Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., Stocks, B.J. Future area burned in Canada. Climatic Change, 2005, 72, 1–16.

[6] Holden, Z.A., Morgan, P., Evans, J.S. A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. Forest Ecology and Management, 2009, 258, 2399–2406.

[7] Bowman, D.M., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., ..., Pyne, S.J. Fire in the earth system. Science, 2009, 324, 481–484.

[8] Khanal, S. Wildfire trends in Nepal based on Moderate Resolution Imaging Spectroradiometer (MODIS) burnt-area data. Banko Janakari, 2015, 25(1), 76–79.

[9] Matin, M.A., Chitale, V.S., Murthy, M.S.R., Uddin, K., Bajracharya, B., Pradhan, S. Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information system and historical fire data. International Journal of Wildland Fire, 2017, 26, 276–286.

[10] Sandberg, D.V., Ottmar, R.D., Cushon, G.H. Characterizing fuels in the 21st century. International Journal of Wildland Fire, 2001, 1, 381–387.

[11] Bradstock, R.A., Hammill, K.A., Collins, L., Price, O. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology, 2010, 25, 607–619.

[12] Estes, B. L., Knapp, E.E., Skinner, C.N., Miller, J.D., Preiser, H.K. Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, & USA. Ecosphere, 2017, 5, e01794.

[13] Mondal N., Sukumar R. Fires in seasonally dry tropical forest: Testing the varying constraint hypothesis across a regional rainfall gradient, PLoS ONE, 2016, 11(7), e0159691.

[14] Bowman, D.M., Balch, J., Artaxo, P., Bond, W.J., Cochrane, M.A., D’Antonio, C.M. ..., Whittaker, R. The human dimension of fire regimes on Earth. Journal of Biogeography, 2011, 38, 2223–2236.

[15] Gonzalez-Olabarria, J.R., Mola-Yudegom, B., Coll, L. Different factors for different causes: Analysis of the spatial aggregations of fire ignitions in Catalonia (Spain). Risk Analysis, 2015, 35, 1197–1209.

[16] Lewis, S.L., Edwards, D.P., Galbraith, D. Increasing human dominance of tropical forests. Science, 2015, 349, 827–832.

[17] Food and Agriculture Organization. Fire Management–Global Assessment 2006. Food and Agriculture Organization (FAO) of the United Nations, Forestry Paper 151, Rome, Italy, 2017.

[18] Guo, F., Innes, L.J., Wang, G., Ma, X., Sun, L., Hu, H., Su, Z. Historic distribution and driving factors of human-caused fires in the Chinese Boreal Forest between 1972 and 2005. Journal of Plant Ecology, 2015, 8, 480–490.

[19] Guo, F., Zhang, L., Jin, S., Tigabu, M., Su, Z., Wang, W. Modeling anthropogenic fire occurrence in the Boreal Forest of China using logistic regression and random forests. Forests, 2016, 7, 250.
[20] Abdi, O., Kamkar, B., Shirvani, Z., Jaime, A., de Silva, T., Manfred, F.B. Spatial-statistical analysis of factors determining forest Fires: A case study from Golestan, Northeast Iran, Geomatics Natural Hazards and Risk, 2018, 9, 267–280.

[21] Ahmad, F., Goparaju, L., Qayum, A., Quli, S.M.S. Forest fire trend analysis and effect of environmental parameters: A study in Jharkhand State of India using geospatial technology. World Scientific News, 2017, 90, 31–50.

[22] Chen, F., Niu, S., Tong, X., Zhao, J., Sun, Y., He, T. The impact of precipitation regimes on forest fires in Yunnan Province, southwest China. The Scientific World Journal, 2014, 326782, 9.

[23] Bajracharya, K.M. Forest fire situation in Nepal. International Forest Fire News, 2002, 26, 84–86.

[24] Division Forest Office. District Forest Five Years Management Plan (DFMP) during the 2013–2017. Division Forest Office (DFO), Nawalparasi, Nepal, 2013.

[25] Department of Forest Research and Survey. State of Nepal's forests. Forest resource assessment Nepal project report 2015, Kathmandu: Department of Forest Research and Survey (DFRS), Government of Nepal, 2015.

[26] Kunwar, R.M., Khaling, S. Forest fire in Nepal: causes and community management interventions. International Forest Fire News, 2006, 34, 46–54.

[27] Bhujel, K.B., Maskey, R., Gautam, A.P., Mandal, R.A. Effect of climatic variables on fire incidence and burnt area in the Tropical Forests in Nepal. e-planet, 2017, 15, 1, 21–28.

[28] Bhujel, K.B., Maskey, R., Gautam, A.P., Mandal, R.A. Wildfire dynamics and occasional precipitation during active fire season in Tropical Lowland of Nepal.

[29] Department of Hydrology and Meteorology. Study of climate and climatic variation over Nepal report 2015. Kathmandu: Department of Hydrology and Meteorology (DHM), Ministry of Science and Technology Government of Nepal, 2015.

[30] Department of Forests. Forest and vegetation types of Nepal. Document Series No.105, Tree Improvement and Silviculture Component, Kathmandu: Department of Forests (DoF), Government of Nepal (GoN), 2002.

[31] Central Bureau of Statistics. National population and housing census report 2011. Kathmandu: Central Bureau of Statistics (CBS), National Planning Commision Secretariat, Government of Nepal, 2011.

[32] Ministry of Federal Affairs and Local Development. Statistics of local road network report 2016. Kathmandu: Ministry of Federal Affairs and Local Development (MOFALD), Government of Nepal, 2016.

[33] Department of Roads. Statistics strategic of road network SSRN (2015/016) report. Kathmandu: Department of Roads (DoR), Ministry of Physical Infrastructure and Transport, Nepal, 2018.

[34] National Aeronautics and Space Administration. MODIS fire and thermal anomalies: General information about the MODIS fire (thermal anomalies) and burned area products. National Aeronautics and Space Administration (NASA). 2017. [Online] Available from: http://modis-fire.umd.edu/ [Accessed 30 June 2017].

[35] MacDicken, K.G. A Guide to monitoring carbon storage in forestry and agroforestry projects. Arlington, Virginia VA: Winrock International Institute for Agricultural Development, United States, 1997.
[36] Department of Forests. Community forest resource inventory guideline 2003. Kathmandu: Community Forests Division, Department of Forests (DoF), Nepal, 2003.

[37] Chave, J.C., Andalo, S., Brown, M.A., Cairns, J.Q., Chambers, D., Eamus, H., Lister, F. Tree allometry and improved estimation of carbon stocks and balance in Tropical Forests. Oecologia, 2005, 145, 87–99.

[38] Tamrakar, P.R. Biomass and volume tables with species description for community forest management report 2000. Kathmandu: Ministry of Forests and Soil Conservation, Government of Nepal, 2000.

[39] Subedi, B.P., Pandey, S.S., Pandey, A., Rana, E.B., Bhattari, S., Banskota, T.R., ..., Tamarkar, R. Forest carbon stock measurement: Guidelines for measuring carbon stocks in community-managed forests. 1st Edition. Kathmandu Nepal: Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Federation of Community Forest Users, Nepal (FECONFUN), International Centre for Integrated Mountain Development (ICIMOD), Norwegian Agency for Development Cooperation (NORAD), 2010, 1–69.

[40] Sharma, E.R., Pukkala, T. Volume equations and biomass prediction of forest trees of Nepal. Kathmandu: Forest Survey and Statistics Division, Nepal, publication No. 47, 1990.

[41] R. CORE TEAM. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2016. [Online] Available from https://www.R-project.org/ [Accessed 20 February 2016].

[42] Randerson, J.T., Chen, Y., van der Werf, G.R., Rogers, B.M., Morton, D.C. Global burned area and biomass burning emissions from small fires. Journal of Geophysical Research Biogeosciences, 2012, 117(G4), 4012.

[43] Chen, A., Tang, R., Mao, J., Yue, C., Li, X., Gao, M., ..., Piao. Spatiotemporal dynamics of ecosystem fires and biomass burning-induced carbon emissions in China over the past two decades. Geography and Sustainability, 2020, 1, 47–58.

[44] Satendra, Kaushik, A.D. Forest fire disaster management report 2014. New Delhi: National Institute of Disaster Management, Ministry of Home Affairs, India, 2014.

[45] Srivastava, P., Garg, A. Forest fire in India: Regional and temporal analysis. Journal of Tropical Forest Science, 2013, 25(2), 228–239.

[46] Badarinath, K.V.S., Vadrevu, K.P. Carbon dioxide emissions from forest biomass burning in India. Global Environmental Research, 2011, 15, 45–52.

[47] Mondal, A., Khare, D., Kundu, S. Spatial and temporal analysis of rainfall and temperature trend of India. Theoretical and Applied Climatology, 2015, 122, 143–158.

[48] Prasad, V.K., Badarinath, K.V.S., Eaturu, A. Biophysical and anthropogenic controls of forest fires in the Deccan Plateau, India. Journal of Environmental Management, 2008, 86(1), 1–13.

[49] Liu, Z., Yang, J., Chang, Y., Weisberg, P.J., He, H.S. Spatial patterns and drivers of fire occurrence and its future trend under climate change in a Boreal Forest of northeast China. Global Change Biology, 2012, 18, 2041–2056.

[50] Charles, W.L., Steven, M. Q. Relationships of fire and precipitation regimes in temperate forests of the eastern United States. Earth Interactions, 2012, 16 (11), 1–15.
[51] Pausas, J.G. Changes in fire and climate in the Eastern Iberian Peninsula (Mediterranean Basin). Climate Change, 2004, 63, 337–350.

[52] Parajuli, A., Gautam, A.P., Sharma, S.P., Bhujel, K.B., Sharma, G, Thapa, P.B., Bist, B.S., Poudel, S. Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. Geomatics Natural Hazards and Risk, 2020, 11(1), 2569–2586.

[53] Alexander, J.D., Seavy, N.E., Ralph, C.J., Hogoboom, B. Vegetation and topographical correlates of fire severity from two fires in the Klamath-Siskiyou region of Oregon and California. International Journal of Wildland Fire, 2006, 15, 237–245.

[54] Holden, Z.A., Jolly, W.M. Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. Forest Ecology and Management, 2011, 262, 2133–2141.

[55] Kumar, S., Meenakshi, B., Vandana, G.D., Kumar, A. Identifying triggers for forest fire and assessing fire susceptibility of forests in Indian Western Himalaya using geo-spatial techniques. Natural Hazards, 2015, 78, 203–217.

[56] Iniguez, J.M., Swetnam, T.W., Yool, S.R. Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology Management, 2008, 256, 295–303.

[57] Wood, S.W., Murphy, B.P., Bowman, D.M.J.S. Firescape ecology: How topography determines the contrasting distribution of fire and rain forest in the south-west of the Tasmanian Wilderness World Heritage Area. Journal of Biogeography, 2011, 38, 1807–1820.

[58] Chen, H., Chang, Y., Hu, Y.M. Load of forest surface dead fuel in Huzhong area of Daxing’anling Mountains and relevant affecting factors. Chinese Journal of Ecology, 2008, 27, 50–55.

[59] Liu, Z., Chang, Y., Chen, H., Zhou, R., Jing, G., Zhang, H., Zhang, C. Spatial pattern of land surface dead combustible fuel load in Huzhong forest area in Great Xing’an Mountains. Chinese Journal of Applied Ecology, 2008, 19, 487–493.

[60] Wu, Z.E., He, H.S., Yang, J., Liu, Z.H., Liang, Y. Relative effects of climatic and local factors on fire occurrence in boreal forest landscapes of northeastern China. The Science of Total Environment, 2014, 493, 472–480.

[61] Alvarez, A., Gracia, M., Castellnou, M., Retana, J. Variables that influence changes in fire severity and their relationship with changes between surface and crown fires in a wind-driven wildfire. Forest Science, 2013, 59, 139–150.

[62] Johnson, E., Miyanishi, K., Bridge, S. Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. Conservation Biology, 2001, 15, 1554–1557.

[63] Bergeron, Y., Gauthier, S., Flannigan, M., Kafka, V. Fire-regimes at the transition between Mixed Wood and Coniferous Boreal Forest in North-western Quebec. Ecology, 2004, 85, 1916–1932.

[64] Karkee, T.B. Forest fire-causes and its relationship with economic variables. Nepal Journal of Forestry, 1991, 6(2), 75–80.

[65] Adab, H., Kannih, K.D., Solaimani, K. Modeling forest fire risk in the northeast of Iran using Remote Sensing and GIS techniques. Natural Hazards, 2013, 65, 1723–1743.

[66] Catry, F.X., Damasceno, P., Silva, J.S. Spatial distribution patterns of wildfire ig-
nitions in Portugal. 2007. [Online] Available from: http://www.eufirelab.org/toolbox2/library/upload/2380.pdf, 2019-02.

[67] Wallenius, T.H., Kuuluvainen, T., Vanha-Majamaa, I. Fire history in relation to site type and vegetation in Vienansalo Wilderness in Eastern Fennoscandia, Russia. Canadian Journal of Forest Research, 2004, 34, 1400–1409.

[68] Gralewicz, N.J., Nelson, T.A., Wulder, M.A. Spatial and temporal patterns of wildfire ignitions in Canada from 1980 to 2006. International Journal of Wildland Fire, 2012, 230–242.

[69] Romero-Calcerrada, R., Novillo, C.J., Millington, J.D.A., Gomez-Jimenez, I. GIS analysis of spatial patterns of human caused wildfire ignition risk in the SW of Madrid (Central Spain). Landscape Ecology, 2008, 23, 341–354.

[70] Maingi, K.J., Henry, M.C. Factors influencing wildfire occurrence and distribution in eastern Kentucky, USA. International Journal of Wildland Fire, 2007, 16(1), 23–33.

[71] Syphard, A.D., Radeloff, V.C., Keuler, N.S., Taylor, R.S., Hawbaker, T.J., Stewart, S.I., Clayton, M.K. Predicting spatial patterns of fire on a southern California Landscape. International Journal of Wildland Fire, 2008, 17, 602–613.

[72] Kasischke, E.S., Rupp, T.S., Verbyla, D.L. Fire trends in the alaskan boreal forest region. In: Alaska’s Changing Boreal Forest. Chapin FS (Ed). Oxford University Press, New York, 2006, 285–301.

[73] Oliveira, S., Oehler, F., San-Miguel-Ayanz, J., Camia, A., Pereira, J.M.C. Modeling spatial patterns of fire occurrence using multiple regression and random forest. Forest Ecology Management, 2012, 275, 117–129.

[74] Niklasson, M., Granström, A. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology, 2000, 81(6), 1484–1499.