Journal of Tropical Forest Science 38(1): 48–64 (2026)
https://doi.org/10.26525/jtfs2026.38.1.48
ISSN: 0128-1283, eISSN: 2521-9847

SPATIAL AND TEMPORAL DISTRIBUTION OF WILDFIRES IN NEPAL HIMALAYAS: A GEOSPATIAL ANALYSIS OF VISIBLE INFRARED IMAGING RADIOMETER SUITE (VIIRS) SATELLITE DATA

Budha PB[1,*], Bhattarai DR[2], Sapkota RP[1], Dhital NB[3], Pokhrel CP[4], Khadka UR[1] & Rijal K[1]

[1]*Central Department of Environmental Science, Tribhuvan University, Kathmandu, Nepal*
[2]*Nepal Environmental Research Institute, Kathmandu, Nepal*
[3]*Department of Environmental Science, Patan Multiple Campus, Tribhuvan University, Nepal*
[4]*Central Department of Botany, Tribhuvan University, Kathmandu, Nepal*

**padambudha88@gmail.com*

Submitted March 2025; accepted July 2025

Wildfires are common in Nepal during the pre-monsoon period (March to May), causing significant damage to forests and wildlife. Understanding their occurrence and distribution is crucial for effective forest management. This study analyses wildfire data from 2012 to 2021, obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS). The active fire product of VIIRS was filtered to identify wildfires in forests, grasslands, and other wooded areas, and these incidents were geospatially analysed across Gandaki Province in the Nepal Himalaya. Wildfire locations were overlaid with environmental and topographic variables, including aspect, elevation, slope, land use and land cover, moisture, soil type, road proximity, and stream density. Nepal recorded 230,077 wildfire occurrences over the decade, with 16,860 in Gandaki Province. Nearly 75% of these fires occurred in March (21%) and April (54%). About 80% of incidents took place below 2000 m elevation, 55% on south to southeast-facing slopes, and 71% on slopes between 10° and 50°. Additionally, 73% of fires were within 500 m of a road, and 77% occurred in areas with drainage densities between 1 km/km^2 and 2 km/km^2. Wildfire frequency reached up to 4 events per km^2 in areas with population densities above 500 people per km^2, which is nearly four times higher than in sparsely populated regions. This study presents the first comprehensive spatiotemporal analysis of wildfire patterns in Gandaki Province using a decade of satellite data integrated with topographic, ecological, and human factors. The findings provide critical insight into wildfire risk areas and influencing factors, offering a data-driven foundation for risk assessment and targeted forest management. The results have direct implications for developing region-specific wildfire prevention and mitigation strategies, particularly in the vulnerable mid-hill landscapes of the Nepal Himalaya.

Keywords: Forest fires, Gandaki Basin, wildfire distribution, forest management

INTRODUCTION

In regions where dry biomass accumulates in large quantities and dry seasons are prolonged, there is a high risk of wildfires, whether they occur naturally or caused by humans (Rouet-Leduc et al. 2021, Williams et al. 2019). Wildfires occur in forests, grasslands, or other wooded lands that are either undeveloped or poorly developed for human settlement (Masri et al. 2021, Viedma et al. 2018). These wildfire-prone areas range from tropical forests to high-altitude grasslands, and their distribution and susceptibility are shaped by the availability of biomass and various conditioning factors (Krawchuk et al. 2009). Conditioning factors include climate, topography, and human activities (Ahmad et al. 2018). Climate change and global warming have significantly influenced wildfire occurrences, with an observed 10% global increase in fire incidents during the second half of the 20th century (Mouillot & Field 2005). This increase, which varies by region, is largely attributed to deforestation in tropical areas (Doerr & Santín 2016). Projections for the future suggest a 29% increase in fire-prone areas by the end of the 21st century, along with an extended fire season (Senande-Rivera et al. 2022). These trends reflect the continuation of fire season lengthening and larger burnt areas observed in the past

(Jolly et al. 2015). The increasing frequency of wildfires and longer fire periods would have a significant impact on biodiversity (Köster et al. 2021, Ré et al. 2021), disrupt water cycles (Mansilha et al. 2019), degrade air quality (Jaffe et al. 2020), increase health risks (Chen et al. 2021, Ye et al. 2022), and accelerate glacier melt (Aubry-Wake et al. 2022). The severity of these impacts is exacerbated by their interconnectedness. Besides, initiatives of forest restorations have failed due to wildfires (Fawzi et al. 2020).

Given that wildfires affect ecological, socio-economic, and climatic conditions, studying their occurrence, patterns, and future projections is crucial (Corona-Núñez & Campo 2023, Senande-Rivera et al. 2025). Remote sensing tools, especially multi-spectral satellites, play a key role in fire detection and mapping burnt areas. The accuracy of fire detection depends on the spatial and temporal resolution of these tools. Coarse resolutions result in less precise data regarding the location and extent of fires. Two key instruments for detecting fires are the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS), both of which provide global fire data coverage. MODIS, aboard the Terra and Aqua satellites launched in 1999 and 2002, respectively, includes 36 spectral bands, with wavelengths ranging from 0.62 µm to 14.39 µm. It has spatial resolutions ranging from 250 m to 1000 m, with 2 bands at 250 m, 5 at 500 m, and 29 at 1 km (Justice et al. 2002a). Active fire detection is carried out using the 4 µm (T4) and 11 µm (T11) channels of MODIS (Justicec et al., 2002b). On the other hand, VIIRS, located on the Suomi National Polar-orbiting Partnership (NPP) satellite (launched in 2011) and NOAA-20 (launched in 2017), operates with 22 spectral bands ranging from 0.41 µm to 12.5 µm. The primary channel for active fire detection is the moderate-resolution M13 channel, covering the spectral range between 3.973 µm and 4.128 µm (Csiszar et al. 2014). For VIIRS's 375 m spatial resolution, the I4 channel (3.55 to 3.93 µm) is the main tool for fire detection (Schroeder et al. 2014). Both MODIS and VIIRS can detect fire hotspots with radii of approximately 500 m and 187 m, respectively.

In the Himalayas, multiple studies have utilised MODIS data to track fires (Ahmad et al. 2018, Bhujel et al. 2021, Bhusal & Mandal 2020, Matin et al. 2017, Parajuli et al. 2020). For instance, MODIS data indicates that about 83% of fire incidents in Nepal occur between March and April, with almost no fire incidents between July and October (Reddy et al. 2019). A total of 353,745 fire incidents were recorded in Nepal from 2000 to 2016, resulting in an annual average of 22,109 fire occurrences (Bhujel et al. 2017a). Burnt area analysis conducted from MODIS data between 2001 and 2014 estimated that the average burnt area in Nepal was around 372,000 ha (Khanal 2015). In community forests of the western Terai region, most fires were found to be human-induced, whether through negligence, deliberation, or accident (Kunwar & Khaling 2006). Fires in tropical areas with limited biomass and less conducive conditioning factors also suggest significant human involvement in their ignition (Krawchuk et al. 2009). March, April, and May, characterized by high temperatures and little rainfall, create ideal conditions for the ignition of accumulated biomass (Bhujel et al. 2017b).

However, previous studies in Nepal have mostly relied on MODIS data, which has a coarser spatial resolution compared to VIIRS. The VIIRS instrument provides a finer spatial resolution of 375 m, which allows for better fire detection, particularly in smaller areas. Moreover, VIIRS has improved night-time fire detection capabilities (Schroeder et al. 2014). VIIRS is found to detect fires 8.28 times more frequently than MODIS (Vadrevu et al. 2022). While earlier studies focused exclusively on MODIS data, the current research employs VIIRS active fire data products to offer a more accurate analysis. VIIRS fire products are categorized into three confidence levels: low (0–29%), nominal (30–79%), and high (80–100%) (Schroeder & Giglio 2018). For this study, VIIRS fire products with nominal and high confidence levels were used to examine wildfire distribution in Gandaki Province, Nepal. The goal is to derive information about wildfire distribution at various spatial scales and identify how different conditioning factors, such as topography, land cover, and anthropogenic activities, influence wildfire occurrence. The results will provide insights into the relationship between wildfires and these various factors, using the more precise VIIRS data.

By focusing on VIIRS data, the study aims to offer more accurate and timely information about wildfire patterns in Nepal, which could help inform future wildfire management and prevention efforts in the region. The study is particularly important as the impacts of wildfires, influenced by climate change and human activities, continue to affect ecosystems, communities, and economies globally. Understanding the factors that contribute to wildfire occurrences, as well as the effectiveness of different detection technologies, is essential for mitigating these impacts and adapting to the evolving threat of wildfires in the face of changing climatic conditions.

MATERIALS AND METHODS

Study area

The study area is Gandaki Province of Nepal located in central part of the country (Figure 1), with an extent ranging from 82.877240º E to 85.197903º E longitudes and from 27.437748º N to 29.331285 º N latitudes. The elevation range is from 89 m to 8146 m as per the DEM used in the assessment. The highest altitude is the height of Dhaulagiri Mountain in this province which is 8167 m which is slightly higher than that shown by DEM and the difference can be attributed to the spatial resolution of the DEM. As there is an increase in altitude northwards, a high degree of variation in the climate can be observed in south-north transects. Southern latitudes have lower elevations and bear tropical to sub-tropical climates. There are places with temperate climates in the mid-altitudes of 2000 m to 3000 m. Similarly, altitudes above 3000 m to 5000 m have sub-alpine and alpine climates, which are very cold in the winter season. The areas above 5000 m are covered with perennial glaciers and snow. The Lumle of Kaski district in this province had the highest rainfall in Nepal. Forest Research and Technical Centre (FRTC) had proposed 69 vegetation types for Nepal of which 54 are forest types based on dominant tree species, 6 are shrub lands (other wooded lands),

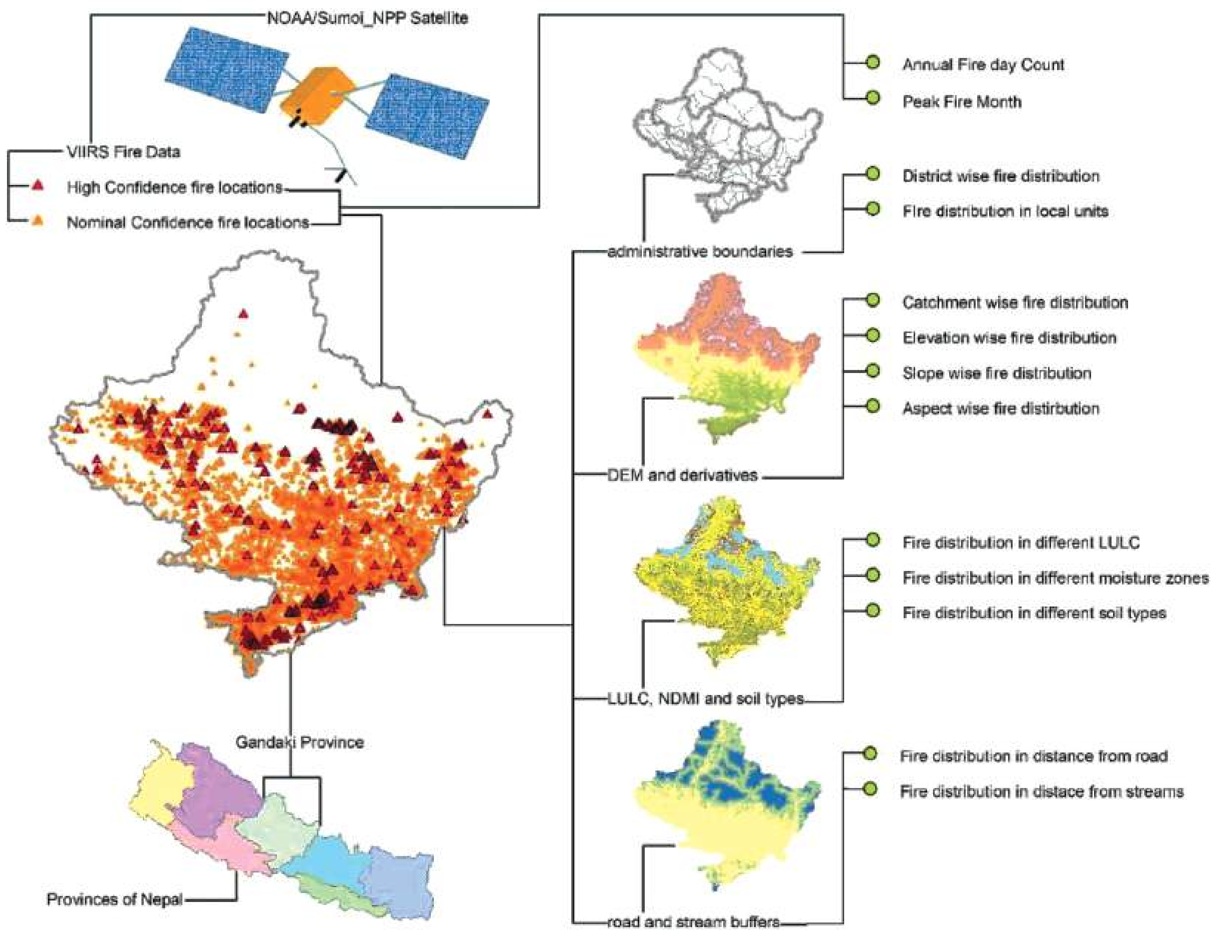

Figure 1 Map of study area showing Gandaki Province in Nepal and the data analysis process

and the remaining 9 are types of grasslands (FRTC 2021). These vegetation types vary with the change in altitude. For example in the Modi Watershed of this Province *Schima wallichii* is among the most frequent at a lower elevation zone of 1000–1800 m, *Rhus succedanea,* and *Rhododendron arboreum* were dominant at the middle elevation zone of 2000–2800 m, and *Betula utulis* was the most frequent in the upper elevation zone of 3000–3800 m (Khanal 2020).

Data sources and types

Datasets compatible to work in geographic information system (GIS) environment, such as administrative boundaries, fire products, digital elevation models, land use land cover, population density, and road network were used in this assessment. The characteristics and sources of those data are summarized in Table 1. Fire locations and information of conditioning factors were related by geospatial analysis in GIS.

Data processing

The raw data were processed to derive specific factors necessary for analysing fire distribution in the study area. VIIRS fire products classify fire pixels into various confidence levels: low (0–29%), nominal (30–79%), and high (80–100%) (Schroeder & Giglio 2018). For this study, only nominal and high-confidence fire pixels were selected. Nominal pixels, free of sunlight contamination, show strong (>15 Kelvin)

Table 1 The data types, their formats, and sources used in this research

	Data Type and data format	Data Source
1	Administrative Boundaries (vector format)	Department of Survey (DoS), Government of Nepal
2	VIIRS active fire products (csv file)	https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms
3	The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (30 m) (raster format)	https://search.earthdata.nasa.gov/search?q=ASTER
4	Land use and land cover (LULC) map (30 m) (raster format)	The International Centre for Integrated Mountain Development (ICIMOD) (http://rds.icimod.org/Home/DataDetail?metadataId=1972729)
5	Road network data (vector format)	The Humanitarian Data Exchange (HDX) platform of the United Nations Office for the Coordination of Humanitarian Affairs (https://data.humdata.org/dataset/nepal-road-network)
6	Population data (tabular data)	The Preliminary Report of National Population 2021, the National Statistics Office (NSO), formerly Central Bureau of Statistics (CBS), Government of Nepal
7	Satellite imageries of Landsat 8 date 2018 October-November (30 m) Paths 141, 142, 143 and rows 40 and 41 (raster format)	The United States Geological Survey (USGS) EarthExplorer.
8	The soil information: Soil and Terrain Database (SOTER) for Nepal (vector format)	The International Soil Reference and Information Centre (ISRIC) Data Hub (https://data.isric.org/geonetwork/srv/api/records/896e61f8-811a-40f9-a859-ee3b6b069733#:~:text=The%20SOTER_Nepal%20database%20provides%20generalized,are%20no%20measured%20soil%20data)

temperature increase, while high-confidence fire pixels are associated with intense heat day or nighttime data (Schroeder & Giglio 2018). Fire pixels located in forests, grasslands, and other wooded lands were retained, while those in settlements and agricultural lands were excluded. LULC data with a 30 m resolution, sourced from the ICIMOD Regional Database System, helped isolate these wild vegetation areas, ensuring the analysis focused solely on wildfires.

Topographic variables were generated from a 30 m Digital Elevation Model (DEM) obtained from ASTER DEM. Elevation, aspect, and slope were derived using spatial analysis in GIS (Bolstad & Stowe 1994), allowing for the examination of topographic variations influencing wildfire occurrence. Watershed characteristics, such as sub-watersheds, were also delineated from the DEM (Datta et al. 2022), and a stream network was created to calculate drainage density (Lu et al. 2023). The distribution of fire events was then analysed within sub-watersheds and at various buffer distances from streams.

In order to assess vegetation water content, the Normalized Difference Moisture Index (NDMI) was calculated using Landsat 8's Near Infrared (NIR) and Shortwave Infrared (SWIR) 1 bands (Ji et al. 2011). NDMI, calculated as (NIR-SWIR) / (NIR+SWIR), ranges from -1 (indicating water stress) to +1 (indicating waterlogging). Additionally, buffering was applied to roads to create distance-from-road maps, using break values of 250 m, 500 m, 1000 m, 2500 m, and 5000 m. Population data from the National Statistics Office (NSO) and shapefiles of municipalities were used to calculate population density at the local administrative level.

All variables were converted into raster format with a 30 m resolution. These variables were classified into appropriate categories, and fire counts for each category were calculated by extracting raster values. Finally, wildfire density was determined by dividing the fire incidents within each variable category by the area of wild vegetation. This density index allowed for the comparison of categories with high and low fire incidences, independent of their respective areas.

RESULTS AND DISCUSSIONS

Wildfire incidences in Nepal

Figure 2 shows the distribution of fire events across seven provinces of Nepal. Between 2012 and 2021, a total of 230,077 forest fire incidents were recorded using both nominal and high-confidence VIIRS data. In comparison, the previous decade (2003–2013) saw 12,269 fire incidents recorded by MODIS (Matin et al. 2017). This indicates that the number of wildfires detected by VIIRS is nearly 18 times greater than those reported by MODIS. The distribution of these fires reveals a higher occurrence in Lumbini Province, while Gandaki Province reported the fewest. Of the total fire occurrences, 4046 were categorised as high-confidence events. The distribution of these high-confidence incidents was particularly high in western Nepal. Sudurpaschim and Karnali Provinces recorded 976 and 865 high-confidence fire events, respectively, while Gandaki Province had the fewest. Additionally, wildfire events were more concentrated in the forests of the Chure area, especially within the protected regions of the Tarai and Siwaliks. These areas, with undisturbed wild vegetation and a high accumulation of dry, combustible plant biomass, were particularly susceptible to fires (Singh et al. 2020).

Wildfire incidences in Gandaki Province

The selection of wildfires in Gandaki Province was made for a detailed distribution analysis. Gandaki Province comprises 11 districts, with the highest vegetation coverage observed in Gorkha District, followed by Mustang, Baglung, and Myagdi districts. In contrast, Parbat District showed the lowest vegetation coverage, followed by Syangja, Manang, and Nawalpur districts. A total of 16,860 wildfires were recorded in the province, encompassing both nominal and high-confidence fire events. Table 2 presents the distribution of these events.

The highest number of fire incidents occurred in Nawalpur and Tanahu districts, with fire incident counts of 5581 and 3050, respectively. These districts also exhibited

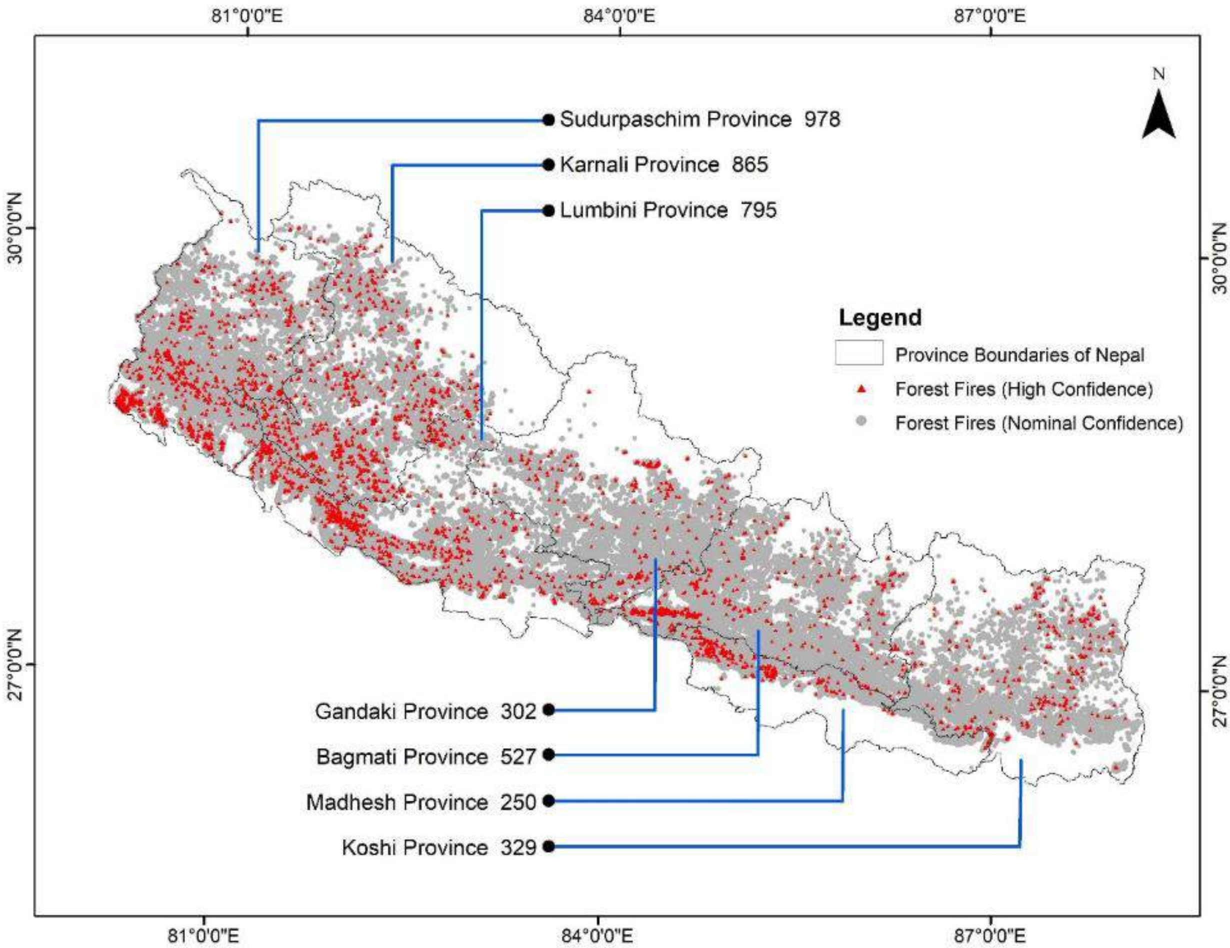

Figure 2 Distribution of wildfire events detected by VIIRS in Nepal (from 2012 to 2021) where value represent high confidence fire counts

Table 2 Fire distribution in districts of Gandaki Province

District	Fire Count (Year 2012–2021)	Wilderness Area (km^2)	Fire Density (number km^{-2})	Peak Fire Month	Average Annual Fire Days
Baglung	405	1483.603	0.2730	April	2
Gorkha	2839	2142.190	1.3253	April	30
Kaski	871	1362.965	0.6390	April	5
Lamjung	1313	1289.099	1.0185	April	14
Manang	334	840.502	0.3974	January	1
Mustang	116	1682.530	0.0689	January	1
Myagdi	1175	1470.035	0.7993	March	10
Nawalpur	5581	973.495	5.7330	April	32
Parbat	299	393.730	0.7594	April	1
Syangja	877	735.788	1.1919	April	3
Tanahu	3050	1160.876	2.6273	April	11

the highest fire densities, at 5.73 and 2.63, respectively. Mustang District reported the lowest number of fire incidents, with only 116 fires, followed by Parbat with 299 fire incidents. While Mustang had the lowest fire density, Parbat's fire density did not follow this trend. Other districts with lower fire densities included Baglung and Manang.

Peak fire month

Figure 3 illustrates the monthly total wildfire occurrences for Gandaki Prorince. It was found that April was the peak month for fire incidents, accounting for more than 50% of all recorded fires. This matches to the earlier studies by Matin et al. (2017) where over 43% of the forests affected by wildfires were impacted in April (Mishra et al. 2023). In Himalayas, fire season spans from March to early June (Mina et al. 2023, Mishra et al. 2023, Pragya et al. 2023, Parajuli et al. 2023). The month of March also saw a notable increase in fire incidents, following April. From July to November, fire occurrences were minimal compared to the rest of the year. Most districts followed the same monthly fire pattern, with exceptions in Manang and Mustang, where January was the peak month. Myagdi saw its peak in March. Additionally, districts like Kaski, Manang, Parbat, and Syangja had no fire incidents from June to September, which corresponds to the summer monsoon season in Nepal. The fire data from VIIRS showed April as the peak month, followed by March, which was consistent with MODIS data (Mishra et al. 2023). The year 2015 saw a peak in December, while 2018 and 2019 experienced higher fire incidents in March.

Total annual fire day trend

Figure 4 shows the annual fire day counts in Gandaki Province. The year 2016 had the highest number of fire days, with 138 days, while 2015 had the fewest, with only 59 fire days. This aligns with MODIS data analysis, which also identified 2016 as the year with the most forest fires (Mishra et al. 2023). On average, from 2012 to 2021, Gandaki Province experienced 110 fire days out of 365 each year. Additionally, a slight increasing trend in the number of fire days per year was observed from 2012 to 2021. This 110-day fire season is consistent with the fire season length in the western Himalayas (Bar et al. 2021).

District-specific data (Table 2) reveals that Nawalpur had the highest average fire day count at 32 days per year, followed by Gorkha with 30 days. Lamjung and Tanahu had 14 and 11 fire days, respectively. Parbat, Manang, and Mustang had the lowest fire day count, averaging just one fire day per year. The maximum fire day counts were experienced by Nawalpur in 2015 with

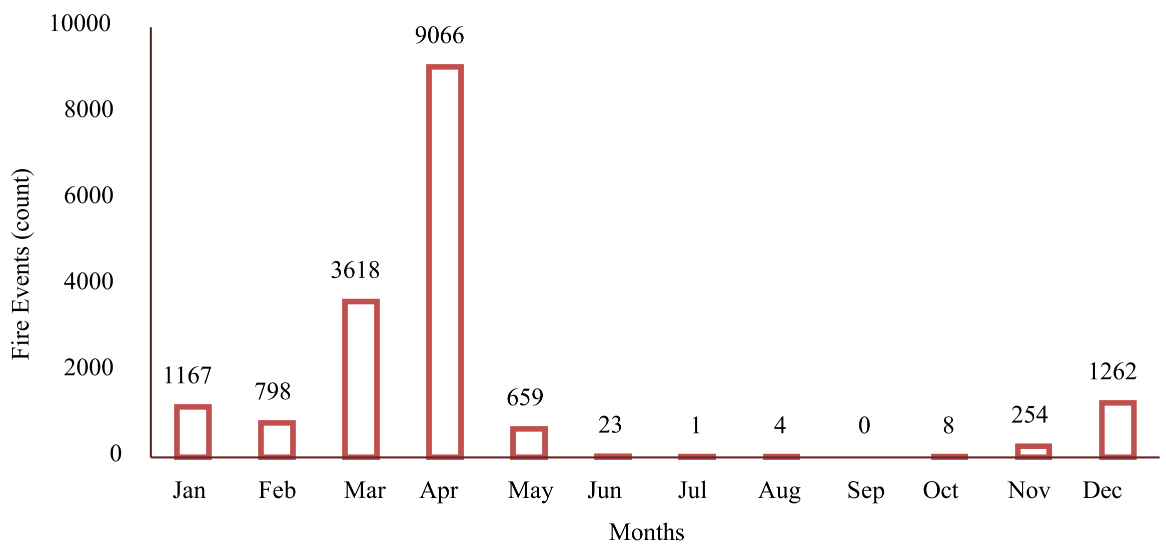

Figure 3 Month wise decadal fire occurrence in Gandaki Province for the period of 2012 to 2021

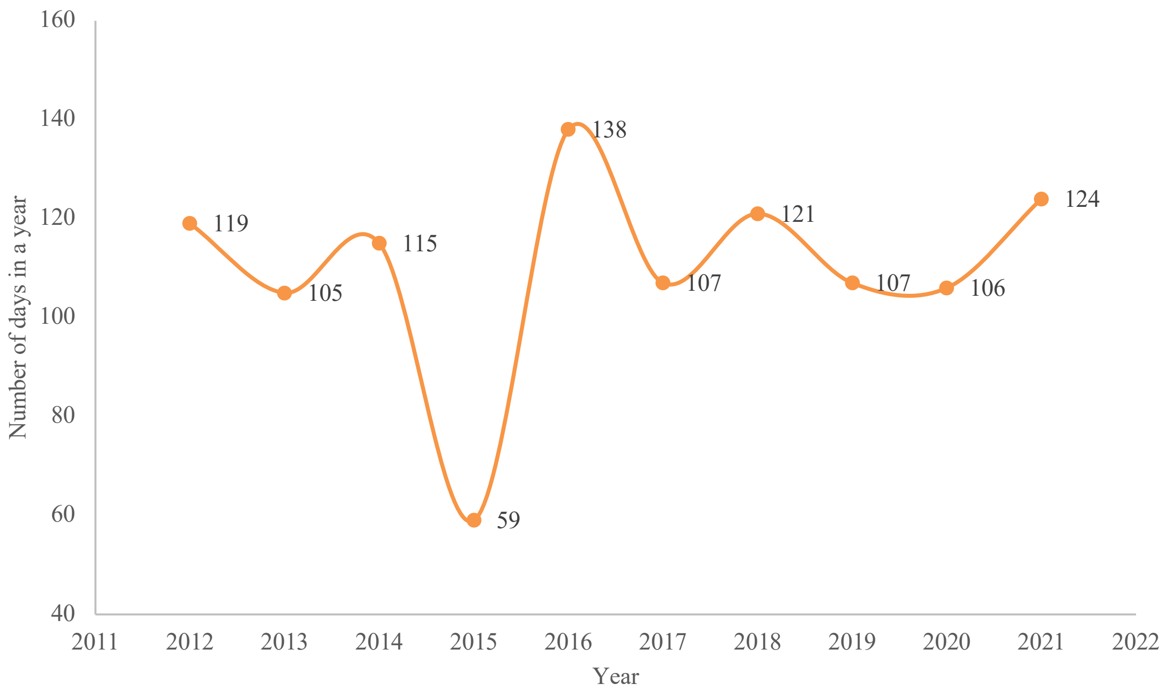

Figure 4 Total number of fire days per year for the period of 2012 to 2021 in Gandaki Province

54 days. Such prolonged fire seasons—up to two months—pose risks, especially if fires occur in a continuous temporal pattern. While traditionally, people might know only the general fire season, this detailed data helps fire managers understand both the specific fire season and the number of fire days per month, allowing for better preparation and management of fire risks.

Wildfire count in the local administrative units

Figure 5 displays the fire count for local units, while Table 3 presents the wildfire density estimated for each unit. Both should be reviewed together, as district codes and local unit codes (arranged alphabetically) need to be matched to understand both fire occurrence and density. The fire count has exceeded 1000 in local units such as Binayee-Tribeni, Gaidakot, and Madhyabindu in Nawalpur district. In contrast, the lowest fire counts are observed in the local units of Manang and Mustang, with Lomanthang having zero fires and Varagung-Muktichhetra, Muktinath, and Narphu of Manang having very few at 2 fire counts. During the data period, 7 fire events were recorded in Chame of Manang, as well as in Dalome and Gharapjhong of Mustang, while Tarakhola of Baglung district had fewer than 10 fires.

Nawalpur district's local units exhibit the highest fire density in Gandaki Province, with densities ranging from 7 to 10 fires per km^2 of wild vegetation. These high-density local units include Binayee-Tribeni, Devchuli, Gaidakot, Madhyabindu, and the Nawalpur portion of Chitwan National Park. In Tanahu district, the first four local units have densities of around 3 to 4 fires per km^2. In Gorkha district, Sahid Lakhan and Gandaki show high fire densities, while local units near Thasang in Mustang have almost no fire activity. Given the administrative changes in Nepal post-federalism in 2015, the present study is crucial for forest managers as it reflects the current local administrative boundaries.

Wildfire distribution in the sub-basins of Gandaki River Basin

For this study, 18 sub-basins were identified in Gandaki Province (Figure 6). The largest of these is Kaligandaki, which originates at the northern border of Mustang district and meets the Narayani River at Devghat. Other major watersheds in the province include Budhigandaki and Trishuli,

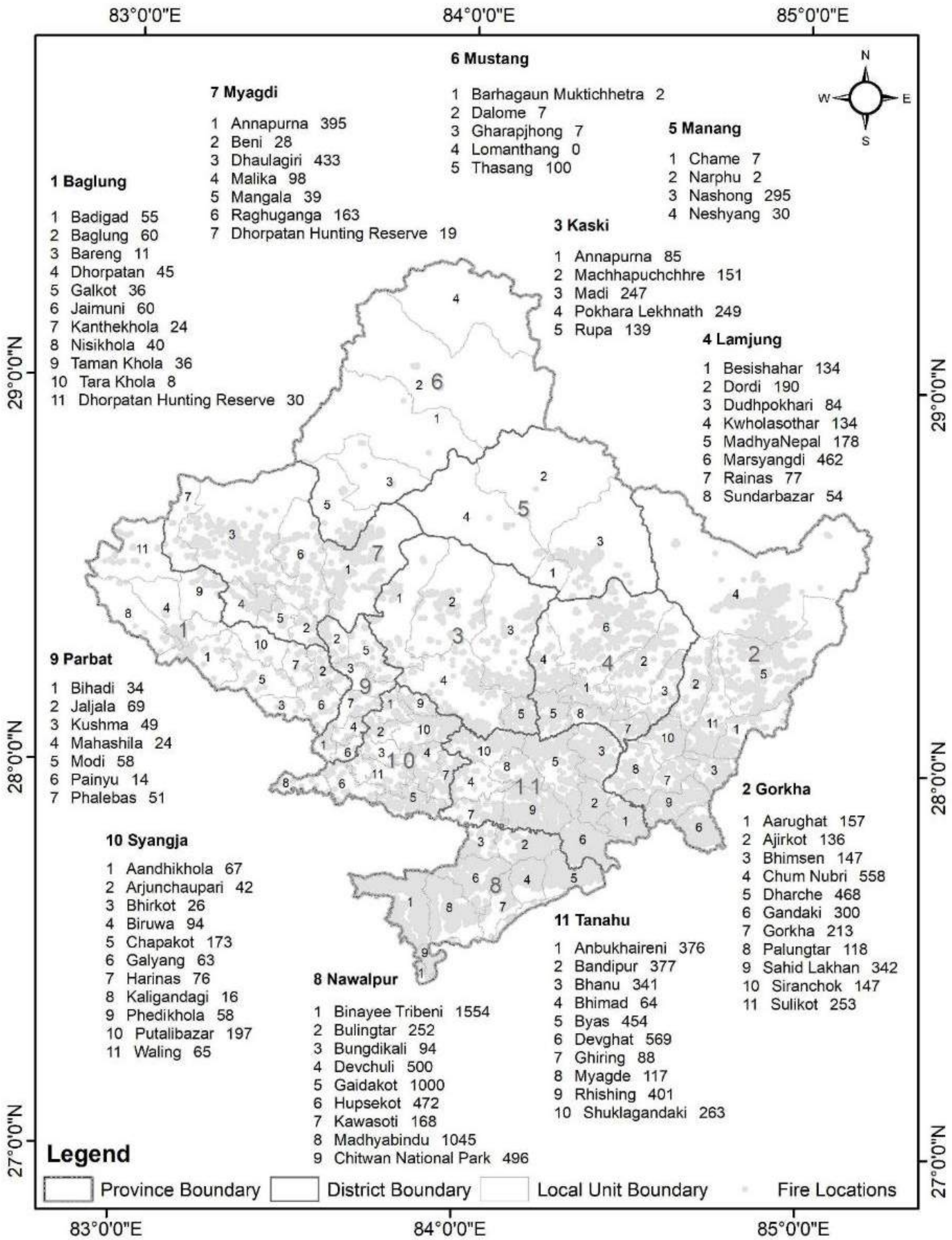

Figure 5 Fire count for each of the local units of Gandaki Province (the name of local units in the figure is preceded by their codes and followed by the fire counts)

Table 3 Fire density (fire-count/km^2) for each local units of Gandaki Province (names of each local units as per the codes illustrated in Figure 5)

	Codes 1 to 11 for local units of each district										
Districts	1	2	3	4	5	6	7	8	9	10	11
Baglung	0.408	1.082	0.187	0.247	0.215	0.764	0.410	0.213	0.239	0.067	0.104
Gorkha	1.285	0.870	2.215	0.797	1.007	3.609	2.440	1.283	3.156	1.590	1.496
Kaski	0.330	0.410	0.601	0.955	2.105						
Lamjung	1.534	0.749	0.657	0.852	2.339	0.937	1.480	1.313			
Manang	0.153	0.011	0.811	0.119							
Mustang	0.006	0.012	0.037	0.000	0.566						
Myagdi	1.087	0.679	0.898	0.835	0.601	0.577	0.160				
Nawalpur	7.141	2.241	1.350	7.188	8.780	3.396	4.602	7.076	7.458		
Parbat	1.053	1.119	0.821	0.746	0.488	0.466	0.864				
Syangja	1.991	1.821	1.445	1.400	1.396	1.208	1.187	0.731	0.681	0.509	0.295
Tanahu	4.899	4.117	3.821	3.301	2.532	2.327	2.246	1.280	0.942	0.709	

The blank cells represent unavailability of local units: as for example Kaski have only 5 local units, 6–11 are blanks

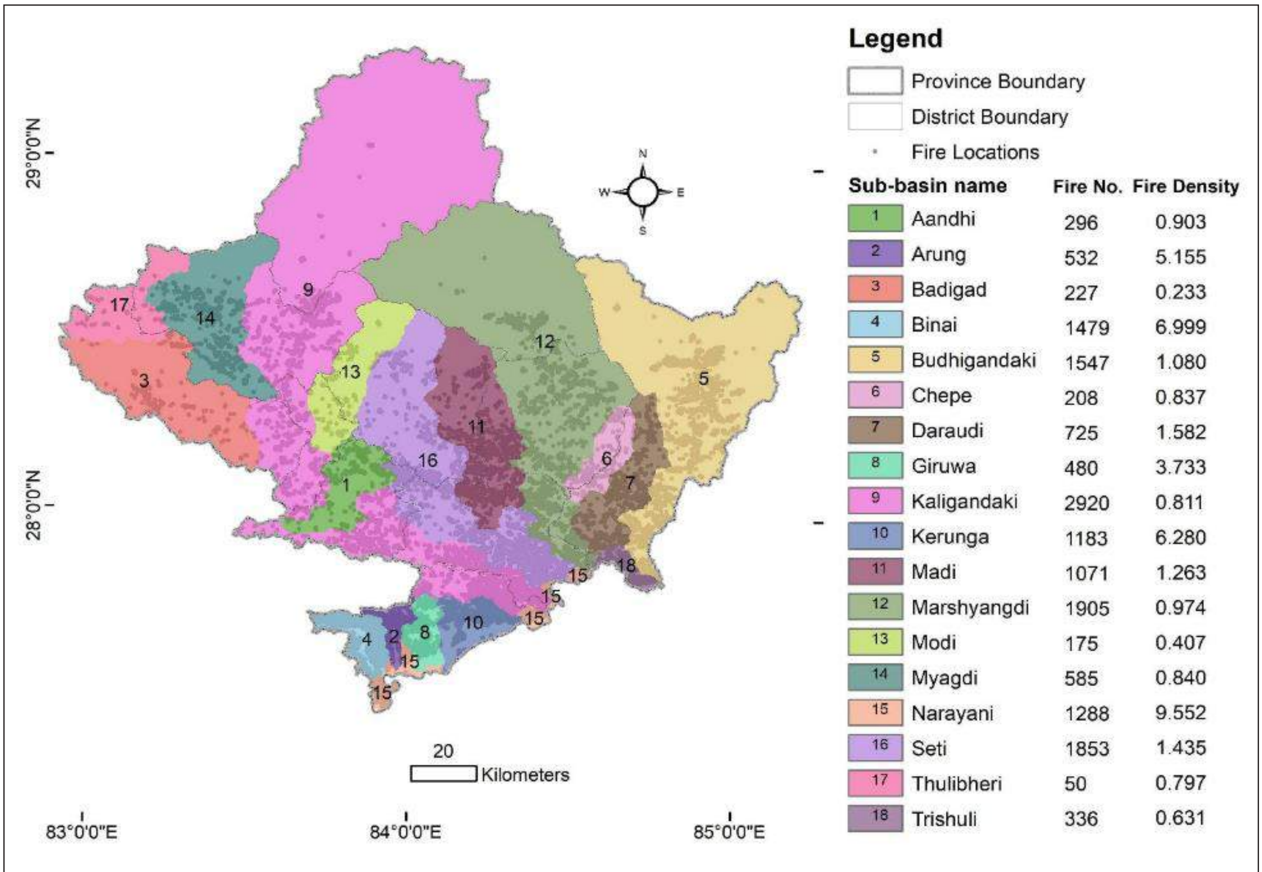

Figure 6 Number of fire events in watersheds of Gandaki province (numbers within the boundary is coding) with corresponding fire density (fire-count/km^2)

with a small portion of the Thulibheri sub-basin in Gandaki, which includes the Uttarganga River in Dhorpatan. The Thulibheri drains into the Karnali River Basin. Smaller watersheds, mostly originating from the Siwalik Hills, are also present in Gandaki. The Kaligandaki and Marshyangdi sub-basins contain larger areas of vegetation, while Trishuli, though larger, has less vegetation coverage.

Kaligandaki recorded the highest fire count of 2920 due to its extensive size, encompassing diverse physiographic zones from the Siwaliks to the Himalayas. Similarly, Marshyangdi and Seti also had high fire counts. However, when fire density was calculated per unit area of wild vegetation, sub-basins originating from the Siwaliks had higher values, indicating that fire counts were higher relative to their vegetation size. The right bank of the Narayani River, though covering only 134.84 km^2 of wild vegetation, had the highest fire density at 9.5 fires per km^2. Other watersheds with high fire density include Binai, Kerunga, Aandhi, and Giruwa. Watersheds such as Badigad and Modi had lower fire densities. This information is crucial for fire management alongside water resource management in these watersheds.

Wildfire with respect to ground properties

The surface cover in this study was characterised using various ground properties, including the LULC map, NDMI map, and SOTER Soil types, as shown in Figure 7. During the study period, fire occurrences were recorded as 13,360 in forests, 2527 in grasslands, and 1027 in other wooded lands. The total area of these categories measured 7879.43 km^2 for forests, 4468.83 km^2 for grasslands, and 1186.55 km^2 for other wooded lands. This resulted in wildfire densities of

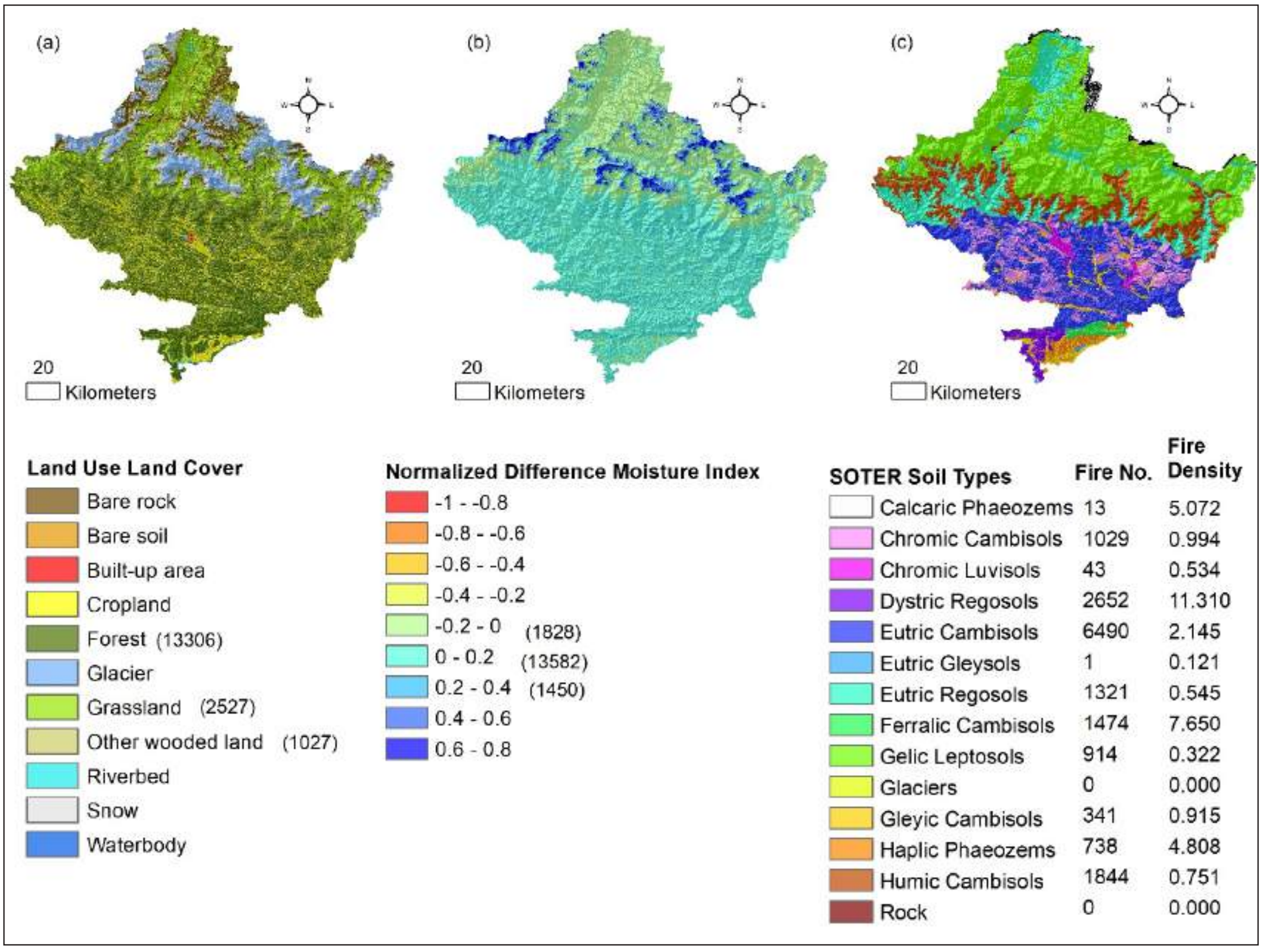

Figure 7 (a) Land use and land cover (fire count in brackets), (b) normalised difference moisture index with fire counts in brackets, and (c) SOTER soil types with fire counts and fire density (fire-count/km^2) of Gandaki Province

1.696, 0.565, and 0.866 per km^2, respectively, suggesting higher fire occurrences in forested areas compared to grasslands and other wooded lands. MODIS fire data, however, indicated higher fire occurrences in scrublands, followed by grasslands and forests, which contrasts with the findings of this study (Reddy et al. 2020). Among forests, tropical and sub-tropical varieties, found at lower elevations, are more vulnerable to fires (Singh & Singha 2024). Certain tree species, such as *Shorea robusta* and *Schima wallichii*, have shown higher fire susceptibility in the Sikkim Himalaya (Sharma & Thapa 2021).

The NDMI values, ranging from -0.2 to 0.4, included fire events in Gandaki Province. Three categories were identified: -0.2 to 0, 0 to 0.2, and 0.2 to 0.4, with 1828, 13,582, and 1450 fire counts respectively. The highest fire density was noted in the 0.2 to 0.4 NDMI range, indicating mid to high canopy cover with high water stress. Soil analysis, derived from the SOTER soil map of Nepal, revealed the highest fire count in Euteric Cambisols, but the highest fire density occurred in Dysteric Regosols, which are more prone to fire due to their varying particle sizes and dry nature.

Wildfire with respect to topography

The study considered three key topographic factors—altitude, slope, and aspect—when estimating the occurrences of forest fires. These factors and their respective categories are presented in Figure 8, alongside their fire counts and densities. Fire density decreased with an increase in altitude. The highest fire densities were observed at elevations below 500 m, likely due to greater land use for cultivation, which reduces vegetation cover. In contrast, the nival zone above 5000 m saw no fire incidents, and the region between 4000 m and 5000 m, with scrubby vegetation, recorded very few fires. Similar trends were observed in the Siwalik (Chure) hills of Nepal, where lower elevations were more prone to fire (Joshi et al. 2024), and future fire risk is projected to increase at elevations around 2000 m (Bar et al. 2023).

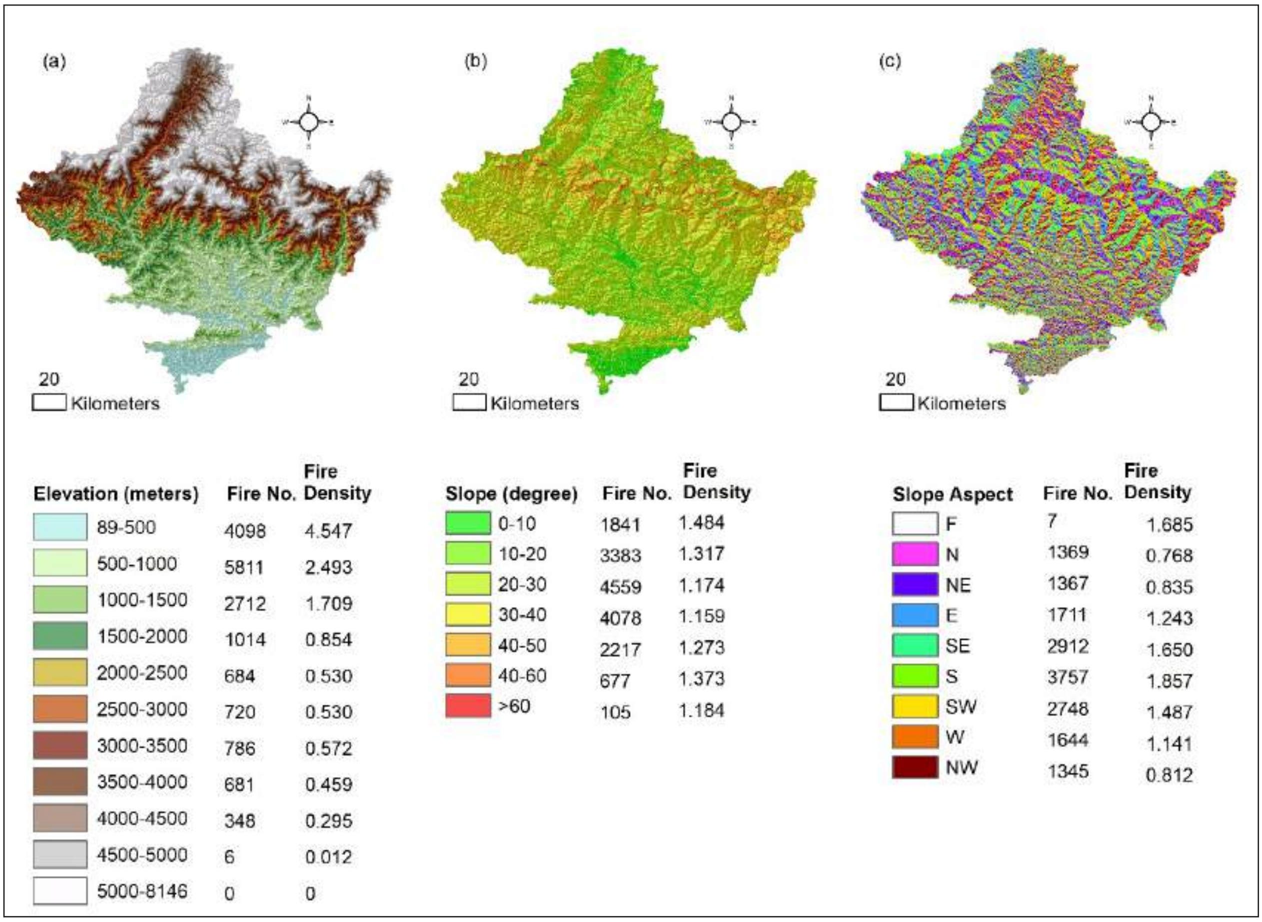

Figure 8 Categories of (a) elevation, (b) slope, and (c) aspect with respective fire count and fire density (fire-count/km^2) of Gandaki Province

Vegetation coverage was greatest on slopes between 20° and 40°, and fire counts mirrored this trend. However, examination of data showed lower fire density in slopes with more vegetation, averaging 1.165 fires per km^2. Moderate slopes with lower altitudes, such as those around 15%, were identified as high-risk areas for forest fires (Matin et al. 2017, Parajuli et al. 2020). The highest fire density of 1.484 fires per km^2 was found on slopes less than 10°, while slopes between 50° and 60° had a density of 1.373 fires per km^2. This finding aligns with research in Northeast India, where moderate slopes (2°–10°) accounted for nearly half of forest fire incidents (Talukdar et al. 2024).

Regarding aspect, southern slopes—particularly south, southwest, and southeast—had higher vegetation cover, fire counts, and fire densities. This pattern is attributed to higher sun exposure, reduced moisture, and lower vegetation water content compared to north-facing slopes (Matin et al. 2017, Tyagi et al. 2023). Thus, lower elevations, gentle to steep slopes, and south-facing aspects emerged as key topographic factors contributing to fire occurrences.

Wildfire with respect to linear features

The wildfire trend was also examined in relation to linear ground features, specifically the proximity to roads and the drainage density of stream networks which are depicted in Figure 9. Fire occurrences were found to be higher near roads, with fire incidents decreasing as the distance from the roads increased. Fire density was notably high within the 250 m to 1000 m range from roads, which suggests a relation with heightened anthropogenic activities near roadways. This observation is consistent with previous findings, where 11 out of 15 fire incidents were located near roads (Parajuli et al. 2020), indicating that roads increase the risk of fire occurrences.

When examining stream density, it was observed that areas with extreme stream density values had lower wilderness areas and fewer forest

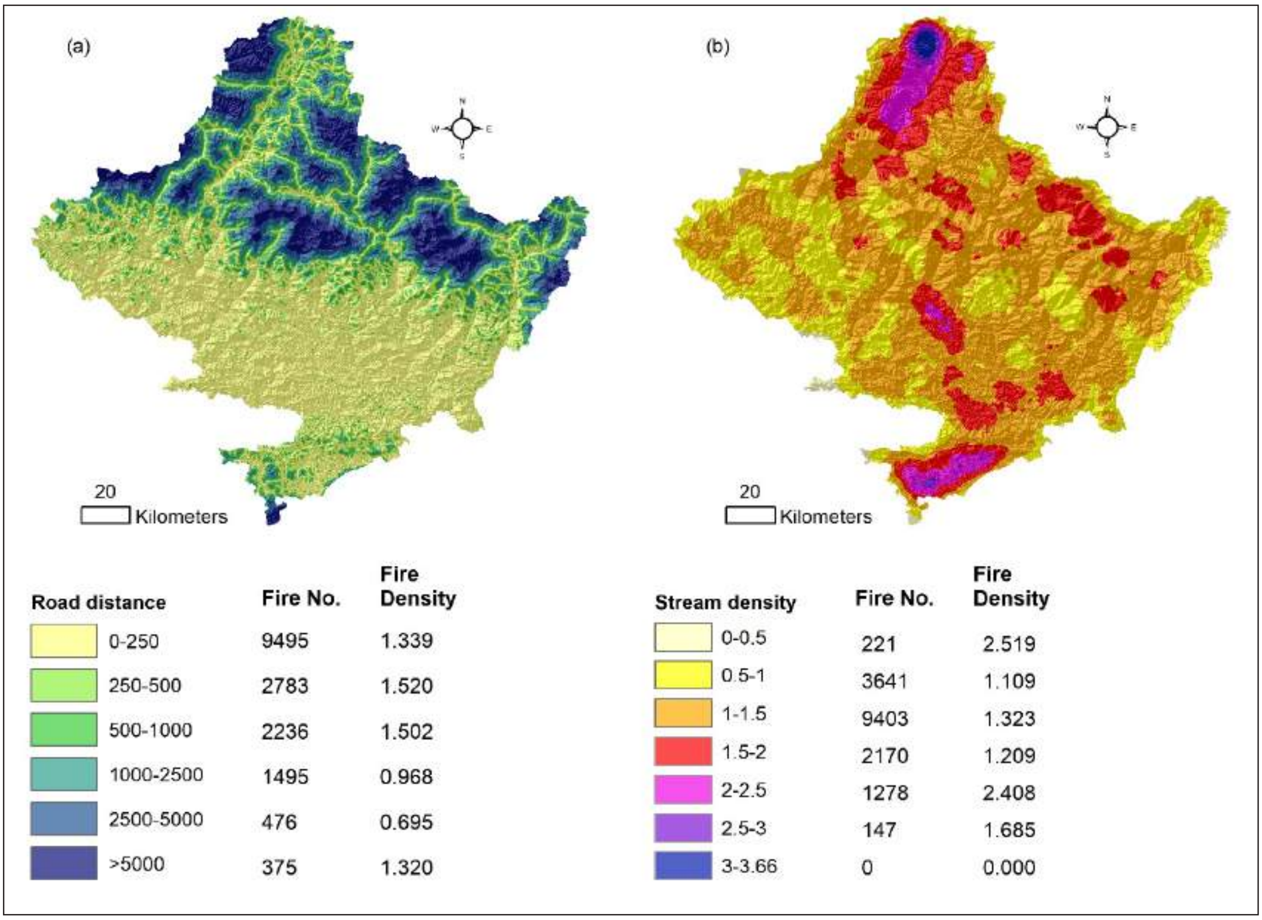

Figure 9 Spatial representation of linear features: (a) after buffering of road network (unit in m), and (b) stream density (unit in km/km^2), along with respective fire count, and fire density (fire-count/km^2) of Gandaki Province

fires. In contrast, stream densities between 0.5 and 2 were associated with high wild vegetation and a significant number of fire incidents. Interestingly, the highest fire density was recorded in areas with the lowest stream density. The southern part of the Narayani River, with its adjoining streams forming the Siwaliks, exhibited higher stream density, as shown in Figure 9, and consequently, higher fire density. However, in the Upper Mustang region around the origin of the Kaligandaki River, despite high stream density, no fire incidents were recorded, resulting in a low fire density. A study on stream buffers found that the risk of fire occurrence increased as one moved away from the streams (Tomar et al. 2021), highlighting the complex relationship between stream network and wildfire risk.

Wildfire with respect to population density

The population density map, derived from 2021 census data for local administrative units, is shown in Figure 10. Pokhara Metropolitan City had the highest population density at 1115 per km^2, followed by Kawasoti Municipality with 804 per km^2. Other areas with a population density between 500 and 800 per km^2 include Gaidakot and Devchuli of Nawalpur district, and Baglung Municipality. Notably, parts of the Dhorpatan Hunting Reserve and Chitwan National Park in Gandaki Province had zero population density. The northern region of the province, which includes Manang, Mustang, and parts of Gorkha, Lamjung, Kaski, and Myagdi districts, had sparse population densities of up to 100 per km^2.

Wild vegetation was found to be more abundant in areas with lower population densities. Regions with population densities up to 400 per km^2 showed higher wild vegetation, whereas areas with higher population densities (>400 per km^2) had less wild vegetation. Fire count patterns mirrored this distribution, with lower fire densities in areas of lower population density. However, fire density was particularly high in regions with a population density between 500 and 1100 per km^2.

While closer proximity to roads correlated with higher fire density, the relationship with

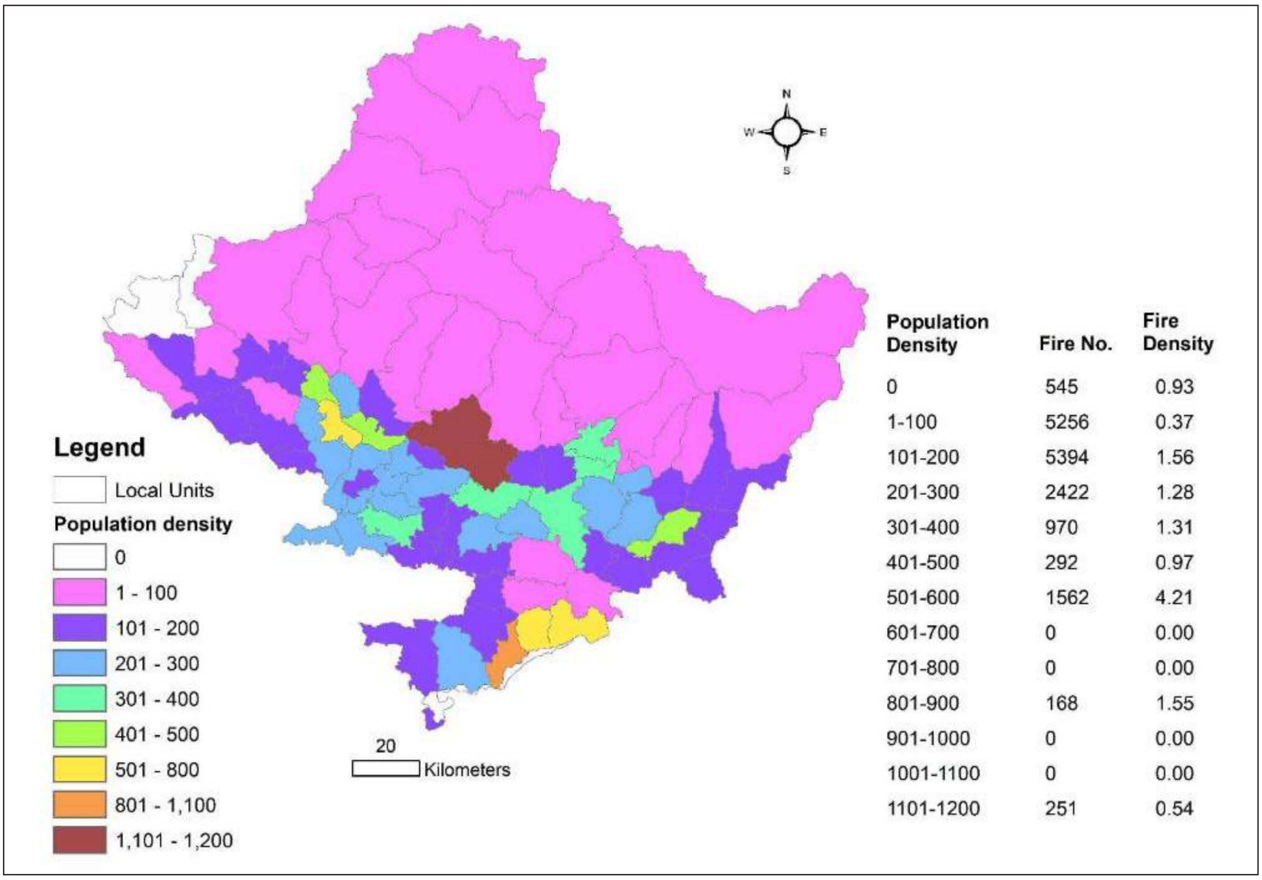

Figure 10 Population density map of local units of Gandaki Province and corresponding fire density (fire-count/km^2)

population density was less clear. Forests near human activity—such as roads, higher population, and livestock densities—are generally more vulnerable to fires (Mishra et al. 2023). This study suggests that fire density can be high in both low and high population density areas, indicating a complex interaction between human presence and fire occurrences.

It reflected that, fire events were strongly influenced by vegetation type, topography, and proximity to roads, with forests and south-facing slopes being most fire-prone. Fire occurrence patterns also correlated with mid-range NDMI values, low stream density, and moderate population densities, revealing complex interactions between ecological and anthropogenic factors. These insights are vital to produce risk maps through wildfire susceptibility assessments (Eslami et al. 2021).

CONCLUSION

This study focused on fire incidents in wilderness areas, specifically forests, grasslands, and wooded vegetation, excluding fires from settlements and agricultural lands—a distinction not often made in previous research. Between 2012 and 2021, the VIIRS instrument recorded 230,077 fire events in Nepal, with 16,860 wildfires in Gandaki Province, which had a fire density of 1.25 fires per square kilometer. Unlike previous studies that relied on MODIS fire products, this study used the higher-resolution VIIRS data, which detects nearly 18 times more fires than MODIS over the past decade, providing more reliable results.

Gandaki Province experiences wildfires for an average of 110 days per year, with 2016 recording the highest at 138 fire days. Nawalpur and Gorkha districts had the highest number of fire days, averaging 32 and 30 annually, respectively. Nawalpur also had the highest fire count and density, with four local units reporting fire densities greater than 7 per square kilometer. Conversely, Manang and Mustang districts had the fewest wildfires, with only 1 fire day each on average. April was the peak month for wildfires, followed by March, and the onset of the monsoon in June significantly reduced fire incidents.

At the sub-basin level, Kaligandaki had the highest fire count due to its large area, while Narayani had the highest fire density. Watersheds from the Siwalik Hills in Nawalpur, such as Arung, Binai, Giruwa, and Kerunga, exhibited higher fire densities. Forests were more commonly affected by wildfires than grasslands or scrublands, contrary to past research. Fires in forests were most prevalent in cambisols. Topographically, lower altitudes and south-facing slopes had the highest fire densities, with nearly 81% of fires occurring below 2 000 meters in elevation. Fire density was highest below 500 meters, and 71% of forest fires occurred on slopes between 10° and 40°.

Regarding aspects, 56% of wildfires occurred on south, southwest, and southeast-facing slopes. Fire density was higher near roads, while stream density showed an inverse relationship with fire frequency. Pokhara, with the highest population density, had a lower fire density than municipalities of Nawalpur. Municipalities with 500–600 people per square kilometer had the highest fire densities.

This study provides valuable insights into wildfire distribution, crucial for forest management and wildfire prevention strategies. The use of VIIRS data enhances the accuracy of these findings, which can aid local governments in wildfire management and awareness.

ACKNOWLEDGEMENTS

This study was made possible by funding from the Research Coordination and Development Council (RCDC), Tribhuvan University, Kathmandu, Nepal [grant number: TU-NPAR-077/78-ERG-03].

REFERENCES

Ahmad F, Goparaju L & Qayum A. 2018. Himalayan forest fire characterization in relation to topography, socio-economy and meteorology parameters in Arunachal Pradesh, India. *Spatial Information Research* 26: 305–315. https://doi.org/10.1007/s41324-018-0175-1

Aubry-Wake C, Bertoncini A & Pomeroy JW. 2022. Fire and ice: The impact of wildfire-affected albedo and irradiance on glacier melt. *Earth's Future* 10: e2022EF002685. https://doi.org/10.1029/2022EF002685

Bar S, Parida BR, Pandey AC et al. 2023. Modeling and prediction of fire occurrences along an elevational gradient in Western Himalayas. *Applied Geography* 151: 102867. https://doi.org/10.1016/j.apgeog.2022.102867

Bar S, Parida BR, Roberts G et al. 2021. Spatio-temporal characterization of landscape fire in relation to anthropogenic activity and climatic variability over the Western Himalaya, India. *GIScience & Remote Sensing* 58: 281–299. https://doi.org/10.1080/15481603.2021.1879495

Bhujel KB, Maskey-Byanju R & Gautam AP. 2017a. Wildfire dynamics in Nepal from 2000–2016. *Nepal Journal of Environmental Science* 5: 1–8. https://doi.org/10.3126/njes.v5i0.22709

Bhujel KB, Maskey R, Gautam A & Mandal R. 2017b. Effect of climatic variables on fire incidence and burnt area in tropical forests in Nepal. *E-Planet* 15: 19–26.

Bhujel KB, Maskey Byanju R, Gautam AP, Sapkota RP & Khadka UR. 2021. Fire-induced carbon emissions from tropical mixed broad-leaved forests of the Terai–Siwalik region, central Nepal. *Journal of Forestry Research* 32: 2557–2565. https://doi.org/10.1007/s11676-020-01256-x

Bhusal S & Mandal RA. 2020. Forest fire occurrence, distribution and future risks in Arghakhanchi district, Nepal. *International Journal of Geography, Geology and Environment* 2: 10–20.

Bolstad PV & Stowe T. 1994. An evaluation of DEM accuracy: elevation, slope, and aspect. *Photogrammetric Engineering & Remote Sensing* 60: 1327–1332.

Chen H, Samet JM, Bromberg PA & Tong H. 2021. Cardiovascular health impacts of wildfire smoke exposure. *Particle and Fibre Toxicology* 18: 1–22. https://doi.org/10.1186/S12989-020-00394-8

Corona-Núñez RO & Campo JE. 2023. Climate and socioeconomic drivers of biomass burning and carbon emissions from fires in tropical dry forests: A pantropical analysis. *Global Change Biology* 29: 1062–1079. https://doi.org/10.1111/gcb.16516

Csiszar I, Schroeder W, Giglio L et Al. 2014. Active fires from the Suomi NPP Visible Infrared Imaging Radiometer Suite: product status and first evaluation results. *Journal of Geophysical Research: Atmospheres* 119: 803–816. https://doi.org/10.1002/2013JD020453

Datta S, Karmakar S, Mezbahuddin S et Al. 2022. The limits of watershed delineation: implications of different DEMs, DEM resolutions, and area threshold values. *Hydrology Research* 53: 1047–1062. https://doi.org/10.2166/nh.2022.126

Doerr SH & Santín C. 2016. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371: 20150345. https://doi.org/10.1098/rstb.2015.0345

Eslami R, Azarnoush M, Kialashki A & Kazemzadeh F. 2021. GIS-based forest fire susceptibility assessment by random forest, artificial neural network and logistic regression methods. *Journal of Tropical Forest Science* 33: 173–184. https://doi.org/10.26525/jtfs2021.33.2.173

Fawzi N, Helms J, Emerson A & Wibawanto M. 2020. Forest restoration progress and lessons learned in Gunung Palung National Park, Indonesia. *Journal of Tropical Forest Science* 32: 195–205. https://doi.org/10.26525/jtfs32.2.195

FRTC. 2021. *Vegetation Types of Nepal: A Report Based on Review of Literature and Expert Knowledge.* EFTMP Technical Working Document, No. 2. Ecosystem and Forest Types Mapping Program (EFTMP), Forest Research and Training Centre (FRTC). Kathmandu, Nepal. https://frtc.gov.np/pages/82/14155754/

Jaffe DA, O'neill SM, Larkin NK et Al. 2020. Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association* 70: 583–615. https://doi.org/10.1080/10962247.2020.1749731

Ji L, Zhang L, Wylie BK & Rover J. 2011. On the terminology of the spectral vegetation index (NIR − SWIR)/(NIR + SWIR). *International Journal of Remote Sensing* 32: 6901–6909. https://doi.org/10.1080/01431161.2010.510811

Jolly WM, Cochrane MA, Freeborn PH et Al. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 6: 7537. https://doi.org/10.1038/ncomms8537

Joshi KP, Adhikari G, Bhattarai D, Adhikari A & Lamichanne S. 2024. Forest fire vulnerability in Nepal's Chure region: investigating the influencing factors using generalized linear model. *Heliyon* 10: e28525. https://doi.org/10.1016/j.heliyon.2024.e28525

Justice C, Townshend JR, Vermote E et Al. 2002. An overview of MODIS Land data processing and product status. *Remote Sensing of Environment* 83: 3–15. https://doi.org/10.1016/S0034-4257(02)00084-6

Justice CO, Giglio L, Korontzi S et Al. 2002. The MODIS fire products. *Remote Sensing of Environment* 83: 244–262. https://doi.org/10.1016/S0034-4257(02)00076-7

Khanal RP. 2020. *Pattern of tree species richness along the elevation gradient of Modi River Basin in Annapurna Conservation Area, Central Nepal.* MSc thesis. Amrit Campus, Institute of Science and Technology, Tribhuvan University, Nepal.

Khanal S. 2015. Wildfire trends in Nepal based on MODIS burnt-area data. *Banko Janakari* 25: 76–79. https://doi.org/10.3126/banko.v25i1.13477

Köster K, Aaltonen H, Berninger F et Al. 2021. Impacts of wildfire on soil microbiome in boreal environments. *Current Opinion in Environmental Science & Health* 22: 100258. https://doi.org/10.1016/J.COESH.2021.100258

Krawchuk MA, Moritz MA, Parisien M-A, Van Dorn J & Hayhoe K. 2009. Global pyrogeography: the current and future distribution of wildfire. *PLoS ONE* 4(4): e5102. https://doi.org/10.1371/journal.pone.0005102

Kunwar R & Khaling S. 2006. Forest fire in the Terai, Nepal: causes and community management interventions. *International Forest Fire News* 34: 46–54.

Lu L, Wang L, Yang Q et Al. 2023. Extracting a connected river network from DEM by incorporating surface river occurrence data and Sentinel-2 imagery in the Danjiangkou Reservoir Area. *Remote Sensing* 15(4): 1014. https://doi.org/10.3390/RS15041014

Mansilha C, Duarte CG, Melo A et Al. 2019. Impact of wildfire on water quality in Caramulo Mountain Ridge (Central Portugal). *Sustainable Water Resources Management* 5: 319–331. https://doi.org/10.1007/s40899-017-0171-y

Masri S, Scaduto E, Jin Y & Wu J. 2021. Disproportionate impacts of wildfires among elderly and low-income communities in California from 2000–2020.

International Journal of Environmental Research and Public Health 18: 3921. https://doi.org/10.3390/IJERPH18083921/S1

Matin MA, Chitale VS, Murthy Msr et al. 2017. Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information system and historical fire data. *International Journal of Wildland Fire* 26: 276. https://doi.org/10.1071/WF16056

Mina U, Dimri AP & Farswan S. 2023. Forest fires and climate attributes interact in Central Himalayas: an overview and assessment. *Fire Ecology* 19: 14. https://doi.org/10.1186/s42408-023-00177-4

Mishra B, Panthi S, Poudel S & Ghimire BR. 2023. Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology* 19: 3. https://doi.org/10.1186/s42408-022-00162-3

Mouillot F & Field CB. 2005. Fire history and the global carbon budget: a 1° × 1° fire history reconstruction for the 20th century. *Global Change Biology* 11: 398–420. https://doi.org/10.1111/j.1365-2486.2005.00920.x

Parajuli A, Gautam Ap, Sharma SP et al. 2020. Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. *Geomatics, Natural Hazards and Risk* 11: 2569–2586. https://doi.org/10.1080/19475705.2020.1853251

Parajuli A, Manzoor SA & Lukac M. 2023. Areas of the Terai Arc landscape in Nepal at risk of forest fire identified by fuzzy analytic hierarchy process. *Environmental Development* 45: 100810. https://doi.org/10.1016/J.ENVDEV.2023.100810

Pragya, Kumar M, Tiwari A et al. 2023. Integrated spatial analysis of forest fire susceptibility in the Indian Western Himalayas (IWH) using remote sensing and GIS-based fuzzy AHP approach. *Remote Sensing* 15: 4701. https://doi.org/10.3390/RS15194701

Ré A, Rocha At, Campos I et al. 2021. Impacts of wildfires in aquatic organisms: biomarker responses and erythrocyte nuclear abnormalities in *Gambusia holbrooki* exposed in situ. *Environmental Science and Pollution Research* 28: 51733–51744. https://doi.org/10.1007/s11356-021-14377-5

Reddy CS, Bird NG, Sreelakshmi S et al. 2019. Identification and characterization of spatio-temporal hotspots of forest fires in South Asia. *Environmental Monitoring and Assessment* 191: 791. https://doi.org/10.1007/s10661-019-7695-6

Reddy CS, Unnikrishnan A, Bird NG et al. 2020. Characterizing vegetation fire dynamics in Myanmar and South Asian countries. *Journal of the Indian Society of Remote Sensing* 48: 1829–1843. https://doi.org/10.1007/s12524-020-01205-5

Rouet-Leduc J, Pe'er G, Moreira F et al. 2021. Effects of large herbivores on fire regimes and wildfire mitigation. *Journal of Applied Ecology* 58: 2690–2702. https://doi.org/10.1111/1365-2664.13972

Schroeder W & Giglio L. 2018. Nasa Viirs Land Science Investigator Processing System (SIPS) Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m & 750 m active fire products: product user's guide version 1.4. https://viirsland.gsfc.nasa.gov/PDF/VIIRS_activefire_User_Guide.pdf

Schroeder W, Oliva P, Giglio L & Csiszar IA. 2014. The new VIIRS 375 m active fire detection data product: algorithm description and initial assessment. *Remote Sensing of Environment* 143: 85–96. https://doi.org/10.1016/j.rse.2013.12.008

Senande-Rivera M, Insua-Costa D & Miguez-Macho G. 2022. Spatial and temporal expansion of global wildland fire activity in response to climate change. *Nature Communications* 13: 1208. https://doi.org/10.1038/s41467-022-28835-2

Senande-Rivera M, Insua-Costa D & Miguez-Macho G. 2025. Climate change aggravated wildfire behaviour in the Iberian Peninsula in recent years. *Climate and Atmospheric Science* 8: 19. https://doi.org/10.1038/s41612-025-00906-3

Sharma K & Thapa G. 2021. Analysis and interpretation of forest fire data of Sikkim. *Forest and Society* 5: 261–276. https://doi.org/10.24259/FS.V5I2.10931

Singh B, Maharjan M & Thapa MS. 2020. Wildfire risk zonation of Sudurpaschim Province, Nepal. *Forestry: Journal of Institute of Forestry, Nepal* 17: 155–173. https://doi.org/10.3126/FORESTRY.V17I0.33633

Singh EI & Singha A. 2024. Climate change and forest fire in Eastern Himalaya: a case study of Sikkim and Darjeeling Himalayas of West Bengal. Pp 215–230 in SINGH AL, JAMAL S, & AHMAD WS (eds) *Climate Change, Vulnerabilities and Adaptation.* Springer, Germany. https://doi.org/10.1007/978-3-031-49642-4_12

Talukdar NR, Ahmad F, Goparaju L et al. 2024. Forest fire estimation and risk prediction using multispectral satellite images: case study. *Natural Hazards Research* 4: 304–319. https://doi.org/10.1016/J.NHRES.2024.01.007

Tomar Js, Kranjčić N, Đurin B, Kanga S & Singh SK. 2021. Forest fire hazards vulnerability and risk assessment in Sirmaur District Forest of Himachal Pradesh (India): a geospatial approach. *ISPRS International Journal of Geo-Information* 10: 447. https://doi.org/10.3390/IJGI10070447

Tyagi V, Singh SP, Singh RD, Gumber S, Thadani R & Pandey R. 2023. Influence of slope position and aspect on the vegetation attributes and tree-water relations in forests of the central Himalayas. *Journal of Mountain Science* 20: 2592–2602. https://doi.org/10.1007/s11629-023-7967-z

Vadrevu K, Eaturu A, Casadaban E et al. 2022. Spatial variations in vegetation fires and emissions in South and Southeast Asia during COVID-19 and pre-pandemic. *Scientific Reports* 12: 18233. https://doi.org/10.1038/s41598-022-22834-5

Viedma O, Urbieta IR & Moreno JM. 2018. Wildfires and the role of their drivers are changing over time in a large rural area of west-central Spain. *Scientific Reports* 8: 17797. https://doi.org/10.1038/s41598-018-36134-4

Williams AP, Abatzoglou JT, Gershunov A et al. 2019. Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* 7: 892–910. https://doi.org/10.1029/2019EF001210

Ye T, Xu R, Yue X et al. 2022. Short-term exposure to wildfire-related PM2.5 increases mortality risks and burdens in Brazil. *Nature Communications* 13: 7651. https://doi.org/10.1038/s41467-022-35326-x