

Journal of **Forest and Livelihood**

Volume 26(1) • June 2026 • ISBN 1684-0186



Forest Fire Management in Nepal

Chief Editor

Prof. Dr Ambika Gautam

Executive Editor

Rahul Karki

Editors

Prof. Dr Bir Bahadur Khanal

Chhetri

Prof. Dr Bharat Babu Shrestha

Dr Kalpana Giri

Dr Rajan Parajuli

Dr Naya Sharma Paudel

Dr Upama Koju

Dr Lila Nath Sharma

Dr Rajesh Bista

Dr Balkrishna Ghimire

Editorial Support

Manish Shrestha

Harshita Thapa

Design and Layout

Sanjeeb Bir Bajracharya

Cover Photo

Manish Shrestha

© ForestAction Nepal

To know more
on the JFL
guideline,
scan the QR



Guidelines for Contributors

Established in 2001, *Journal of Forest and Livelihood* or *JFL* is a peer-reviewed journal that documents and disseminates the insights, lessons and innovations taking place in sociocultural, political and economic aspects of environmental governance and rural livelihoods in Nepal.

JFL aims to inform environmental policy processes by facilitating dialogue among politicians, professionals, activists, researchers and policymakers. The journal publishes original scientific papers, short communications and review articles. We welcome articles analysing contemporary issues on nature–society interactions that have direct implications on both local livelihoods and resource sustainability. We particularly encourage papers that are guided by critical social sciences perspectives and enriched by insights from deliberative governance, political economy, political ecology, social learning and institutional theories. The authors are fully responsible for the originality of their contributions and formal correctness and for ensuring that their contributions have not been published previously.

Types of contribution: Contributors may consider two options: a) long articles of up to 5,000 words or not exceeding 15 pages, including tables, figures, references, and abstract and b) short technical communications of around 1,500 words or four printed pages. They are required to specify the type of contribution while submitting the article.

Abstract and key words: Abstract is a short summary of the whole paper. Authors are required to include an abstract not exceeding 250 words and 5 keywords. The abstract should describe all essential facts of their papers. It is an important part of the paper and cited in world databases. Key words should be taken from the body text of the paper and must not include the words that are contained in the title of the papers.

The text in the article should be divided into the following sections: Introduction, Materials and methods, Results, Discussion, Acknowledgement, References, Tables and figures, Legends.

Introduction should outline the main reasons why the research was conducted; describe a brief review of literature consisting of refereed periodicals, journals and books, and the goal of the author/s.

Language: Articles should be submitted in **British** English, and there should be uniformity in the language used.

Formatting: Papers should be submitted in the A4 standard page size, with a 2.5 cm margin on each side, and the font and font size should be Times New Roman 12 pt. The heading levels should be properly identified.

The author should provide her or his full name, organisational affiliation and position, and an email address. In case of multiple authors, the corresponding author should be identified.

References: All publications cited in the text must be included in a reference list at the end of the document. Authors are strongly advised to follow standard scientific referencing conventions and format all citations and references according to the APA 7th edition (American Psychological Association) guidelines.

The publication of this special issue was supported in part by the Australian Himalayan Foundation (AHF) and the Australian Government's Department of Foreign Affairs and Trade (DFAT) through the Direct Aid Program (DAP). Researchers from ForestAction Nepal and Institute for Study and Development Worldwide (IFSD) collaboratively undertook the review and editorial processes for the manuscripts included in this special issue. The editors sincerely thank the anonymous reviewers for their valuable feedback. We also gratefully acknowledge the managerial support of Mr. Amrit Adhikari and the editorial support of Mr. Aayush Gautam and Ms. Yojana Bhattarai.

The views expressed in the articles are entirely those of the author(s) and do not necessarily reflect the views of ForestAction Nepal or the projects from which information have been extracted to develop the articles.

Editorial

Nepal's forest fires have escalated from seasonal events to a recurring hazard, with more than 34,700 incidents recorded since 2008. While hotter and drier conditions elevate fire weather risks, impacts are amplified by institutional fragmentation and weak incentives for prevention and response. Post 2015 federal restructuring has delegated authority across different government tiers, though the clarity of roles and responsibilities and the outcomes is still a question. On the other hand, contributions of local communities and community-based response to forest fires have largely remained voluntary, that is compounded by lack of tools and capacity, thus posing risks to lives and property. A shift from episodic suppression to risk-based stewardship is required, centered on a clarified operational command structure, dedicated preparedness financing, and formal recognition of community's role as an essential service. Effective fire management in federal Nepal demands clearly delineated roles across a range of actors. Nevertheless, a well-established, operational chain of command remains absent. In practice, overlapping mandates can leave municipalities accountable for outcomes but constrained in both authority and resources. To address these concerns, this special issue of the Journal of Forest and Livelihood brings together interdisciplinary research and perspectives on forest fire management, highlighting the key issues, challenges, and emerging approaches in the Nepalese context.

The article by Adhikari *et al.* draws on the lessons from 136 local administrative units of Madhesh province to analyse municipal fire counts using a linear model. The authors make a case for accounting for spatial heterogeneity in improved forest fire risk mapping across the lowlands of Nepal. Similarly, using a mixed method approach, Bhattarai and Pandey examine the forest fire incidences, spatial risk patterns, causes and management practices in Bagmati province. They highlight limited resources, weak coordination and lack of early warning systems as major constraints to effective forest fire response, despite the presence of community forest institutions.

Drawing on primary data from interviews and spatial data analysed through GIS and remote sensing, Sharma *et al.* document the seasonal and spatial fire risk in Lumbini province. They underline the need for increased funding and training in early warning systems to support sustainable forest management in the region.

Increasing forest fires is closely attributed to decline in forest-people interaction in recent decades. Building on this argument, Parajuli *et al.* argue on the need to build up on the lessons and practices of community engagement as a pathway to sustainable forest fire management in Nepal highlighting the need for enabling policies and a strategic framework for collaborative governance in the sustainable management of forest fires across the Nepalese landscape.

While human interaction with forests has been closely linked to rising forest fire incidents in Nepal, economic and institutional factors are equally important in shaping forest management outcomes. Rai argues that the absence of incentive mechanisms leading to lack of forest management, has contributed to increasing forest fires in Nepal. He argues for aligning forest fire management with incentive structures to ensure sustainable forest management in Nepal.

In similar line, Shrestha *et al.* examine the shift toward incentive-based management taking the case of pilot project implemented in community forests. They argue for a transition from a volunteerism approach to incentive-based approaches, and call for corresponding policy alignment in support of sustainable forest fire management.

Ojha and Koirala examine the policy and institutional evolution of forest fire management in Nepal across federal, provincial, and local governance levels. Their review reveals that forest fire governance in Nepal continues to face challenges arising from institutional fragmentation, weak coordination, and uneven implementation capacity despite recent policy advancements. The article highlights the importance of strengthening governance coherence, improving institutional preparedness, and supporting community-based approaches for effective forest fire management in the country.

Hill and Shrestha explore the legal and institutional ambiguities that have hindered effective forest fire management in Nepal proposing a standardised and expertise-based command structure that builds on the existing community forestry structure to address prevailing challenges in national fire management.

Finally, drawing on the disaster risk reduction principles and lessons from New South Wales, Australia, Bhattarai *et al.* analyse and propose an anticipatory approach to forest fire risk governance. This perspective paper contextualises Nepal's federal governance structure and community forestry institutions within a multi-level governance framework for fire risk management.

Content

Spatial non-stationarity in forest fire driving factors in the lowlands of Nepal: A case study of Madhesh Province	1-23
Gunjan Adhikari, Nabin Kumar Yadav, Khagendra Prasad Joshi, Sandip Mahara, Dristee Chad, Damodar Gaire, Rajan Subedi	
Assessment of forest fire incidences, causes, and management practices in Bagmati Province, nepal	24-44
Kalpana Bhattarai, Chandra Lal Pandey	
Assessing forest fire risks using geo-spatial techniques in western Nepal	45-67
Sirjan Sharma, Ambika P. Gautam, Ashok Parajuli, Mahesh Parajuli	
Maintaining people-forests interactions is critical to managing forests fires in Nepal	68-82
Rabindra Parajuli, Asha Paudel, Lila Nath Sharma	
Challenges and opportunities in forest fire management in Nepal: An economic perspective	83-88
Rajesh Kumar Rai	
From voluntarism to incentivised forest fire management in Nepal: Evidence on labour costs and risk perceptions from four CFUGs	89-107
Manish Shrestha, Dipesh K.C., Rahul Karki, Madan Bashyal	
Forest fire policy efforts in Nepal: Present status and future vision	108-128
Kanchan Ojha, Ankit Koirala	
Institutional fragmentation and forest fire management in federal Nepal: Bridging the governance gap through incident management systems	129-141
Alan Hill, Manish Shrestha	
Anticipatory forest-fire risk governance in Nepal	142-154
Basundhara Bhattarai, Kenisha Shrestha, Priyanka Gurung, Hemant Ojha	

Spatial non-stationarity in forest fire driving factors in the lowlands of Nepal: A case study of Madhesh Province

Gunjan Adhikari^{1*}, Nabin Kumar Yadav², Khagendra Prasad Joshi³, Sandip Mahara⁴, Dristee Chad⁵, Damodar Gaire⁶, Rajan Subedi^{4,7}

¹ College of Forestry, Wildlife and Environment, Auburn University, Auburn, AL, USA

² Ministry of forest and environment, Madhesh Province, Janakpur, Nepal

³ Kathmandu Forestry College, Kathmandu, Nepal

⁴ Tribhuvan University, Institute of Forestry, Pokhara Campus, Pokhara, Nepal

⁵ Department of Geography and Environmental Sustainability, University of Oklahoma, USA

⁶ Tribhuvan University, Institute of Forestry, Hetauda, Nepal

⁷ Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, USA

*Corresponding author: gunjanadhikari58@gmail.com

Abstract

Madhesh Province, located in the southern lowlands of Nepal, experiences frequent forest fires under strong human–forest interactions. Previous fire-risk studies in Nepal rarely account for spatial non-stationarity in the relationships between fire occurrence and its drivers. We aggregated VIIRS (2012–2023) active-fire detections to 136 local administrative units and modelled municipal fire counts using a Poisson generalised linear model (GLM) and a Poisson geographically weighted regression (GWR). Across the province, aspects, land surface temperature, rangeland and agricultural area, canopy height, NDVI, and road length were generally positively associated with fire counts, whereas precipitation and wind speed were negative; several land-cover and anthropogenic variables showed spatially varying effects in the GWR. The local GWR improved model fit (deviance explained = 0.994) compared with the global GLM (0.913), both trained with fire incidents from 2012–2022, and produced a more accurate prediction map (AUC = 0.825 vs 0.769, validated using 2023 fire detections). Both models indicated that ~22 per cent of Madhesh Province falls within high fire-risk zones. Overall, accounting for spatial heterogeneity improves forest-fire risk mapping in Nepal's lowlands and supports locally tailored prevention and preparedness strategies.

Keywords: Forest fires, Generalised linear model (GLM), Geographic weighted regression (GWR), Risk map, Spatial heterogeneity

INTRODUCTION

Forests play a crucial role in facilitating soil and water conservation efforts, as well as serving as regulators of climate and carbon cycles (Piao *et al.*, 2018). However, forest fires have caused significant adverse impacts on wildlife, forest ecosystems, and greenhouse gas emissions. The GFED5 database estimates global burned area of about 774 ± 63 million

ha per year for 2001–2020 (Chen *et al.*, 2023; Robinne, 2021). In addition, it is anticipated that the potential risk will further escalate given the projected 2°C global temperature increases under current and future climatic conditions (Aponte *et al.*, 2016). Forest fire is one of the major factors impacting forest ecosystems in Hindu Kush region negatively (Bhattarai *et al.*, 2022). Analysing historical data in Nepal reveals that approximately

40,000 hectares of forest land are affected by fire issues each year and, that this area has been increasing over time (Bajracharya, 2002; Mishra *et al.*, 2023).

Forest fires can be attributed to a range of factors that can be broadly categorised as climatic, topographic, vegetative, and socioeconomic factors (Zhang *et al.*, 2011). It is important to note that these factors exhibit variations across different temporal and spatial scales. Climatic variables regulate the water content and forest fuel accumulation (Sharples, 2009) and have effects at larger scales than other determinants (Turco *et al.*, 2013). Forest fuels, as a primary determinant in forest fire originate from vegetation and have a direct influence on flammability (İnan *et al.*, 2017). Topography which shapes the structure and distribution of plants, plays a pivotal role in determining the likelihood, speed, and direction of forest fires (Maingi and Henry, 2007; Yang *et al.*, 2021). The frequency of forest fires is influenced by socioeconomic variables, as urban expansion, growing transportation networks, and human activities increase pressure on wildlands and bring potential ignition sources closer to forests (Cardille *et al.*, 2001; Kolanek *et al.*, 2021).

In recent years, advancements in technology have improved access to remotely sensed data on forest cover, bioclimatic conditions, and anthropogenic factors, thereby enabling significant research into their effects on forest fires (Matin *et al.*, 2017). Furthermore, modelling tools have been developed to analyse and visualise forest fires. However, when conducting extensive geographic studies, it is more reasonable to consider diverse relationships rather than uniform ones. For instance, Koutsias *et al.* (2010) observed a noteworthy improvement in the explanatory power of classical linear regression

when incorporating varying relationships instead of constant ones in modelling fire densities. Their study, conducted at the provincial level (NUTS-3) across countries in the European Mediterranean Basin, utilised geographically weighted regression (GWR), thus pioneering the application of GWR in fire modelling studies (Martínez-Fernández *et al.*, 2013). Previous studies conducted in Nepal have primarily focused on mapping vulnerable areas prone to forest fires (Matin *et al.*, 2017; Parajuli *et al.*, 2020; Parajuli *et al.*, 2023; Adhikari *et al.*, 2025). These studies have employed various modelling approaches to examine the relationship between different drivers and the extent of forest fires (Qadir *et al.*, 2021; Mishra *et al.*, 2023; Joshi *et al.*, 2024). However, the spatial variability among these drivers has not been adequately addressed in these studies.

In Madhesh province, forest ecosystem values have increased over the past decade, indicating a high dependence of local people on forest resources in the region (Shah *et al.*, 2022). Community people depend on forest resources, like timber, fuelwood, fodder and other non-timber forest products (NTFPs), to sustain their agro-economic livelihoods, with studies indicating that poorer families rely on these resources to a greater extent (Posavec, 2023). Consequently, the subsistence livelihood of residing communities, especially the marginalised communities, is affected if these forest resources are lost or damaged. The increasing forest fires are degrading the forests in an alarming rate (Adhikari *et al.*, 2025). Despite numerous efforts to understand the drivers of forest fires, predictive models such as GLM (Joshi *et al.*, 2024), MaxEnt (Paudel *et al.*, 2024) and deep learning approaches (Mishra *et al.*, 2023; Dhakal *et al.*, 2024) often generalise these variables, thereby overlooking their spatial heterogeneity (Li *et al.*, 2022). To address this gap, we hypothesise that (i) the

relationships between forest fire occurrence and its driving factors exhibit spatial non-stationarity across Madhesh Province, and (ii) a Poisson GWR model, by explicitly accounting for spatial heterogeneity, provides improved explanatory power and model performance compared to a global Poisson generalised linear model (GLM). We therefore compare GLM and GWR results and validate the best-fitting model using ROC/AUC. The results reveal spatial patterns of forest fires and dominant local drivers, providing actionable insights for provincial and local governments to develop site-specific fire-risk management policies and precautionary measures, with potential applicability to other lowland regions of Nepal.

MATERIAL AND METHODS

Study area

The study area encompasses the entire geographical region of Madhesh Province, located between 26°23'N - 27°28'N latitude and 84°27'E - 86°54'E longitude, with an elevation range of up to 918 meters. It comprises eight districts: Parsa, Bara, Rautahat, Sarlahi, Mahottari, Dhanusha, Siraha, and Saptari. Madhesh Province is bordered by the Shiwalik hills to the north, India to the south, the Koshi river to the east, and Bagmati Pradesh to the west. Forests occupy approximately 27.29 per cent of the province's total land area, with those in the Chure region alone comprising 152,339

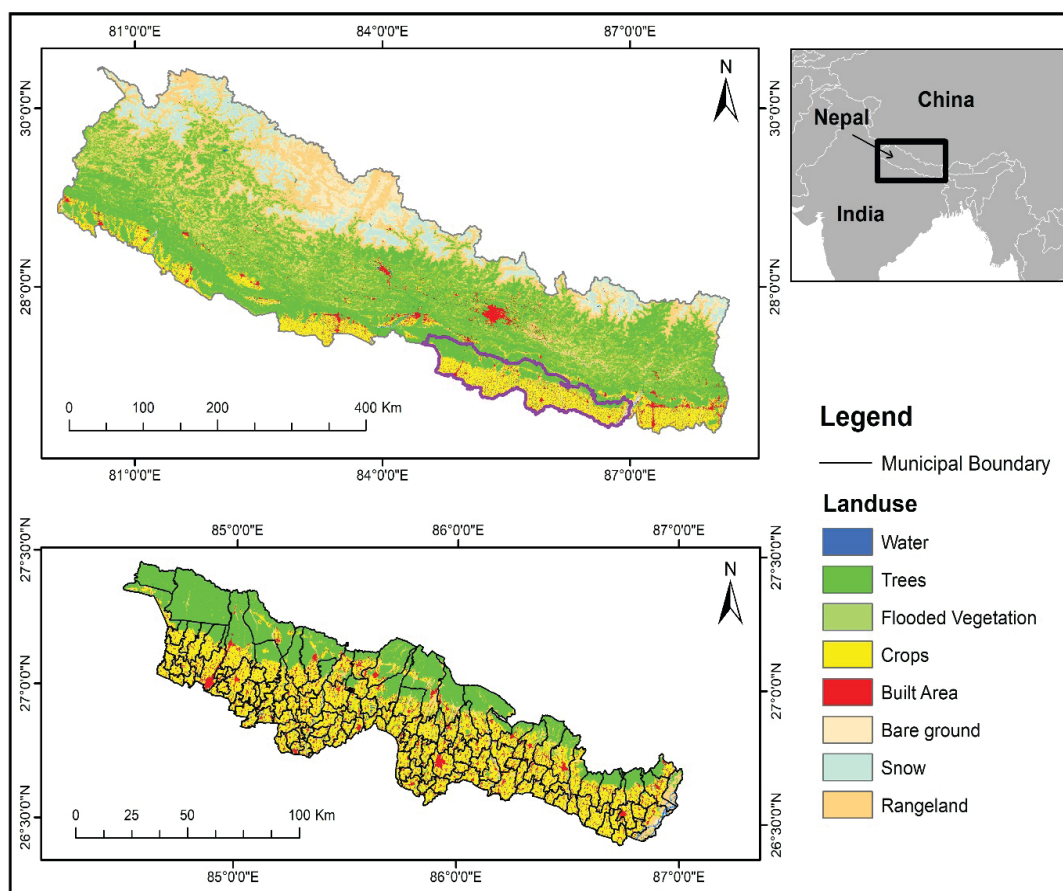


Figure 1: Study area map showing the land cover classes at the local level division within the region

hectares, of the province's total area. Most of the province, nearly 90 per cent of its land area, lies in the lower tropical climate zone, while the remaining part belongs to the upper tropical climate zone. Administratively, the province comprises 136 local units (73 municipalities, 59 rural municipalities, 3 sub-metropolitan cities, and 1 metropolitan city), all of which were used as analytical units in the regression models. In addition, three protected areas within the province, Parsa National Park, Chitwan National Park, and Koshi Tapu Wildlife Reserve, were included among the local units. The GWR method requires a minimum of 20 features for computation and achieves optimal results with larger datasets (Devkota *et al.*, 2014). The number of municipal divisions in the province meets this requirement, as shown in Figure 1.

Data acquisition and processing

The data employed in this study were classified into two categories: forest fire records spanning various time periods, and forest fire drivers selected based on existing literature, as presented in Table 1. In the modelling analysis, forest fire records served as the dependent variable, while other factors were treated as independent variables to identify the key drivers of forest fires. Predictive modelling was then applied to examine the impact of each driver at varying spatial scales.

Dependent variable (Forest fire data)

Historical fire data from the Visible Infrared Imaging Radiometer Suite (VIIRS) product for the period 2012-2023 were obtained from NASA's Fire Information for Resource Management System (FIRMS, <https://firms.modaps.eosdis.nasa.gov/>). The dataset contains the coordinates of the fire location,

the date and time, and the confidence level. For fire incidents, the VIIRS 375m active fire data product provides the highest spatial resolution among freely available fire datasets (Sofan *et al.*, 2020) and is therefore preferred over MODIS (Moderate Resolution Imaging Spectroradiometer) due to its greater accuracy (Coskuner, 2022). Despite some limitations in detecting forest fire due to the dense canopy cover (Giglio *et al.*, 2006), this method is still frequently used for monitoring forest fire. For better accuracy, only points with high and normal confidence levels are considered in order to filter out false alarms (Giglio *et al.*, 2020). This helped eradicating potential smaller fires, which occurred mainly in agricultural area.

As for the burned area, the Terra and Aqua combined MCD64A1 monthly 500 m global gridded data was used. This technique uses 1 km MODIS active fire data combined with 500 m MODIS Surface Reflectance images (Giglio *et al.*, 2020). The data on burned areas for the years 2012-2023 were compiled and analysed using ArcGIS Pro 3.0 (ESRI, 2022) and were used to summarise inter-annual burned-area trends (Figure 3). However, they were not used as a dependent variable in the regression models.

Independent variable

The independent variables used in the study included various terrain factors, weather factors, vegetative factors, and anthropogenic factors, as indicated in Table 1. The Aster global Digital Elevation Model (DEM) with a spatial resolution of 30 meters was obtained from the USGS website (<https://earthexplorer.usgs.gov/>). In addition, slope and aspect were derived using the spatial analyst tool in ArcGIS Pro 3.0. For the weather factor, precipitation data for the years 2000-2018 were downloaded from



Table 1: Datasets used in the study along with relevant and their information

Variables		Data	Classes	Unit	Resolu- tion	Year	Source
Forest fire records (Dependent variables)		2012-2023 fire incidents records (point data)	-	-	375 m	2012- 2023	FIRMS/NASA
		Burnt Area (2012-2023)	-	Km ²	500m	2012- 2023	MODIS (MCD64A1 monthly global grided product)
(Inde- pendent variable)	Weather factor	Land Surface Temperature	Continuous	°C	1000 m	2012- 2023	LAADSDAAC/ MOD11C3
		Wind speed	Continuous	m/s	250 m	2023	Global wind atlas
		Precipitation	Continuous	mm	4500m	2000- 2018	Worldclim
	Terrain factor	Slope	Continuous	°	30 m	2023	USGS Earth Explorer (ASTER GDEM v3)
		Elevation		m	30 m	2023	
		Aspect		°	30 m	2023	
	Vegetative factor	Land cover type (area)	Categorical	m	10 m	2022	ESRI 2022
		Normalised Vegetative Index (NDVI)	Continuous		10 m	2023	Copernicus sentinel 2
		Canopy Height	Continuous	m	30 m	2019	GLAD
	Anthro- pogenic factors	Above ground biomass	Continuous	Mg/ha	100 m	2020	ESA CCI Global Forest AGB
		Population density	Continuous	per km ²	1000 m	2020	SEDAC
		Length of road	Vector	m	-	2015	Department of survey

Worldclim (Fick and Hijmans, 2017). Land Surface Temperature (LST) was derived by filtering the mean monthly values during the pre-monsoon season (March-May) of each year, using compiled MODIS Level-1 B 1-km LST HDF files for 2012-2023 obtained from NASA/MODIS and processed in ArcGIS Pro 3.0. Windspeed data were sourced from the Global Wind Atlas (<https://globalwindatlas.info/>), while land use type information with a spatial resolution of 10 meters was accessed from ESRI (<https://livingatlas.arcgis.com/landcover/>). The Level 1c format Sentinel-2A NDVI data covering May 30, 2021 to March 1, 2023, specifically for the summer period (March-May), were downloaded from the Copernicus Open Access Hub. Previous studies on forest fires in Nepal have shown that the pre-monsoon months represent the peak fire season (Parajuli *et al.*, 2020; Joshi *et al.*, 2024; Adhikari *et al.*, 2025), and we therefore used NDVI from this period to better understand its relationship with fire occurrence. NDVI was then calculated using the near-infrared (NIR) and red spectral bands as shown in the equation (1).

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \quad (1)$$

Canopy height data was obtained from the Global Ecosystem Dynamics Investigation (GEDI) dataset available at (<https://glad.umd.edu/dataset/gedi>). The Above Ground Biomass dataset, generated as part of the European Space Agency's (ESA's) Climate Change Initiative (CCI) program by the Biomass CCI team, was accessed through (<https://climate.esa.int/>).

Forest fires are also influenced by anthropogenic factors like road networks, urban areas, and recreational areas (Ganteaume *et al.*, 2013). Therefore, population density, an anthropogenic variable, was acquired from the

Socioeconomic Data and Application Center (CIESIN, 2018). Road networks were obtained from the Department of Survey through (<https://opendatanepal.com/dataset>), and the length of the road networks was determined using spatial join tools. Once all the variables were acquired, they were resampled to a consistent resolution of 30x30 meters using ArcGIS Pro 3.0 for spatial alignment and consistency during spatial overlay, zonal statistics, and model implementation. Next, the zonal statistics tool was used to calculate the corresponding average values from the raster datasets of all influencing drivers at the municipal level. Subsequently, the drivers were normalised using Equation (2) to account for differences in scale level among the variables. Normalisation facilitates the interpretation and comparison of coefficients by aligning all variables on a common scale, without impacting the model predictions (Zeng and Tao, 2023).

$$\chi_i = \frac{\chi - \chi_{\min}}{\chi_{\max} - \chi_{\min}} \quad \dots\dots\dots (2)$$

Where, χ_i is the normalised value

$\chi_{\max}$ is the maximum value in dataset

$\chi_{\min}$ is the minimum value in the dataset

The Appendix Table 1 shows the variation in forest fire driving variables across the study area, highlighting the need for to apply a GWR model to better capture local patterns and dynamics.

Data Analysis

Multicollinearity test

Since not all variables may contribute equally to forest fire occurrence and some may be independent, the variance inflation factor



(VIF) was computed among variables using the Equation (3) to reduce information redundancy.

$$VIF = \frac{1}{1-R^2} \dots\dots\dots (3)$$

In this context, R² represents the squared multiple correlations of the

independent variable when it is regressed on other independent variables. To address multicollinearity, the variables with VIF>5 were removed (Chatterjee and Hadi, 2015) sequentially (from highest value), and VIF was recalculated after each removal step until all retained variables had VIF<5 (Table 2).

Table 2: Variables selected for modelling forest fire risk. Only the variables with VIF less than 5 were selected for modelling purposes.

Variables	Abbreviation	Before	After
Elevation	E	6.204	
Aspect	A	1.198	1.084
Precipitation	PPT	2.021	1.793
Slope	S	5.687	
Wind speed	WS	1.981	1.857
Canopy height	CH	7.515	4.272
Area under water	AW	5.371	
Forest Area	AF	1.988	1.558
Agriculture Area	AA	1.845	1.753
Built-up Area	AB	1.339	1.27
Bare land area	ABL	5.999	
Rangeland Area	AR	3.202	1.202
Population density	PD	1.646	1.621
Above ground biomass	AGB	7.699	
Normalised difference vegetation index	NDVI	2.677	2.045
Land surface temperature	LST	5.01	4.47
Road length	RL	2.713	2.307

Model

We used both global (GLM) and local (GWR) models across the entire Madhesh province to compare the performance and spatial non-stationery properties of forest fire driving variables. We used incidents from 2012-2022 after filtering incidents with low confidence to reduce false detections and agricultural residue burning.

GLM is the most preferred regression analysis due to its precise prediction and estimation for non-uniform distributed data (Meyers *et al.*, 2012). It uses various types of distributions such as the binary (presence-absence) and Poisson (count). For our study, a GLM was fitted using a Poisson distribution, as it is well-suited for non-negative count data, representing count of fire occurrences in each

feature (Chen *et al.*, 2018). The following is the probability of mass function for the Poisson distribution:

$$P(Y=y) = P(Y=y) = \frac{e^{-\lambda} \lambda^y}{y!} \dots\dots\dots(4)$$

Where y represents count variable, and λ is both the variance and the mean, and is greater than zero. In the Poisson distribution the mean is equal to the variance and over-dispersion is when the variance is greater than mean (Mullahy, 1986; Xiao *et al.*, 2015). We used Arc GIS Pro 3.0 for GLM model selecting the Poisson distribution (ESRI, 2022). The tool uses the explanatory variables (forest fire variables) to predict the count distribution along the features.

Likewise, we employed the GWR Model, a widely discussed and utilised method in various publications (Koutsias *et al.*, 2010; Sá *et al.*, 2011). Unlike the global logistic regression model, which overlooks the spatial non-stationarity of forest fires and their causes, the GWR model exhibited enhanced prediction accuracy and a better fit (Li *et al.*, 2022). This model allowed us to examine the regression coefficients for each location, providing insights into the specific associations between fire incidences and explanatory factors within distinct regions (Koutsias *et al.*, 2010; Sá *et al.*, 2011). The general relationship of GWR is as follows (Brunsdon *et al.*, 1996):

$$y = \beta_0(u, v) + \sum_{j=1}^p \beta_j(u, v)X_j + \varepsilon \dots\dots(5)$$

Where y is a dependent variable, X_j is the j *th* independent variable, p is the number of independent variables, ε is the remaining of

model and β_j is the regression coefficients that are a function of the position of observational points (u, v) .

A total of 136 municipal units were used as features for local observation in the GWR model. The GWR analysis yielded several diagnostic outputs (such as standard errors, influence index, Cook's D statistics, local R^2 statistic, and local standard deviation) and parameter estimates (local coefficients for each independent variable) that were visualised within a GIS environment (Charlton and Fotheringham, 2009). A fixed bi-square kernel was selected to define spatial weights, emphasising nearby observations while limiting the influence of distant ones (Li *et al.*, 2022). Both fixed and adaptive bandwidth approaches were initially evaluated using corrected Akaike Information Criterion (AICc). Finally, the optimal bandwidth was determined using a golden search rule for obtaining the minimum AICc value, and the final model, with 30 fixed neighbours, was used for prediction in Arc GIS 3.0 (ESRI, 2022). Then we used the spatial autocorrelation (global Moran's I) tool on residuals for assessing biasness and dispersion (Comber *et al.*, 2023; Yu *et al.*, 2022). The model's performance was assessed using Receiver Operating Characteristics (ROC) curves and Area Under Curve (AUC) values which ranges from 0-1 with higher values indicating better results (Flach, 2016; Hosmer, 2013). We used 2012-2022 fire incidents for modelling, while fire occurrences in 2023 were used exclusively for validation. The ArcSDM tool was used to validate the final predicted outputs from both models using ArcGIS Pro 3.0. Finally, the outputs for the fire risk maps were prepared using the Natural Jenks method to classify risk levels.

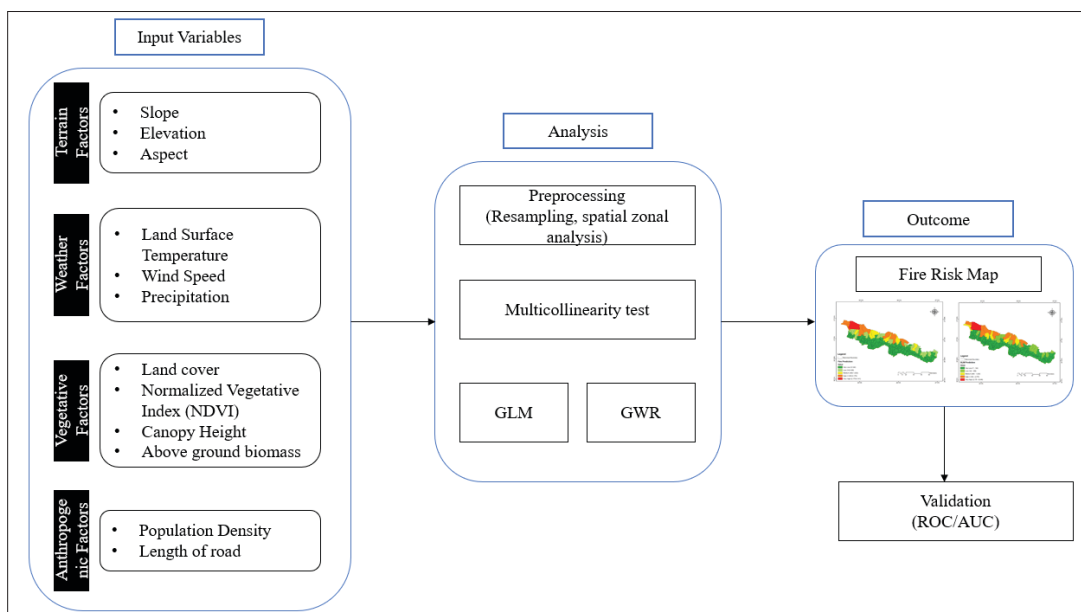


Figure 2: Methodological framework of the research

RESULTS

Trend of forest fire in Madhesh Province

Between 2012 and 2023, Madhesh Province experienced a significant number of fire incidents, with a total of 27,594 cases, resulting in a cumulative burnt area of 3460.52 km². On an annual average, the province experienced approximately 2299 fire incidents and a burnt area of 288.38 km². 2021 was the peak year for fire incidents, with a staggering 3743 cases, closely followed by 2016, which recorded 3406 incidents. In addition, 2021 recorded the highest burnt area, reaching 465.23 km², while 2014 ranked just behind with 461.31 km² (Figure 3). These statistics highlight the substantial impact and variability of fire incidents and burnt area within Madhesh Province over the study period. These findings emphasise the significant impact of fire occurrences on the affected areas. The data shown in Figure

3 offer valuable insights into the changing patterns of burnt area and fire incidence over the years.

Forest fire driving variables

The GLM model showed that 11 variables were significant (Appendix Table 2), with only the built-up area being insignificant. In contrast, the GWR model demonstrated significant results for variables that varied according to the features. Figure 4 illustrates the estimates of forest fire driving variables for both the GLM and GWR models. Several variables, including Aspect, Canopy Height, LST, rangeland area, agricultural area, and NDVI, showed positive estimates in both models. Windspeed was consistently negative across both GLM and GWR. However, Population Density exhibited a positive relationship in the GLM but a negative one in GWR, while Road Length was negative in the GLM but positive in the GWR. Notably, the forest area showed a positive estimated value

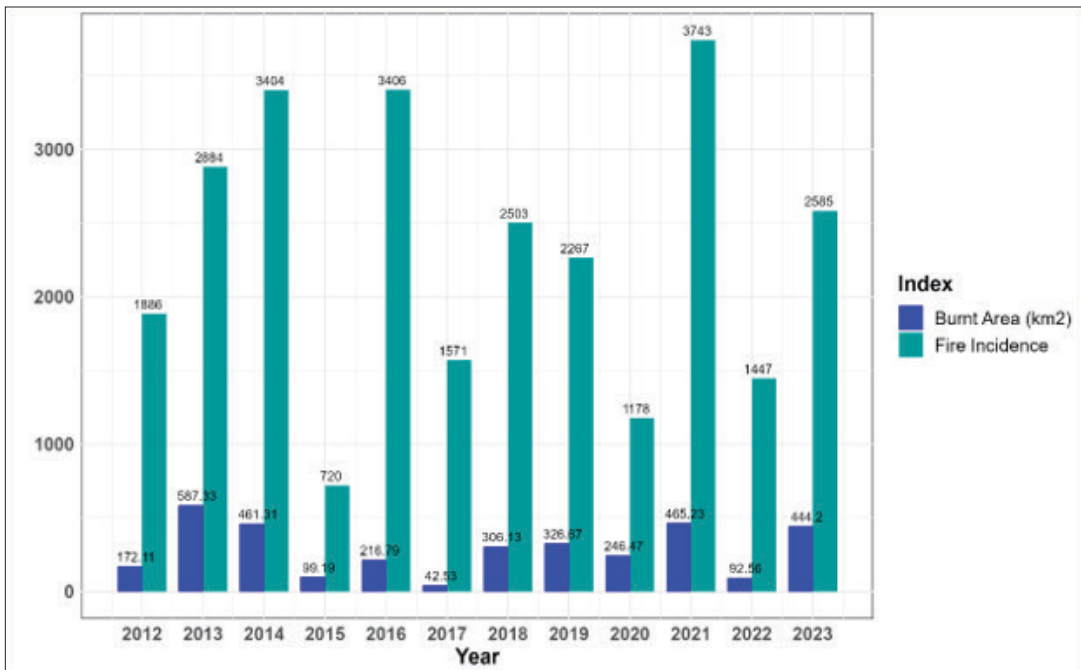


Figure 3: Forest fire incidents and burnt area in Madhesh province.

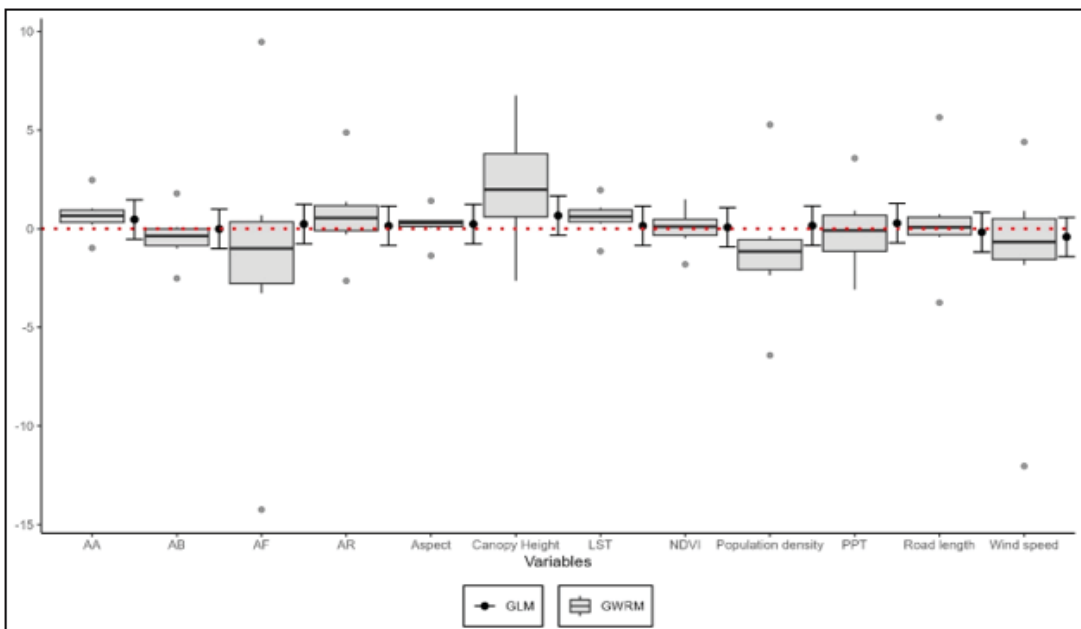
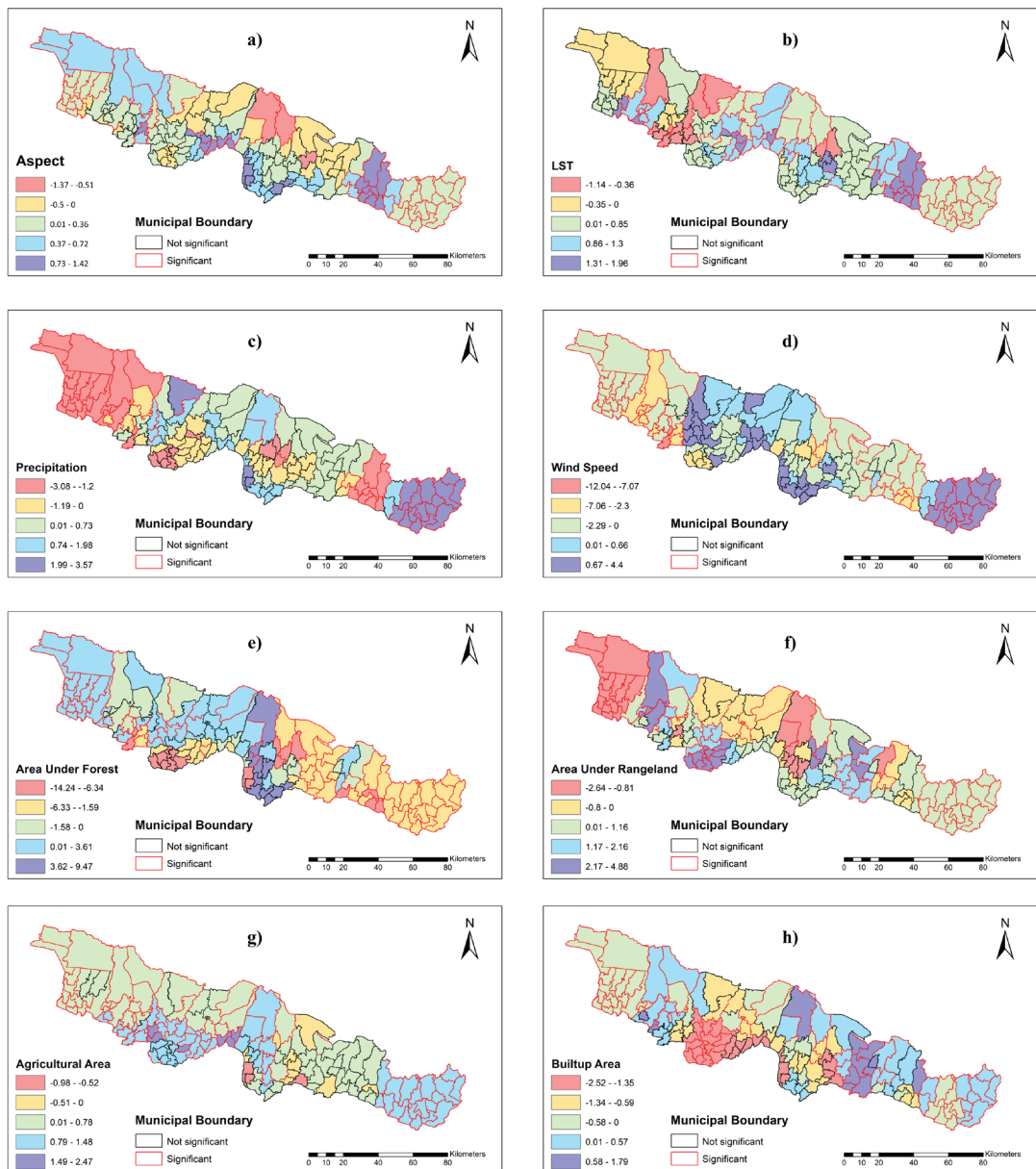


Figure 4: Estimates for forest fire driving variables from GLM and GWR model

in the GLM, whereas in the GWR model, despite a mean estimated value of -1.315, it took on both positive and negative values depending on the region, reflecting spatial variability.

To analyse the spatial non-stationarity of the variables in the GWR, a spatial mapping of

the estimates was conducted. Additionally, to identify the significance of each variable, t-test values were calculated at a 5% level of significance. Based on these test values, municipalities were categorised as either significant or insignificant, with the results illustrated in the spatial map (Figure 5).



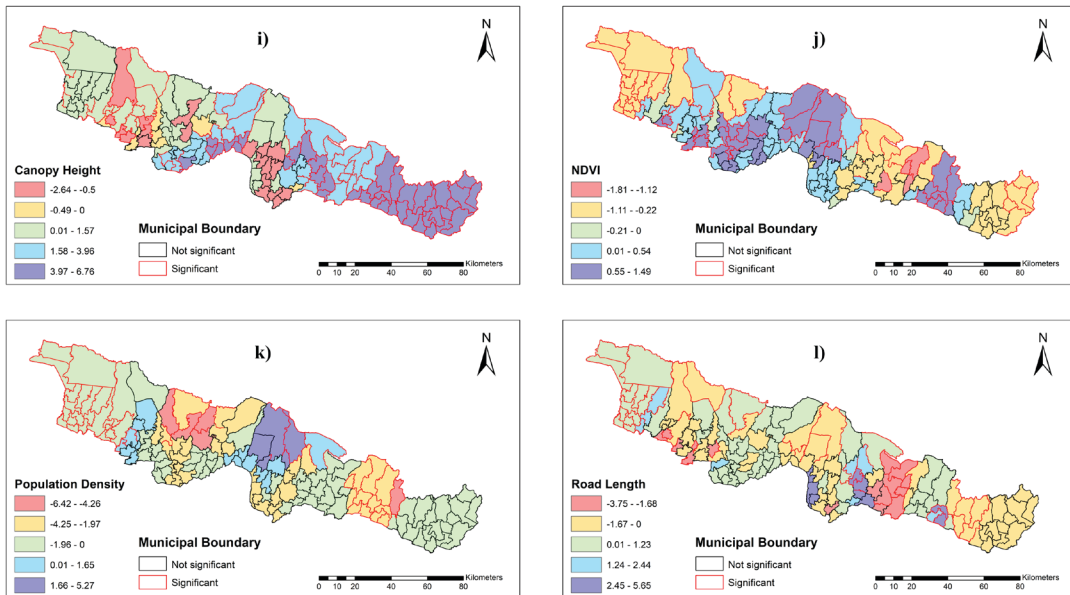


Figure 5: Spatial distribution of GWR estimates with significant (red outline) and insignificant municipalities (black outline): a) Aspect, b) Land surface temperature, c) Precipitation, d) Wind speed, e) Forest area, f) Rangeland area, g) Agricultural area, h) Built-up area, i) Canopy height, j) NDVI, k) Population density and l) Road length

Forest fire occurrence prediction map

The model used the variables and generated a final predicted map of forest fire occurrence, as shown in Figure 6. To depict the risk levels across the area, the predicted number of fire incidents was classified into five distinct risk categories. As illustrated in Table 3 and Figure 6, a clear difference in the predictions of the two models is apparent. The GWR model predicted a larger area of low and medium risk, whereas the GLM model predicted a larger area of very low risk (52.73%) compared to the GWR model (50.18%), indicating that the GLM tends to classify more areas as lower risk. Interestingly, both models predicted a similar high-risk area, with over 6000 fire incidents (Figure 6), is located in a protected national park. Other differences in the risk area suggest

that GWR may capture local variations in fire risk more effectively, especially in the low to medium risk categories.

Table 3: Fire risk area Madhesh province

	GLM area (sq. km)	GWR area (sq. km)	GLM % Of risk area	GWR % Of risk area
Very low	5098	4846	52.77	50.18
Low	1486	1654	15.38	16.88
Medium	798	1012	8.26	10.53
High	1804	1674	18.67	17.45
Very High	475	475	4.92	4.96
Total	9661	9661	100.00	100.00

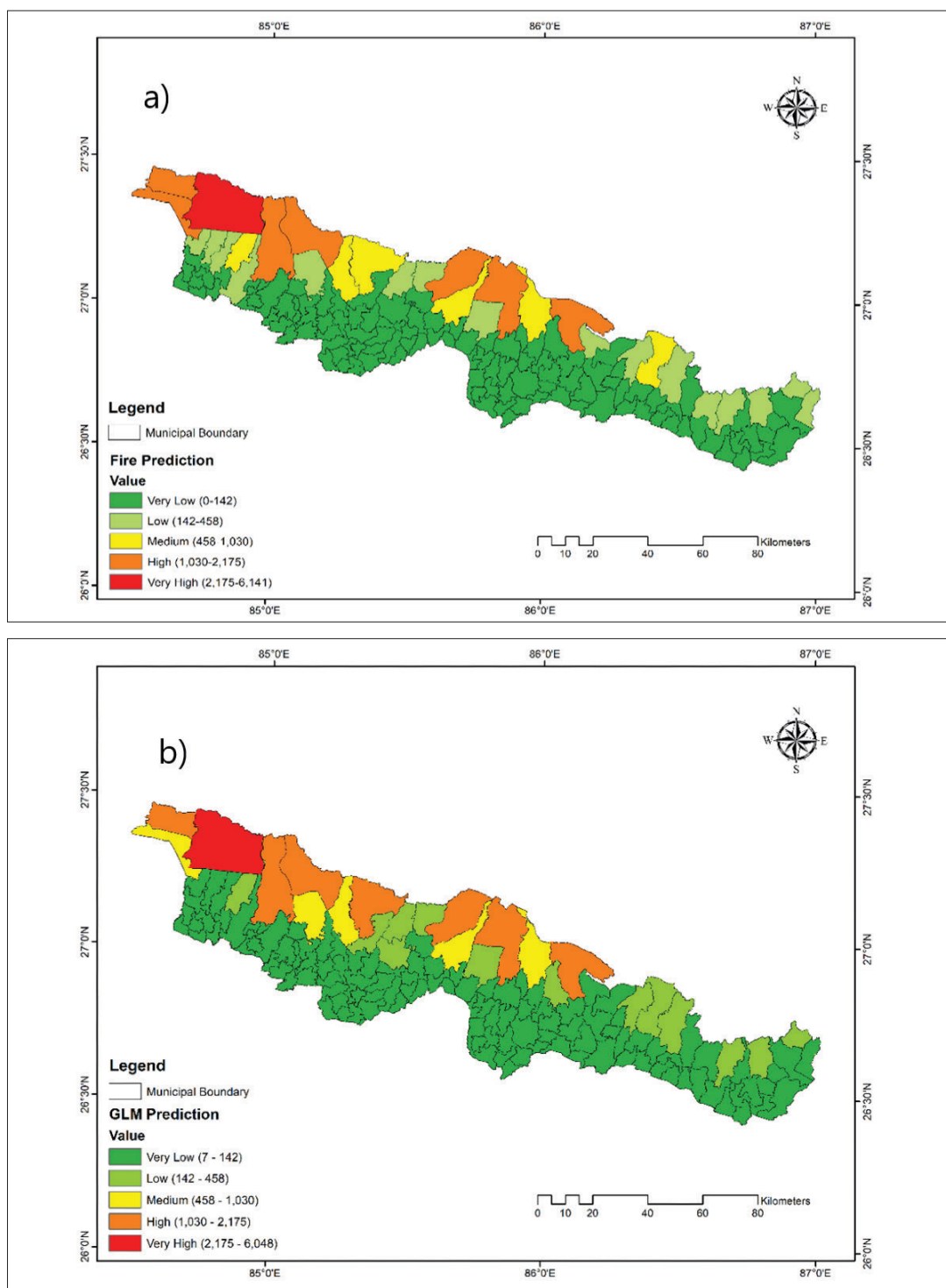


Figure 6: Fire occurrence prediction map of Madhesh province a) GWR model b) GLM model

Model diagnostic and validation

Model diagnostic results show that both the local and global models explained the variation very well. The global model assuming spatial homogeneity explains approximately 91.3 per cent of the variability in the response variable which is increased to 99.4 per cent by the local model utilising spatial heterogeneity of GWR. Moreover, the model shows a 92.7 per cent improvement when using local models instead of global models. The low AICc value of 942.849 also confirms the adequacy of the model fit, indicating its ability to balance goodness-of-fit and complexity for GWR.

Table 4: Model diagnostic for global (GLM) and local (GWR) model

Deviance explained by the global model (non-spatial)	0.913
Deviance explained by the local model	0.994
Deviance explained by the local model vs global model	0.927
AICc	942.849
Effective Degrees of Freedom	142.638
Adjusted Critical Value of Pseudo-t Statistics	2.665

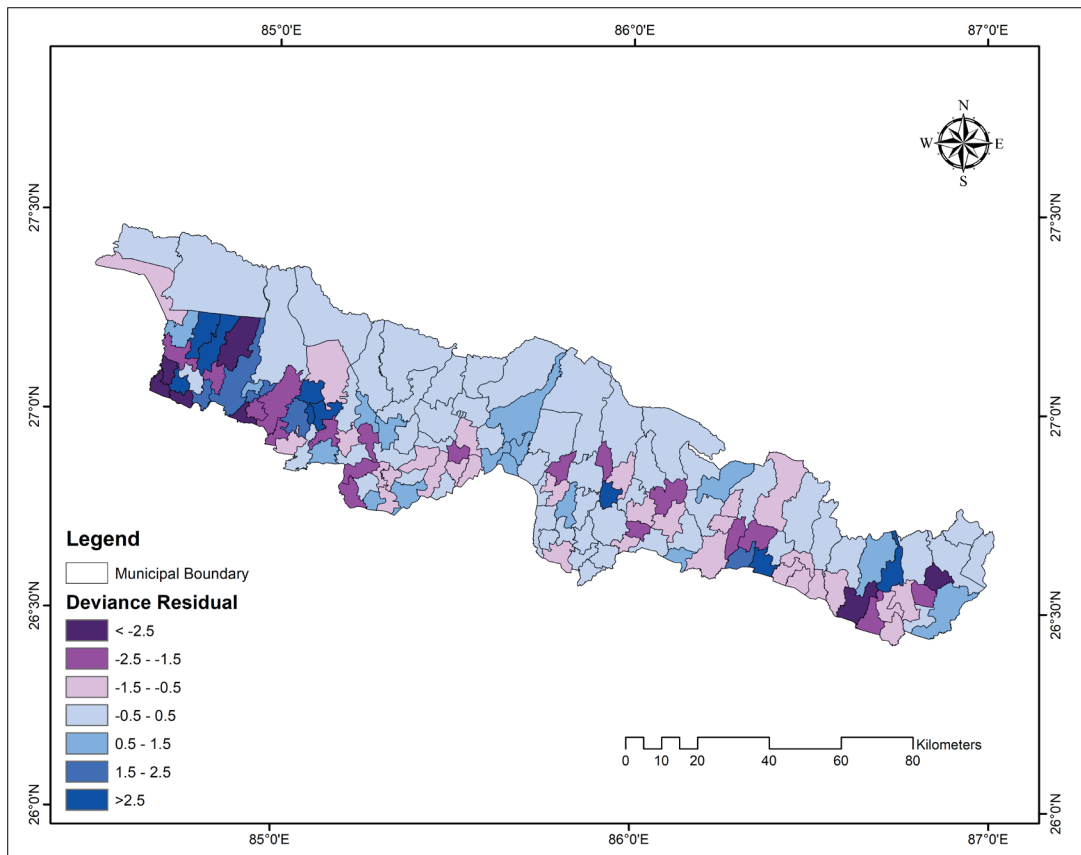


Figure 7: Map showing residual values across various municipal level from GWR model

Figure 7 displays the deviance residual map, illustrating the residual values across various municipal levels for GWR. In order to enhance the model and examine any potential clustering of the residuals, Moran's Index was employed for this study. The test results indicate that the pattern of residuals does not exhibit statistically significant spatial clustering. Therefore, it is interpreted as a random pattern.

In addition, using ROC method, we obtained an AUC value of 0.825 for GWR, which corresponds to an accuracy rate of 82.5 per cent. But the GLM performed poorly compared to GWR with an AUC value of 0.769. This outcome indicates that the results produced by the prediction map are deemed accurate based on the evaluation performed.

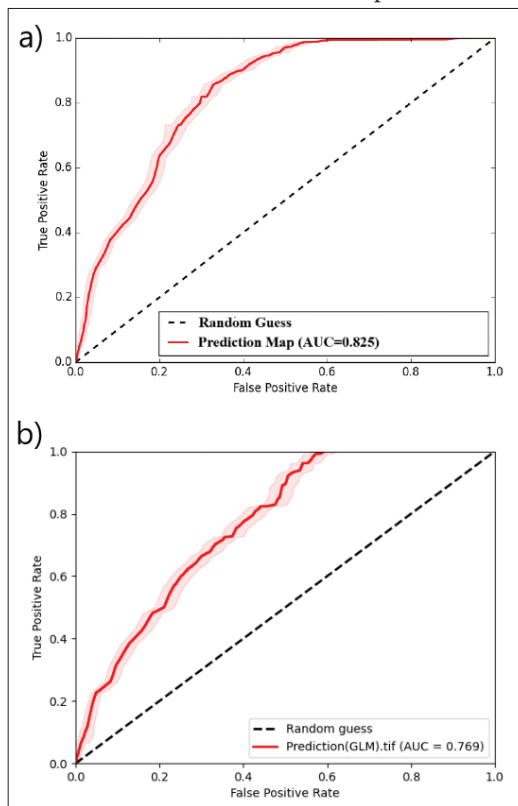


Figure 8: ROC/AUC of prediction map
a) GWR model b) GLM model

DISCUSSION

Variable influence and spatial heterogeneity

Throughout the 12-year period, the burnt area fluctuated, with some years experiencing heightened destruction, while others saw a reduction. These fluctuations in burnt area and fire incidence demonstrate the unpredictable nature of fire occurrences. They also highlight the need for effective fire management and prevention strategies to mitigate the devastating impact of fires on the environment, ecosystems, and human lives. The effect of different drivers is discussed below.

Vegetation

In this study, the vegetation layers- forest area, rangeland, agriculture, NDVI and canopy height were used. All the variables revealed positive relations with both GLM and GWR models, but forest area showed a negative relationship with the GWR model. The study by Joshi *et al.* (2024), using a GLM model in the Chure region of Nepal, showed that an increase forest area was associated with a higher probability of fire occurrence, likely due to greater fuel availability in larger forested areas. While this trend is evident in our GLM results, the model does not capture spatial heterogeneity. The GWR model estimates for forest area ranged from 9.472 to -14.240 with an average estimate of -1.315 showing negative influence overall (Figure 5). The negative impact was observed in municipalities lying in the southern part dominated by agricultural zones. In the GLM, NDVI showed a positive relationship with forest fires, consistent with the results of Quan *et al.* (2022). However, the GWR results suggest a more nuanced, spatially

varying relationship. Areas with lower NDVI values, often indicative of vegetation under stress, such as drought conditions or sparse cover, were more susceptible to forest fires, likely because drier vegetation has lower resilience to ignition and fire spread (Chuvieco *et al.*, 2010), as illustrated in Figure 5(j). In addition, the province's forest consists of both deciduous species, such as Sal (*Shorea robusta*), and evergreen species, such as Sissoo (*Dalbergia sissoo*). Deciduous species shed their leaves seasonally, which reduces NDVI values and increases the risk of ground fires, as the accumulation of dry leaf litter on the forest floor provides abundant fuel (Aryal *et al.*, 2017).

For canopy height and rangeland positive estimates were observed in both models. Similar results for fire susceptibility in rangeland were also observed in the study of Joshi *et al.* (2024). Notably, canopy height had the highest average estimate value (0.66) and (2.04) for GLM and GWR respectively, among all the variables. Estimates of these variables also differed from -0.836 to 5.067, with most of the negative estimates concentrated in the western part of the province, pre-dominated by the protected area (Figure 5i). Interestingly, the canopy height distribution is also higher in the west and lower in the east of the province. This may indicate the possibility of ground fire being more prevalent but further research would be required to confirm it.

Climate and topography

As for climatic variables, LST displayed a significant and positive correlation with forest fire occurrences for both the GLM and GWR models. This finding aligns with previous research conducted by Guo *et al.* (2016) and Jolly *et al.* (2015). Summer

temperatures in Madhesh province ranges from 32-38 degree Celsius (Fick and Hijmans, 2017). Higher surface temperatures lead to increased evapotranspiration conditions in trees, making the forest understory dry and more vulnerable (Li *et al.*, 2022) which in turn increases the probability of forest fires. In the case of precipitation, the GLM shows a positive relationship with forest fire occurrence. However, the GWR model reveals spatial variability, with a positive association towards the eastern part of the study area and a more negative influence of the variable in western region. In terms of topography, Madhesh province comprises Bhabhar, Dun Valley, and Chure in the north, which serve as sources of numerous rivulets and springs. Overall, occasional precipitation has been shown to reduce forest fire occurrence in Nepal (Bhujel *et al.*, 2017), whereas fire activity tends to increase in drier regions (Lafon and Quiring, 2012). However, areas with high precipitation and abundant fuel loads may also be susceptible to fire (Verhoeven *et al.*, 2020), while low precipitation can increase chances of drought and dry fuels, facilitating rapid spread of fire (Janizadeh *et al.*, 2023). Since the eastern region receives more rainfall than the western region (Mishra *et al.*, 2023), the GWR model is better at capturing this spatial heterogeneity than the GLM model. Although the effect of aspect was found to be significant by the GLM model, the GWR results reveal spatial variability, showing a positive relationship in the southwestern regions and a negative relationship in other areas, indicating that north-facing slopes may be more susceptible to fire. The study by Li *et al.* (2022), using the GWR model, suggests a similar trend at the global spatial scale. Furthermore, higher wind speeds can transport moist air from nearby water bodies, increasing humidity and reducing vegetation susceptibility to ignition.

This likely explains the predominantly negative relationship between wind speed and forest fire occurrence observed across a big part of the study area.

Anthropogenic drivers

In this analysis, key anthropogenic factors including population density, built-up area, and road length were considered. The GLM indicates a uniformly positive impact of population density, while road length and built-up area were not found to be significant. Fires near residential areas are often actively managed and suppressed by locals, which may explain why anthropogenic variables are often found to be less influential (Mishra *et al.*, 2023). In contrast, the GWR shows clear spatial variability in these associations. All these variables show negative relationships in the southern, densely populated regions (Figure 5), but positive relationships in the more forest dominated areas, particularly in the Chure region of the province. This supports the findings of Hussin *et al.* (2008), indicating that fire-setting activities are more likely to occur farther from settlements.

Forest governance mechanisms

The forests of Madhesh are managed under the community forest program, and local communities depend on these resources to meet their daily needs, including fodder, fuelwood and timber (Shah *et al.*, 2022). Furthermore, to ensure the sound growth of yield, silvicultural management practices (weeding, thinning, pruning, controlled burning, etc.) are routinely implemented, resulting in a regular outflow of forest biomass (Dahal and Cao, 2017). Community forest user groups (CFUGs) and divisional forest offices (DFOs) are also pro-actively engaged in protecting these forests from fire, which helps to explain the negative relationship

observed in some areas. However, as shown in Figure 5 (e), a positive relationship exists in the western part of Madhesh province. This region pre-dominantly falls under the protected area regime, including Parsa National Park, which covers an area of 637.37 sq. km (DNPWC, 2019). Under the National Parks and Wildlife Conservation Act of 1974, the collection or removal of any forest vegetation is prohibited in protected areas. Consequently, the accumulation of biomass in these regions can increase fire susceptibility during the dry season, explaining the positive relationship shown by the GWR model. In the context of agricultural areas (AA) there was a strong positive correlation with fire risk in both models. This aligns with the findings of Saikawa *et al.* (2020), who reported that the increasing prevalence of agricultural residue burning contributed to the spread of fire into adjacent forested areas.

Predictive model performance of GLM and GWR

Both the GLM and GWR models were used to predict the number of forest fires for the final forecast. Previous studies on the forest fire risk in Nepal have consistently identified the Terai Arc Landscape (TAL) region as the area with the highest risk (Parajuli *et al.*, 2020; Qadir *et al.*, 2021). Our research aligns with these findings and highlights a similar vulnerability in the Madhesh province. For validation the AUC value for both models was calculated. Figure 8 shows that the AUC value of the prediction map developed using GWR (AUC=0.825) is higher than that of the GLM (AUC=0.765), indicating the higher efficiency of the local model over the global model. Our findings are consistent with Cao *et al.* (2021), who showed that the GWR model provides a better fit than global models, producing more realistic spatial distributions

of forest fires. In our study, the GWR model also explains higher deviance than global GLM model. We considered the possibility of overfitting, however, the improved AICc, lack of spatial autocorrelation in residuals, and increased ROC/AUC values from independent validation indicate that GWR inherently retains the spatial heterogeneity. Moreover, the prediction maps generated by GWR closely resemble those from the GLM at the administrative unit level, but provide greater spatial detail, demonstrating that GWR refines the global model rather than contradicting it. This approach facilitates the development of tailored strategies for different municipalities, enabling more effective measures against forest fires. Future studies on spatial prediction of forest fires need to consider the heterogeneity in scales among different drivers (Li *et al.*, 2022).

Management and livelihood implications

The fire occurrence prediction map (Figure 6) clearly indicates the municipalities that are at higher risk of forest fires. Municipal government, forest department and other relevant agencies can use these findings to reduce damage to forest resources and minimise risks to the livelihoods of people dependent them. The DFOs and CFUGs can strategically adapt and implement fire lines in higher risk areas, with targeted efforts to segregate forest from settlement zones (Bhujel *et al.*, 2022). Similarly, several studies in the Asian context recommend the use of controlled burning in high-risk areas to reduce fuel loads and lower the potential intensity of fires during seasonal peaks (Parajuli *et al.*, 2022, Wang *et al.*, 2023). The models used in this study indicate that around 22 per cent of Madhesh province falls under high risk of fire, although the drivers vary spatially.

Provincial and municipal governments can use this information to allocate site specific resources and budgets during their annual planning. Priority measures could include awareness programs, distribution of firefighting equipment and tools, and insurance policies for staff involved in fire risk management, strategies that have proven to be effective at the community level (Parajuli *et al.*, 2022). This research categorised municipalities according to their level of fire risk, enabling the prioritisation of targeted awareness programs and the implementation of early warning systems based on risk levels. SMS alerts, drill simulations and school/community awareness programs are for example some common early warning practices prevalent in south Asian context (Shah *et al.*, 2023). The province includes both, community forests which are governed and utilised to meet productive requirements of forest dependent livelihoods, and protected areas (Parsa National Park), conserved and managed for biodiversity protection. The municipal-scale fire risk prediction maps developed in this study can support Madhesh province in allocating and justifying resources for fire control across both protected and productive forest areas.

LIMITATIONS

The study provides insights on spatial drivers of forest fires and the non-stationary nature of these variables. While we studied the long-term patterns from 2012-2022, it does not explicitly account for short-term variations in climatic drivers, land-use practices, or fire management interventions. Future studies incorporating seasonal modelling frameworks could provide additional insights into these dynamics. Also, the inclusion of additional variables, like fuel moisture content, lightning-induced ignitions, and

controlled burning practices could further enhance the prediction of risk maps. As GWR estimates spatially varying parameters, model complexity increases relative to the number of observations. Although bandwidth selection and diagnostic checks were used to mitigate overfitting in this study, some degree of uncertainty may remain in local estimates, warranting cautious interpretation and more detailed studies.

CONCLUSION

The forest fire drivers in Madhesh province exhibited non stationery characteristics varying significantly on a spatial scale. We used both GLM and GWR models to predict forest fire scenarios, with the GWR model outperforming the GLM model, as indicated by the AIC values and AUC curves. The analysis demonstrates that aspect, LST, rangeland and agricultural area, canopy height, and NDVI values are positively related with fire risk, whereas precipitation, wind, vegetation coverage, and built-up area exhibit negative associations. The resulting prediction map indicates that around 22 per cent of Madhesh is exposed to high fire risk.

These insights have important implications for forest fire management planning. We recommend that GWR-based risk maps be used to guide local governmental and institutional bodies in designing context-specific interventions, such as directing controlled burning practices, building fire lines in high-risk zones, etc. Policymakers in the lowland regions of Nepal can integrate these highresolution risk maps into provincial land-use planning and community forest operational plans (CFOPs), as well as use them to allocate firefighting resources based on local needs, thereby enhancing preparedness and strengthening the resilience

of local communities. For future research, we recommend incorporating socio-institutional variables (e.g., governance, law enforcement, community forest user group capacity, etc.) to better capture the human dimensions of fire risk. In addition, developing models that incorporate climate change scenarios would allow assessment of how shifting temperature and precipitation regimes may alter the spatial distribution of fire-prone zones over time.

Funding: The authors received no specific funding for this work

Competing interests: The authors have declared that no competing interests exist.

Declaration on AI-assisted technologies: AI-assisted tools were used only for language editing and improvement of sentence structure during manuscript preparation. The authors take full responsibility for the content of the manuscript.

REFERENCES

- Adhikari, G., Joshi, K. P., Chand, D., Ghimire, A., & Mahara, S. (2025). Spatial dynamics and risk mapping of forest fires in Madhesh Province, Nepal: A multi-criteria decision approach. *Journal of Environment and Natural Resources*, 23(1), 80–94. <https://doi.org/10.32526/ennrj/23/20240124>
- Aponte, C., De Groot, W. J., & Wotton, B. M. (2016). Forest fires and climate change: Causes, consequences and management options. *International Journal of Wildland Fire*, 25(8), i–ii. <https://doi.org/10.1071/WFv25n8-FO>
- Aryal, B., Bhattarai, B. P., Pandey, M., & Devkota, S. (2017). Carbon sequestration in a fired ecosystem of *Pinus roxburghii* forest in Rasuwa District, Nepal. *Tropical Plant Research*, 4(2), 297–306. <https://doi.org/10.22271/tp.r.2017.v4.i2.039>
- Bajracharya, K. (2002). Forest fire situation in Nepal. *International Forest Fire News*, 26, 84–86.

- Bhattarai, N., Dahal, S., Thapa, S., Pradhananga, S., Karki, B. S., Rawat, R. S., Windhorst, K., Watanabe, T., Thapa, R. B., & Avtar, R. (2022). Forest fire in the Hindu Kush Himalayas: A major challenge for climate action. *Journal of Forest and Livelihood*, 21(1), 14–31.
- Bhujel, K. B., Maskey-Byanju, R., & Gautam, A. P. (2017). Wildfire dynamics in Nepal from 2000–2016. *Nepal Journal of Environmental Science*, 5, 1–8. <https://doi.org/10.3126/njes.v5i0.22709>
- Bhujel, K., Sapkota, R., & Khadka, U. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Brunsdon, C., Fotheringham, A. S., & Charlton, M. E. (1996). Geographically weighted regression: A method for exploring spatial nonstationarity. *Geographical Analysis*, 28(4), 281–298. <https://doi.org/10.1111/j.1538-4632.1996.tb00936.x>
- Cao, Q., Zhang, L., Su, Z., Wang, G., Sun, S., & Guo, F. (2021). Comparing four regression techniques to explore factors governing the number of forest fires in Southeast China. *Geomatics, Natural Hazards and Risk*, 12(1), 499–521. <https://doi.org/10.1080/19475705.2021.1884609>
- Cardille, J. A., Ventura, S. J., & Turner, M. G. (2001). Environmental and social factors influencing wildfires in the Upper Midwest, United States. *Ecological Applications*, 11(1), 111–127. [https://doi.org/10.1890/1051-0761\(2001\)011\[0111:EASFIW\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011[0111:EASFIW]2.0.CO;2)
- Charlton, M., Fotheringham, A. S., & Brunsdon, C. (2009). *Geographically weighted regression*. National Centre for Geocomputation, National University of Ireland Maynooth.
- Chatterjee, S., & Hadi, A. S. (2015). *Regression analysis by example*. John Wiley & Sons. <https://doi.org/10.1002/0470055464.ch4>
- Chen, W., Qian, L., Shi, J., & Franklin, M. (2018). Comparing performance between log-binomial and robust Poisson regression models for estimating risk ratios under model misspecification. *BMC Medical Research Methodology*, 18(1), 63. <https://doi.org/10.1186/s12874-018-0519-5>
- Chen, Y., Hall, J., van Wees, D., Andela, N., Hantson, S., Giglio, L., van der Werf, G. R., Morton, D. C., & Randerson, J. T. (2023). Multi-decadal trends and variability in burned area from the fifth version of the Global Fire Emissions Database (GFED5). *Earth System Science Data*, 15, 5227–5259. <https://doi.org/10.5194/essd-15-5227-2023>
- Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M. P., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J. R., Herrera, M. A., & Zamora, R. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, 221(1), 46–58. <https://doi.org/10.1016/j.ecolmodel.2008.11.017>
- CIESIN. (2018). *Gridded Population of the World, Version 4 (GPWv4): Population density, revision 11*. NASA Earthdata.
- Comber, A., Brunsdon, C., Charlton, M., Dong, G., Harris, R., Lu, B., Lu, Y., Murakami, D., Nakaya, T., Wang, Y., & Harris, P. (2023). A route map for successful applications of geographically weighted regression. *Geographical Analysis*, 55(1), 155–178. <https://doi.org/10.1111/gean.12316>
- Coskuner, K. A. (2022). Assessing the performance of MODIS and VIIRS active fire products in the monitoring of wildfires: A case study in Turkey. *iForest: Biogeosciences and Forestry*, 15(2), 85–94. <https://doi.org/10.3832/ifer3754-015>
- Dahal, D. S., & Cao, S. (2017). Sustainability assessment of community forestry practices in Nepal: Literature review and recommendations to improve community management. *Proceedings of the National Academy of Sciences*, 87(1), 1–11. <https://doi.org/10.1007/s40011-015-0627-5>
- Devkota, M., Hatfield, G., & Chintala, R. (2014). Effect of sample size on the performance of ordinary least squares and geographically weighted regression. *British Journal of Mathematics & Computer Science*, 4(1), 1–21. <https://doi.org/10.9734/BJMCS/2014/6050>

- Dhakal, M., Bhatta, B., Lamichhane, P., & Parajuli, A. (2024). Synergistic approaches in forest fire risk mapping using fuzzy AHP and machine learning models in the Chure Tarai Madhesh Landscape (CTML) of Nepal. *Geomatics, Natural Hazards and Risk*, 15(1), 2436540. <https://doi.org/10.1080/19475705.2024.2436540>
- Department of National Parks and Wildlife Conservation. (2019). *Parsa National Park*. https://dnppwc.gov.np/protected_areas/details/parsawildlifereserve
- Environmental Systems Research Institute. (2022). *ArcGIS Pro (Version 3.0)* [Software]. <https://www.esri.com/>
- Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302–4315. <https://doi.org/10.1002/joc.5086>
- Flach, P. A. (2016). ROC analysis. In C. Sammut & G. I. Webb (Eds.), *Encyclopedia of machine learning and data mining* (pp. 1–8). Springer. https://doi.org/10.1007/978-1-4899-7502-7_739-1
- Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M., & Lampin, C. (2013). A review of the main driving factors of forest fire ignition over Europe. *Environmental Management*, 51(3), 651–662. <https://doi.org/10.1007/s00267-012-9961-z>
- Giglio, L., Schroeder, W., & Hall, J. V. (2020). *MODIS collection 6 active fire product user's guide revision C*. NASA.
- Giglio, L., van der Werf, G. R., Randerson, J. T., Collatz, G. J., & Kasibhatla, P. (2006). Global estimation of burned area using MODIS active fire observations. *Atmospheric Chemistry and Physics*, 6(4), 957–974. <https://doi.org/10.5194/acp-6-957-2006>
- Guo, F., Wang, G., Su, Z., Liang, H., Wang, W., Lin, F., & Liu, A. (2016). What drives forest fire in Fujian, China? Evidence from logistic regression and random forests. *International Journal of Wildland Fire*, 25(5), 505–519. <https://doi.org/10.1071/WF15121>
- Hussin, Y. A., Matakala, M., & Zagdaa, N. (2008). The applications of remote sensing and GIS in modeling forest fire hazard in Mongolia. In *XXI ISPRS Congress 2008: Silk Road for Information from Imagery*.
- Inan, M., Bilici, E., & Akay, A. E. (2017). Using airborne LiDAR data for assessment of forest fire fuel load potential. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-4/W4, 255–258. <https://doi.org/10.5194/isprs-annals-IV-4-W4-255-2017>
- Janizadeh, S., Bateni, S. M., Jun, C., Im, J., Pai, H. T., Band, S. S., & Mosavi, A. (2023). Combination four different ensemble algorithms with the generalized linear model (GLM) for predicting forest fire susceptibility. *Geomatics, Natural Hazards and Risk*, 14(1), 2206512. <https://doi.org/10.1080/19475705.2023.2206512>
- Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., & Bowman, D. M. J. S. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6(1), 7537. <https://doi.org/10.1038/ncomms8537>
- Joshi, K. P., Adhikari, G., Bhattarai, D., Adhikari, A., & Lamichhane, S. (2024). Forest fire vulnerability in Nepal's Chure region: Investigating the influencing factors using generalized linear model. *Heliyon*, 10(7), e28525. <https://doi.org/10.1016/j.heliyon.2024.e28525>
- Kolanek, A., Szymanowski, M., & Raczky, A. (2021). Human activity affects forest fires: The impact of anthropogenic factors on the density of forest fires in Poland. *Forests*, 12(6), Article 728. <https://doi.org/10.3390/f12060728>
- Koutsias, N., Martínez-Fernández, J., & Allgöwer, B. (2010). Do factors causing wildfires vary in space? Evidence from geographically weighted regression. *GIScience & Remote Sensing*, 47(2), 221–240. <https://doi.org/10.2747/1548-1603.47.2.221>
- Lafon, C. W., & Quiring, S. M. (2012). Relationships of fire and precipitation regimes in temperate forests of the eastern United States. *Earth Interactions*, 16(11), 1–15. <https://doi.org/10.1175/2012EI000442.1>

- Li, W., Xu, Q., Yi, J., & Liu, J. (2022). Predictive model of spatial scale of forest fire driving factors: A case study of Yunnan Province, China. *Scientific Reports*, 12(1), 19029. <https://doi.org/10.1038/s41598-022-23697-6>
- Maingi, J. K., & Henry, M. C. (2007). Factors influencing wildfire occurrence and distribution in eastern Kentucky, USA. *International Journal of Wildland Fire*, 16(1), 23–33. <https://doi.org/10.1071/WF06007>
- Martínez-Fernández, J., Chuvieco, E., & Koutsias, N. (2013). Modelling long-term fire occurrence factors in Spain by accounting for local variations with geographically weighted regression. *Natural Hazards and Earth System Sciences*, 13(2), 311–327. <https://doi.org/10.5194/nhess-13-311-2013>
- Matin, M. A., Chitale, V. S., Murthy, M. S. R., Uddin, K., Bajracharya, B., & Pradhan, S. (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(4), 276–286. <https://doi.org/10.1071/WF16056>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19(1), 3. <https://doi.org/10.1186/s42408-022-00162-3>
- Mullahy, J. (1986). Specification and testing of some modified count data models. *Journal of Econometrics*, 33(3), 341–365. [https://doi.org/10.1016/0304-4076\(86\)90002-3](https://doi.org/10.1016/0304-4076(86)90002-3)
- Myers, R. H., Montgomery, D. C., Vining, G. G., & Robinson, T. J. (2012). *Generalized linear models: With applications in engineering and the sciences*. John Wiley & Sons.
- Parajuli, A., Gautam, A. P., Sharma, S. P., Bhujel, K. B., Sharma, G., Thapa, P. B., Bist, B. S., & Poudel, S. (2020). Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. *Geomatics, Natural Hazards and Risk*, 11(1), 2569–2586. <https://doi.org/10.1080/19475705.2020.1853251>
- Parajuli, A., Gautam, A. P., Sharma, S., Lamichhane, P., Sharma, G., Bist, B., Aryal, U., & Basnet, R. (2022). A strategy for involving community forest managers in effective forest fire management in Nepal. *Banko Janakari*, 32(1), 41–51. <https://doi.org/10.3126/banko.v32i1.45476>
- Parajuli, A., Manzoor, S. A., & 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>
- Paudel, G., Pandey, K., Lamsal, P., Bhattarai, A., Bhattarai, A., & Tripathi, S. (2024). Geospatial forest fire risk assessment and zoning by integrating MaxEnt in Gorkha District, Nepal. *Heliyon*, 10(11), e31305. <https://doi.org/10.1016/j.heliyon.2024.e31305>
- Piao, S., *et al.* (2018). Lower land-use emissions responsible for increased net land carbon sink during the slow warming period. *Nature Geoscience*, 11(10). <https://doi.org/10.1038/s41561-018-0204-7>
- Posavec, S., Barčić, D., Vuletić, D., Vučetić, V., Čavlina Tomašević, I., & Pezdevšek Malovrh, Š. (2023). Forest fires, stakeholders' activities, and economic impact on state-level sustainable forest management. *Sustainability*, 15(22), 16080. <https://doi.org/10.3390/su152216080>
- Qadir, A., Talukdar, N. R., Uddin, M. M., Ahmad, F., & Goparaju, L. (2021). Predicting forest fire using multispectral satellite measurements in Nepal. *Remote Sensing Applications: Society and Environment*, 23, 100539. <https://doi.org/10.1016/j.rsase.2021.100539>
- Quan, D., Quan, H., Zhu, W., Lin, Z., & Jin, R. (2022). A comparative study on the drivers of forest fires in different countries in the cross-border area between China, North Korea and Russia. *Forests*, 13(11), Article 1939. <https://doi.org/10.3390/f13111939>
- Robinne, F. N. (2021). *Impacts of disasters on forests, in particular forest fires*. United Nations Forum on Forests Secretariat.

- Sá, A. C. L., Pereira, J. M. C., Charlton, M. E., Mota, B., Barbosa, P. M., & Fotheringham, A. S. (2011). The pyrogeography of sub-Saharan Africa: A study of the spatial non-stationarity of fire-environment relationships using GWR. *Journal of Geographical Systems*, 13(3), 227–248. <https://doi.org/10.1007/s10109-010-0123-7>
- Saikawa, E., Wu, Q., Zhong, M., Avramov, A., Ram, K., Stone, E. A., Stockwell, C. E., Jayarathne, R., Panday, A. K., & Yokelson, R. J. (2020). Garbage burning in South Asia: How important is it to regional air quality? *Environmental Science & Technology*, 54(16), 9928–9938. <https://doi.org/10.1021/acs.est.0c02830>
- Shah, A., Ullah, A., Khan, N., Khan, A., Tariq, M., & Xu, C. (2023). Community social barriers to non-technical aspects of flood early warning systems and NGO-led interventions: The case of Pakistan. *Frontiers in Earth Science*, 11. <https://doi.org/10.3389/feart.2023.1068721>
- Shah, S., Gautam, N. P., Dhakal, B. P., Sah, J. N., & Sharma, S. C. (2022). Impact of land cover dynamics on ecosystem services value of Siwalik range of Madhesh Province Nepal. *International Journal of Agricultural and Applied Sciences*, 3(2), 94–99. <https://doi.org/10.52804/ijaas2022.3217>
- Sharples, J. J. (2009). An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. *International Journal of Wildland Fire*, 18(7), 737–754. <https://doi.org/10.1071/WF08041>
- Sofan, P., Bruce, D., Schroeder, W., Jones, E., & Marsden, J. (2020). Assessment of VIIRS 375 m active fire using tropical peatland combustion algorithm applied to Landsat-8 over Indonesia's peatlands. *International Journal of Digital Earth*, 13(12), 1695–1716. <https://doi.org/10.1080/17538947.2020.1791268>
- Turco, M., Llasat, M. C., von Hardenberg, J., & Provenzale, A. (2013). Impact of climate variability on summer fires in a Mediterranean environment (northeastern Iberian Peninsula). *Climatic Change*, 116(3), 665–678. <https://doi.org/10.1007/s10584-012-0505-6>
- Verhoeven, E. M., Murray, B. R., Dickman, C. R., Wardle, G. M., & Greenville, A. C. (2020). Fire and rain are one: Extreme rainfall events predict wildfire extent in an arid grassland. *International Journal of Wildland Fire*, 29(8), 702–711. <https://doi.org/10.1071/WF19087>
- Wang, J., Hong, R., Ma, C., Zhu, X., Xu, S., Tang, Y., Li, X., Yan, X., Wang, L., & Wang, Q. (2023). Effects of prescribed burning on surface dead fuel and potential fire behavior in *Pinus yunnanensis* in Central Yunnan Province, China. *Forests*, 14(9), 1915. <https://doi.org/10.3390/f14091915>
- Xiao, Y., Zhang, X., & Ji, P. (2015). Modeling forest fire occurrences using count-data mixed models in Qiannan Autonomous Prefecture of Guizhou Province in China. *PLOS ONE*, 10(3), e0120621. <https://doi.org/10.1371/journal.pone.0120621>
- Yang, X., Jin, X., & Zhou, Y. (2021). Wildfire risk assessment and zoning by integrating MaxEnt and GIS in Hunan Province, China. *Forests*, 12(10), Article 1299. <https://doi.org/10.3390/f12101299>
- Yu, S., Ye, Q., Zhao, Q., Li, Z., Zhang, M., Zhu, H., & Zhao, Z. (2022). Effects of driving factors on forest aboveground biomass (AGB) in China's Loess Plateau by using spatial regression models. *Remote Sensing*, 14(12), 2842. <https://doi.org/10.3390/rs14122842>
- Zeng, G., & Tao, S. (2023). A generalized linear transformation and its effects on logistic regression. *Mathematics*, 11(2), 467. <https://doi.org/10.3390/math11020467>
- Zhang, J.-H., Yao, F.-M., Liu, C., Yang, L.-M., & Boken, V. K. (2011). Detection, emission estimation and risk prediction of forest fires in China using satellite sensors and simulation models in the past three decades: An overview. *International Journal of Environmental Research and Public Health*, 8(8), 3156–3178. <https://doi.org/10.3390/ijerph8083156>

Assessment of forest fire incidences, causes, and management practices in Bagmati Province, Nepal

Kalpna Bhattarai^{1,*}, Chandra Lal Pandey¹

¹Department of Development Studies, Kathmandu University, Dhulikhel, Kavrepalanchowk 45210, Nepal

*Corresponding author: kalbha55@gmail.com

Abstract

Forest fires pose a growing environmental and socio-economic threat in Nepal, driven by both anthropogenic and natural factors. This study examines forest fire incidence, spatial risk patterns, causes, and management practices in Bagmati province using a mixed-methods approach. Spatial and temporal data from MODIS/FIRMS (2014 to 2024) were analysed in ArcGIS to generate a fire risk map using a weighted overlay model. Model validation was conducted using Kernel Density Estimation and Visible Infrared Imaging Radiometer Suite fire hotspots data. Qualitative data were collected through purposively sampled key informant interviews with 29 stakeholders from Community Forest User Groups (CFUGs) and Forest Officers, as well as three focus group discussions conducted in high-fire risk zones. The findings reveal that a total of 46,546 fire incidents were recorded in Bagmati Province during the study period, with 92.87 per cent occurring during the pre-monsoon season (March to May). Approximately 34 per cent of the province falls within very high fire risk zones, particularly in the districts of Sindhuli, Ramechhap, Makawanpur, and Chitwan. Human-induced factors dominated fire ignition, accounting for over 75 per cent of reported causes. Despite existing community forest institutions, fire management effectiveness remains constrained by limited resources, weak coordination, and lack of early warning systems. The lessons from the findings highlight the need for coordinated, community-centered technological innovations to strengthen institutional capacities and enhance policy implementation which are vital for reducing fire risks and fostering sustainable forest fire management in the region.

Keywords: Bagmati province, Community-based approach, Fire risk, Forest fires, GIS

INTRODUCTION

Forest fires, defined as uncontrolled combustion events in vegetated areas where the flame height exceeds 1.8 meters, constitute a significant menace to ecosystem integrity, biodiversity, and human well-being (Kane, 2024). Globally, an estimated 400 million hectares of land burn annually, contributing substantially to deforestation and land degradation (Robinne and Secretariat, 2021; Mishra *et al.*, 2023). The severity of this issue is underscored by several recent mega fires, including those in Australia (2019–2020), the Amazon rainforest (2019–2020), the western United States (2018, 2020), and British

Columbia, Canada (2017, 2018) (Xu *et al.*, 2020). South Asia is recognised as a global fire hotspot, with more than half of the forested terrain impacted by fires between 2003 and 2017 (Reddy *et al.*, 2019). Within the region, Bangladesh exhibits the highest concentration of forest fire hotspots (34%), followed by India (32%) and Nepal, where 20.5 per cent of forest areas are susceptible to annual burning (Reddy *et al.*, 2019; Pandey *et al.*, 2022). In Nepal specifically, approximately 40,000 hectares of forest burn annually, with a peak incidence between March and May (Kalwar, 2022). The Chure region is identified as the most fire-prone area in the country (Mishra *et al.*, 2023).

The etiology of forest fires is multifaceted, encompassing a complex interplay of natural and anthropogenic drivers. Rising temperatures, diminished precipitation, and protracted droughts driven by climate change exacerbate extreme fire weather, thereby extending fire seasons and expanding fire-prone landscapes (Pandey, 2021; Wang *et al.*, 2021; Pandey, 2025). For instance, significant warming across California over the last century, particularly in the late summer and early autumn, has heightened the risk of hydrological drought and consequently prolonged the fire season (Goss *et al.*, 2020). Nevertheless, in numerous regions, particularly developing countries such as Nepal, human activities are the predominant ignition catalysts. In Nepal, anthropogenic ignitions, often intentional, are estimated to account for 58 per cent of all forest fires (Kunwar and Khaling, 2006). The confluence of these anthropogenic pressures with shifting climatic patterns establishes a complex fire regime, presenting formidable challenges for forest management.

Forest fires have severe ecological consequences, including biodiversity loss, habitat destruction, and long-term shifts in forest composition (Wang *et al.*, 2021). In response to these threats, management strategies such as Community-Based Fire Management (CBFiM) have been developed (FAO, 2007). It seeks to engage local communities in the judicious management of land-use fires through coordinated planning, supervision of prescribed burning activities, and integrated fire monitoring and response systems (FAO, 2007). While Nepal has a long history of community forestry, the effectiveness of such approaches is increasingly challenged by socio-economic and political changes at both national and international scales (Shahi *et al.*, 2022). Although

community ownership is widely recognised as essential for proactive fire management initiatives, the growing frequency and severity of fires necessitate a critical reassessment of community-based regimes (Kunwar and Khaling, 2006; Tiwari *et al.*, 2022).

In Nepal, forest fires constitute a pressing and escalating environmental and socioeconomic problem, with forests in over 30 districts sustaining annual damage (ICIMOD, 2019). Bagmati Province, in particular, experiences a high incidence of forest fires, resulting in environmental degradation, economic losses, and fatalities (DPNet Nepal, 2024). Several knowledge and research gaps emerge from the literature. Despite numerous studies examining the spatial and temporal distribution of forest fires in Nepal (Parajuli *et al.*, 2015; Matin *et al.*, 2017; Parajuli *et al.*, 2020; Bhujel *et al.*, 2022), research on fire management practices and vulnerability assessments remains limited. For instance, Bhusal and Mandal's (2020) study on fire occurrence in the Arghakhanchi district, while informative, may not be generalisable to other regions. However, Mishra *et al.* (2023) briefly mentioned anthropogenic causes of forest fires, up-to-date and accurate vulnerability assessment, and a deep learning-based model (DNN) needed for better fire management. Similarly, only a limited number of studies, including Pandey *et al.* (2022) and Tiwari *et al.* (2022), have explicitly focused on forest fire management. Comprehensive fire research in developing countries and regions like the Himalayas is still lacking. Many studies (e.g., Goss *et al.*, 2020; Wang *et al.*, 2021) discussed the impacts of climate change on fire regimes, although considerable uncertainty remains in these projections. The prevalence of forest fires is exacerbated by watershed scarcity and prolonged dry seasons characteristic of the region. The complex

interactions between climate, vegetation, and human activities are often oversimplified in predictive models. Furthermore, there is a lack of rigorous, comparative studies evaluating the effectiveness of different fire management strategies, particularly in developing countries.

Compounding the issue, Nepal faces significant institutional, financial, and technological capacity constraints in combating forest fires and possesses limited comprehensive data on fire occurrence and its impacts (GoN, 2013). Because of its ecological relevance, high fire frequency, and increasing human stress on forest resources, the Bagmati Province was selected as a study area for this research. The province contains approximately 27.29 per cent forest cover and has experienced significant fire impacts, with nearly 4000 hectares affected (DPNet Nepal, 2024).

Moreover, Bagmati Province encompasses parts of the Terai Arc Landscape (TAL) and the Siwalik region, which are recognised as vulnerable to forest fires in Nepal, due to a combination of dry climatic conditions, flammable broadleaved forest types, and intensive human activities (Parajuli *et al.*, 2023). Previous studies on forest fire management have often overlooked Bagmati Province despite its high vulnerability to fires; consequently, research on effective fire management practices and community-based mitigation strategies in the province remains inadequate (Matin *et al.*, 2017; Kalwar, 2022; Mishra *et al.*, 2023; Pandey and Bhattarai, 2025). In this context, we investigate two research questions: i) What are the major causes, spatial-temporal patterns, and risk zones of forest fires in Bagmati Province? ii) How can local experiences and community knowledge contribute to understanding forest dynamics and improving forest fire management strategies in Bagmati Province?

Theoretical framework

The theoretical framework employed in this study is a dual-component model that combines the Social-Ecological System (SES) framework (Ostrom, 2009; McGinnis and Ostrom, 2014) with Collective Action Theory (CAT) (Ostrom, 1990; Poudyal *et al.*, 2023). The SES framework serves as the overarching structure, enabling a holistic analysis by identifying the key variables that influence fire dynamics across different system levels: the forest and its ecological characteristics (resource system), the local communities and their behaviours (users), the policies and institutions (governance systems), and the interactions among these components. In this study, SES variables were chosen according to Ostrom's (2009) framework and tailored to the context of forest fires in Nepal, supported by empirical literature and field considerations. This allows the study to explain why ecological factors alone are insufficient to predict fire incidents where social drivers override ecological susceptibility.

CAT becomes particularly relevant because forests in Bagmati Province are common-pool resources managed through Community Forest User Groups (CFUGs) that require coordinated action among multiple stakeholders. For this study, three core principles of Collective Action are central to analysing fire management:

1. **Communication and Coordination:** focuses on how effectively CFUGs, Division Forest Offices (DFOs), and local government exchange information and jointly plan strategies for prevention and suppression
2. **Capacity:** assesses the adequacy of financial resources, equipment, training, and institutional support that enable or constrain collective action

3. Trust and Reciprocity: evaluates the social capital and confidence among stakeholders that enable sustained cooperation

Thus, the framework addresses the social and ecological dimensions of the issue, connects research questions to collective action interventions, and offers a structured lens for examining management gaps and strengthening collective action for sustainable fire management.

MATERIAL AND METHODS

Study area

The study was conducted in Bagmati Province as shown in Figure 1, which covers 20,300 km² and accounts for approximately 13.79 per cent of Nepal's total land area (Bagmati Province, 2024). Topographically, the province is divided into four main regions, starting from the high Himalayan region (7,422m) in the north to the low plain Terai in the south (Bagmati Province, 2024). The province's wide elevation range allows it to support nearly all forest types found in Nepal. Tree species, including Sal (*Shorea robusta*), Sisoo (*Dalbergia sissoo*), and Khair (*Senegalia catechu*), predominate in the lowland Terai region. The forest composition changes with elevation, favouring temperate species, including pine (*Pinus roxburghii*), oak (*Quercus* spp.), and rhododendron (*Rhododendron arboreum*). Medicinal herbs and alpine vegetation are predominantly found in the northern parts of the province. In total, these forested areas cover 27.29 per cent of the provincial territory (Bagmati Province, 2024). Collectively, Bagmati Province has five protected areas, among which four are national parks (Chitwan National Park, Langtang National Park, Shivapuri Nagarjun National Park, and part of Parsa National Park) and one conservation

area (Gaurishankar Conservation Area) (DNPWC, 2024).

Due to the province's elevational gradient, the climate within Bagmati Province fluctuates greatly. The lowland Terai region has a humid, subtropical climate with hot summers and mild winters. The hilly regions have a temperate climate, while the northern mountainous areas are covered with ice and glaciers, resembling an alpine to tundra climate. On average, the province receives between 1,000 and 4,000 mm of precipitation annually, most of which occurs between June and September during the summer monsoon season (DHM, 2024). Annual rainfall is highest in Bharatpur, Chitwan (2550.1mm), making it one of the wettest areas, while Kathmandu receives the least rainfall (1360 mm), indicating a relatively drier climate in the valley compared to other regions (Bagmati Province, 2024). The winter season (December – February) brings snow to the northern areas, resulting in cold and dryness, while it is relatively warmer in the southern plains.

RESEARCH DESIGN

The study employs a mixed-methods approach, with qualitative research methods predominating, followed by quantitative data to complement and support the findings. The qualitative component of this research draws primarily on data collected through Key Informant Interviews (KIIs) and Focus Group Discussions (FGDs). Utilising a purposive sampling approach, the study conducted KII with 13 representatives from CFUGs and 16 forest officers from DFOs, while sites and CFUGs for the FGDs were selected based on the frequency of forest fire identified through Moderate Resolution Imaging Spectroradiometer (MODIS) data overlays and risk classification. To deepen the understanding, a spatial and temporal

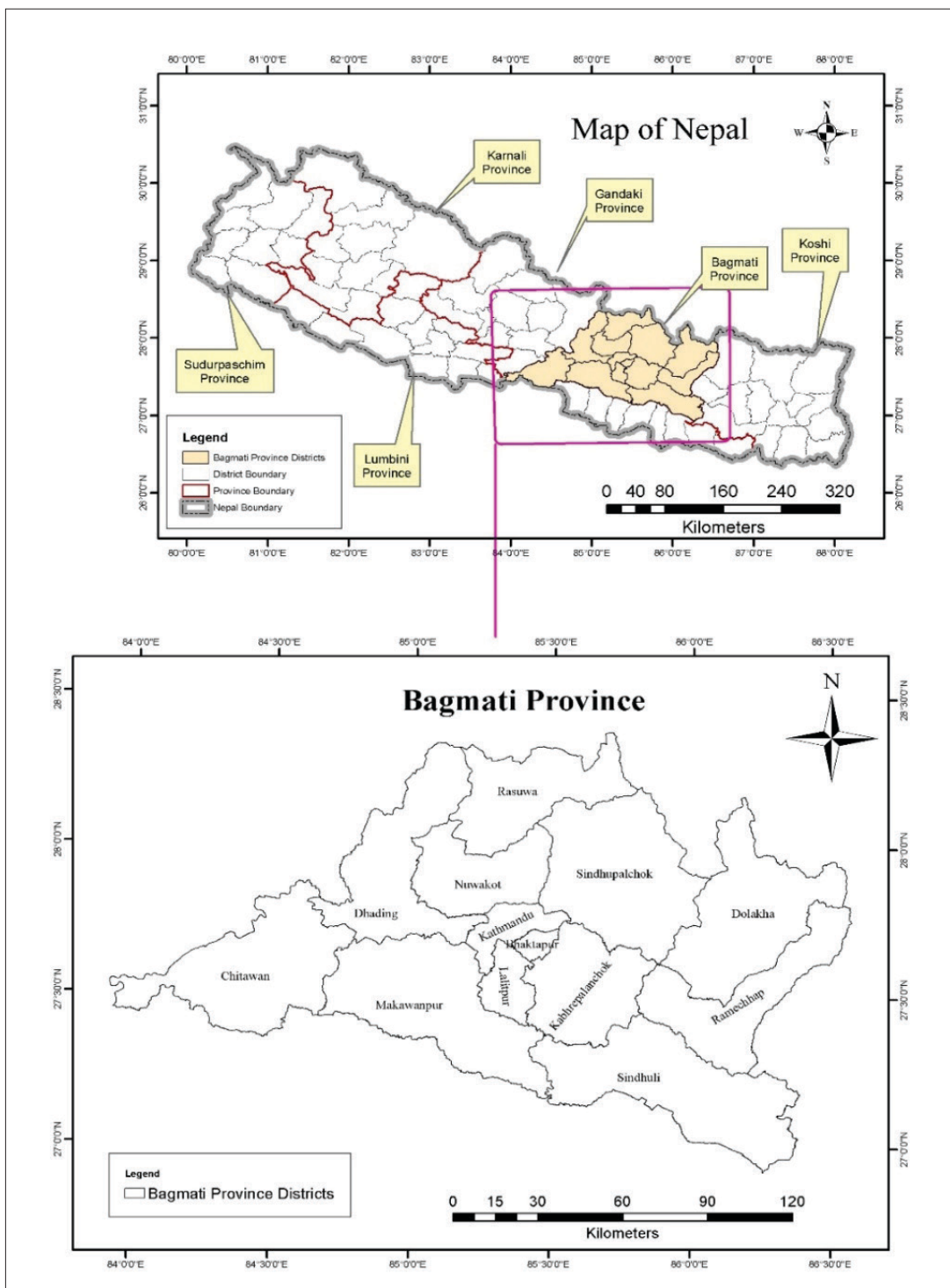


Figure 1: Map of the study area

perspective on forest fire events in Bagmati Province was examined using quantitative data. In particular, data from the MODIS and the Fire Information Resource Management System (FIRMS) were analysed to track forest fire occurrences over time and space. The real experience of local people from qualitative data and satellite data complements each other, contributing to the findings and analysis.

Primary data collection

- i) Key Informant Interview: A total of 29 key informants were interviewed. Initially, representatives of CFUGs were interviewed via phone calls using a questionnaire that included both open-ended and closed-ended questions. Additionally, forest officers, including two from Chitwan, were interviewed using a separate set of questionnaires administered through Google Forms. These interviews aimed to explore the major causes of forest fires, existing management practices in community forests, challenges encountered, and potential improvements, while also assessing the preparedness of forest officers in dealing with forest fires.
- ii) Focus Group Discussions: Three focus group discussions involving 6 to 12 participants each were conducted with different community forest groups in the study area. FGDs were carried out with Susheli and Piple Pokhara CFUGs in Makawanpur district, and Bandevi Shanti CFUGs in Godawari, Lalitpur district.

Quantitative data

MODIS data

The historical data were taken from NASA's FIRMS. A polygon encompassing the study area surrounding the temporal data from 2014 to 2024 was created using fire spots from

the EOSDIS Archive Data Tool. Confidence levels below 30 per cent of the total number of forest fires and fires discovered in agricultural and water bodies, as identified by MODIS, were removed to improve the accuracy and reliability of the fire dataset for the study area from 2014 to 2024. This eliminated thermal anomalies that false alarms, such as sun glint over water or marginal surface heating, could have caused. For the burnt area detections, the MODIS burned area product was downloaded in shapefile format from the University of Maryland "ba1" ftp server, which is now consolidated with Fuoco into a single server. These data significantly contribute to the research by providing objective, long-term, and spatially explicit information on forest fire occurrences in Bagmati Province from 2014-2024. They facilitate the identification of high-risk fire zones by detecting fire hotspots and burnt areas over time, enabling the creation of fire frequency maps and risk categorisation.

In order to do vegetation analysis, the land cover ICIMOD data (FRTC, 2022) were grouped into ten distinct classes. Vegetation extraction was carried out using ArcGIS by estimating the proportion of vegetation types in the research regions. Monthly mean land surface temperatures for Bagmati Province were derived from NASA/MODIS data for the period between 2014 and 2024. The average temperature in the province ranges from 5°C to over than 35°C. The slope is an extremely important factor among topographic factors that largely affect fire, especially when it is spreading (Goldammer and de Ronde, 2004; Yakubu *et al.*, 2015). Hence, for the slope study, DEM 90 M from DFRS was used, and the slope was extracted using GIS. The surface slope in this study varies from less than 5° to over 35°, while elevation ranges from below 1000m to 4000m. Elevation was incorporated into the

model based on its assumed direct relationship with humidity and fuel combustion. The aspect was generated using DEM and classified into nine classes. Distance from the road, including highway and associated roads, was extracted from ICIMOD, and proximity to settlements, including clusters of settlements in the study area, was extracted from the Department of Survey (2024). The distance has been grouped into 0-1000m, 1000-2000m, 2000-3000m, 3000-4000m, and 4000m and above.

In the findings and discussion section, these datasets are merged by triangulating insights from primary data (KII and FGD) with spatial and environmental variables derived from secondary data (MODIS, ICIMOD, DEM, and NASA datasets). For instance, the perceptions of CFUG members and forest officers regarding fire causes and management challenges are contextualised with MODIS fire frequency and burnt area data to validate spatial fire patterns. Similarly, vegetation classification, slope, elevation, temperature, and proximity to roads and settlements help explain the underlying environmental and anthropogenic drivers identified during the fieldwork. Overlaying these variables allows a spatial-temporal understanding of fire-prone zones and management gaps, enhancing the discussion by linking insights with geospatial evidence to draw meaningful conclusions and develop targeted fire management strategies.

Data analysis

In qualitative research, thematic analysis was used to examine the data and identify patterns in participants' responses. Firstly, all the interviews were transcribed and read multiple times, and codes were worked out based on the major points of the data. The selected codes were refined to ensure the consistency and coherence of the data. Similar types of code were grouped to form the main

themes, representing the core part of the data. The scale of qualitative data has been relatively small and manageable using Excel, which allowed for efficient categorisation, coding, and summarisation without the need for advanced statistical tools. Quantitative analysis was done in SPSS and ArcGIS 10.8. In ArcGIS, other than the basic function, buffering, kernel density function, and weighted overlay, different variables and results were analysed using weighted overlay. The weighted overlay is a GIS spatial analysis technique used to combine multiple raster layers with different influences to generate a single output layer. It is particularly useful in decision-making and suitability analysis (Jaiswal *et al.*, 2002).

Determining the risk model

Various indices have been proposed in literature to estimate fire risks using biophysical (vegetation, humidity, elevation, slope, aspect) and anthropogenic (proximity to settlements and roads) parameters (Jaiswal *et al.*, 2002; Filippidis and Mitsopoulos, 2004; Saglam *et al.*, 2008; Ca'ceres, 2011; Adab *et al.*, 2013; Mohammadi *et al.*, 2014; Sivrikaya *et al.*, 2014; Zhang *et al.*, 2017). The relative weights for variables were chosen (Parajuli *et al.*, 2020); hence, the risk model was developed with the equation below.

$$\text{FRI} = 40 \text{ LC} + 20 \text{ LST} + 10 \text{ S} + 10 \text{ RD} + 10 \text{ PS} + 5 \text{ A} + 5 \text{ E}$$

Where,

FRI = Fire Risk Index,

LC = Land Cover,

LST = Land Surface Temperature,

S = Slope,

DR = Distance from the Road,

PS = Proximity to the Settlement,

A = Aspect and

E = Elevation.

Table 1: Table showing the value assigned to determine the risk model

Variable	Weight (%)	Class	Value Assigned	Fire Rating Classes
Land Cover	40	Broad-leaved Closed Forest	1	Very High
		Broadleaved Open Forest	2	High
		Grassland	3	Medium
		Shrubland	4	Low
		Needle-leaved Open Forest	4	Low
		Needle-leaved Closed Forest	4	Low
		Barren Land	5	Very Low
Temperature Degree C	20	>30	1	Very High
		25-30	2	High
		20-25	3	Medium
		Oct-20	4	Low
		<10	5	Very Low
		<5	1	Very High
Slope (%)	10	5-15	2	High
		15-25	3	Medium
		25-35	4	Low
		>35	5	Very Low
		<1000	1	Very High
Distance to Road (M)	10	1000-2000	2	High
		2000-3000	3	Medium
		3000-4000	4	Low
		4000-5000	5	Very Low
		<1000	1	Very High
Proximity to Settlement (M)	10	1000-2000	2	High
		2000-3000	3	Medium
		3000-4000	4	Low
		>4000	5	Very Low
		<1000	1	Very High
Elevation(M)	5	1000-2000	2	High
		2000-3000	3	Medium
		3000-4000	4	Low
		>4000m	5	Very Low
		Flat/South	1	Very High
Aspect	5	East/South East/ South West	1	High
		West	3	Medium
		North West/ North East	4	Low
		North	5	Very Low

Ultimately, these parameter evaluations led to the creation of a fire risk zone map. In this study, spatial modelling has been done to obtain the combined effect of the aforesaid variables. Different weights were assigned as per the importance of the particular variable, as shown in the table 1. The highest weight was given to the land cover as it indicates forest type, fuel load, and fuel accumulation, which strongly influence fire susceptibility due to fuel inflammability. The second-highest weight was given to land surface temperature, which directly affects the likelihood of forest fires. The third highest weights were given to slope, distance to road, and proximity to settlement. Steeper slopes facilitate convective preheating, enhancing fire ignition and spread, while closer proximity to settlements and roads increases access for local people, grazers, and tourists, potentially contributing to fire occurrences. Elevation and aspect were assigned next, since human activity generally decreases with altitude, and sun-facing aspects receive more direct sunlight, making fuels drier and more combustible. Ratings for all variables were assigned from high to low based on their relative risk potential. Following the determination of each weight, ArcGIS 10.8 was used to overlay all layers.

Model validation

Model validation was conducted to assess its predictive accuracy, by combining it with a real-world dataset (Beguería, 2006). Since the model was based on seven independent factors, the resulting fire risk map was validated using data from individual forest fire incidents. First, assuming that higher fire counts correspond to the higher risk rating in the designated category, archived fire counts were superimposed in each fire risk zone. Second, the outcomes of the fire risk model were compared using KDE (Parajuli

et al., 2020). By calculating event intensity as density estimation, KDE aimed to create a smooth density surface of point events across space (Serra-Sogas *et al.*, 2008). The VIIRS hotspots served as input for both validation techniques.

RESULTS

Areas most susceptible to forest fires

Altogether, 46,546 fire incidents were recorded in Bagmati Province between 2014 and 2024. 92.87 per cent of fire incidents were recorded in the pre-monsoon season from March to May, where April alone accounted for 52.67 per cent of fire incidents from 2014 to 2024. The highest number of forest fires was recorded in 2016 (11,044), followed by 2021 (10,381) and 2023 (7,341) as shown in the Figure 2.

At the district level, as represented in Figure 3, Chitwan was the most affected, with a staggering 12,480 fire incidents reported between 2014 and 2024. Similarly, Makwanpur also faces a high number of incidents, with 10,770 reported cases, followed by Sindhuli with 9,091 incidents. In contrast, urban districts such as Lalitpur, Kathmandu, and Bhaktapur report significantly fewer incidents, likely due to limited forest cover and better access to emergency services. Moderate fire activity was observed in Dhading, Kavrepalanchok, Sindhupalchok, and Nuwakot.

Forest fire risk zonation map

Approximately 34 per cent of the study area was identified as having a very high fire risk, followed by 56 per cent that are at moderate risk, and only 10 per cent falling into the 'very low risk' category. Sindhuli district recorded the largest burnt area, totalling 1274.12 km², followed by 965.91 km² in Ramechhap,

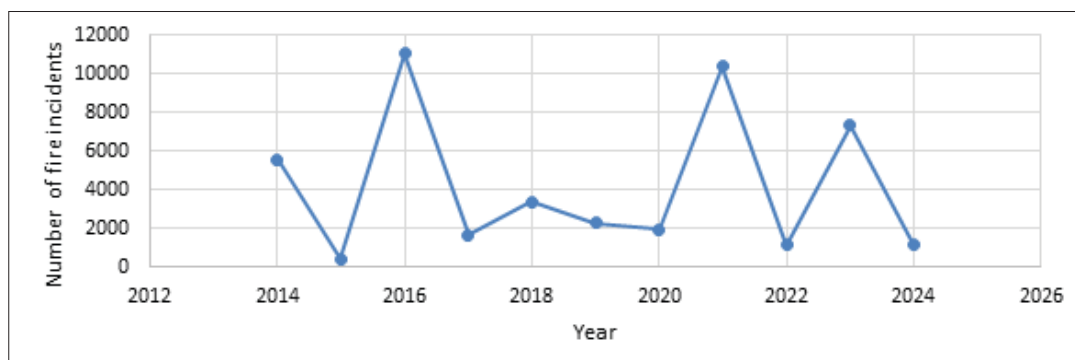


Figure 2: Trends of fire incidents in Bagmati Province from 2014 to 2024 (MODIS Data)

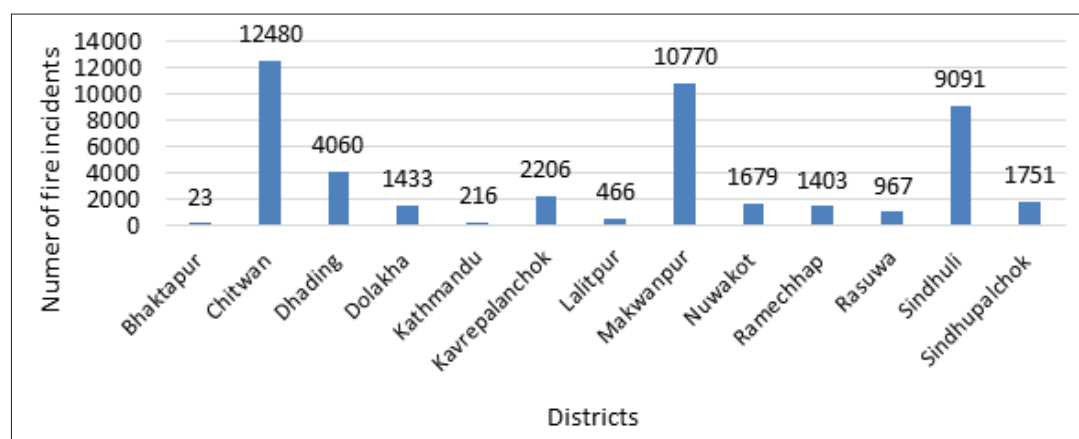


Figure 3: District-wise fire incidents (MODIS Data, 2024)

836.62 km² in Makawanpur, and 826.55 km² in Chitwan district. These burned areas largely correspond to zones identified as very high fire risk, as highlighted in Figure 4.

Among the districts, Ramechhap has the highest proportion of land area classified as very high risk of fire, at 55 per cent, followed by Sindhuli at 51 per cent. Chitwan also presents a significant concern, with 37 per cent of its land categorised as high fire risk. Similarly, 34 per cent of the land area in Dolakha, Kavrepalanchok, and Makawanpur falls within the high-risk category. Nuwakot has the largest proportion of land classified as moderate fire risk, with 72 per cent of its area falling into this category. This is followed by

Lalitpur, where 64 per cent of the district's land area is at moderate risk, and Makawanpur with 59 per cent of its land classified similarly. In contrast, Rasuwa shows a different pattern, with the largest proportion of land area (32%) classified as low fire risk, which is the highest among all districts of Bagmati Province.

Model validation

KDE has been widely applied as a validation tool for forest fire maps. According to Zhang *et al.* (2017), KDE can also serve as a useful component of decision support systems (Parajuli *et al.*, 2020). Very high-risk areas are nearly identical to those produced by the fire risk map, as demonstrated by the comparison

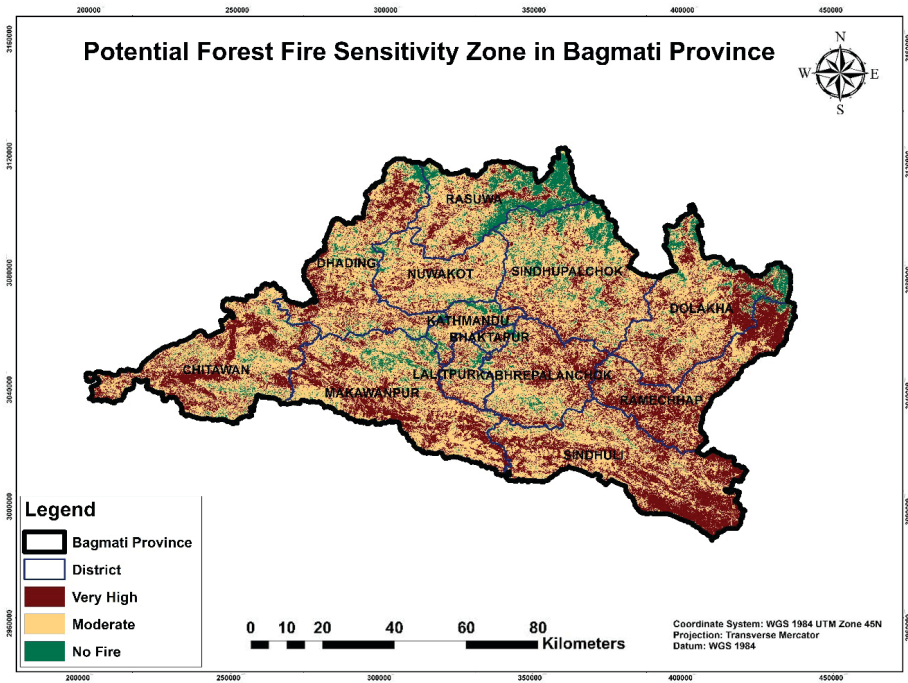


Figure 4: Forest fire-sensitive zones in Bagmati Province were developed by combining all influencing variables. *Source: MODIS/FIRMS (2024); GIS analysed*

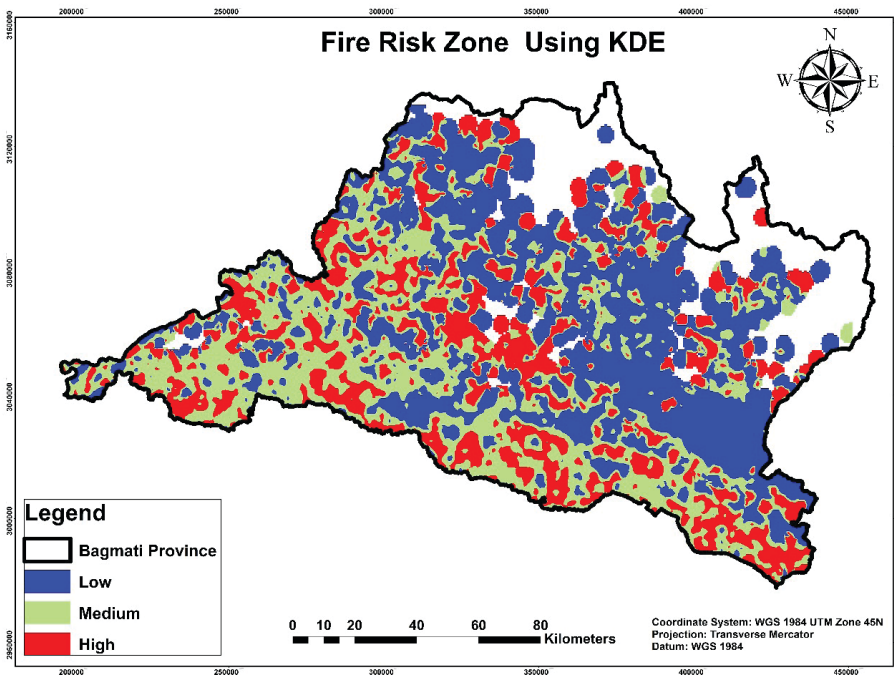


Figure 5: Fire risk map produced by the KDE Method from MODIS fire hotspots

of risk areas obtained through the validation of fire spots and KDE, as shown in Figure 5. On the other hand, KDE has expanded the low-risk zone. It might be as a result having fewer concentrated fire points.

In addition to spatial validation, perceptions of local people also highlight the evolving nature of fire risk. A majority (75%) of the interviewed participants reported an increase in forest fire risk over the past five years, highlighting rising concerns about the frequency and intensity of such events. Meanwhile, 18.8 per cent of respondents felt that there had been no significant change in fire risk levels during the same period. This suggests that while the majority perceive a growing threat, a small proportion of the population perceives that the situation has remained unchanged.

Major causes of forest fires in Bagmati Province

Figure 6 highlights human negligence as the most significant cause of forest fires in Bagmati Province, accounting for 75.86 per cent of the responses. This includes careless activities such as the improper disposal of burning materials like cigarettes. Agricultural practices represent the second most common cause with 24.13 per cent, including slash-and-burn techniques, the clearing of land

through controlled burns, and accidental fires spreading from farmlands to the nearby forests. Deliberate actions account for 13.8 per cent of the causes, primarily involving intentional fires set for land clearing or driven by vindictive motives. Natural causes account for the smallest share, at 3.45 per cent.

The results overall suggest a dominant perception among respondents that human activities are the primary drivers of forest fire incidences, with the “very high” category far outweighing the others. According to the Chairperson of Piple Pokhara CFUG (Makawanpur), personal or professional disputes can also trigger forest fires. He further noted that while forest cover has increased, the declining dependence of local communities on forest resources has contributed to fuel accumulation, making forests more susceptible to ignition during the dry season. As communities have become more independent from forest resources, local people's concern regarding forest fires has also decreased. Consequently, the reduced use of wood, timber, and other forest products over the years has contributed to an increased risk of forest fires. Similarly, the Chairman of Susheli CFUG emphasised that limited awareness and inadequate environmental education among residents remain key drivers of rising fire incidents. He explained that the adoption of alternative materials,

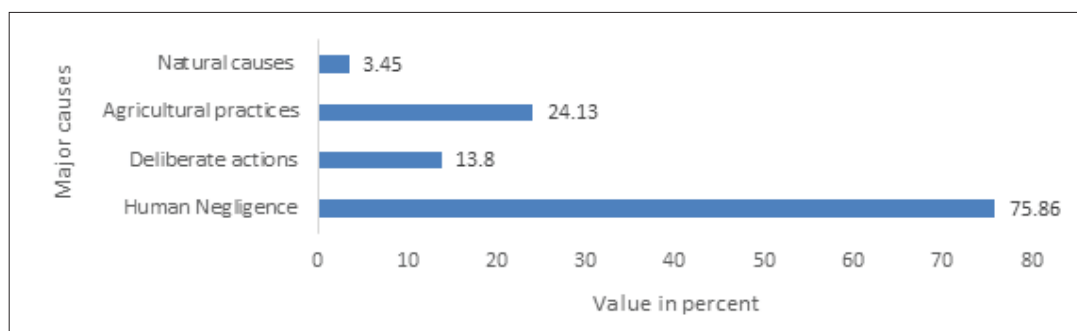


Figure 6: Major causes of forest fires (Note: The total percentage may exceed 100, due to overlapping categories)

such as metal furniture instead of wood and synthetic mats for livestock care, has reduced community dependence on forests. As a result, responsibility for fire prevention and forest management has increasingly shifted to the CFUGs alone.

Existing forest fire management practices employed in the Bagmati Province

Figure 7 represents that forest fire management in Bagmati Province is predominantly community-led, with CFUGs playing a central role in fire suppression and prevention. The use of water for firefighting is the most widely practiced method, reported by 90 per cent of respondents, followed by community education and awareness activities (75.86%), underscoring the importance of public engagement in reducing fire risk. The establishment of firebreaks and firelines is also commonly practiced by CFUGs and forest officers (72.41%), indicating their widespread adoption as a preventive measure (Figure 7).

At the community level, CFUGs primarily rely on basic hand tools and traditional knowledge, including backfiring and locally constructed firelines. In contrast, the Forest

officers focus on controlled burning, seasonal patrolling, and awareness-raising programs. Fuel load reduction through leaf litter collection is additionally practiced to limit fire intensity.

Local governments support fire response by coordinating with DFOs and providing firefighting equipment. Despite these efforts, the use of early warning systems remains limited. Only a small number of respondents reported receiving fire alerts based on MODIS satellite data, which were widely perceived as ineffective due to the lack of supporting technical infrastructure. Fire-related information is largely communicated through informal channels, particularly mobile phone calls. Forest officials and CFUGs representatives further noted that MODIS alerts often fail to align with the actual timing of fire ignition, frequently occurring at night, thereby reducing their effectiveness for timely response and suppression.

Preparedness

The absence of a “very well prepared” response indicates a lack of perceived readiness for forest fire events among respondents, attributed to limited resources and ongoing

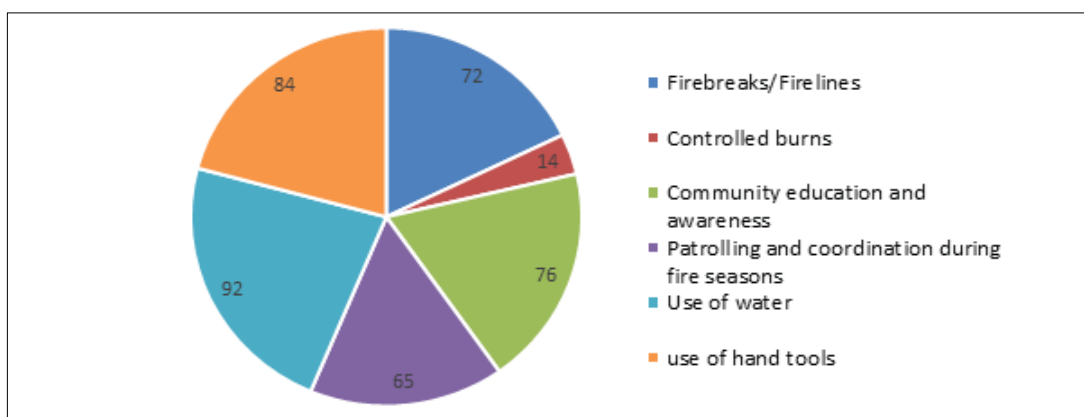


Figure 7: Existing management practices (in per cent) (Note: the total percentage may exceed 100, due to overlapping categories)

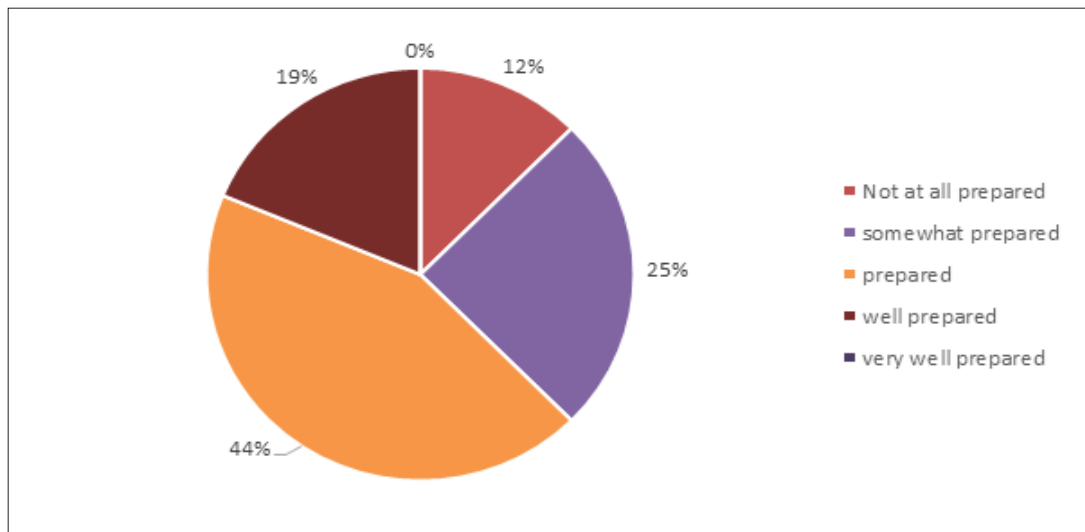


Figure 8: Area's preparedness for forest fires from interviews

vulnerabilities (Figure 8). A member of Susheli Community Forest (CF) noted that preparatory measures are minimal, mainly limited to discussions, with no effective prevention or response mechanisms in place. Further, he added key challenges, including adequate budget allocation, insufficient funding, and a lack of proper firefighting equipment.

Gaps in existing management

The existing management of forest fires in the study area reveals significant gaps, particularly in coordination and communication between CFUGs and government bodies. While forest officers often report that there is regular collaboration with local communities, many CFUG members express a contrasting experience, citing a lack of timely support and proactive engagement from local governments or the DFOs. For instance, *"We were given training after the fire took place, and it is quite difficult to complain and punish someone within our community if found igniting the fire,"* said a member of Bandevi Shanti CF. Furthermore, the absence of dedicated fire

control committees in some areas points to poor coordination and inadequate planning, ultimately undermining efforts to prevent and manage forest fires effectively.

Beyond coordination, limited capacity building is another critical barrier to successful forest fire management. A large proportion of respondents reported inadequate or completely unavailable resources for fire control, including essential equipment and financial support. The lack of budget allocation within CFUGs, primarily due to insufficient income sources, has made it difficult to invest in vital components such as training programs and hiring forest watchers. This situation is worsened by limited public awareness and a general lack of interest in fire management among residents. As pointed out by CFUG leaders, community members are often more motivated by training allowances than by a genuine commitment to forest protection. This disconnect between people and the forest, driven by minimal engagement and economic constraints, poses a major obstacle to building a resilient and participatory fire management system.

Role of community involvement and local knowledge in mitigating forest fires

The role of community involvement and local knowledge is central to effectively mitigating forest fires in the region, as highlighted by both CFUGs and forest officials. CFUG emphasises that meaningful participation in activities such as fire prevention campaigns, budget planning, and coordination meetings is essential for strengthening collaboration between local communities and government bodies. They argue that engagement should go beyond formalities, such as being rooted in practical, on-the-ground involvement. They further believe that the responsibility for forest protection should be more widely shared, including among local governments, rather than resting solely with forest departments or federations like FECOFUN.

In addition, improvements in infrastructure and livelihood alternatives are viewed as vital strategies for forest fire management. There is a strong demand for better firefighting tools, equipment, and protective gear. Forest officers' emphasise the need for enhanced training and a dedicated budget for fire management. Additionally, providing insurance for local people involved in fire control would offer protection and encourage more active participation in firefighting and rescue operations. These infrastructure improvements would increase community capacity and reduce risks during fire incidents.

Another important aspect is the need for sustainable livelihood alternatives. CFUGs believe that the collection of forest litter and waste, often a major fuel source for fires, could be integrated with income-generating activities such as compost production. Providing financial incentives to community members for these activities could not

only help manage forest waste but also support vulnerable households, creating a mutually beneficial solution for both forest conservation and community development.

DISCUSSION

Forest fire incidence in Bagmati Province is attributable more to a combination of climatic stressors, user behaviour, and governance limitations than biophysical factors alone. Drawing on Ostrom's SES framework and CAT, this study demonstrates that forest fires are produced through mutually reinforcing feedbacks among the resource system (dry and fuel-rich forests), resource users (local communities), and governance systems (community forestry institutions and state agencies). These interactions explain the persistence and intensification of fires despite the expansion of community forestry and existing management interventions. From a SES perspective, fire is a disturbance that arises when poor governance, ecological sensitivity, and deteriorating collective action come together, and CAT explains why cooperation does not materialise at the size and speed necessary for effective prevention and response.

Seasonal climate variability, particularly the dry pre-monsoon period, functions as an enabling condition rather than a causal driver of forest fires in Bagmati Province. Consistent with national-level studies, our analysis confirms that the majority of fires occur between March and May, when high temperatures, prolonged dry spells, and low humidity increase fuel flammability (Matin *et al.*, 2017; Kalawar, 2022; Mishra *et al.*, 2023). Approximately 92.87 per cent of recorded fires occurred during this period, closely aligning with earlier estimates that around 89 per cent of fires in Nepal happen in the dry season, alongside an annual

increase of approximately 0.6 per cent in burned area (Matin *et al.*, 2017; Mishra *et al.*, 2023). The SES theory emphasises that ecological susceptibility alone does not produce disturbance events unless it is triggered by human activity and governance failures. Comparative studies from India and Southern Europe show that similar climatic conditions result in divergent fire outcomes depending on land-use practices, institutional capacity, and enforcement effectiveness (Somlai *et al.*, 2018; López-Rodríguez *et al.*, 2021). The sharp decline in fire incidence during COVID-19 mobility restrictions in Nepal, marked by a 4.54 per cent decrease in fire events and an 11.36 per cent reduction in fire radiative power, further confirms that climate stress becomes consequential only when coupled with human activity, as documented by Paudel (2020). Human ignition emerged as the most immediate and decisive driver of forest fires in Bagmati Province, underscoring the central role of resource users within the SES. Negligent activities, intentional burning, agricultural practices, and grazing-related practices dominate ignition sources, indicating that user behaviour frequently overrides biophysical constraints. This aligns with findings from Mediterranean Europe, where anthropogenic ignitions account for over 90 per cent of wildfire events (Moreno *et al.*, 2021) and are increasingly dominant across South Asia (Doerr and Santin, 2016). In Nepal, Tiwari *et al.* (2022) link increasing fire incidence to livelihood transitions, declining forest dependence, and reduced incentives for stewardship. From the SES perspective, this reflects a weakening feedback loop between resource users and the resource system: as economic and cultural reliance on forests diminishes, so does collective responsibility for protection. Similar dynamics have been documented in Ethiopia and Southeast

Asia, where livelihood diversification erodes shared norms and collective monitoring, increasing fire risk (Somlai *et al.*, 2018). The convergence of these findings suggests that human behaviour constitutes not merely any driver of contemporary wildfire regimes, but a structural one.

The spatial distribution of forest fires in Bagmati Province further illustrates how socio-institutional processes shape fire risk beyond environmental determinants. High-risk zones were concentrated near settlements, roads, and forest-agriculture interfaces, reflecting patterns of human access and land-use intensity. While slope, vegetation type, and fuel load influence fire spread, they do not fully explain spatial clustering. Comparable studies from Europe and Australia consistently show that proximity to infrastructure and human access outperform biophysical variables in predicting fire occurrence (Doerr and Santín, 2016; Charnley *et al.*, 2020). Within the SES framework, these interface zones represent areas where interaction between resource users and the resource systems is most intense, yet governance oversight is often weakest. The KDE-based spatial validation applied in this study identifies zones of intensified interaction between resource users and the resource system, where governance oversight tends to be weakest. It further corroborates this interpretation by delineating low-risk zones in areas with less concentrated human activities, thereby illustrating that fire risk is socially produced and spatially mediated through governance gaps.

Institutional capacity within the governance system critically mediates the extent to which human ignition escalates into large-scale fire events. Despite Nepal's progressive forest policies, including community forestry, fire management remains under-resourced

and weakly enforced. Less than 0.5 per cent of the forestry budget is allocated to fire management, severely constraining investments in training, equipment, and early warning systems (Pandey *et al.*, 2022). Evidence from decentralised governance systems suggests that increased local responsibility without adequate institutional support often leads to management failure (Laschi *et al.*, 2019). In Bagmati Province, decentralisation has expanded the number of actors involved in fire management but has not strengthened coordination or accountability, resulting in delayed responses and ineffective prevention. As Kirschner *et al.* (2023) demonstrated, inclusive governance enhances the collective capacity to manage wildfire risk, suggesting that institutional design, rather than decentralisation alone, is decisive.

This study further reveals how weak collective action exacerbates institutional limitations. CFUGs reported insufficient firefighting tools, a lack of standardised training, and an inability to hire forest watchers due to financial constraints. From a CAT perspective, deficiencies in communication and coordination are particularly salient: fire response remains informal and reactive, often relying on phone calls, which delays mobilization and reduces effectiveness (Sapkota *et al.*, 2015). While the ICIMOD web portal demonstrates the potential of digital early warning systems, detecting and communicating fire events within approximately 20 minutes (Thapa *et al.*, 2021), its limited uptake underscores persistent investment and capacity gaps. The reported tendency for fires to ignite at night, when alert systems and coordination mechanisms are weakest, further exposes temporal mismatches between risk and response capacity. These findings are consistent with Charnley *et al.* (2020), who

documented that insufficient institutional support undermines local wildfire governance, as well as with Oslon's (2012), who argues that collective action tends to fail when individual costs outweigh shared benefits.

Declining trust and reciprocity, central to CAT, further weaken cooperation between communities and state institutions. Livelihood insecurity, limited incentives, and weak state presence reduce voluntary participation in fire prevention and suppression, reinforcing a cycle of disengagement. Similar issues are highlighted in the studies by Pandey *et al.* (2022) and Tiwari *et al.* (2022), suggesting that Bagmati's challenges reflect broader governance failures in managing fire as a common-pool risk rather than isolated local shortcomings. To address this, the study suggests innovative solutions like providing insurance mechanisms for individuals involved in fire control, a recommendation that aligns with findings from earlier research (Bhattarai *et al.*, 2022). This offers a promising avenue to rebalance risk and incentives, aligning individual participation with collective benefits.

Overall, the interplay of climate stress, human ignition, institutional weakness, and collective action capacity perpetuates a feedback loop that heightens forest fire risk in Bagmati Province. This cycle, observed across diverse socio-ecological contexts, combines heightened ecological vulnerability within anthropogenic fire use and inadequate governance, progressively eroding trust, coordination, and motivation. Effective strategies to mitigate this risk must involve behavioural modification, improved institutional coordination, and re-engagement of community–state collaboration, rather than just focusing on ecological restoration or fire suppression alone. Embedding fire management within a robust SES-informed

governance framework, supported by incentives that enhance trust and reciprocity, is essential for fostering long-term resilience to forest fires in Bagmati Province and similar socio-ecological systems.

Despite the analytical strengths of this study, several limitations should be acknowledged. The large geographical extent and complex topography of Bagmati Province constrained field access, potentially leading to the underrepresentation of remote forest areas. The analysis relies on data from NASA's FIRMS and other secondary sources, which are subject to limitations including the omission of small fires, cloud cover interference, and reduced detection accuracy in dense forests. Additionally, the use of a 90m DEM, rather than higher-resolution data (e.g., 30 m), may have constrained the precision of topographic variables in fire risk zonation. The exclusion of wind as a parameter, despite its known influence on fire spread (Weise and Biging, 1997), may have further affected the accuracy of the zonation results.

CONCLUSION

This study addressed two research questions by examining the spatial-temporal patterns and causes of forest fire in Bagmati Province and assessing how community knowledge and institutional capacity influence fire management. By integrating GIS-based analysis with community-level insights, the study shows that forest fire risk in Bagmati province is highly uneven and strongly seasonal. Approximately 34 per cent of the province is classified as being at very high fire risk, primarily concentrated in Chitwan, Makwanpur, and Sindhuli, where most fires occurred during the pre-monsoon season. These findings reinforce the discussion that anthropogenic factors such as negligence, agricultural burning, and intentional fires outweigh biophysical drivers alone. Further

studies demonstrate that while community forestry institutions play a central role in fire management, their effectiveness is constrained by limited financial and technical capacity, weak coordination, insufficient training, and the absence of reliable early warning systems. From social-ecological systems and collective action perspectives, these institutional gaps undermine cooperation, delay response, and intensify fire impacts, especially in areas with high human-forest interaction.

The unique contribution of this study lies in its integrated approach, combining long-term satellite-derived fire data with community-level experiences to produce a validated fire risk map while simultaneously diagnosing governance and collective action challenges. Future efforts should prioritize strengthening institutional coordination, expanding technology-based early warning systems, and linking livelihood incentives with fuel management.

ACKNOWLEDGMENTS

I would like to thank the National Trust for Nature Conservation, Lalitpur, for its financial support of the research. Similarly, I would like to acknowledge the active support of forest officers and CFUG, as well as FECOFUN, for their coordination. The author gratefully acknowledges Mr. Sujan Khanal and Mr. Navaraj Adhikari for their support and valuable contributions.

Generative AI statement: The authors declare that no generative AI was used in the creation of this manuscript.

REFERENCES

- Adab, H., Kanniah, K. D., & Solaimani, K. (2013). Modeling forest fire risk in the northeast of Iran using remote sensing and GIS techniques. *Natural Hazards*, 65(3), 1723–1743. <https://doi.org/10.1007/s11069-012-0450-8>

- Bagmati Province. (2024). *Bagmati Province profile*. Wikipedia. https://en.wikipedia.org/wiki/Bagmati_Province
- Beguñría, S. (2006). Validation and evaluation of predictive models in hazard assessment and risk management. *Natural Hazards*, 37(3), 315–329. <https://doi.org/10.1007/s11069-005-5182-6>
- Bhattarai, N., Dahal, S., Thapa, S., Pradhananga, S., Karky, B. S., Rawat, R. S., Windhorst, K., Watanabe, T., Thapa, R. B., & Avtar, R. (2022). Forest fire in the Hindu Kush Himalayas: A major challenge for climate action. *Journal of Forest and Livelihood*, 21(1), 14–31. <https://doi.org/10.3126/jfl.v21i1.56576>
- Bhujel, K. B., Sapkota, R. P., & Khadka, U. R. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Bhusal, S., & Mandal, R. A. (2020). Forest fire occurrence, distribution and future risks in Arghakhanchi District, Nepal. *International Journal of Geography, Geology and Environment*, 2(1), 10–20.
- Cáceres, C. F. (2011). Using GIS in hotspots analysis and for forest fire risk zones mapping in the Yeguaré Region, Southeastern Honduras. *Papers in Resource Analysis*, 13, 1–14.
- Charnley, S., Kelly, E. C., & Fischer, A. P. (2020). Fostering collective action to reduce wildfire risk across property boundaries in the American West. *Environmental Research Letters*, 15(2), 025007. <https://doi.org/10.1088/1748-9326/ab639a>
- Department of Hydrology and Meteorology. (2024). *State of climate of Nepal*. Government of Nepal.
- Department of National Parks and Wildlife Conservation. (2024). *Protected areas*. <https://dnpwc.gov.np>
- Department of Survey. (2024). *Nepal road network statistics (2012–2015): Road length by category and pavement*. Government of Nepal.
- Doerr, S. H., & 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(1696), 20150345. <https://doi.org/10.1098/rstb.2015.0345>
- DPNet Nepal. (2024). *Discussion program on recent fire incidents in Nepal*. <https://dpnet.org.np/news/detail/discussion-program-on-recent-fire-incidents-in-nepal>
- Filippidis, E. I., & Mitsopoulos, I. D. (2004). Mapping forest fire risk zones based on historical fire data in Mount Olympus, Greece, using geographical information systems. *WIT Transactions on Ecology and the Environment*, 77.
- Food and Agriculture Organization of the United Nations. (2007). *Fire management: Global assessment 2006* (FAO Forestry Paper 151). FAO. <https://www.fao.org>
- Forest Research and Training Centre. (2022). *Dataset*. <https://rds.icimod.org/Home/DataDetail?metadataId=1972729>
- Goldammer, J. G., & De Ronde, C. (Eds.). (2004). *Wildland fire management handbook for sub-Sahara Africa*. African Minds.
- Goss, M., Swain, D. L., Abatzoglou, J. T., Sarhadi, A., Kolden, C. A., Williams, A. P., & Diffenbaugh, N. S. (2020). Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters*, 15(9), 094016. <https://doi.org/10.1088/1748-9326/ab83a7>
- Government of Nepal. (2013). *Nepal disaster report 2013*. Ministry of Home Affairs.
- ICIMOD. (2019). *Annual report*. International Centre for Integrated Mountain Development.
- Jaiswal, R. K., Mukherjee, S., Raju, K. D., & Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS. *International Journal of Applied Earth Observation and Geoinformation*, 4(1), 1–10. [https://doi.org/10.1016/S0303-2434\(02\)00006-5](https://doi.org/10.1016/S0303-2434(02)00006-5)
- Kalwar, O. P. P. (2022). *Forest fire hazard distribution mapping in Nepal using satellite imagery* [Unpublished manuscript].
- Kane, J. (2024). Forest fire. In *Encyclopædia Britannica*. <https://www.britannica.com/science/forest-fire>
- Kirschner, J. A., Clark, J., & Boustras, G. (2023). Governing wildfires: Toward a systematic analytical framework. *Ecology and Society*, 28(2), 280206. <https://doi.org/10.5751/ES-13920-280206>

- Kunwar, R. M., & Khaling, S. (2006). Forest fire in the Terai, Nepal: Causes and community management interventions. *International Forest Fire News*, 34, 46–54.
- Laschi, A., Foderi, C., Fabiano, F., Neri, F., Cambi, M., Mariotti, B., & Marchi, E. (2019). Forest road planning, construction and maintenance to improve forest fire fighting: A review. *Croatian Journal of Forest Engineering*, 40(1), 207–219.
- López-Rodríguez, G., Rodríguez-Vicente, V., & Marey-Pérez, M. F. (2021). Study of forest productivity in the occurrence of forest fires in Galicia (Spain). *Sustainability*, 13(15), 8472. <https://doi.org/10.3390/su13158472>
- Matin, M. A., Chitale, V. S., Murthy, M. S., Uddin, K., Bajracharya, B., & Pradhan, S. (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(4), 276–286. <https://doi.org/10.1071/WF16056>
- McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: Initial changes and continuing challenges. *Ecology and Society*, 19(2), 28. <https://doi.org/10.5751/ES-06387-190230>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19(1), 1–15. <https://doi.org/10.1186/s42408-022-00162-3>
- MODIS FIRMS. (2024). *Fire information for resource management system archive download*. NASA. <https://firms.modaps.eosdis.nasa.gov/download/>
- Mohammadi, F., Bavaghar, M. P., & Shabanian, N. (2014). Forest fire risk zone modeling using logistic regression and GIS: An Iranian case study. *Small-Scale Forestry*, 13(1), 117–125.
- Moreno, J. M., Morales-Molino, C., Torres, I., & Arianoutsou, M. (2021). Fire in Mediterranean pine forests: Past, present and future. In *Pines and their mixed forest ecosystems in the Mediterranean basin* (pp. 421–456). Springer International Publishing.
- Olson, M. (2012). *The logic of collective action*. Harvard University Press.
- Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press.
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422. <https://doi.org/10.1126/science.1172133>
- Pandey, C. L. (2021). Managing urban water security: Challenges and prospects in Nepal. *Environment, Development and Sustainability*, 23(1), 241–257. <https://doi.org/10.1007/s10668-019-00577-0>
- Pandey, C. L. (2025). Climate change, floods, and community resilience: A study of the Kamala River Basin, Nepal. *Journal of Flood Risk Management*, 18(2), e70069. <https://doi.org/10.1111/jfr3.70069>
- Pandey, C. L., & Bhattarai, K. (2025). Rethinking forest fire management in Nepal: Lessons from Bagmati Province. *Spotlight Nepal*, 18(21). <https://www.spotlightnepal.com>
- Pandey, H. P., Pokhrel, N. P., Thapa, P., Paudel, N. S., & Maraseni, T. N. (2022). Status and practical implications of forest fire management in Nepal. *Journal of Forest and Livelihood*, 21(1), 32–45. <https://doi.org/10.3126/jfl.v21i1.56583>
- Parajuli, A., Chand, D. B., Rayamajhi, B., Khanal, R., Baral, S., Malla, Y., & Poudel, S. (2015). Spatial and temporal distribution of forest fires in Nepal. In *Proceedings of the XIV World Forestry Congress*, Durban, South Africa.
- Parajuli, A., Gautam, A. P., Sharma, S. P., Bhujel, K. B., Sharma, G., Thapa, P. B., Bist, B. S., & Poudel, S. (2020). Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. *Geomatics, Natural Hazards and Risk*, 11(1), 2569–2586. <https://doi.org/10.1080/19475705.2020.1853251>
- Parajuli, A., Manzoor, S. A., & 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.
- Paudel, J. (2020). Short-run environmental effects of COVID-19: Evidence from forest fires. *World Development*, 137, 105120. <https://doi.org/10.1016/j.worlddev.2020.105120>

- Poudyal, B. H., Paudel, D., Marquardt, K., & Khatri, S. (2023). Examining forest transition and collective action in Nepal's community forestry. *Land Use Policy*, 134, 106872. <https://doi.org/10.1016/j.landusepol.2023.106872>
- Reddy, C. S., Bird, N. G., Sreelakshmi, S., Manikandan, T. M., Asra, M., Krishna, P. H., Jha, C. S., Rao, P. V. N., & Diwakar, P. G. (2019). Identification and characterization of spatio-temporal hotspots of forest fires in South Asia. *Environmental Monitoring and Assessment*, 191(Suppl. 3), 791. <https://doi.org/10.1007/s10661-019-7695-6>
- Robinne, F. N. (2021). *Impacts of disasters on forests, in particular forest fires*. United Nations Forum on Forests Secretariat.
- Saglam, B., Bilgili, E., Durmaz, B. D., Kadioğulları, A. İ., & Küçük, Ö. (2008). Spatio-temporal analysis of forest fire risk and danger using Landsat imagery. *Sensors*, 8(6), 3970–3987. <https://doi.org/10.3390/s8063970>
- Sapkota, L. M., Shrestha, R. P., Jourdain, D., & Shivakoti, G. P. (2015). Factors affecting collective action for forest fire management: A comparative study of community forest user groups in Central Siwalik, Nepal. *Environmental Management*, 55(1), 171–186. <https://doi.org/10.1007/s00267-014-0404-x>
- Serra-Sogas, N., O'Hara, P. D., Canessa, R., Keller, P., & Pelot, R. (2008). Visualization of spatial patterns and temporal trends for aerial surveillance of illegal oil discharges in western Canadian marine waters. *Marine Pollution Bulletin*, 56(5), 825–833. <https://doi.org/10.1016/j.marpolbul.2008.02.005>
- Shahi, N., Bhusal, P., Paudel, G., & Kimengsi, J. N. (2022). Forest–people nexus in changing livelihood contexts: Evidence from community forests in Nepal. *Trees, Forests and People*, 8, 100223. <https://doi.org/10.1016/j.tfp.2022.100223>
- Sivrikaya, N. U., Saglam, B., Akay, A., & Bozali, N. (2014). Evaluation of forest fire risk with GIS. *Polish Journal of Environmental Studies*, 23(1), 187–194.
- Somlai, I. G., Karakatsoulis, J., Gardner, W., Gautam, A. P., Sharma, S. P., & Adhikari, B. (2018). Forest governance in Nepal: Rationale for centralised forest and wildfire management. *Journal of Management and Development Studies*, 28, 16–35. <https://doi.org/10.3126/jmds.v28i0.24956>
- Thapa, S., Chitale, V. S., Pradhan, S., Shakya, B., Sharma, S., Regmi, S., Bajracharya, S., Adhikari, S., & Dangol, G. S. (2021). Forest fire detection and monitoring. In *Earth observation science and applications for risk reduction and enhanced resilience in Hindu Kush Himalaya region: A decade of experience from SERVIR* (pp. 147–167). Springer International Publishing.
- Tiwari, S., Paudel, N. S., Sze, J., & Karki, R. (2022). Unravelling the local dynamics of increasing fires in community forests of mid-hills of Nepal. *Journal of Forest and Livelihood*, 21(1), 60–71.
- Wang, S. W., Lim, C. H., & Lee, W. K. (2021). A review of forest fire and policy response for resilient adaptation under changing climate in the Eastern Himalayan region. *Forest Science and Technology*, 17(4), 180–188. <https://doi.org/10.1080/21580103.2021.1979108>
- Weise, D. R., & Biging, G. S. (1997). A qualitative comparison of fire spread models incorporating wind and slope effects. *Forest Science*, 43(2), 170–180. <https://doi.org/10.1093/forestscience/43.2.170>
- Xu, R., Yu, P., Abramson, M. J., Johnston, F. H., Samet, J. M., Bell, M. L., Haines, A., Ebi, K. L., Li, S., & Guo, Y. (2020). Wildfires, global climate change, and human health. *New England Journal of Medicine*, 383(22), 2173–2181. <https://doi.org/10.1056/NEJMSr2028985>
- Yakubu, I., Mireku-Gyimah, D., & Duker, A. A. (2015). Review of methods for modelling forest fire risk and hazard. *African Journal of Environmental Science and Technology*, 9(3), 155–165. <https://doi.org/10.5897/AJEST2014.1820>
- Zhang, Z., Feng, Z., Zhang, H., Zhao, J., Yu, S., & Du, W. (2017). Spatial distribution of grassland fires at the regional scale based on the MODIS active fire products. *International Journal of Wildland Fire*, 26(3), 209–218. <https://doi.org/10.1071/WF16026>

Assessing forest fire risks using geo-spatial techniques in western Nepal

Sirjan Sharma^{1*}, Ambika P. Gautam¹, Ashok Parajuli², Mahesh Parajuli¹

¹*Kathmandu Forestry College, Kathmandu, Nepal*

²*Ministry of Forests and Environment, Bagmati Province, Nepal*

*Corresponding author: sirjansharma7@gmail.com

Abstract

Forest fires are a significant threat to Nepal's ecological and socio-economic stability, particularly in vulnerable regions. Despite increasing fire frequency and intensity, research on spatially explicit risk assessment in Nepal remains limited; therefore, this study maps forest fire risks, identifies key contributing factors, and proposes actionable management strategies for Lumbini Province. Fire incidents and burned areas (2012–2024) were derived from MODIS and VIIRS datasets, while topographic, climatic, biophysical, and anthropogenic data were sourced from open-access repositories. Primary data from key informant interviews revealed causes, impacts, challenges, and preventive measures. Spatial layers were processed using GIS/RS techniques and integrated using a Weighted Linear Combination (WLC) model to create a forest fire risk map, categorising the region into five risk levels. The WLC model identified land cover (20%), road proximity (15%), settlement proximity (15%), NDVI (15%), and temperature (10%) as the dominant drivers, revealing that 57.42 per cent of forests are in very-high to high-risk zones. The findings revealed fires peak in the pre-monsoon season (March-May), with April accounting for 76.85 per cent of occurrences. High-risk areas feature broad-leaved closed forests, temperatures >40°C, gentle slopes <15%, south-facing aspects, and proximity to humans. The risk model correctly predicted 78.22 per cent of historical fire incidents within the identified high-to-very-high risk zones, supported by a confusion matrix (Kappa: 0.94) and ROC curve analysis (AUC: 0.803). Furthermore, perception analysis of forest managers emphasised the urgent need for proactive measures, including increased funding, specialised training, and the development of early warning systems to support sustainable forest management.

Keywords: Forest fire risk, Geospatial techniques, Weighted linear combination, Lumbini Province, Fire management

INTRODUCTION

Forest fires are increasing across the globe due to climate change, human activity, and rising temperatures, leading to increased fires and deforestation (You, 2023). The fires are major contributors to greenhouse gas emissions, biodiversity loss, and land degradation, impacting ecosystems and human communities worldwide (Keeley *et al.*, 2016). Around 0.4 per cent of the global land

surface is reportedly burned annually, covering 30 - 46 million km² (Randerson *et al.*, 2012).

Forest fires are a persistent issue in Nepal, especially during the dry season, leading to significant ecological and socio-economic impacts. According to Khanal (2015), between 2001 and 2015, approximately 375,000 hectares of forests were burned, impacting 18 districts throughout the country. Past studies have shown that climatic variables such as

rising temperatures and decreasing rainfall are the major drivers of increased forest fire frequency in South Asia and the Hindu Kush Himalayan region (Matin *et al.*, 2017; Sharma, 2006). In Nepal, the frequency of forest fires rose sharply in between 2000 and 2017, coinciding with altered precipitation patterns and extended drought periods (Bhujel *et al.*, 2017).

Geographic Information Systems (GIS) and remote sensing (RS) technologies are crucial in identifying, categorising, and mapping areas susceptible to forest fires (Zhang, 2024). Satellite technology has revolutionised the tracking and analysis of critical environmental parameters, including vegetation, topography, historical fire patterns, burned areas, and climatic factors (Chuvieco and Congalton, 1989). Integrating Earth observation data with GIS technology enables accurate assessment and mapping of forest fire dynamics. This approach has proven effective for estimating emissions (Cruz-López *et al.*, 2019) and identifying areas prone to forest fire hazards (Adaktylou *et al.*, 2020). Fischer *et al.* (2016) highlight the critical role of evidence-based analysis in assisting policymakers, planners, and authorities in disaster prevention.

Fire risk mapping in Nepal was initiated, integrating MODIS data with the help of RS and GIS technologies. Among these, a notable work was contributed by (Bhujel *et al.*, 2022; Matin *et al.*, 2017; Parajuli *et al.*, 2015; Qadir *et al.*, 2021) proposed a spatially distributed fire risk index using historic fire data, land cover, temperature, and topography. Likewise, Parajuli *et al.* (2020) further analysed fire risk in the Terai Arc Landscape (TAL) and Chitwan Annapurna Landscape (CHAL) regions using variables such as aspect, slope, elevation, vegetation, and proximity to roads and settlements.

The growing frequency and severity of forest fires in Nepal have become a critical environmental and socio-economic issue, severely threatening forest ecosystems, biodiversity, and local communities (Pandey *et al.*, 2022). Lumbini Province, with 48.8 per cent forest cover (Province Planning Commission, 2076), is highly vulnerable, with fires impacting livelihoods, biodiversity, air quality, and climate due to its extensive forest cover, representative ecological conditions, high vulnerability in national NDRRMA/MODIS datasets, and research gap amid prior focus on TAL/Chure/Sudurpashchim regions (Bhujel *et al.*, 2022; Matin *et al.*, 2017; NDRRMA, 2024); however, comprehensive studies on spatial-temporal fire patterns remain lacking in this critical region.

This study fills this critical knowledge gap by mapping forest fire risks in Lumbini Province (2012–October 2024) using GIS, RS, and the Weighted Linear Combination (WLC) method. The WLC approach was prioritised over complex machine learning algorithms because it facilitates a knowledge-driven framework that integrates expert-defined weightings with biophysical variables (Ersoy *et al.*, 2025). The method also provides greater transparency in representing fuel availability (land cover/NDVI), ignition sources (road and settlement proximity), and fire propagation drivers (topography and climate), making it particularly suitable for Nepal's data-scarce context (Nikolić *et al.*, 2023). The research aims to assess forest fire hazards and create a fire risk map to inform policymakers, planners, and stakeholders, contributing to improved fire management and future planning in Nepal.



METHODOLOGY

Study area

The research was conducted in the Lumbini Province of Nepal, which lies in the western part of the country, covering an area of 22,288 km². The Province area equals 15.1 per cent of the country’s total land (Province Planning Commission, 2024). It shares borders with Karnali Province to the north, while Sudurpashchim Province lies to the west. Gandaki forms its eastern and northern parts, while Uttar Pradesh of India shares the southern border with the province. Geologically, it ranges between 27°20’ N to 29°00’ N latitude and 81°21’ E to 84°02’ E longitude (Figure 1).

The Province administratively comprises 12 districts and 109 local administrative units: four sub-metropolitan cities, 32 municipalities, and 73 rural municipalities, divided into 983 wards (Constitution of Nepal, 2015).

Topographically, it is divided into five regions: High Himalayas (3.1%), High Mountains (9.1%), Middle Mountains (32.2%), Siwalik (27.9%), and Terai (27.6%), with elevation ranging from below 500 meters to above 5,000 meters (National Statistics Office, 2024). Climatically, Lumbini Province experiences mild winters, hot summers, and varied monsoon rainfall, with some areas experiencing droughts and others above-normal precipitation (Department of Hydrology and Meteorology, 2024).

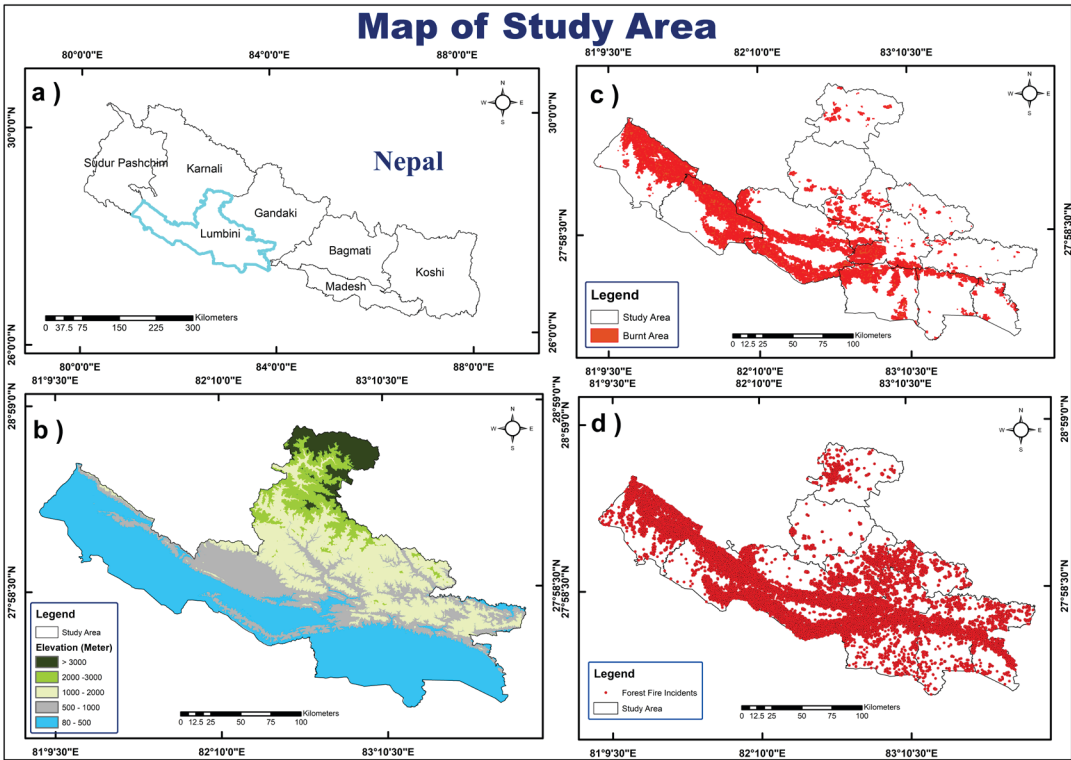


Figure 1: a) Map of Nepal b) Elevation of study area c) Brunt area of study area (2012-2024) d) Fire incidents in study area (2012-2024).

Data and collection methods

The research used both primary and secondary data. Primary data required to understand the causes, impacts, and management strategies for forest fires were collected through interviews with selected key informants, including Divisional Forest Office (DFO) staff such as forest officers and rangers. A purposive sampling method was used to select the key informant based on their role in managing and mitigating forest fire risk in their respective district. Five informants per district were selected to ensure proper representation to maintain the feasibility across all 12 districts, yielding a target sample of 60 respondents. Out of these, 41 responses were received, yielding a response rate of 68.3 per cent. The perception data were collected using a structured questionnaire with a five-point Likert scale (1 = strongly disagree/very poor to 5 = strongly agree/very good). Respondents rated statements across five preparedness dimensions: (i) availability of firefighting equipment and resources; (ii) adequacy of staff training and institutional capacity; (iii) effectiveness of early warning and communication systems; (iv) inter-agency coordination; and (v) community participation in fire management. Each participant's response was grouped into a category and averaged to form a readiness value for each section. Then the scores were interpreted using ranges, such as values from 1.00-1.80 were considered very poor, while 1.81- 2.60 were considered poor. Between 2.61 and 3.40 reflected moderate performance. Anything from 3.41 through 4.20 showed good standing, whereas 4.21 to 5.00 indicated very good outcomes. Data were collected using Google Forms and subsequently processed and analysed in Microsoft Excel.

Forest fire incidents data for the period 2012-2024, which are based on the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the three satellites: VIIRS S-NPP, NOAA-20, and NOAA-21, were acquired from NASA's Earth data FIRMS. Detection confidence, a measure ranging from 0 per cent to 100 per cent, is used to estimate the reliability of fire detection. Confidence levels above 30 per cent are considered more accurate (Giglio *et al.*, 2013). In this study, data with confidence levels exceeding 30 per cent have been utilised to enhance the accuracy of results. Burnt area data were derived from the MODIS MCD64A1 product, which has a spatial resolution of 500 meters and covers the period from 2012 to 2024 under Window 18 (South Asia). The dataset was downloaded from the University of Maryland server (<ftp://ba1.geog.umd.edu/>). The shape files were subsequently projected and clipped to the study area, and the burnt area was calculated using ArcGIS 10.8.

Variable used in the forest fire risk mapping

Based on the literature review, ten key variables influencing forest fires were identified and used to develop the forest fire risk map. For this study, satellite imagery, along with various vector and raster data products, was utilised. Table 1 presents the data models and sources for the different criteria maps. The variables were selected to prioritise the most accurate data available. These variables are categorised into four groups: topographical factors (elevation, slope, and aspect), climatic factors (temperature, precipitation, and wind speed), anthropogenic factors (proximity to settlements and distance from roads), and biophysical factors (land cover classes and NDVI).



Table 1: Variables and data used to assess forest fire risks

S.N.	Variables	Spatial Resolution	Data Period	Data Type	Source
1	Elevation	30 m	2000-2013	Raster	Aster DEM
2	Aspect	30 m	2000-2013	Raster	Aster DEM
3	Slope	30 m	2000-2013	Raster	Aster DEM
4	LULC	30 m	2010	Raster	ICIMOD
5	Temperature	1 km	2012-2024	Raster	MODIS
6	Precipitation	5.5 Km	2012-2024	Raster	Climate Hazards Group at UCSB (CHIRPS)
7	Distance From Road	1:25000	2024	vector	Humanitarian Data Exchange
8	Wind Speed	250m	2023	Raster	Global wind Atlas
9	NDVI	10 m	2023	Raster	Sentinel 2
10	Proximity to Settlement	1:25000	2015	Vector	OCHA Nepal
11	Forest Fire Points	375m	2012-2024	Vector	FIRMS
12.	Burnt Area	500m	2012-2024	Vector	NASA MODIS
13.	Perception Data			Likert Scale	Primary data

Data processing and analysis

Forest fire risk analysis

This study collected data and fire points from several sources to identify fire risk locations. Using ArcGIS software, the study processed data for extraction, projection, and clipping to the area of interest. To ensure uniformity, all raster datasets were resampled to a pixel size of 30 x 30 meters.

The WLC method integrated all variables to produce the final fire risk map. The study validated the risk map using three approaches: overlaying historical fire data, generating a confusion matrix, and performing AUC-ROC analysis (Figure 2).

Processing and analysis of spatial data

Topographic information, Aster Global DEM downloaded from USGS (<https://earthexplorer.usgs.gov/>) was mosaicked, projected, and clipped into the area of interest. Slope and aspect layers were then derived in the ArcGIS spatial analyst tool- ArcGIS 10.8.

Temperature data for 2012 to 2024, which was obtained from MODIS, were processed in Google Earth Engine to develop a Layer representing the mean monthly temperature for the pre-monsoon season, i.e., from March to May. Similarly, the wind speed data for the year 2023 at a resolution of 250 m were downloaded from the Global Wind Atlas <https://globalwindatlas.info/en>. The

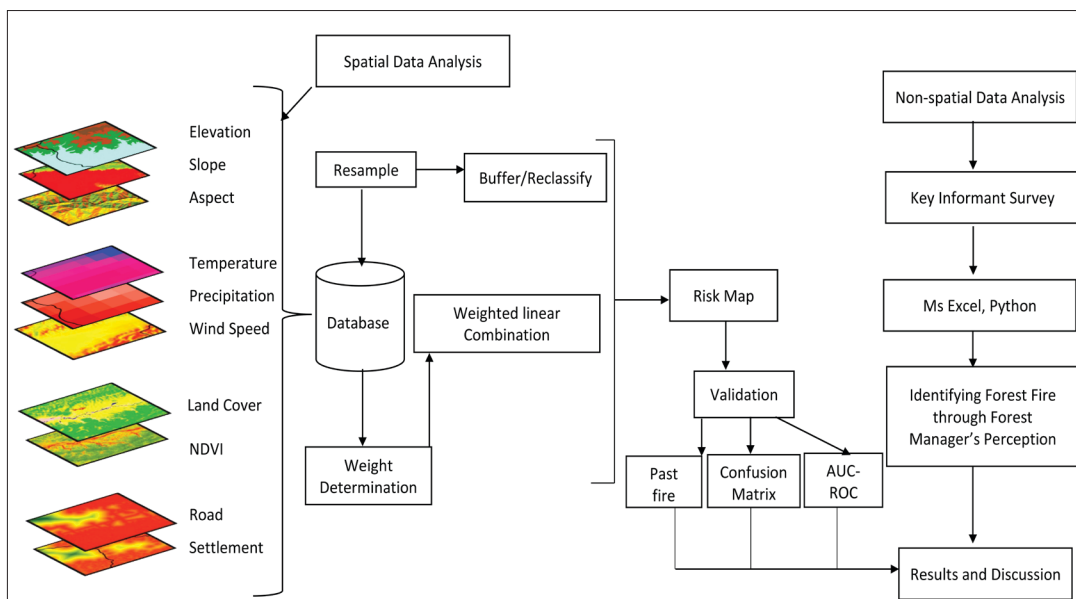


Figure 2: Framework for identifying forest fire risk zone in Lumbini Province

precipitation data for 2012-2024 were sourced from CHIRPS, available at a spatial resolution of 5.5 km.

Land cover classification data for the years 2010 and 2019, with a spatial resolution of 30 meters, were obtained from ICIMOD. Data on roads and settlements was obtained from the HOTOSM Nepal Roads dataset via the Humanitarian Data Exchange and OCHA Nepal. These vector point shape files were converted into a raster format using the Euclidean distance tool in the ArcGIS spatial analyst tool.

Also, the NDVI data from 2023 was extracted in 10 m resolution using Sentinel-2 imagery. The forest fire point data for 2012-2024 were derived from NASA FIRMS at a resolution of 375 m.

Development of forest fire risk model

Finally, the study reclassified and weighted ten critical parameters-land cover, NDVI,

temperature, slope, distance to roads, proximity to settlement areas, elevation, aspect, wind speed, and precipitation-to analyse forest fire risk. Since many factors exhibit highly variant fire frequency patterns dependent on intensity and severity, weights were assigned through an extensive literature review, rating each variable by established fire potential (Adab *et al.*, 2011; Chuvieco *et al.*, 2010; Mohajane *et al.*, 2021; Parajuli *et al.*, 2020). Land cover received the highest weight (0.20) as the primary fuel source (Ajin *et al.*, 2016), followed by distance to roads, proximity to settlements, and NDVI (0.15 each) due to anthropogenic ignition dominance and fuel continuity (Chuvieco *et al.*, 2010; Sivrikaya *et al.*, 2014), temperature as desiccation driver (0.10) (Matin *et al.*, 2017), and topographic/climatic factors at 0.05 each. Each variable was scored 1-5 (5=highest risk), combined through WLC for the final risk map.

The WLC method was employed to calculate the Forest Fire Risk Map (FFRM). The equation used was:

$$\begin{aligned} \text{FFRM} = & \text{LC} * 0.20 + \text{DR} * 0.15 + \text{PS} \\ & * 0.15 + \text{ND} * 0.15 + \text{T} * 0.10 + \text{A} * 0.05 \\ & + \text{E} * 0.05 + \text{S} * 0.05 + \text{P} * 0.05 + \text{WS} * \\ & 0.05 \dots \dots \dots \text{equation 1} \end{aligned}$$

where, FFRM is the forest fire risk map, LC is the Landover, DR stands for the distance from the road, PS is the proximity to the settlement, ND means normalised difference vegetation index, T is the temperature, A is the aspect, E is the elevation, S means slope, P stands for precipitation and WS is the wind speed. Each variable's contribution to fire risk was calculated based on its percentage influence. The weighted linear combination method is used because it is flexible and can merge different kinds of data. It offers a structured, transparent, and easy-to-apply risk assessment process.

Model validation

This study used three validation methods. The first method overlaid the 2024 forest fire points on the Forest Fire Risk Map, assuming that many forest fires would likely occur in medium- to extremely high-risk zones. This year was selected as a temporal benchmark due to its highest fire incidents and burnt area in the study period.

The second validation method calculated the various metrics of the user's accuracy, producer's accuracy, kappa coefficient, and overall accuracy using a confusion matrix developed with a support vector machine. This was done similarly to Jensen (1996) (cited in Jung *et al.*, 2013). A total of 100 random points were generated in ArcGIS and validated against a ground-based map available in Google Earth Pro. Each point was categorised into one of five risk levels (from 1

to 5), ranging from extremely low to very high risk. Additionally, these points were analysed with respect to surrounding features, such as forest density, towns, and roads, to verify their risk categorisation. Correct and incorrect classifications were recorded in the confusion matrix, and the following metrics have been computed by the corresponding equations:

$$1. \text{Producer's Accuracy} = \frac{C_{aa}}{C.a} * 100\% \quad \text{equation 2}$$

where, C_{aa} is the value at the intersection of a column, and $C.a$ is the row total.

$$2. \text{Overall Accuracy} = \frac{\sum_{a=1}^U C_{aa}}{Q} * 100\% \quad \text{equation 3}$$

where U is the total number of classes and Q is the total number of pixels

$$3. \text{Kappa Coefficient} = \frac{\frac{\sum_{a=1}^U C_{aa}}{Q} - \frac{\sum_{a=1}^U C.a C.a}{Q^2}}{1 - \frac{\sum_{a=1}^U C.a C.a}{Q^2}} \quad \text{equation 4}$$

where $C.a$ is the row total.

Finally, the cross-validation of the forest fire risk model was performed using the ROC curve approach. This method evaluates the performance by showing the area under the curve, representing the true positive rate, or sensitivity, versus the false positive rate, or 1-specificity. In constructing the ROC-AUC, the final risk map, forest fire points, and non-fire points were used. The non-fire points were generated in ArcGIS using spatially balanced sampling, and historical fire incidences of 2024 were used as validation points. The ROC tool from the ArcSDM toolset in ArcGIS was used to develop the ROC-AUC curve based on the methodology by (Das *et al.*, 2023; Mabdeh *et al.*, 2024). ArcSDM was very efficient in categorical map analysis.

RESULTS

Distribution of forest fires

Table 2 illustrates notable variation in forest fire incidents and burnt areas among 12 districts in the study area from 2012 to October 2024. Dang reported the highest number of incidents (27,164 or 24.74%), followed by Bardiya (22,953 or 20.90%) and Banke (21,281 or 19.38%), collectively accounting for over two-thirds of the total incidents. The mentioned districts also reported considerable areas affected by burning, with Dang representing the highest of 2,254.78 km², followed by Bardiya and Banke, thus clearly representing the strong association between the frequency of fire incidents and the extend of area affected. The overall fire density of Lumbini Province was 11.68 incidents per km² of forest area during 2012-2024.

Annual trends of forest fire

Fire incidents in Lumbini Province, Nepal, based on VIIRS data (2012–2024), shows significant variation over the years. In 2024, fire incidents peaked at 26,146, followed by 19,679 incidents in 2021 and 12,310 in 2023. In contrast, 2015 recorded the lowest number of incidents at 1,241, while 2020 had only 801 incidents. Fire incidents were relatively higher in 2016 and 2022, with counts reaching 11,154 and 7,734, respectively (Figure 3). On average, Lumbini Province experienced approximately 8,446 fire incidents per year over the past 13 years, with notable peaks occurring in 2024, 2021, and 2023. Most fire incidents were recorded in the pre-monsoon season, i.e. March - May taking a considerable share of 98.0 per cent. The respective shares for April and May are 76.85 per cent and 13.45 per cent of the fire outbreaks, with another 7.74 per cent happening during March.

Table 2: Fire incidents and burnt area in different districts of Lumbini Province during 2012-2024

S.N.	District Name	No. of fire Incidents	% of fire incidents	Burnt Area(sq. km)	District Area(sq. km)
1.	Arghakhanchi	8563	7.80	969.66	1239.66
2.	Banke	21281	19.38	1407.38	1879.78
3.	Bardiya	22953	20.90	1468.06	1999.68
4.	Dang	27164	24.74	2254.78	3001.97
5.	Gulmi	3040	2.77	324.57	1108.64
6.	Kapilbastu	7591	6.91	1057.64	1651.72
7.	Nawalparasi_west	2747	2.50	352.57	727.15
8.	Palpa	5332	4.86	686.46	1463.73
9.	Pyuthan	5444	4.96	1128.70	1321.12
10.	Rolpa	846	0.77	383.76	1885.13
11.	Rukum_east	739	0.67	1272.52	1682.37
12.	Rupandehi	4099	3.73	467.85	1305.68
Grand Total		109,799	100	11773.95	19266.63

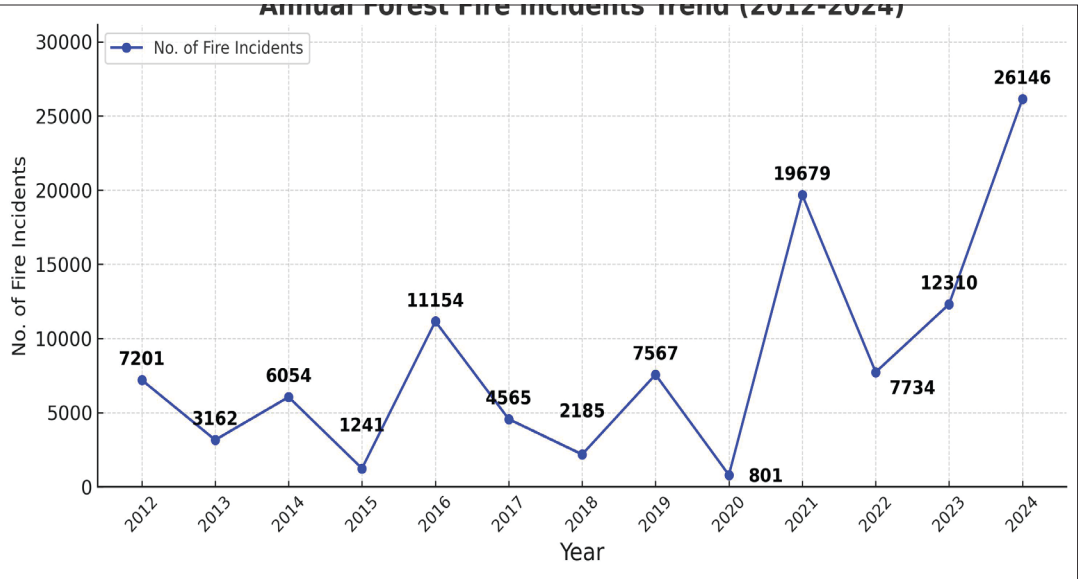


Figure 3: Annual forest fire incidents

Fire incidents in protected area within Lumbini Province

The study investigated the distribution patterns of forest fire incidents in protected areas on a yearly basis from 2012 to 2024. Over the past 13 years, Bardiya National Park recorded the highest number of incidents at 20,507, followed by Banke National Park with 15,543 incidents. In contrast, Dhorpatan Hunting Reserve recorded very few fire incidents, with a total of 35, while Krishnasaar Conservation Area had no recorded fire incidents (Figure 4).

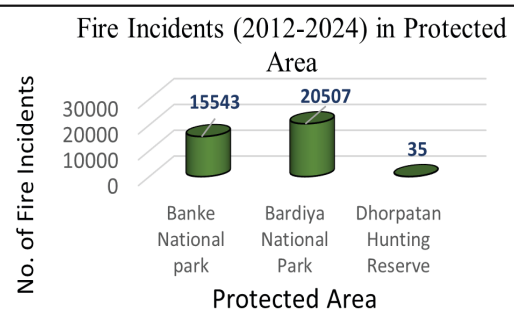


Figure 4: Fire incidents records in protected area

Local unit with the highest fire incidents

Out of the 109 local government units in the Province, Rapti Sonari rural municipality in Banke (17,435), Rajpur in Dang (8,631), and Gadhawa in Dang (4,436) experienced the most fire incidents during 2012 to 2024. Of the municipalities, Sitganga in Arghakhanchi had the most incidents (6,970), followed by Lamahi in Dang (3,122) and Shivaraj in Kapilbastu (2,620). The number of incidents is lower in sub-metropolitan cities, such as Butwal (1,073), Tulsipur (382), and Nepalgunj (1), while Ghorahi in Dang reported 2,876 fire incidents (Table 3).

Magnitude of burnt area

The burnt area record indicated that the years 2016, 2024, and 2023 had the highest burnt area: precisely, the year 2016 recorded the highest burnt area of 2718.79 km², followed by the year 2024 with a burn of 2385.70 km², and the year 2023 with a 1526.72 km². It is

reported that the lowest burnt areas in 2015 and 2020 were 65.27 km² and 28.64 km², respectively (Figure 5). The average burnt

area per year from 2012 to 2024 of Lumbini province is approximately 1052.51 km².

Table 3: Local unit with highest fire incidents in the study area

Administrative Zone	Local Unit Name	District Name	No. of Fire Incidents
Rural Municipality	Rapti Sonari	Banke	17435
	Rajpur	Dang	8631
	Gadhawa	Dang	4436
	Babai	Banke	2955
	Banglachuli	Dang	2134
	Sitganga	Arghakanchi	6970
Municipality	Lamahi	Dang	3122
	Shivaraj	Kapilbastu	2620
	Buddhabhumi	Kapilbastu	2469
	Kohalpur	Banke	2145
Sub Metropolitan city	Ghorahi	Dang	2876
	Butwal	Rupandehi	1073
Tulsipur		Dang	382
	Nepalgunj	Banke	1

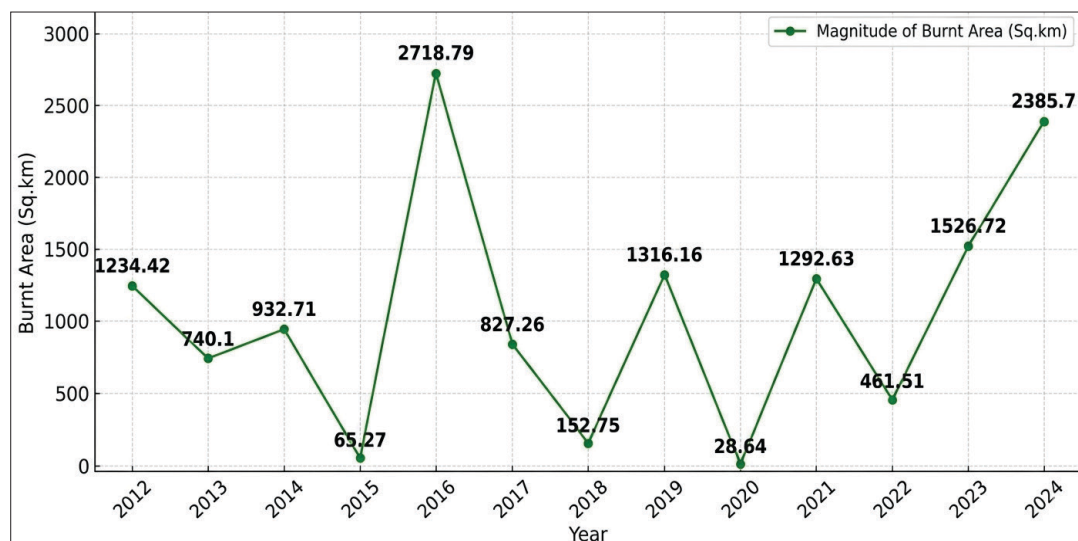


Figure 5: Annual trend of burnt area



Fire incidents comparison with the variables

Table 4 shows a good association between various environmental and geographical factors and fire hazard levels. By land cover, fire risk tends to be relatively high, especially within "Broad-leaved Closed Forest," accounting for as much as 74.3 per cent of fires. Accordingly, its range on a vegetative density scale referred to as the Normalised Difference Vegetation Index (NDVI)-NDVI provides evidence for higher amounts of fire events with particularly intensive vegetative mass, although confined to "0.4-0.5."

Also, fire risk is related to the proximity to roads and settlements, showing higher risk

near roads (<1000m) at 34.2 per cent and settlements (<1000m) at 34.94 per cent. Temperature was one of the critical variables, incidents above 90.9 per cent for temperatures >40°C. Low elevations, like 80 to 500 meters, contributed 48 per cent towards incidents. Aspect analysis shows that slopes oriented towards the south aspect had the highest incidents with a share of 31.42 per cent. Gentle slopes (<15%) and areas with moderate precipitation (100-150mm) yielded the highest values of fire risk, contributing 29.36 per cent and 57.89 per cent, respectively. Lastly, wind speed analysis showed that the highest fire incidents were associated with moderate winds at 2-3 m/s, contributing 47.34 per cent.

Table 4 Fire incidents comparison with the variables used in the study.

Variables	Weight (%)	Classes	Fire Rating Classes	Value	% of Fire Incidents	No. of Fire Incidents	% of Pixel Count
Land Cover	20	Bare area, Building /river/lake	Very Low Risk	0	0.25	270	5.32
		Agriculture	Very Low Risk	1	0.00	0	42.95
		Shrub land/Grass-land	Low Risk	2	0.68	744	1.98
		Needle leaved Open Forest	Medium Risk	3	0.77	843	4.59
		Needle leaved closed Forest/ Broad leaved Open Forest	High Risk	4	24.01	26362	17.42
		Broad leaved Closed Forest	Very High Risk	5	74.30	81580	27.74
NDVI	15	<0.2	Very Low Risk	1	0.30	332	11.49
		0.2-0.3	Low Risk	2	3.65	4004	24.15
		0.3-0.4	Medium Risk	3	36.79	40398	30.87
		0.4-0.5	High Risk	4	56.99	62579	28.21
		>0.5	Very High Risk	5	2.26	2486	5.28

Distance to Road (Meter)	15	>4000	Very Low Risk	1	17351	15.80	7.64
		3000-4000	Low Risk	2	12147	11.06	6.07
		2000-3000	Medium Risk	3	20133	18.34	13.99
		1000-2000	High Risk	4	22613	20.59	20.81
		<1000	Very High Risk	5	37555	34.20	51.49
Proximity to Settlement (Meter)	15	>4000	Very Low Risk	1	13.55	14876	5.34
		3000-4000	Low Risk	2	8.93	9802	3.06
		2000-3000	Medium Risk	3	19.97	21929	7.05
		1000-2000	High Risk	4	22.61	24827	10.92
		<1000	Very High Risk	5	34.94	38365	73.63
Temperature (Degree C)	10	<25	Very Low Risk	1	0.13	141	0.31
		25-30	Low Risk	2	0.24	268	2.96
		30-35	Medium Risk	3	0.36	399	5.68
		35-40	High Risk	4	8.36	9180	13.39
		>40	Very High Risk	5	90.90	99811	77.65
Elevation (Meter)	5	>3000	Very Low Risk	1	0.12	132	4.95
		2000-3000	Low Risk	2	0.60	663	7.37
		1000-2000	Medium Risk	3	12.15	13341	24.24
		500-1000	High Risk	4	39.13	42959	20.50
		80-500	Very High Risk	5	48.00	52704	42.94
Aspect	5	Flat	Very Low Risk	1	8.41	9232	8.94
		North	Low Risk	2	9.52	10450	15.25
		East	Medium Risk	3	19.39	21288	22.65
		West	High Risk	4	31.26	34327	25.49
		South	Very High Risk	5	31.42	34502	27.67
Slope (%)	5	>45	Very Low Risk	1	26.14	28697	30.81
		35-45	Low Risk	2	15.37	16873	10.33
		25-35	Medium Risk	3	15.97	17537	9.39
		15-25	High Risk	4	13.17	14460	7.45
		<15	Very High Risk	5	29.36	32232	42.03
Precipitation (mm)	5	>250	Very Low Risk	1	1.68	1844	3.33
		200-250	Low Risk	2	3.41	3745	13.39
		150-200	Medium Risk	3	31.96	35089	34.42
		100-150	High Risk	4	57.89	63558	38.31
		<100	Very High Risk	5	5.07	5563	10.55
Wind Speed (m/s)	5	<1	Very Low Risk	1	0.75	822	2.51
		1-2	Low Risk	2	23.90	26240	22.04
		2-3	Medium Risk	3	47.34	51976	45.76
		3-4	High Risk	4	20.01	21969	23.21
		>4	Very High Risk	5	8.01	8792	6.49



Forest fire risk index model of Lumbini Province

The final map was created using derived weights based on fire risk effects. The Figure 6 below shows that the regions at risk of fire include 2.85 per cent of the study area with very high risk, 54.57 per cent with a high risk, and 36.11 per cent at medium risk. Approximately 5.18 per cent of the area is classified as very low risk. For the study area, this distribution reflects that more than two-thirds of the area is at risk of forest fires, as 57.42 per cent of the forest area falls within the high to very high-risk classification, making this Province highly susceptible to forest fire.

District with forest fire risk zone

Table 5 illustrates the distribution of forest fire zones among the districts in the study area. Dang has the highest proportion of its area (58.03%) categorised under medium to very high-risk zones. This is followed by

Bardiya (44.45%) and Banke (35.79%), which also exhibit considerable fire risk. In contrast, districts such as Nawalparasi West (9.37%) and Gulmi (13.61%) have the lowest proportions of areas under fire risk zones.

Table 5 Distribution of forest fire risk zone by districts

Districts	Medium to very high risk zone (%)	Districts	Medium to very high risk zone (%)
Dang	58.03	Pyuthan	17.23
Bardiya	44.45	Palpa	17.00
Banke	35.79	Arghakhan-chi	16.96
Kapilbastu	32.46	Rukum_ east	14.82
Rolpa	22.99	Gulmi	13.61
Rupandehi	17.33	Nawalpara-si_ west	9.37

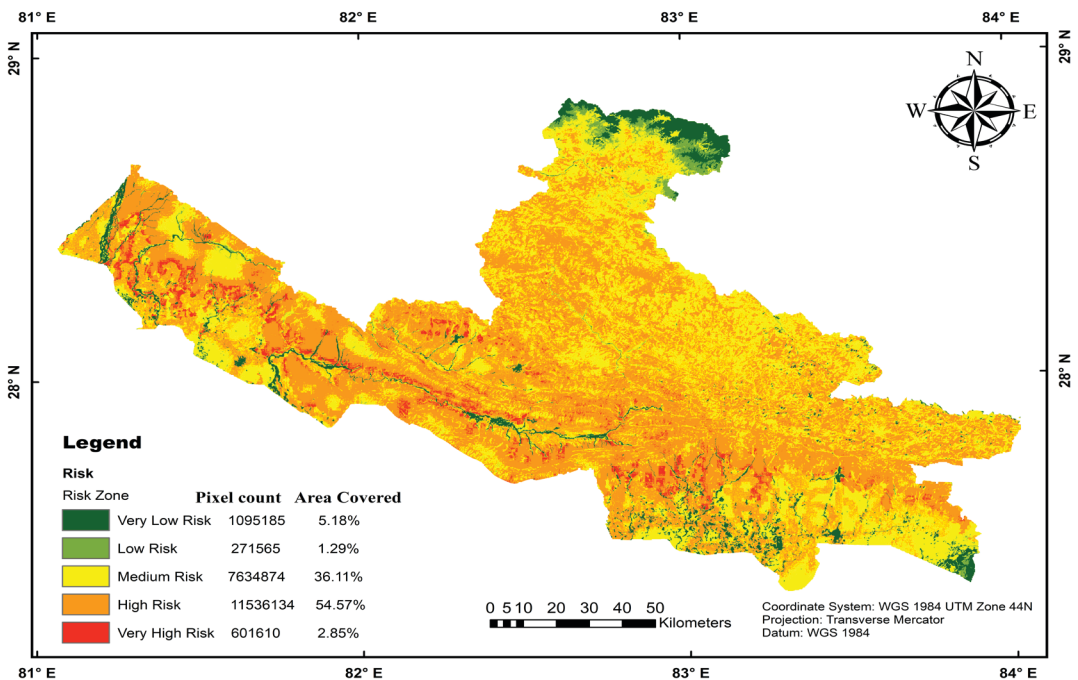


Figure 6: Forest fire risk map of Lumbini Province including the percentage of risk areas

Table 6 Risk area covered in each zone and past forest fire (2024) overlaid in each zone

Fire Risk	% Area of Fire risk zone	No. of Fire Incidents (2024)	% of Fire incidents
Very Low	5.18%	84	0.32 %
Low	1.29%	21	0.08 %
Medium	36.11%	5,590	21.38 %
High	54.57%	19,498	74.57 %
Very High	2.85%	953	3.65 %
Total		26,146	

Validity of the findings

This study validated fire risk maps using three approaches: overlaying 2024 fire points for consistency, generating a confusion matrix to assess reliability via user accuracy and kappa coefficient, and evaluating performance through an ROC curve using the ARC SDM toolbox.

First, the 2024 fire incidents were overlaid over the fire risk map (Kanga and Singh, 2017; R S *et al.*, 2016). In this validation step, 99.6 per cent of fire incidents in 2024 occurred at medium to very high-risk areas (Figure 8). A confusion matrix, which helps validate the generated risk map when there are more than two classes (Shinga *et al.*, 2024). Classes such as true positives, true negatives, false positives,

and false negatives display classification outcomes. Random points were generated across the study area to estimate this. Table 7 shows that user accuracy reached 100 per cent in the very low, low, and very high classes. In contrast, the medium class showed the lowest accuracy, at 89 per cent, highlighting areas that may require model improvement. The kappa coefficient reached 0.94, indicating a very high agreement between predicted and observed classifications.

This study evaluated the fire risk map's performance using the AUC, which measures the map's efficiency in distinguishing between high- and low-risk zones. The ROC-curve for the forest fire risk map is shown in Figure 7. The overall AUC-value of 0.803, indicates a very good predictive accuracy.

Table 7 Result obtained from the confusion matrix

Class Value	Very Low	Low	Medium	High	Very High	Total	User Accuracy	Kappa
Very Low	10.00	0.00	0.00	0.00	0.00	10.00	1.00	
Low	0.00	10.00	0.00	0.00	0.00	10.00	1.00	
Medium	0.00	3.00	32.00	1.00	0.00	36.00	0.89	
High	0.00	0.00	1.00	54.00	0.00	55.00	0.98	
Very High	0.00	0.00	0.00	0.00	10.00	10.00	1.00	
Total	10.00	13.00	33.00	55.00	10.00	121.00		
Producer Accuracy	1.00	0.77	0.97	0.98	1.00	0.00	0.96	
Kappa								0.94

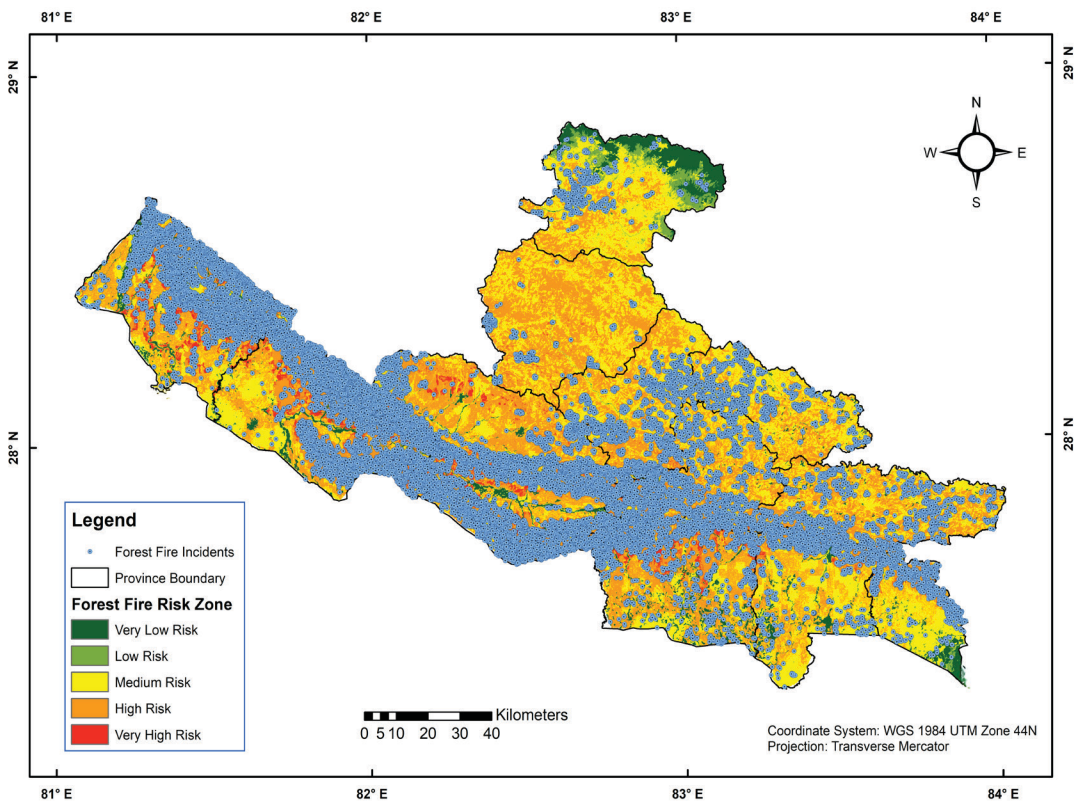


Figure 8: Forest fire incidents on forest fire risk map

Perception of key informants about forest fire in Lumbini Province

The increasing recurrence of forest fires in Nepal points to a need for more available management strategies and technologies in tackling the problem effectively (Parajuli *et al.*, 2022). Human intervention and support have conventionally been used to mitigate risks in fire-prone areas. (Doerr and Santín, 2016).

Types and causes of forest fire

Based on the information gathered from the key informants, the three leading causes of forest fires within the study area are given in (Figure 9). Deliberate causes were cited by 55 per cent as the primary cause, Accidental causes by 36 per cent, and fire from agriculture

activities like slash and burn by 9 per cent. In Nepal, human activities are also identified as the primary origin of forest fires. The

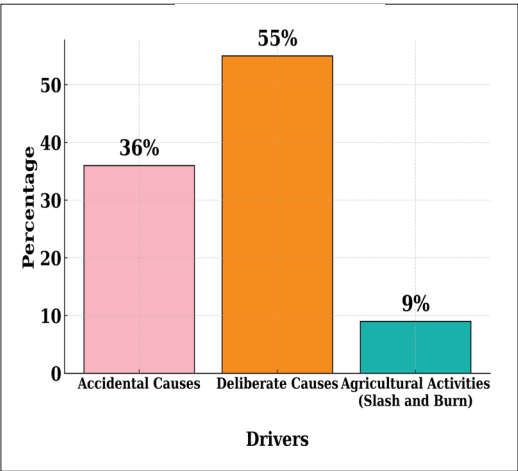


Figure 9: Drivers of forest fire

same respondents, however, clarified that in the studied area, most fires occur either on the ground (31%) or on the surface (61%), crown fires are minimal, just 8 per cent. The respondents reported March (8.3%) and April (83.4%) as forest fire-prone months.

Impact of forest fires on forest types and management systems

The analysis showed that forest fire affect community forest the most, with 83.3 per cent of respondents identifying them as highly affected, compared to 16.7 per cent for government-managed forests. A majority, 84 per cent of respondents reported an increase in forest fire occurrences over time, while 16 per cent reported no increase, and none observed a decrease. Sub-tropical broad-pine forests were identified as the most affected forest type (41.7%), with tropical forests and sub-tropical broad-leaved forests (25% each) and lower temperate broad-leaved forests (8.3%) being the least affected.

Perceived challenges, preparedness, and preventive measures in forest fire management

The results show the challenges of forest fires, district-level preparedness, and prevention

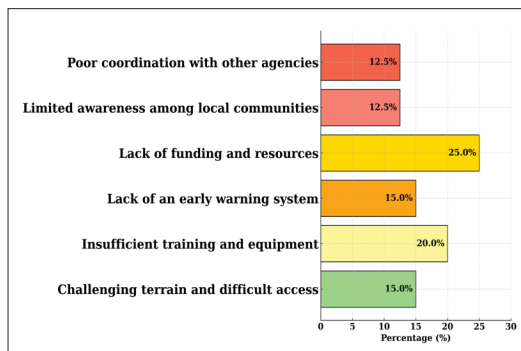


Figure 10: Key challenges in forest fire management

measures. Lack of funding and resources (25%) is the single most obstructive component, followed by insufficient training and equipment (20%) and lack of early warning systems (15%) (Figure 10). According to the district-wise preparedness score, Nawalparasi West, Rukum East, and Rupandehi have comparatively better preparedness, with a score of 4.0. At the same time, Banke and Dang are the least prepared, with scores of 2.0 and 2.5, respectively (Figure 11). In terms of preventive measures applied in the districts, firebreaks/fire lines (33.3%) and community education and awareness (30%) were the strategies identified as being most effective, followed by controlled burning (20%) (Figure 12).

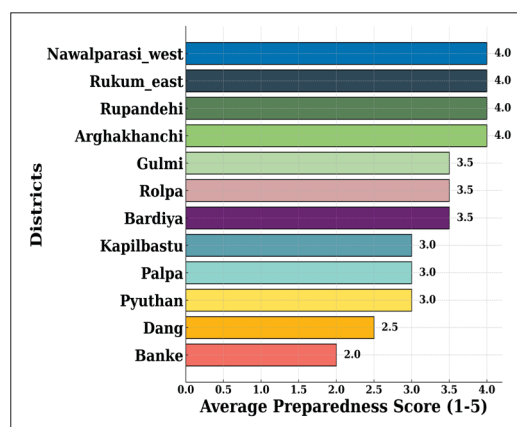


Figure 11: District wise preparedness score

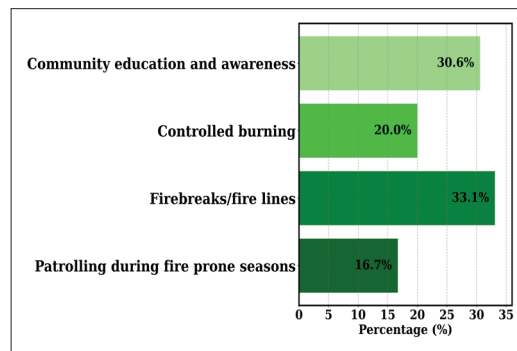


Figure 12: Effective preventive measures in the study area

DISCUSSION

Assessing the status and trends of forest fire

This study highlights how environmental and human factors interact to shape forest fire patterns. In this case, land cover appeared to be one of the decisive elements influencing the fire risk. Considering the rest of the categories, the class of broadleaved closed forests reported 74.30 per cent of the fire incidents. Sal-dominated broadleaved forests exhibit extreme pre-monsoon fire proneness due to March-April leaf shedding creating continuous litter layers (8-12% moisture) and live fuel moisture declining to 60-80 per cent, forming highly flammable surface fuel beds under 35-42°C conditions (Timilsina *et al.*, 2007). The same findings were recorded by Ajin *et al.* (2016) in the deciduous forests of India. Likewise, temperature increased the probability of fire incident occurrences, with 90.90 per cent occurring at temperatures above 40°C. This finding is supported by recent studies such as Ma *et al.* (2024) and Matin *et al.* (2017), which stated that high temperatures and drought conditions raise the probability of forest fires by increasing the drying of fuels. Aspect also plays an essential role; southern aspects witnessed 31.42 per cent of the fire incidents. It has been consistent with Adab *et al.* (2011), who concluded that the Southern aspects have higher temperatures and robust winds, lower humidity and reduced fuel moisture, which results in a high vulnerability to fire incidents.

Elevation also influences fire patterns, with lowland areas (80-500 meters) experiencing 48 per cent of incidents, reflecting increased human activities and drier conditions (Matin *et al.*, 2017). Proximity to roads and settlements is another critical factor, with 34.20 per cent of fires occurring within 1 km

of roads and 34.94 per cent within 1 km of settlements. This result is also supported by the work of Sivrikaya *et al.* (2014) and Parajuli *et al.* (2020), who also documented more fire occurrences near anthropogenic activities due to accidental ignition.

Interestingly, areas with high NDVI values (>0.5) recorded fewer fire incidents despite being classified as high-risk zones. Dense vegetation with higher moisture content inhibits ignition (Chuvieco *et al.*, 2008), and these areas are often remote with limited human interference, reducing fire occurrences (Archibald *et al.*, 2013).

Developing a forest fire risk map of Lumbini Province

The WLC method successfully combined ten key variables to create a forest fire risk map, categorizing 57.42 per cent of forests are in very-high to high-risk zones. Variables such as land cover, proximity to roads, and NDVI received the highest weights, emphasising their importance in fire risk (Akay and Erdoan, 2017; Chuvieco *et al.*, 2010). Susceptibility mapping for forest fires uses a dependent variable such as a forest fire inventory along with several independent variables, usually topographic factors—elevation, slope, and aspect—climatic factors including rainfall, temperature, humidity, and wind, anthropogenic factors concerning proximity to settlements and roads, and land use characteristics, as suggested by (Carmel *et al.*, 2009; Jaiswal *et al.*, 2002; Mohajane *et al.*, 2021).

Accuracy assessment

Validation is one of the important parts of preparing the risk map (Feizizadeh & Blaschke, 2014; Pourghasemi *et al.*, 2016). Overlaying

2024 fire incidents revealed a strong correlation, with high-risk zones (54.57% of the area) accounting for 74.57 per cent of fire incidents and very high-risk zones (2.85% of the area) capturing 3.65 per cent, consistent with the role of historical data highlighted by (Ajin *et al.*, 2016; Kanga and Singh, 2017; Vadrevu *et al.*, 2010).

In this study, the user accuracy was 96 per cent, and the kappa coefficient was approximately 0.94, indicating that the map was accurately produced. Kappa coefficients in this range represent substantial and reliable agreement (Rwanga *et al.*, 2017). Similarly, Parajuli *et al.* (2023) reported comparable results, with 95 per cent overall accuracy and a kappa coefficient of 0.93, further supporting the reliability of such validation methods.

The ROC-AUC analysis, with an AUC value of 0.803, confirmed a predictive accuracy of 80.3 per cent, aligning with another similar research. As Carter *et al.* (2016) suggests that an AUC value exceeding 0.7 reflects good predictive performance, further validating the model. Similarly, research conducted in the Halgurd-Sakran Core Zone achieved an AUC score of 0.76, indicating a reliable predictive capability in assessing forest fire risk (Khan *et al.*, 2024).

Perception analysis

The study found that 55 per cent of forest fires were caused deliberately, aligning with Kunwar *et al.* (2006), who reported that 58 per cent of anthropogenic forest fires were due to deliberate burning by grazers, poachers, hunters, and non-timber forest product harvesters. These activities reflect significant unsustainable human pressure on forest ecosystems.

Additionally, 36 per cent of the fires in this study were accidental, while 9 per cent were linked to agricultural activities such as slash-and-burn. Likewise, numerous authors claim that whether intentional or not, human activity is the main reason behind the majority of fires worldwide (Ryan and Hamin, 2008; Shindler *et al.*, 2009).

Likewise, the study found that the most vulnerable month to fire is March to May, i.e., the pre-monsoon season. To support this, many scholars have also concluded that the majority of forest fires in Nepal take place in the hotter, drier pre-monsoon season (March-May) (Bhujel *et al.*, 2017; Khanal, 2015; Matin *et al.*, 2017; Parajuli *et al.*, 2015).

Limitations of the study

This study has some limitations that might have affected the findings and their interpretations. The reliance on VIIRS data (2012 onward) limited the use of longer-term MODIS trends (since 2001). The MODIS burnt area product (MCD64A1) resolution (500 meters) likely missed smaller fires and finer details. Though helpful, validation using historical fire points and confusion matrices did not fully capture dynamic fire behaviour or spatial inconsistencies, and ROC curves were confined to risk zone comparisons.

The WLC method assumes variable independence, potentially ignoring interactions such as wind direction and slope effects, which may influence fire behaviour. Critical variables like fuel moisture and community fire practices were excluded due to data gaps, reducing model comprehensiveness. This study utilised the 2010 land cover dataset from ICIMOD due to the absence of a reclassified forest category in the more recent land cover datasets of Nepal.

CONCLUSION AND RECOMMENDATION

Conclusion

This study provides a comprehensive geospatial evaluation of forest fire risks in Lumbini Province, Nepal, utilising the WLC approach. The findings highlight significant temporal and spatial patterns of forest fires, alongside key drivers that exacerbate these risks. Among the districts, Dang, Bardiya, and Banke stand out as critical hotspots, collectively accounting for over 65 per cent of fire incidents and more than 43 per cent of the total burnt area.

Temporal analysis shows that forest fires are heavily concentrated during the pre-monsoon season, with 98.04 per cent of incidents occurring in March, April, and May. April emerges as the peak month for fire activity. Anthropogenic factors, such as proximity to settlements and roads, along with biophysical characteristics like land cover type (e.g., broad-leaved closed forests), low elevation, and southern aspects, predominantly influence fire frequency and spread.

The fire risk model developed in this study demonstrated good predictive accuracy, classifying 57.4 per cent of Province Forest into high to very high-risk zones, as validated by historical fire data and an AUC value of 80.3 per cent. Validation using a confusion matrix confirmed the model's reliability, with an overall accuracy of 96 per cent and a kappa coefficient of 0.94, indicating a strong agreement between the predicted and observed classifications.

The study identifies key challenges in forest fire management, with funding (25%), training (20%), and early warning systems (15%) highlighted as primary obstacles. Districts like Nawalparasi West and Rukum East appear

more prepared (score: 4.0), whereas Banke and Dang exhibit lower levels of preparedness (scores: 2.0 and 2.5, respectively). Effective prevention strategies include firebreaks (33.3%) and community education (30%). The study highlights an important need for management of fires in the pre-monsoon months, specifically in high fire occurrence regions like Dang, Bardiya, and Banke. Such findings highlight the need for early warning systems, community participation, and resource allocation strategies to reduce fire risks, thus providing tangible insights to policymakers, planners, and forest managers.

Recommendation

Policy and planning should focus on high-risk districts, including Dang, Bardiya, and Banke, emphasising integrating forest fire risk maps into regional disaster management plans for optimising resource allocation and preparedness. The rural municipalities require special attention, specifically, those labelled high-risk, such as Rapti Sonari of Banke and Rajpur of Dang, with advanced early warning mechanisms, training, and resource allocations at all levels.

Protected areas, notably Bardiya National Park and Banke National Park, are under very high forest fire risk zones, necessitating the adoption of preventative measures such as controlled burning operations. Proactive fire management should be done during the pre-monsoon season, from March to May, with particular emphasis on April, which is usually the peak month for fires due to the accumulated dry fuel. It is recommended that future researchers focus on investigating the occurrence of fire incidents in protected areas, where, despite low anthropogenic activities, significant fire events are reported, to understand the underlying natural and ecological factors driving these occurrences.

Interventions should, therefore, focus on zones of high to very high risks, representing 57.4 per cent of the forest area, while introducing sustainable land-use management practices in the low-risk areas for long-term resilience. Provincial and landscape-level analyses using refined climatic data, scrutinized field data on fire scars, species-specific fuel, and burnt areas should be the focus of future works. While the existing work on fire occurrence and risk is great, the implementation of high-resolution satellite data (like Sentinel-2, WorldView-3) will provide the granularity needed to understand the main drivers of the fire risk by detecting the finer details of vegetation.

ACKNOWLEDGMENTS

The research was financially supported by the Ministry of Forests and Environment, Lumbini Province, Nepal. We thank Prashid Kandel, Reecha Basnet, Pankaj Jha, and Rabin Timalsina for their support in different aspects of the research.

Data availability statement: The data will be made available with a reasonable request to the corresponding author.

Declaration of generative AI in writing:

During the preparation of this work, the author(s) used ChatGPT and Gemini in the writing process for improving clarity, conciseness and readability of the manuscript. After using AI-assisted content, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Conflicts of interest: There are no conflicts of interest among the authors.

REFERENCES

- Adab, H., Kanniah, K. D., & Solaimani, K. (2011). GIS-based probability assessment of fire risk in grassland and forested landscapes of Golestan Province, Iran. In *Proceedings of the 2011 International Conference on Environmental and Computer Science* (Vol. 19, pp. 170–175). IACSIT Press.
- Adaktylou, N., Stratoulis, D., & Landenberger, R. (2020). Wildfire risk assessment based on geospatial open data: Application on Chios, Greece. *ISPRS International Journal of Geo-Information*, 9(9), 516. <https://doi.org/10.3390/ijgi9090516>
- Ajin, R. S., Loghin, A.-M., Vinod, P. G., & Jacob, M. K. (2016). Forest fire risk zone mapping using RS and GIS techniques: A study in Achankovil Forest Division, Kerala, India. *Journal of Earth, Environment and Health Sciences*, 2, 109. <https://doi.org/10.4103/2423-7752.199288>
- Ajin, R. S., Loghin, A.-M., Jacob, M. K., Vinod, P. G., & Krishnamurthy, R. R. (2016). The risk assessment study of potential forest fire in Idukki Wildlife Sanctuary using RS and GIS techniques. *International Journal of Advanced Earth Science and Engineering*, 5(1), 308–318. <https://doi.org/10.23953/cloud.ijaese.201>
- Akay, A. E., & Erdoğan, A. (2017). GIS-based multi-criteria decision analysis for forest fire risk mapping. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-4/W4, 25–30. <https://doi.org/10.5194/isprs-annals-IV-4-W4-25-2017>
- Archibald, S., Lehmann, C. E. R., Gómez-Dans, J. L., & Bradstock, R. A. (2013). Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy of Sciences*, 110(16), 6442–6447. <https://doi.org/10.1073/pnas.1211466110>
- Brhujel, K. B., Maskey-Byanju, R., & Gautam, A. P. (2017). Wildfire dynamics in Nepal from 2000–2016. *Nepal Journal of Environmental Science*, 5, 1–8. <https://doi.org/10.3126/njes.v5i0.22709>

- Bhujel, K. B., Sapkota, R. P., & Khadka, U. R. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Carmel, Y., Paz, S., Jahashan, F., & Shoshany, M. (2009). Assessing fire risk using Monte Carlo simulations of fire spread. *Forest Ecology and Management*, 257(1), 370–377. <https://doi.org/10.1016/j.foreco.2008.09.039>
- Carter, J. V., Pan, J., Rai, S. N., & Galandiuk, S. (2016). ROC-ing along: Evaluation and interpretation of receiver operating characteristic curves. *Surgery*, 159(6), 1638–1645. <https://doi.org/10.1016/j.surg.2015.12.029>
- Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M. P., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J. R., Herrera, M. A., & Zamora, R. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, 221(1), 46–58. <https://doi.org/10.1016/j.ecolmodel.2008.11.017>
- Chuvieco, E., & Congalton, R. G. (1989). Application of remote sensing and geographic information systems to forest fire hazard mapping. *Remote Sensing of Environment*, 29(2), 147–159. [https://doi.org/10.1016/0034-4257\(89\)90023-0](https://doi.org/10.1016/0034-4257(89)90023-0)
- Chuvieco, E., Giglio, L., & Justice, C. (2008). Global characterization of fire activity: Toward defining fire regimes from Earth observation data. *Global Change Biology*, 14(7), 1488–1502. <https://doi.org/10.1111/j.1365-2486.2008.01585.x>
- Constitution of Nepal. (2015). *The constitution of Nepal 2072*. Government of Nepal. https://www.moljpa.gov.np/wp-content/uploads/2017/11/Constitution-of-Nepal-English-with-1st-Amendment_2.pdf
- Cruz-López, M. I., Manzo-Delgado, L. de L., Aguirre-Gómez, R., Chuvieco, E., & Euihua-Benítez, J. A. (2019). Spatial distribution of forest fire emissions: A case study in three Mexican ecoregions. *Remote Sensing*, 11(10), 1–18. <https://doi.org/10.3390/rs11101185>
- Das, J., Mahato, S., Joshi, P. K., & Liou, Y. A. (2023). Forest fire susceptibility zonation in Eastern India using statistical and weighted modelling approaches. *Remote Sensing*, 15(5), 1340. <https://doi.org/10.3390/rs15051340>
- Department of Hydrology and Meteorology. (2024). *January 2024 preliminary precipitation and temperature summary*. Government of Nepal. https://www.dhm.gov.np/uploads/dhm/climateService/January_2024-Preliminary_precipitation_and_temperature_summary.pdf
- Doerr, S. H., & 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(1696), 20150345. <https://doi.org/10.1098/rstb.2015.0345>
- Ersoy, İ., Ünsal, E., & Gürsoy, Ö. (2025). A multi-criteria forest fire danger assessment system on GIS using literature-based model and analytical hierarchy process model for Mediterranean Coast of Manavgat, Türkiye. *Sustainability*, 17(5), 1971. <https://doi.org/10.3390/su17051971>
- Feizizadeh, B., & Blaschke, T. (2014). An uncertainty and sensitivity analysis approach for GIS-based multicriteria landslide susceptibility mapping. *International Journal of Geographical Information Science*, 28(3), 610–638. <https://doi.org/10.1080/13658816.2013.869821>
- Fischer, A. P., Spies, T. A., Steelman, T. A., Moseley, C., Johnson, B. R., Bailey, J. D., Ager, A. A., Bourgeron, P., Charnley, S., Collins, B. M., Kline, J. D., Leahy, J. E., Littell, J. S., Millington, J. D. A., Nielsen-Pincus, M., Olsen, C. S., Paveglio, T. B., Roos, C. I., Steen-Adams, M. M., ... Bowman, D. M. J. S. (2016). Wildfire risk as a socioecological pathology. *Frontiers in Ecology and the Environment*, 14(5), 276–284. <https://doi.org/10.1002/fee.1283>
- Giglio, L., Randerson, J., & van der Werf, G. (2013). Analysis of daily, monthly, and annual burned area using the fourth-generation Global Fire Emissions Database (GFED4). *Journal of Geophysical Research: Biogeosciences*, 118, 317–328. <https://doi.org/10.1002/jgrg.20042>

- Jaiswal, R. K., Mukherjee, S., Raju, K. D., & Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS. *International Journal of Applied Earth Observation and Geoinformation*, 4(1), 1–10. [https://doi.org/10.1016/S0303-2434\(02\)00006-5](https://doi.org/10.1016/S0303-2434(02)00006-5)
- Jung, J., Kim, C., Jayakumar, S., Kim, S., Han, S., Kim, D. H., & Heo, J. (2013). Forest fire risk mapping of Kolli Hills, India, considering subjectivity and inconsistency issues. *Natural Hazards*, 65(3), 2129–2146. <https://doi.org/10.1007/s11069-012-0465-1>
- Kanga, S., & Singh, S. K. (2017). Forest fire simulation modeling using remote sensing and GIS. *International Journal of Advanced Research in Computer Science*, 8(5), 326–332.
- Keeley, J. E., & Syphard, A. D. (2016). Climate change and future fire regimes: Examples from California. *Geosciences*, 6(3), 37. <https://doi.org/10.3390/geosciences6030037>
- Khan, M. A., Gupta, A., Sharma, P., & Roy, A. (2024). Investigation of wildfire risk and its mapping using GIS-integrated AHP method: A case study over Hoshangabad Forest Division in Central India. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-024-05225-w>
- Khanal, S. (2015). Wildfire trends in Nepal based on MODIS burnt-area data. *Banko Janakari*, 25(1), 76–79. <https://doi.org/10.3126/banko.v25i1.13477>
- Kunwar, R. M. (2006). Forest fire in the Terai, Nepal: Causes and community management interventions. *International Forest Fire News*, 34, 46–54.
- Ma, B., Liu, X., Tong, Z., Zhang, J., & Wang, X. (2024). Coupled effects of high temperatures and droughts on forest fires in Northeast China. *Remote Sensing*, 16(20), 3784. <https://doi.org/10.3390/rs16203784>
- Mabdeh, A. N., Al-Fugara, A., Khedher, K. M., Mabdeh, M., Al-Shabeeb, A. R., Al-Adamat, R., Sahu, V., Khan, M. A., & Madguni, O. D. (2024). Assessing forest fire dynamics and risk zones in Central Indian forests: A comparative study of the Khandwa and North Betul forest divisions of Madhya Pradesh. *Environmental Monitoring and Assessment*, 196(9), 810. <https://doi.org/10.1007/s10661-024-12960-0>
- Matin, M. A., Chitale, V. S., Murthy, M. S. R., Uddin, K., Bajracharya, B., & Pradhan, S. (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(4), 276–286. <https://doi.org/10.1071/WF16056>
- Mohajane, M., Costache, R., Karimi, F., Bao Pham, Q., Essahlaoui, A., Nguyen, H., Laneve, G., & Oudija, F. (2021). Application of remote sensing and machine learning algorithms for forest fire mapping in a Mediterranean area. *Ecological Indicators*, 129, 107869. <https://doi.org/10.1016/j.ecolind.2021.107869>
- National Disaster Risk Reduction and Management Authority. (2024). *Nepal disaster report 2024: Focus on reconstruction and resilience*. Government of Nepal. <https://ndrrma.gov.np/nr/report/184>
- National Statistics Office. (2024). *National population and housing census 2021*. Government of Nepal, Office of the Prime Minister and Council of Ministers.
- Nikolić, G., Vujović, F., Golijanin, J., Šiljeg, A., & Valjarević, A. (2023). Modelling of wildfire susceptibility in different climate zones in Montenegro using GIS-MCDA. *Atmosphere*, 14(6), 929. <https://doi.org/10.3390/atmos14060929>
- Pandey, H. P., Pokhrel, N. P., Thapa, P., Paudel, N. S., & Maraseni, T. N. (2022). Status and practical implications of forest fire management in Nepal. *Journal of Forest and Livelihood*, 21(1), 32–45. <https://doi.org/10.3126/jfl.v21i1.56583>
- Parajuli, A., Chand, D. B., Rayamajhi, B., Khanal, R., Baral, S., Malla, Y., & Poudel, S. (2015, September 7–11). Spatial and temporal distribution of forest fires in Nepal [Paper presentation]. *XIV World Forestry Congress*, Durban, South Africa.
- Parajuli, A., Gautam, A. P., Sharma, S. P., Bhujel, K. B., Sharma, G., Thapa, P. B., Bist, B. S., & Poudel, S. (2020). Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. *Geomatics, Natural Hazards and Risk*, 11(1), 2569–2586. <https://doi.org/10.1080/019475705.2020.1853251>

- Parajuli, A., Gautam, A. P., Sharma, S. P., Lamichhane, P., Sharma, G., Bist, B. S., Aryal, U., & Basnet, R. (2022). A strategy for involving community forest managers in effective forest fire management in Nepal. *Banko Janakari*, 32(1), 41–51. <https://doi.org/10.3126/banko.v32i1.45476>
- Parajuli, A., Manzoor, S. A., & 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>
- Pourghasemi, H. R., Beheshtirad, M., & Pradhan, B. (2016). A comparative assessment of prediction capabilities of modified analytical hierarchy process (M-AHP) and Mamdani fuzzy logic models using Netcad-GIS for forest fire susceptibility mapping. *Geomatics, Natural Hazards and Risk*, 7(2), 861–885. <https://doi.org/10.1080/19475705.2014.984247>
- Province Planning Commission. (2024). *Lumbini Province profile*. Government of Nepal. https://ppc.lumbini.gov.np/media/publications/Lumbini_Profile_To_Print.pdf
- Qadir, A., Talukdar, N. R., Uddin, M. M., Ahmad, F., & Goparaju, L. (2021). Predicting forest fire using multispectral satellite measurements in Nepal. *Remote Sensing Applications: Society and Environment*, 23, 100539. <https://doi.org/10.1016/j.rsase.2021.100539>
- Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M., & Morton, D. C. (2012). Global burned area and biomass burning emissions from small fires. *Journal of Geophysical Research: Biogeosciences*, 117(4), 1–23. <https://doi.org/10.1029/2012JG002128>
- Rwanga, S. S., & Ndambuki, J. M. (2017). Accuracy assessment of land use/land cover classification using remote sensing and GIS. *International Journal of Geosciences*, 8(4), 611–622. <https://doi.org/10.4236/ijg.2017.84033>
- Ryan, R. L., & Hamin, E. (2008). Wildfires, communities, and agencies: Stakeholders' perceptions of postfire forest restoration and rehabilitation. *Journal of Forestry*, 106(7), 370–379. <https://doi.org/10.1093/jof/106.7.370>
- Sharma, S. P. (2006). Participatory forest fire management: An approach. *International Forest Fire News*, 34, 35–45.
- Shindler, B. A., Toman, E., & McCaffrey, S. M. (2009). Public perspectives of fire, fuels and the Forest Service in the Great Lakes Region: A survey of citizen-agency communication and trust. *International Journal of Wildland Fire*, 18(2), 157–164. <https://doi.org/10.1071/WF07135>
- Shinga, P. S., Tesfamichael, S. G., Sibandze, P., Kalumba, A. M., & Afuye, G. A. (2024). Modelling spatiotemporal patterns of wildfire risk in the Garden Route District biodiversity hotspots using analytic hierarchy process in South Africa. *Natural Hazards*, 121(2), 1945–1969. <https://doi.org/10.1007/s11069-024-06877-7>
- Sivrikaya, F., Sağlam, B., Akay, A. E., & Bozali, N. (2014). Evaluation of forest fire risk with GIS. *Polish Journal of Environmental Studies*, 23(1), 187–194.
- Timilsina, N., Ross, M. S., & Heinen, J. T. (2007). A community analysis of sal (*Shorea robusta*) forests in the western Terai of Nepal. *Forest Ecology and Management*, 241(1), 223–234. <https://doi.org/10.1016/j.foreco.2007.01.012>
- Vadrevu, K. P., Eaturu, A., & Badarinath, K. V. S. (2010). Fire risk evaluation using multicriteria analysis: A case study. *Environmental Monitoring and Assessment*, 166(1–4), 223–239. <https://doi.org/10.1007/s10661-009-0997-3>
- You, X. (2023). Surge in extreme forest fires fuels global emissions. *Nature*. <https://doi.org/10.1038/d41586-023-04033-y>
- Zhang, Y. (2024). Carbon emissions dynamics and environmental sustainability in China's tourism sector: A 22-year comprehensive regional study. *Sustainability*, 16(16), 7091. <https://doi.org/10.3390/su16167091>

Maintaining people-forest interactions is critical to managing forests fires in Nepal

Rabindra Parajuli^{1, 2, 3*}, Asha Paudel³, Lila Nath Sharma⁴

¹ Odum School of Ecology, University of Georgia, Athens, GA, USA

² Center for Geospatial Research, Department of Geography, University of Georgia, Athens, GA, USA

³ Department of Geosciences, Florida Atlantic University, Boca Raton, FL, USA

⁴ ForestAction Nepal, Ashram Road, Bagdol, Lalitpur, Bagmati, Nepal

* Corresponding author: Rabindra.Parajuli@uga.edu and parajuli.rabindra@gmail.com

Abstract

Forest fire is an important ecological process; however, it can cause ecological and societal harm due to anthropogenic mismanagement and natural adversities leading to long-term socio-economic and environmental consequences. Extreme forests fire events have increased worldwide over the last decade, and events in Nepal are consistent with this trend. Nepalese forestry practices have already set an example of successful forest management by communities and thus demonstrate precedent in effective community mobilisation. Recent studies suggest that local people's participation in community forest management is declining consequently weakening forest-people relationships. Here, we argue on why Nepal should build upon its long legacy of people-forest interactions and strengthen community engagement as a key component of sustainable forest fire management. Synthesised evidence and experiences demonstrate that community-led fire management is among the most viable preventive approaches for reducing fuel loads in forest ecosystems. The Government of Nepal should therefore establish clear policies and strategic frameworks that enable forest scientists, private sectors and non-profits to contribute collaboratively toward the national goal of creating resilient forest landscape in the era of socio-ecological transition.

Keywords: Wildfires, Healthy forests, Sustainable forest management, Community engagement, Forest fuel reduction, Resilient forest landscapes

BACKGROUND AND CONTEXT

Forest ecosystems are vital hotspots for biodiversity and regulators of the global carbon budget. Globally, forests cover around one third of Earth's land surface yet support more than 80 per cent of terrestrial biodiversity by providing a variety of habitats and resources for diverse organisms (CBD, 2024; FAO, 2022; Parajuli and Markwith, 2023; Stokland *et al.*, 2012). In addition, forests play critical role in global climate regulation by absorbing atmospheric CO₂ and storing it as biomass as well as transferring

it to the soil via various biogeochemical processes (FAO, 2022; Lorenz and Lal, 2010; Ryan *et al.*, 2010). However, various natural and anthropogenic disturbances influence forests' ability to regulate atmospheric carbon, with forest fires as one dominant driver among them (FAO, 2022; Williams *et al.*, 2016). Importantly, forest management practices determine whether forest ecosystems act as net carbon sinks or sources (Kaarakka *et al.*, 2021; Parajuli *et al.*, 2025). This highlights the critical importance of management practices and anthropogenic influences for practical applications such as forest carbon

budgets, risk reduction and environmental restoration and mitigation (Carle *et al.*, 2025; Kaarakka *et al.*, 2021; Parajuli *et al.*, 2025).

The overarching idea of forest management is to identify, design and implement practices that are sustainable and appropriate for achieving specific economic, socio-cultural and environmental services from a given forest ecosystem (FAO, 2022). One of the key ecological goals is to maintain healthy and resilient forests that continue providing ecosystem services while overcoming disturbances (Cantarello *et al.*, 2024; Messier *et al.*, 2019; Mina *et al.*, 2022). With around 25 per cent of the world population directly relying on forest resources for their livelihoods, rising demand for carbon sequestration and Nature-based Solutions to reducing atmospheric CO₂, and the ongoing climate crisis leading to unprecedented changes in global forests, sustainable management of forests has been more important than ever for planetary health and human wellbeing (FAO, 2022; Kaarakka *et al.*, 2021; UNFFS, 2021). Due to forests' potential as a natural climate solution (Griscom *et al.*, 2017), the Paris Agreement and later United Nations conventions continued to highlight the role of sustainable forest management to reduce carbon emissions and enhance sequestration as a fight against global warming and its worst impacts (IPCC, 2018; UNFCCC, 2015).

The last two decades have witnessed an increase in the frequencies and intensities of devastating wildfires globally, with the most extreme events occurring in recent years (Cunningham *et al.*, 2024). While uncharacteristically large fires with extreme behaviour were observed in the temperate conifer forests of the United States and boreal forests of North America and Russia,

wildfires have generally become larger and more severe around the world (Cunningham *et al.*, 2024; Hagemann *et al.*, 2021). Nepal has likewise experienced a rising trend in wildfire frequency and burned area, including some of the most severe forest fires recorded in recent years (Mishra *et al.*, 2023; Nepali Times, 2021). For example, the catastrophic forest fire in Gatlang area of Rasuwa district destroyed the forest stand with long-term effects on soil and vegetation still evident even after one and half decades (Dhungana *et al.*, 2024).

Wildfire behaviour is governed primarily by three major elements, famously called the 'fire behaviour triangle', namely fuel (or vegetation), topography, and weather (or climate); and fuel is always a dominant factor controlling fire at different spatial and temporal scales (Keeley, 2009; Moritz *et al.*, 2005; Pyne *et al.*, 1996). Since fuels (i.e., vegetation, living or dead) are the components over which humans have the most direct influence, effective management of forest structure and vegetation plays a crucial role in reducing forest fire impacts (Parajuli *et al.*, 2025). Various management tools, technically referred to as 'fuel reduction treatments', are used to reduce fuel and help minimise the risk of devastating fires and associated hazards and maintain healthy forests. In developed countries such as United States and Canada, forest fuel reduction most commonly involves mechanical treatments such as thinning (tree removal), mastication (flailing, chipping and breaking), raking (collecting/piling), often combined with prescribed burning (Agee and Skinner, 2005). Whereas in developing countries, such as Nepal, India and Mexico, active community engagement for regulated resource extractions e.g., timber and fuelwood via thinning and pruning, and surface dead fuel and fodder collection, as well as some controlled or community-led burning are

common and generally effective in fire management (Charmakar *et al.*, 2021; Dogra *et al.*, 2018; Pandey *et al.*, 2022; Van Vleet *et al.*, 2016). Regular harvesting of surface biomass such as leaf litter and dead woody materials by locals, either as a part of the subsistence farming or for various innovative uses, contribute to reduced dry fuel loads in the Himalayan forests (Chandran *et al.*, 2011; Charmakar *et al.*, 2021). Despite a recognised need to strengthen people-forest relationships (Baral *et al.*, 2025; Poudyal *et al.*, 2023), recent research shows declining community involvement in community managed forests of Nepal (Cook *et al.*, 2025). These weakening people-forest interactions particularly reduced resource extractions and lower participation in management activities and thereby contributed to excessive fuel accumulation leading to increased fire events (Tiwari *et al.*, 2022). Here, we discuss why

strengthening people-forest relationships is critically important for sustainable forests fire management in Nepal, particularly focusing on maintaining fuel loads in community forests (CFs) via active engagement of local communities primarily the community forest user groups (CFUGs).

Why is maintaining strong interactions between people and forests critically important?

Nepal's community forestry is globally recognised for the involvement of forest user groups (i.e., local people) in regenerating and conserving forests while supporting livelihood and local economy (Gautam *et al.*, 2004; Niraula *et al.*, 2013). Over 23,000 CFUGs, largely self-governing local institutions, engage more than 16 million



Figure 1: Leaf litter collected for animal bedding and composting in Chaumala, Kailali district of western Nepal. Such practice of surface dead-fuel harvesting by local users is helpful in maintaining fuel load in the forests and reducing severe fire incidents. Photo: Lila Nath Sharma.

people to manage around 35 per cent of the country's forest resources (Gentle *et al.*, 2020). Being within the guidelines set by operational plans, users routinely harvest forest resources such as timber, fuelwood, fodder, dead leaves and beds, as well as non-timber products, and in return voluntarily contribute to various forest management activities. Such participatory biomass removal activities are low cost yet highly effective to maintain fuel loads and reduce forest fire hazards (Charmakar *et al.*, 2021; Markwith and Paudel, 2022; Pandey *et al.*, 2022). There are many success stories in Nepal in which

the regular and regulated harvesting of living and dead biomass (e.g., leaf litters; Figure 1) from CF by local people as a part of their livelihoods has effectively reduced forest fire risks. See, for example, Charmakar *et al.* (2021) and Box 1 for cases from the Dolakha and Kavrepalanchok districts. Essentially, these community engaged fuel management practices are analogous to modern mechanical fuel reduction treatments in many developed countries, which are technically and financially resource intensive (Chang *et al.*, 2023; Markwith and Paudel, 2022; Wibbenmeyer *et al.*, 2025).

Box 1: Traditional Farm-Forest interactions maintain low-severity fires and lower fire hazards

Hile Jaljale community forest (CF) 'Kha' is in Kavrepalanchok district of Nepal, spans from 1500 to 2000 meters above sea level with an area of 190 hectares. It is a mixture of both planted and natural stands of pine and broad leaf tree species. This CF has 430 household user members from various settlements, which are close to Banepa town centre and around an hour of driving distance from the capital city, Kathmandu. By capitalising their proximity to markets, CF users are heavily engaged in animal husbandry and vegetable production as a major source of income. They produce milk, fresh vegetables, potatoes and various cash crops and all go to the market centres in Banepa and Kathmandu. Their active interactions with the nearby forest, mainly to extract resources to sustain animal husbandry and farming, have significantly contributed to maintaining both live and dead biomass in the forest. People-forest interactions are strong, yet systematically regulated through CF operational plan, as local users largely depend on forestry resources such as firewood, timber, fodder and leaf litter.

Forest fires are common during dry season, however, users of Hile Jaljale CF consider that those fires are not hazardous, i.e., they are low-severity fires without any serious threats to forest health and local communities. Key to such successful fire management lies in maintained fuel loads due to sustainable forest resources use. While timber and firewood harvest are done at certain times of the year, leaf-litter collection is allowed all year round. Harvested leaf litter creates multiple additional benefits, including improving nutrients and organic matter content in the soil, a major portion of which is carbon. These kinds of healthy people-forest interactions generate multiple socio-ecological benefits particularly sustaining the local economy and enhancing carbon benefits through soil-amendment and reduced pyrogenic emissions from low severity forest fires. Similar to Hile Jaljale CF, where traditional farm-forest interactions are well maintained, benefiting both the local people and the forests, forest fire should not be hazardous issue to worry about if community engagement remains intact in the long term.

The role of local communities in reducing forest fuel continuity – horizontal and vertical distribution of flammable materials – and supporting effective fire management is not unique to Nepal. Similar patterns are observed in other countries such as India (e.g., Chandran *et al.*, 2011), Mexico (e.g., Van Vleet *et al.*, 2016), and historically in Australia (e.g., Mariani *et al.*, 2024) and among Native American societies in the pre-Columbian era in North America (e.g., Anderson and Moratto, 1996; Markwith and Paudel, 2022). The case of Mexico is worth highlighting here, as it illustrates how community engagement should extend beyond ecological goals to also include substantial economic benefits for local communities. Mexico's community forestry model, that integrates technical forest management, indigenous governance and community owned forest enterprises, has proven to be highly effective in ensuring the economic resilience of participating communities while simultaneously enhancing ecological resilience and promoting sustainable forest management (Cubbage *et al.*, 2015; Mitchell, 2006; Van Vleet *et al.*, 2016). For example, in Sierra Norte of Oaxaca, Mexico, community-managed forests supported increased biodiversity, experienced fewer large wildfires, and supported livelihoods and local economy (Farthing, 2024; Van Vleet *et al.*, 2016). This Mexican example could be relevant for Nepal, where similar enterprise-based community forestry approaches that maximise economic benefits for local communities may help strengthen people's engagement in forest management (Cook *et al.*, 2025). This approach should be a priority for Nepal, particularly in the context that people's interest in managing CFs is eroding due to insufficient economic benefits and lack of employment opportunities in rural areas (Cook *et al.*, 2025; Poudyal *et*

al., 2023). Introducing enterprise modality could bring multiple synergistic benefits, for example, timber entrepreneurship, creates income opportunities and help addressing national timber demand while reducing current imports (Dangi, 2025). However, adequate scientific, socio-economic and policy research is needed to support the Government of Nepal in developing clear guidelines and pragmatic policies prior to introducing entrepreneurship into community forestry.

While Nepal's efforts in increasing forests and enhancing carbon sequestration, including a recent US\$9.4 million carbon credits grant (World Bank, 2025), can be considered as a success, it is equally concerning that fuel loads are accumulating in Nepalese forests, especially in the mid-hills. Without timely intervention, these fuel loads could reach hazardous levels, and if burned, may release large amounts of carbon, reversing decades of sequestration gains within a short period of time. Once a forest attains hazardous fuel conditions, restoring it to healthy and resilient status is very challenging and often requires substantially greater effort and cost than maintaining it through regular management and fuel treatments (Alcasena *et al.*, 2022; Chang *et al.*, 2023). This is evident in the United States, which is constantly fighting devastating wildfires each year and spending up to \$7 billion annually on fire management interventions (US Congress, 2024).

With declining community and stakeholder participation in Nepal's community forestry (Benedum *et al.*, 2025; Cook *et al.*, 2025; Poudyal *et al.*, 2023), if proactive early measures are not implemented, forest fires could be a major nationwide problem in the near future. The recent increase in frequency and severity of forest fires in Nepal (Mishra *et al.*, 2023) suggests that the country may

already be moving in that direction. Since Nepal currently has very limited technical and financial strength to manage catastrophic large-scale forest fires, strengthening people's interactions with forests and mobilising local communities for forest and fire management appears to be the most viable strategy. In a similar context of strong rural dependence on forest resources, India, the world's third-largest economy, has also recognised community engagement as one of the top strategies for effective fire management, stressing that the active involvement of local communities is essential for its success (Dogra *et al.*, 2018).

Considering the changing socio-economic dynamics in Nepal, which are accompanied by outmigration and remittance income,

enhancing affordability and promoting alternative energy sources such as Liquefied Petroleum Gas (LPG), questions remain about whether strengthened community engagement can ensure full local utilisation of forest products. Firstly, although firewood use may have declined and will likely continue to do so, it still remains a dominant source of household energy, especially for cooking and heating (Kandel *et al.*, 2016; Paudel *et al.*, 2021). Secondly, there are multiple innovative ways to utilise forest biomass for various products (Cabiyo *et al.*, 2021; Chandran *et al.*, 2011), including composting leaf litter and forest residues into compost manure (see Figure 2, and Box 2 for a case study from Jhapa, Nepal). Thirdly, recent technological advances allow forest residues, including fine and coarse down woody



Figure 2: Invasive species and leaf litter biomass piled for composting in Diyalo community forest in Jalthal forest, Jhapa district of eastern Nepal. Semi-dried and chopped biomass in the foreground and ready-to-use compost manure at the back (black colour partially covered with blue tarpaulin). Photo: Lila Nath Sharma.

materials, to be converted into carbon-friendly products such as biochar, biofuels and coco peat. Experiences from developed countries demonstrate that forest biomass conversion into biochar through the process of pyrolysis is cost effective and technically feasible (Cabiyo *et al.*, 2021; Shabangu *et al.*, 2014). In order for such technical investments to be sustainable, they should be profitable. Therefore, this could be implemented through private sectors and business entities. However, the Government of Nepal should formulate policies and regulations to facilitate the establishment of pyrolysis plants in the

country and their clear operation, including the extents of resource utilisation from community and other forests. Furthermore, in addition to composting (see Box 2), invasive species issues in forests can also be addressed using this innovative approach, as any forest residue and waste can be converted into biochar via pyrolysis. Biochar soil amendments can store carbon for many years, help mitigate climate change, improve soil fertility in agricultural lands, and partially substitute chemical fertilisers (Bai *et al.*, 2022; Shyam *et al.*, 2025).

Box 2: Harvesting forest residue reduces fires and improves restoration

Multiple incidents of forest fires were common each year during dry season, generally between January to May, in Jalthal remnant forest of Jhapa, South-eastern lowland of Nepal. Those highly frequent fire events were a main challenge in forest restoration where invasive alien plant species (IAPS) mainly *Chromolaena odorata* (L.) R.M.King & H.Rob., *Mesosphaerum suaveolens* (L.) Kuntze and *Mikania micrantha* Kunth, have a large share in total biomass that serve as surface (on the ground vegetation or dead items) and ladder (live or dead vegetation connecting ground to the canopy that provide vertical continuity for fire to climb) fuels, particularly in the invaded patches. Generally, encroachment by IAPS is an unnatural addition and alteration of fuel loads in forested and grassland ecosystems. Local communities, with support from ForestAction Nepal led Darwin Initiative project, initiated compost manure production using forest residue primarily focusing on the biomass of IAPS in four different community forests (CFs) namely Diyalo, Bishal, Pathibhara Kalika and Kamaldhap Rampokhari CFs of Jalthal from December 2019 to October 2025. Although *Lantana camara* L. is also present in the forest, this invasive species was not used considering its potential allelopathic effect that may result in poor quality manure. As a part of this innovative initiative, Community Forest User Groups (CFUGs) collected forest biomass, converted it into compost manure, and applied it to local farms, helping to improve fertility and soil health. During this trial period, approximately 75 metric tons of forest biomass (mix of both semi-dried and dried) harvested from 50 hectares of forest patches invaded by IAPS have been converted into compost manure. Over the years, local people have witnessed and reported reduced fire incidents in forest patches where such an innovative approach to biomass harvesting is implemented. Additionally, this biomass management initiative has created jobs for local people, promoted organic farming and reduced chemical fertiliser use. Most importantly, this has contributed to forest restoration by supporting seedling growth while reducing fire incidences in forests.

Should controlled burning be an option?

Traditionally, fire has been used as a management tool in different countries around the globe and stands as a successful strategy to maintain fuels, resources and services (Anderson and Moratto, 1996; Long *et al.*, 2021; Mariani *et al.*, 2024). Occurrence of fire is inevitable in ecosystems ranging from grasslands to forests, with varying fire return intervals (Lauvaux *et al.*, 2016; Mariani *et al.*, 2024). For example, grasslands are well adapted and can be burned annually, while forest ecosystems such as conifers have an average return interval of 11 years and shrublands of 25 years in the United States (Lauvaux *et al.*, 2016). There is rich evidence of how local people have passed on traditional knowledge about fire ecology in order to adapt their natural regions to specific types of fire frequency and intensity (Christianson *et al.*, 2022). This pattern of human interactions with fire ranges broadly from mixed-conifers of California in the United States and the boreal region of North America to the bushland of Australia and the forests and pastures of India and Nepal (Anderson and Moratto, 1996; Burrows *et al.*, 2020; Christianson *et al.*, 2022; Dogra *et al.*, 2018; Mukul and Byg, 2020; Paudel *et al.*, 2020).

There are examples in Nepal where people have been using fire as a tool to manage forests, rangelands, and pastures to promote various ethnobotanically useful plants, prepare agriculture land (e.g., shifting cultivation), regenerate palatable species and maintain overall ecosystem health (Lama *et al.*, 2001; Mukul and Byg, 2020; Paudel *et al.*, 2020). However, the complexity of using fire as a management tool and generalising its role to all ecosystems and across forest types can be misleading. Here, Nepal can

learn from the experiences of the U.S. Forest Service and the consequences of their decades-long fire suppression policy, which aimed to extinguish fires as quickly as possible, regardless of its ecological role (Pyne, 1982). This resulted in extreme changes in historical vegetation dynamics and fire regimes, creating a highly challenging situation despite continued efforts by U.S. federal agencies to introduce prescribed burning that mimics pre-Columbian Indigenous fire practices, manages fuel loads, and restores historical ecological conditions. In the U.S., forest and fire management actions are often criticised for failing to significantly reduce fuel accumulation despite their high resource demands. Moreover, such measures are often constrained by safety concerns associated with the urban-wildland interface, as well as potential risks to recreational and critical biodiversity areas (North *et al.*, 2015). Prescribed burning is also increasingly called into question for high pyrogenic emissions (i.e., greenhouse gases and aerosols released into the atmosphere) leading to negative impacts on air quality and public health (Campbell *et al.*, 2012; Ravi *et al.*, 2019). Therefore, given the country's high biological diversity and the long-standing interactions between people, forests, and rangelands, a landscape specific as well as ecologically and culturally informed approach to fire management is vital in Nepal, specifically weighing up the risks and benefits of fire.

Historical community-led fire management in Nepal represents a deliberate and carefully regulated technique, closely linked to agropastoral livelihoods, seasonal grazing patterns, and Indigenous land-management systems that rely on intimate knowledge of vegetation cycles, microclimates, and fuel conditions (Mukul and Byg, 2020; Schmidt-Vogt, 1990). In this context, controlled

or managed burning is not simply an operational activity; it constitutes a culturally rooted practice, integrated into community norms, collective decision-making, and generational ecological understanding (Nikolakis and Roberts, 2020). Where these traditions persist, there is strong justification for supporting their continuation as a management tool. Community-led burning can maintain open rangelands, promote fresh grass growth, limit encroachment by shrubs and invasive species, promote forest regeneration, and enhance habitat heterogeneity (Paudel *et al.*, 2020). For example, in a CF of Chitwan district in central Nepal, user groups led a pile-burning initiative

that both reduced forest fires and helped in tree regeneration (see Box 3). Community elders and traditional practitioners often possess tacit knowledge such as appropriate seasons, ideal humidity and wind conditions, burning intervals, and safe ignition patterns that allow them to manage fire in ways that align with local ecological dynamics (Vázquez-Varela *et al.*, 2022). Safeguarding these practices helps preserve cultural and community identities while utilising traditional ecological knowledge that modern fire management frameworks often undervalue. However, community-led burning, such as the one presented in Box 3, should carefully be studied and

Box 3: Community-led burning reduces fire incidences in community forests

Forest fire used to be a common phenomenon during dry season, with high incidences in March-April, every year in Ranikhola Community Forest (Ranikhola CF) in Chitwan district, Nepal. Leaf litter and dry biomass from the invasive species *Chromolaena odorata* acted as an unnatural and excessive addition to the fuel load, a problem that is especially severe in the degraded forest patches. Regeneration of trees in these areas has been disrupted by annual wildfires, which have intensified in recent decades with the increasing infestation of invasive weeds. Aiming to support forest restoration, local communities initiated experimental controlled burning in six hectares of degraded patches before and during the dry season as a part of Participatory Action Research (PAR). In January 2023, Ranikhola CF engaged its members in collecting leaf litter and invasive species biomass. The collected dry biomass, apart from some fraction that was used as animal bedding and ultimately converted to compost manure, was piled up in safe sites and cautiously brunt in small heaps considering the suitable weather conditions – a community led controlled burning initiative technically referred to as pile burning. Another round of accumulated biomass was safely burnt again in February. During peak dry season of that year, the forest patch managed through experimental controlled burning remained free of fire, while adjoining areas and similar landscapes experienced several incidents of wildfire. By preventing fire events, this controlled burning helped protect over 5000 naturally regenerated native tree seedlings. This was a pilot initiative and one year of experience may not be sufficient to draw firm conclusions. But pile burning is a proven technique for fire management, primarily to reduce dead fuel loads in forests. Therefore, this case demonstrates that community-led burning and fuel reduction treatments conducted in advance can help reduce fire risk during the dry season.

technically monitored for several years to track the long-term ecological implications and most importantly it must be ensured that communities are equipped with necessary tools, knowledge and skills for both ecological and social safeguards.

In the global North, the United States has experienced forest destruction from devastating wildfires linked to historical fire mismanagement and disconnected people-forest interactions that recent research urges reviving for better fire management, risks reduction, and broader benefits (Markwith and Paudel, 2022; Parajuli *et al.*, 2025). In contrast, many countries in the Global South, including Nepal, India, and Mexico, provide substantial evidence of communities utilising their traditional ecological knowledge to maintain healthy forests, promote biodiversity, and sustain their livelihoods through regular engagement with forests, including the use of fire as a management tool (Dogra *et al.*, 2018; Farthing, 2024; Pandey *et al.*, 2022; Sharma *et al.*, 2021; Van Vleet *et al.*, 2016). By valuing its own traditions and strengthening long-standing community-based practices, Nepal can provide a socio-ecological prototype of people-led, sustainable forest fire management.

CONCLUSION

The core principle of creating fire-resilient forests through various fuel-reduction activities aims to decrease biomass on the ground (i.e., surface fuel), in the crown (i.e., canopy fuel), and in the layers between (i.e., ladder fuel). Nepal's long legacy of community engagement, combining traditional knowledge of sustainable resource extraction with technical assistance from the government and other partner agencies, including non-profit organisations, has helped

apply these principles in practice and has contributed to preventing large, devastating forest fires. It is vital to maintain the intricate ties between people and forests for mutual benefits: people contribute to the stewardship of healthy ecosystems that sustain essential services, while forests continue to provide diverse ecosystem services to support local livelihoods. Controlled burning can help manage surface and ladder fuels and may be ecologically beneficial in certain landscapes. Therefore, it should be continued where it has been historically practiced and where its application is informed by both traditional and modern ecological knowledge. However, initiating new burning practices is generally not recommended, or should at least involve careful research and planning, because: a) not all landscapes are adapted to fire, and b) escaped fires can lead to severe impacts on biodiversity, carbon budgets, infrastructures and public health and safety. Moreover, experiences from developed countries show that the technical and financial resources required for managed burning are substantial, making such approaches economically less feasible for a developing economy such as Nepal's.

Nepal's forests are experiencing increased fire risks driven by multiple factors, including shifting fuel patterns and changing climatic conditions. At the same time, weakening people-forest interactions, partly due to low economic benefits and reduced dependence on forest resources, underscore the urgency of strengthening national strategies for sustainable forest and fire management. We emphasise the need for collaborative action among government agencies, scientists, non-profits, the private sector, and local institutions to support communities through research, technical and financial assistance, and pragmatic policies that promote fire-

resilient forest management while maintaining healthy people-forest relationships. In addition to acknowledging community-based forest management as an entrepreneurial endeavour, the Government of Nepal should timely introduce policies and regulations that create enabling environments for forest-based enterprises and private-sector investments in modern technologies capable of converting forest residues into net carbon-beneficial products such as biochar. Additionally, government policies should also recognise and promote farm-forest interface dynamics in rural areas as a key strategy for building resilient forest landscapes. Active community involvement, particularly in preventive measures such as forest fuel reduction, is critically important and represents one of the most effective pathways for sustainable forest and fire management in Nepal.

ACKNOWLEDGEMENT

We thank Charles B. van Rees, Assistant Professor at Odum School of Ecology, University of Georgia (USA) and Bishnu Timilsina, PhD Research Fellow, The Arctic University Museum of Norway, Tromsø, Norway, for the constructive comments and linguistic corrections, which helped enhance the quality of the manuscript. Lila Nath Sharma was supported by UK International Development's Reversing Environmental Degradation in Africa and Asia (REDAA) program in collecting data for case studies. We would like to thank the editors and two anonymous reviewers for their feedback on an earlier draft, which helped to improve the manuscript. The authors declare that they did not use any generative AI or AI-assisted technologies in the creation of this manuscript.

REFERENCES

- Agee, J. K., & Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management*, 211, 83–96. <https://doi.org/10.1016/j.foreco.2005.01.034>
- Alcasena, F., Ager, A. A., Belavenutti, P., Krawchuk, M., & Day, M. A. (2022). Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk. *Journal of Environmental Management*, 309, 114650. <https://doi.org/10.1016/j.jenvman.2022.114650>
- Anderson, M. K., & Moratto, M. J. (1996). Native American practices and ecological impacts. In *Sierra Nevada ecosystem project: Final report to Congress* (pp. 187–206). University of California, Centers for Water and Wildland Resources.
- Bai, S. H., Omidvar, N., Gallart, M., Kämper, W., Tahmasbian, I., Farrar, M. B., Singh, K., Zhou, G., Muqadass, B., Xu, C.-Y., Koech, R., Li, Y., Nguyen, T. T. N., & van Zwieten, L. (2022). Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis. *Science of the Total Environment*, 808, 152073. <https://doi.org/10.1016/j.scitotenv.2021.152073>
- Baral, S., Subedi, S., Ford, R., Rai, R. K., Chhetri, B. B. K., Ojha, S., Tiwari, K. R., Kafle, G., Puri, L., & Rai, D. (2025). Resilience pathways through community-based forest management for navigating the triple planetary crisis. *Trees, Forests and People*, 22, 100972. <https://doi.org/10.1016/j.tfp.2025.100972>
- Benedum, M. E., Cook, N. J., & Vallury, S. (2025). Remittance income weakens participation in community-based natural resource management. *Ecology and Society*, 30, 300334. <https://doi.org/10.5751/ES-16436-300334>
- Burrows, N., Rampant, P., Loewenthal, G., & Wills, A. (2020). Fire, plant species richness and plants of significance to Australian desert Aboriginal people. *International Journal of Wildland Fire*, 29(10), 939–942. <https://doi.org/10.1071/WF20057>

- Cabiyo, B., Fried, J. S., Collins, B. M., Stewart, W., Wong, J., & Sanchez, D. L. (2021). Innovative wood use can enable carbon-beneficial forest management in California. *Proceedings of the National Academy of Sciences*, 118(49), e2019073118. <https://doi.org/10.1073/pnas.2019073118>
- Campbell, J., Harmon, M. E., & Mitchell, S. R. (2012). Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions? *Frontiers in Ecology and the Environment*, 10(2), 83–90. <https://doi.org/10.1890/110057>
- Cantarello, E., Jacobsen, J. B., Lloret, F., & Lindner, M. (2024). Shaping and enhancing resilient forests for a resilient society. *Ambio*, 53, 1095–1108. <https://doi.org/10.1007/s13280-024-02006-7>
- Carle, H., Bauman, D., Evans, M. N., Coughlin, I., Binks, O., Ford, A., Bradford, M., Nicotra, A., Murphy, H., & Meir, P. (2025). Aboveground biomass in Australian tropical forests now a net carbon source. *Nature*, 646(8085), 611–618. <https://doi.org/10.1038/s41586-025-09497-8>
- Convention on Biological Diversity. (2024). *The forest factor: The role of protection, restoration and sustainable management of forests for the implementation of the Kunming-Montreal Global Biodiversity Framework*. Secretariat of the Convention on Biological Diversity.
- Chandran, M., Sinha, A., & Rawat, R. (2011). Replacing controlled burning practice by alternate methods of reducing fuel load in the Himalayan long leaf pine (*Pinus roxburghii* Sarg.) forests [Paper presentation]. *5th International Wildland Fire Conference*, Cape Town, South Africa.
- Chang, H., Han, H.-S., Anderson, N., Kim, Y.-S., & Han, S.-K. (2023). The cost of forest thinning operations in the western United States: A systematic literature review and new thinning cost model. *Journal of Forestry*, 121, 193–206. <https://doi.org/10.1093/jofore/fvac037>
- Charmakar, S., Oli, B. N., Joshi, N. R., Maraseni, T. N., & Atreya, K. (2021). Forest carbon storage and species richness in FSC certified and non-certified community forests in Nepal. *Small-Scale Forestry*, 20, 199–219. <https://doi.org/10.1007/s11842-020-09464-3>
- Christianson, A. C., Sutherland, C. R., Moola, F., Gonzalez Bautista, N., Young, D., & MacDonald, H. (2022). Centering Indigenous voices: The role of fire in the boreal forest of North America. *Current Forestry Reports*, 8, 257–276. <https://doi.org/10.1007/s40725-022-00168-9>
- Cook, N. J., Khatri, D. B., Poudel, D. P., Paudel, G., & Acharya, S. (2025). Dropping out of environmental governance: Why Nepal's community-based forestry program is losing participants. *Elementa: Science of the Anthropocene*, 13(1), 00059. <https://doi.org/10.1525/elementa.2024.00059>
- Cubbage, F. W., Davis, R. R., Rodríguez Paredes, D., Mollenhauer, R., Kraus Elsin, Y., Frey, G. E., Gonzalez Hernandez, I. A., Albarran Hurtado, H., Cruz, A. M. S., & Salas, D. N. C. (2015). Community forestry enterprises in Mexico: Sustainability and competitiveness. *Journal of Sustainable Forestry*, 34, 623–650. <https://doi.org/10.1080/10549811.2015.1040514>
- Cunningham, C. X., Williamson, G. J., & Bowman, D. M. J. S. (2024). Increasing frequency and intensity of the most extreme wildfires on Earth. *Nature Ecology and Evolution*, 8(8), 1420–1425. <https://doi.org/10.1038/s41559-024-02452-2>
- Dangi, R. B. (2025). Why is Nepal struggling to halt timber imports despite being rich in forest cover: A critical review from a theoretical lens? *Banko Janakari*, 35(1), 62–70. <https://doi.org/10.3126/banko.v35i1.63355>
- Dhungana, B. P., Chhetri, V. T., Baniya, C. B., Sharma, S. P., Ghimire, P., & Vista, S. P. (2024). Post-fire effects on soil properties in high altitude mixed-conifer forest of Nepal. *Trees, Forests and People*, 17, 100633. <https://doi.org/10.1016/j.tfp.2024.100633>
- Dogra, P., Mitchell, A. M., Narain, U., Sall, C., Smith, R., & Suresh, S. (2018). *Strengthening forest fire management in India*. World Bank.
- Food and Agriculture Organization of the United Nations. (2022). *The state of the world's forests 2022: Forest pathways for green recovery and building inclusive, resilient and sustainable economies*. FAO.

- Farthing, L. (2024, April 22). Fewer wildfires, great biodiversity: What is the secret to the success of Mexico's forests? *The Guardian*.
- Gautam, A. P., Shivakoti, G. P., & Webb, E. L. (2004). A review of forest policies, institutions, and changes in the resource condition in Nepal. *International Forestry Review*, 6(2), 136–148. <https://doi.org/10.1505/for.6.2.136.38397>
- Gentle, P., Maraseni, T. N., Paudel, D., Dahal, G. R., Kanel, T., & Pathak, B. (2020). Effectiveness of community forest user groups (CFUGs) in responding to the 2015 earthquakes and COVID-19 in Nepal. *Research in Globalization*, 2, 100025. <https://doi.org/10.1016/j.resglo.2020.100025>
- Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., ... Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, 114, 11645–11650. <https://doi.org/10.1073/pnas.1710465114>
- Hagmann, R. K., Hessburg, P. F., Prichard, S. J., Povak, N. A., Brown, P. M., Fulé, P. Z., Keane, R. E., Knapp, E. E., Lydersen, J. M., Metlen, K. L., Reilly, M. J., Sánchez Meador, A. J., Stephens, S. L., Stevens, J. T., Taylor, A. H., Yocom, L. L., Battaglia, M. A., Churchill, D. J., Daniels, L. D., Falk, D. A., ... Waltz, A. E. M. (2021). Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications*, 31(8), e02431. <https://doi.org/10.1002/eap.2431>
- Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. IPCC.
- Kaarakka, L., Cornett, M., Domke, G., Ontl, T., & Dee, L. E. (2021). Improved forest management as a natural climate solution: A review. *Ecological Solutions and Evidence*, 2(3), e12090. <https://doi.org/10.1002/2688-8319.12090>
- Kandel, P., Chapagain, P. S., Sharma, L. N., & Vetaas, O. R. (2016). Consumption patterns of fuelwood in rural households of Dolakha District, Nepal: Reflections from community forest user groups. *Small-Scale Forestry*, 15(4), 481–495. <https://doi.org/10.1007/s11842-016-9335-0>
- Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: A brief review and suggested usage. *International Journal of Wildland Fire*, 18(1), 116–126. <https://doi.org/10.1071/WF07049>
- Lama, Y., Ghimire, S., & Aumeeruddy-Thomas, Y. (2001). *Medicinal plants of Dolpo: Amchis' knowledge and conservation*. WWF Nepal Program.
- Lauvaux, C. A., Skinner, C. N., & Taylor, A. H. (2016). High severity fire and mixed conifer forest-chaparral dynamics in the southern Cascade Range, USA. *Forest Ecology and Management*, 363, 74–85. <https://doi.org/10.1016/j.foreco.2015.12.016>
- Long, J. W., Lake, F. K., & Goode, R. W. (2021). The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management*, 500, 119597. <https://doi.org/10.1016/j.foreco.2021.119597>
- Lorenz, K., & Lal, R. (2010). *Carbon sequestration in forest ecosystems*. Springer. <https://doi.org/10.1007/978-90-481-3266-9>
- Mariani, M., Wills, A., Herbert, A., Adeleye, M., Florin, S. A., Cadd, H., Connor, S., Kershaw, P., Theuerkauf, M., Stevenson, J., Fletcher, M.-S., Mooney, S., Bowman, D., & Haberle, S. (2024). Shrub cover declined as Indigenous populations expanded across southeast Australia. *Science*, 386(6721), 567–573. <https://doi.org/10.1126/science.adn8668>
- Markwith, S. H., & Paudel, A. (2022). Beyond pre-Columbian burning: The impact of firewood collection on forest fuel loads. *Canadian Journal of Forest Research*, 52, 365–371. <https://doi.org/10.1139/cjfr-2021-0207>

- Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., Mina, M., Aquilué, N., Fortin, M.-J., & Puettmann, K. (2019). The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, 6, 21. <https://doi.org/10.1186/s40663-019-0166-2>
- Mina, M., Messier, C., Duveneck, M. J., Fortin, M.-J., & Aquilué, N. (2022). Managing for the unexpected: Building resilient forest landscapes to cope with global change. *Global Change Biology*, 28(14), 4323–4341. <https://doi.org/10.1111/gcb.16197>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19(1), 3. <https://doi.org/10.1186/s42408-022-00162-3>
- Mitchell, R. E. (2006). Environmental governance in Mexico: Two case studies of Oaxaca's community forest sector. *Journal of Latin American Studies*, 38(3), 519–548. <https://doi.org/10.1017/S0022216X06001155>
- Moritz, M. A., Morais, M. E., Summerell, L. A., Carlson, J. M., & Doyle, J. (2005). Wildfires, complexity, and highly optimized tolerance. *Proceedings of the National Academy of Sciences*, 102(50), 17912–17917. <https://doi.org/10.1073/pnas.0508985102>
- Mukul, S. A., & Byg, A. (2020). What determines Indigenous Chepang farmers' swidden land-use decisions in the central hill districts of Nepal? *Sustainability*, 12(13), 5326. <https://doi.org/10.3390/su12135326>
- Nepali Times. (2021, April 30). Wildfires ravage Nepal mountains. <https://nepalitimes.com/news/wildfires-ravage-nepal-mountains>
- Nikolakis, W., & Roberts, E. (2020). Indigenous fire management: A conceptual model from literature. *Ecology and Society*, 25(4). <https://doi.org/10.5751/ES-11945-250411>
- Niraula, R. R., Gilani, H., Pokharel, B. K., & Qamer, F. M. (2013). Measuring impacts of community forestry program through repeat photography and satellite remote sensing in the Dolakha district of Nepal. *Journal of Environmental Management*, 126, 20–29. <https://doi.org/10.1016/j.jenvman.2013.04.006>
- North, M., Brough, A., Long, J., Collins, B., Bowden, P., Yasuda, D., Miller, J., & Sugihara, N. (2015). Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. *Journal of Forestry*, 113(1), 40–48. <https://doi.org/10.5849/jof.14-058>
- Pandey, H. P., Pokhrel, N. P., Thapa, P., Paudel, N. S., & Maraseni, T. N. (2022). Status and practical implications of forest fire management in Nepal. *Journal of Forest and Livelihood*, 21(1), 32–45. <https://doi.org/10.3126/jfl.v21i1.56583>
- Parajuli, R., & Markwith, S. H. (2023). Quantity is foremost but quality matters: A global meta-analysis of correlations of dead wood volume and biodiversity in forest ecosystems. *Biological Conservation*, 283, 110100. <https://doi.org/10.1016/j.biocon.2023.110100>
- Parajuli, R., Paudel, A., & Markwith, S. H. (2025). Integrating the physical harvesting of dead wood into fuel treatments to reduce wildfire hazards and enhance carbon benefits. *Journal of Environmental Management*, 376, 124535. <https://doi.org/10.1016/j.jenvman.2025.124535>
- Paudel, A., Coppoletta, M., Merriam, K., & Markwith, S. H. (2022). Persistent composition legacy and rapid structural change following successive fires in Sierra Nevada mixed conifer forests. *Forest Ecology and Management*, 509, 120079. <https://doi.org/10.1016/j.foreco.2022.120079>
- Paudel, A., Markwith, S. H., Konchar, K., Shrestha, M., & Ghimire, S. K. (2020). Anthropogenic fire, vegetation structure and ethnobotanical uses in an alpine shrubland of Nepal's Himalaya. *International Journal of Wildland Fire*, 29(3), 201–214. <https://doi.org/10.1071/WF19098>
- Paudel, D., Jeuland, M., & Lohani, S. P. (2021). Cooking-energy transition in Nepal: Trend review. *Clean Energy*, 5(1), 1–9. <https://doi.org/10.1093/ce/zkaa022>
- Poudyal, B. H., Khatri, D. B., Paudel, D., Marquardt, K., & Khatri, S. (2023). Examining forest transition and collective action in Nepal's community forestry. *Land Use Policy*, 134, 106872. <https://doi.org/10.1016/j.landusepol.2023.106872>

- Pyne, S. J. (1982). *Fire in America: A cultural history of wildland and rural fire*. University of Washington Press.
- Pyne, S. J., Andrews, P. L., & Laven, R. D. (1996). *Introduction to wildland fire*. John Wiley & Sons.
- Ravi, V., Vaughan, J. K., Wolcott, M. P., & Lamb, B. K. (2019). Impacts of prescribed fires and benefits from their reduction for air quality, health, and visibility in the Pacific Northwest of the United States. *Journal of the Air and Waste Management Association*, 69(3), 289–304. <https://doi.org/10.1080/10962247.2018.1526721>
- Ryan, M. G., Harmon, M. E., Birdsey, R. A., Giardina, C. P., Heath, L. S., Houghton, R. A., Jackson, R. B., McKinley, D. C., Morrison, J. F., & Murray, B. C. (2010). A synthesis of the science on forests and carbon for U.S. forests. *Issues in Ecology*, 13, 1–16.
- Schmidt-Vogt, D. (1990). Fire in high altitude forests of the Nepal Himalaya. In J. G. Goldammer & M. J. Jenkins (Eds.), *Fire in ecosystem dynamics: Mediterranean and northern perspectives* (pp. 191–199). SPB Academic Publishing.
- Shabangu, S., Woolf, D., Fisher, E. M., Angenent, L. T., & Lehmann, J. (2014). Techno-economic assessment of biomass slow pyrolysis into different biochar and methanol concepts. *Fuel*, 117, 742–748. <https://doi.org/10.1016/j.fuel.2013.08.053>
- Sharma, L. N., Tamang, S. R., Poudel, Y. B., Subba, A., Timsina, S., Adhikari, B., Shrestha, H., Gautam, A. P., Kandel, D. R., Watson, M. F., & Paudel, N. S. (2021). Biodiversity beyond protected areas: Gaps and opportunities in community forest. *Journal of Forest and Livelihood*, 20(1), 45–61. <https://doi.org/10.3126/jfl.v20i1.59634>
- Shyam, S., Ahmed, S., Joshi, S. J., & Sarma, H. (2025). Biochar as a soil amendment: Implications for soil health, carbon sequestration, and climate resilience. *Discover Soil*, 2. <https://doi.org/10.1007/s44378-025-00041-8>
- Stokland, J. N., Siitonen, J., & Jonsson, B. G. (2012). *Biodiversity in dead wood*. Cambridge University Press.
- Tiwari, S., Paudel, N. S., Sze, J., & Karki, R. (2022). Unravelling the local dynamics of increasing fires in community forests of mid-hills of Nepal. *Journal of Forest and Livelihood*, 21(1), 60–71. <https://doi.org/10.3126/jfl.v21i1.56587>
- United Nations Framework Convention on Climate Change. (2015). *The Paris agreement*. <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>
- United Nations Forum on Forests Secretariat. (2021). *The global forest goals report 2021*. United Nations Department of Economic and Social Affairs.
- U.S. Congress. (2024). *Funding for wildfire management: FY2024 appropriations for the Forest Service and Department of the Interior* (IF12398). Congressional Research Service. <https://www.congress.gov/crs-product/IF12398>
- Van Vleet, E., Bray, D. B., & Durán, E. (2016). Knowing but not knowing: Systematic conservation planning and community conservation in the Sierra Norte of Oaxaca, Mexico. *Land Use Policy*, 59, 504–515. <https://doi.org/10.1016/j.landusepol.2016.09.010>
- Vázquez-Varela, C., Martínez-Navarro, J. M., & Abad-González, L. (2022). Traditional fire knowledge: A thematic synthesis approach. *Fire*, 5(2), 47. <https://doi.org/10.3390/fire5020047>
- Wibbenmeyer, M., Zhu, Y., & Wear, D. N. (2025). *The costs of achieving forest resilience in California*. Resources for the Future.
- Williams, C. A., Gu, H., MacLean, R., Masek, J. G., & Collatz, G. J. (2016). Disturbance and the carbon balance of U.S. forests: A quantitative review of impacts from harvests, fires, insects, and droughts. *Global and Planetary Change*, 143, 66–80. <https://doi.org/10.1016/j.gloplacha.2016.06.002>
- World Bank. (2025, November 16). Nepal receives \$9.4 million for forest carbon credits under the Forest Carbon Partnership Facility [Press release]. <https://www.worldbank.org/en/news/press-release/2025/11/16/nepal-receives-9-4-million-for-forest-carbon-credits-under-the-forest-carbon-partnership-facility>

Challenges and opportunities in forest fire management in Nepal: An economic perspective

Rajesh Kumar Rai^{1*}

¹*School of Forestry and Natural Resource Management, Institute of Forestry, Tribhuvan University, Kathmandu, Nepal*

**Corresponding author: rjerung@gmail.com*

Abstract

Climate change and human negligence are often cited as main drivers of forest fires in Nepal. However, this perspective argues that these factors are the result of underlying economic and institutional failures in forest management. Reduced interactions between forests and people, protection-oriented forest management practices, and weakened forest-agriculture interactions have led to underutilisation of forest biomass and the accumulation of combustible fuel. Consequently, recurrent and intense forest fires have emerged as negative externalities, where social costs exceed private benefits. Although they have caused significant economic, environmental, and health costs, the prevention and suppression of forest fires are not viewed as co-benefits of forest management. Hence, aligning forest fire management with biomass utilisation, incentive mechanisms, and climate policy commitments can help convert fire prevention into a long-term investment for sustainable forest management in Nepal.

Keywords: Biomass, Climate change, Externalities, Forest management, Incentive

FOREST FIRES BEYOND CLIMATE CHANGE: AN ECONOMIC INTERPRETATION

Forest fires constitute both an ecological and a socio-economic challenge in Nepal, as they impose substantial costs on forest resources, rural livelihoods, public health, climate change and national development. Every year, thousands of hectares of forest are affected during the dry season, particularly in the middle mountains and Chure regions of Nepal (Joshi *et al.*, 2025). Climate change is frequently cited as the major driver of these fire incidents (Rajbhandari *et al.*, 2025). In addition to climate change, forest fires are also linked to the underutilisation of forest biomass and the erosion of forest-agriculture linkages in Nepal. From an economic lens, forest fires should therefore be understood not only as natural hazards but

also as outcomes of weak forest management incentives and the inefficient utilisation of forest resources (Qadir *et al.*, 2021; Rajbhandari *et al.*, 2025).

Historically, forest-people interactions in Nepal were intensive, primarily driven by subsistence activities such as the extraction of fuelwood, fodder, leaf litter, grasses, and small timber (Acharya, 2006). Forest products constituted essential inputs into the farm household production function. The regular collection of these materials contributed to the reduction of combustible biomass, while livestock-based agriculture, compost production, and seasonal grazing served as effective fuel management systems. In addition, the daily movement of farmers to collect fuelwood and fodder led to the formation of walking trails, which functioned as firebreaks.

However, the gradual transition from a non-monetised subsistence economy to a monetised and market-oriented economy has altered these traditional forest–agriculture linkages. Increased access to alternative energy sources, off-farm employment, migration, and rising opportunity costs of labour have collectively reduced the incentives for rural households to collect forest materials, leading to the accumulation of combustible biomass (KC *et al.*, 2021). Therefore, forest fires should be understood not only as environmental phenomenon but also as outcomes of declining forest resource utilisation driven by structural transformations in rural economies.

DECLINING FOREST–PEOPLE INTERACTION

Forests in Nepal are increasingly managed under a protection-oriented paradigm, resulting in the excessive accumulation of biomass (Shahi *et al.*, 2022; Van Winckel *et al.*, 2025). Moreover, rural-to-urban migration, the gradual shift away from livestock-based agriculture, and the complexity of forest-product harvesting processes have reduced interactions between forests and local communities. This has disrupted the socio-ecological dynamics of fire management that historically contributed to fire prevention. As a result, the frequency, intensity and coverage of forest fires have been increasing each year (Mishra *et al.*, 2023). The effects of forest fires are multidimensional, encompassing socio-psychological, economic, and environmental dimensions (Kalogiannidis *et al.*, 2023). These evidences show that forest-fire are destructive and economically inefficient tool to remove accumulated biomass.

This situation reflects a case of market failure and negative externalities from a welfare economics perspective. Forest biomass,

which previously served as a raw material for both households and industries, is now left unused and instead contributes to the fuel component of the fire triangle. As a result, society bears the costs of forest fires, in terms of air pollution, carbon emissions, biodiversity loss, and disaster response expenditures (Poduška and Stajić, 2024). The absence of appropriate incentives, including an enabling environment for active forest management, shifts costs from forest managers and users to the broader public, thereby reducing overall economic efficiency.

ECONOMIC COSTS OF FOREST FIRES AND POLICY GAPS

In Nepal, the economic costs of forest fires are significant but remain inadequately accounted for (Paudel, 2022). Forest fires generate both direct and indirect costs. Direct damages include the loss of standing timber and non-timber forest products, carbon emissions, and delayed forest regeneration, which in turn reduces forest production and productivity. Indirect costs of forest fires encompass soil erosion, disruptions to water regulation, biodiversity reduction, declines in agricultural and hydropower production, and increased public health expenditures associated with smoke-related illnesses. Existing empirical studies suggest that prevention costs are substantially lower than post-fire recovery costs (Amacher *et al.*, 2006; Simon *et al.*, 2022). This provides a strong economic rationale for investing in preventive measures, such as active forest management aimed at sustainably utilising forest products.

Community Forest User Groups (CFUGs), which manage a large portion of Nepal's forests located near settlements, occupy a central position in forest fire economics. Their contributions to conservation and livelihood benefits have been widely

acknowledged (Aryal *et al.*, 2020). However, incentive structures, which were appropriate in a subsistence economy context now discourage active forest management in an increasingly monetised economy. Complex harvesting procedures and unfavourable market conditions increase transaction costs associated with thinning, harvesting, and transportation (Aryal *et al.*, 2020; Poudyal *et al.*, 2022). As a result, CFUGs often adopt protection-oriented forest management approaches despite rising forest fire risks. This is an example of incentive misalignment, in which forest users must internalise forest management costs, but externalise damages caused by forest fire.

Forest fires generate broad environmental impacts, including carbon emissions, biodiversity loss, and air pollution, many of which extend beyond local communities and are largely borne by society at national or global scales rather than by local actors (Gajendiran *et al.*, 2024; Hadiwijoyo *et al.*, 2026). In contrast, local impacts such as public health effects from smoke, land degradation, and limited availability of forest products are mostly borne by individuals. As a result, they are not reported as costs of the CFUG as a whole. CFUGs neither directly bear the economic costs of external damages nor receive private benefits from removing biomass. Therefore, they often have limited or no financial incentives to invest in fuel management practices such as cleaning, thinning, and harvesting (g, 2022).

Nepal's Forest Act 2019 provides a legal basis for sustainable forest management, emphasising protection, utilisation, silvicultural operations, and community participation (GoN, 2019). However, its practical implementation, particularly with regard to biomass utilisation, remains weak due to lengthy administrative procedures

(Poudyal *et al.*, 2020). Existing policies, including the act, regulations and directives, need to recognise silvicultural operations such as thinning, pruning, and harvesting as economically productive and legally protected activities, rather than treating them as strictly controlled interventions. Integrating these activities into routine forest management, rather than subjecting them to special approval processes, would better align policy frameworks with forest fire management strategies. This is particularly important as forest-fire mitigation should be understood as a co-benefit of active forest management.

INCENTIVES FOR FOREST FIRE MANAGEMENT

Nepal's Nationally Determined Contributions (NDCs) highlight emission reduction, climate resilience, and sustainable land management (GoN, 2025). Forest fires play a dual role in undermining these commitments by releasing stored carbon and reducing the carbon sequestration potential of forests. Given that the costs of forest fire prevention are lower than the damages caused by forest fire, prevention represents a cost-effective climate mitigation strategy (Pacheco and Claro, 2021). This situation calls for the systematic integration of fire prevention into NDC implementation in order to generate co-benefits for livelihoods, biodiversity, and public health. In addition, Forest fire mitigation is essential for achieving the goal of Nepal's Long-term Strategy for Net-Zero Emissions (2021), which aims to achieve net-zero greenhouse gas emissions by 2045. This integration can be supported through targeted budget allocations, performance-based grants, and enhanced access to climate finance.

Forest fire mitigation in Nepal, particularly through forest management aimed at reducing fuel loads, does not necessarily require

substantial financial investment. Rather, it depends on the establishment of market-oriented policies for timber and non-timber forest product harvesting, such as demand-based forest management, harvesting plans aligned with technical rotation ages, long-term auction mechanisms, and royalty reforms. Similarly, existing economic studies highlight the importance of restoring forest–agriculture linkages, as the decline of livestock-based farming systems has reduced demand for forest fodder and bedding materials, thereby contributing to fuel accumulation (KC *et al.*, 2021).

An ecosystem-based approach that boosts demand for local products can help restore forest–farm relationships. For this, Community Forest Operational Plans (CFOPs) should emphasise silvopastoral systems, controlled grazing, and demand-driven management. Such measures not only contribute to reducing fire risk but also boost overall forest productivity.

The cost–return gap often discourages local communities and the private sector to undertake restoration initiatives. Economic valuation tools, such as cost–benefit analysis and avoided damage assessment, can support more effective policy design to incentivise these actors to undertake restoration efforts. Incentive-based mechanisms such as payments for ecosystem services, carbon market instruments, and market creation for restoration benefits can help internalise the social and environmental benefits of restored forest ecosystems, while compensating stakeholders for opportunity costs and management efforts (Al Abri, 2022; Thompson, 2021)..

Post-fire restoration initiatives are costly, require long-term investment, and involve uncertain outcomes (Amacher *et al.*,

2006; Poduška and Stajić, 2024; Ryu *et al.*, 2017). As a result, local communities and public finance in developing countries often lack the capacity to bear restoration costs independently. In this context, a co-investment model involving governments, communities, donors and the private sector is essential to reduce upfront financial burdens and to align ecological recovery with livelihood, biodiversity and climate objectives (Besacier *et al.*, 2021). Private finance may be attracted if restoration investments are aligned with corporate net-emission-reduction commitments, sustainable supply chain goals, and branding opportunities (Löfqvist *et al.*, 2023).

Leveraging private finance may create opportunities to redirect public funds toward higher return interventions. For example, investment in early warning systems, fire lines, and community fire brigades yield higher returns compared to suppression costs (Simon *et al.*, 2022). Therefore, a co-investment model helps lower financial barriers, distributes risks, and aligns restoration efforts with biodiversity and climate objectives.

Nepal's federal governance system presents both challenges and opportunities for economically rational forest fire management. Local governments are in a strategic position to design context-specific incentive schemes, while provincial and federal governments can provide funding and coordination. Linking fiscal transfers to fire-risk reduction indicators (e.g. area under forest management, fire-line maintenance, or reduced incidence of forest fire) can further encourage preventive actions by CFUGs and local governments. Such performance-based fiscal transfers have the potential to incentivise proactive local government interventions in biomass reduction.

CONCLUSION

While climate change and individual actions are often cited as causes of forest fires in Nepal, the underlying driver is economic neglect. Forests have become a source of combustible fuel because of weak economic incentives, deteriorating forest–agriculture interactions, and regulatory barriers to forest management. Linking forest biomass to markets, simplifying forest use policies, and aligning fire management with forest management and NDC commitments can transform Nepal's forests from liabilities into productive assets that simultaneously support climate mitigation, biodiversity conservation, and rural livelihoods.

REFERENCES

- Acharya, K. P. (2006). Linking trees on farms with biodiversity conservation in subsistence farming systems in Nepal. *Biodiversity and Conservation*, 15(2), 631–646. <https://doi.org/10.1007/s10531-005-2091-7>
- Al Abri, I. (2022). Evaluating incentive-driven policies to reduce social losses associated with wildfire risk misinformation. *Forests*, 13(12), 2071. <https://doi.org/10.3390/f13122071>
- Amacher, G. S., Malik, A. S., & Haight, R. G. (2006). Reducing social losses from forest fires. *Land Economics*, 82(3), 367–383. <https://doi.org/10.3368/le.82.3.367>
- Aryal, K., Laudari, H. K., & Ojha, H. R. (2020). To what extent is Nepal's community forestry contributing to the Sustainable Development Goals? An institutional interaction perspective. *International Journal of Sustainable Development and World Ecology*, 27(1), 28–39. <https://doi.org/10.1080/13504509.2019.1627681>
- Aryal, K., Rijal, A., Maraseni, T., & Parajuli, M. (2020). Why is the private forest program stunted in Nepal? *Environmental Management*, 66(4), 535–548. <https://doi.org/10.1007/s00267-020-01343-z>
- Besacier, C., Garrett, L., Iweins, M., & Shames, S. (2021). *Local financing mechanisms for forest and landscape restoration: A review of local-level investment mechanisms*. FAO.
- Gajendiran, K., Kandasamy, S., & Narayanan, M. (2024). Influences of wildfire on the forest ecosystem and climate change: A comprehensive study. *Environmental Research*, 240, 117537. <https://doi.org/10.1016/j.envres.2023.117537>
- Government of Nepal. (2019). *Forest act, 2076*. Ministry of Forests and Environment.
- Government of Nepal. (2025). *Nationally determined contribution (NDC) 3.0*. Ministry of Forests and Environment.
- Gong, Y. (2022). Which is better, selective disclosure or fair disclosure? The effects of information asymmetry and incentive misalignment. *Asia-Pacific Journal of Accounting and Economics*, 29(1), 154–178. <https://doi.org/10.1080/16081625.2019.1674163>
- Hadiwijoyo, E., Abdullah, N., & Rijal, H. B. (2026). A systematic review: Impact of forest fire chemical emissions on atmospheric composition and ozone layer. *IOP Conference Series: Earth and Environmental Science*, 1582(1), 012019. <https://doi.org/10.1088/1755-1315/1582/1/012019>
- Joshi, K. P., Giri, S., Kuinkel, D., Kuinkel, S., Devkota, R., Pradhananga, D., Marahatta, S., & Pokharel, B. (2025). Forest fire dynamics in Nepal: Regional trends and socio-ecological drivers. *Trees, Forests and People*, 21, 100942. <https://doi.org/10.1016/j.tfp.2025.100942>
- Kalogiannidis, S., Chatzitheodoridis, F., Kalfas, D., Patitsa, C., & Papagrigoriou, A. (2023). Socio-psychological, economic and environmental effects of forest fires. *Fire*, 6(7), 280. <https://doi.org/10.3390/fire6070280>
- KC, B., Race, D., Fisher, R., & Jackson, W. (2021a). Changing rural livelihoods and forest use transition in the middle hills of Nepal. *Small-Scale Forestry*, 20(3), 479–501. <https://doi.org/10.1007/s11842-021-09477-6>

- Löfqvist, S., Garrett, R. D., & Ghazoul, J. (2023). Incentives and barriers to private finance for forest and landscape restoration. *Nature Ecology and Evolution*, 7(5), 707–715. <https://doi.org/10.1038/s41559-023-02037-5>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19(1), 3. <https://doi.org/10.1186/s42408-022-00162-3>
- Pacheco, R. M., & Claro, J. (2021). Prescribed burning as a cost-effective way to address climate change and forest management in Mediterranean countries. *Annals of Forest Science*, 78(4), 100. <https://doi.org/10.1007/s13595-021-01115-7>
- Paudel, J. (2022). Environmental disasters and property values: Evidence from Nepal's forest fires. *Land Economics*, 98(1), 115–131. <https://doi.org/10.3368/le.98.1.110519-0159R2>
- Poduška, Z., & Stajić, S. (2024). The cost of forest fires: A socioeconomic analysis. In J. Rodrigo-Comino & L. Salvati (Eds.), *Fire hazards: Socio-economic and regional issues* (pp. 123–135). Springer International Publishing. https://doi.org/10.1007/978-3-031-50446-4_10
- Poudyal, B. H., Maraseni, T., & Cockfield, G. (2020). An assessment of the policies and practices of selective logging and timber utilisation: A case study from natural forests of Tarai Nepal and Queensland Australia. *Land Use Policy*, 91, 104422. <https://doi.org/10.1016/j.landusepol.2019.104422>
- Poudyal, B. H., Maraseni, T. N., Aryal, S., & Cockfield, G. (2022). An assessment of selective logging policies and practices in Nepal. In *Agriculture, natural resources and food security: Lessons from Nepal* (pp. 357–374). Springer. https://doi.org/10.1007/978-981-16-4092-3_19
- Qadir, A., Talukdar, N. R., Uddin, M. M., Ahmad, F., & Goparaju, L. (2021). Predicting forest fire using multispectral satellite measurements in Nepal. *Remote Sensing Applications: Society and Environment*, 23, 100539. <https://doi.org/10.1016/j.rsase.2021.100539>
- Rajbhandari, A., Bhatta, S., Joshi, R., & Ghimire, S. (2025). Analysing forest fire trends, influencing factors, and strategies for effective management: A spatial examination in Madhesh Province of Nepal. In H. Singh & N. Kumar (Eds.), *Forest fire and climate change: Insights into science* (pp. 507–542). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-89967-6_27
- Ryu, S.-R., Choi, H.-T., Lim, J.-H., Lee, I.-K., & Ahn, Y.-S. (2017). Post-fire restoration plan for sustainable forest management in South Korea. *Forests*, 8(6), 188. <https://doi.org/10.3390/f8060188>
- Shahi, N., Bhusal, P., Paudel, G., & Kimengsi, J. N. (2022). Forest–people nexus in changing livelihood contexts: Evidence from community forests in Nepal. *Trees, Forests and People*, 8, 100223. <https://doi.org/10.1016/j.tfp.2022.100223>
- Simon, B., Crowley, C., & Franco, F. (2022). The costs and costs avoided from wildfire fire management: A conceptual framework for a value of information analysis. *Frontiers in Environmental Science*, 10, 804958. <https://doi.org/10.3389/fenvs.2022.804958>
- Thompson, B. S. (2021). Corporate payments for ecosystem services in theory and practice: Links to economics, business, and sustainability. *Sustainability*, 13(15), 8307. <https://doi.org/10.3390/su13158307>
- Van Winckel, S., Simons, J., Lhermitte, S., & Muys, B. (2025). Assessing the effect of forest management on above-ground carbon stock by remote sensing. *Biogeosciences*, 22(16), 4291–4307. <https://doi.org/10.5194/bg-22-4291-2025>

From voluntarism to incentivised forest fire management in Nepal: Evidence on labour costs and risk perceptions from four CFUGS

Manish Shrestha^{1,*}, Dipesh K.C.², Rahul Karki¹, Madan Bashyal¹

¹ForestAction Nepal, Ashram Road, Bagdol, Lalitpur, Bagmati, Nepal

²Ministry of Industry, Tourism, Forest and Environment, Birendranagar, Surkhet, Karnali, Nepal

*Corresponding author: manish.shrestha1979@gmail.com

Abstract

Nepal's community forestry model, recognised for decentralised governance, has long relied on voluntary collective action. Rural out-migration and rising labour opportunity costs are weakening this model as climate-driven forest fire risks intensify. This study examines a shift toward incentive-based management through a pilot program that introduced wages, personal protective equipment (PPE), and technical training across four Community Forest User Groups (CFUGs). Using a convergent mixed-methods design, the study analysed quantitative data from 87 participants, along with 24 key informant interviews and 8 focus group discussions. McNemar's chi-squared and Wilcoxon signed-rank tests show that although daily wages were only 6.1 per cent above market rates, the effective hourly wage premium reached 32.01 per cent. This higher valuation encouraged participation among households previously excluded due to the opportunity cost of unpaid labour. Technical knowledge scores improved significantly ($p < 0.001$). However, a clear "risk gap" emerged. Participants preferred institutional insurance over PPE, reflecting concern about income loss from injury. Willingness to participate was assessed through stated preference scenarios with and without wage incentives, not observed behaviour over time. Governance challenges remain. Risks of elite capture persist, and gender barriers limit participation. Women formed 55 per cent of trainees but remained underrepresented in fire response leadership. Overall, the findings from this pilot study suggest that the long-term viability of community forestry in transitioning economies depends on a gradual shift from "free labour" assumptions toward more incentive-compatible models. These results provide indicative evidence to inform future research and policy design in similar contexts.

Keywords: Community forestry, Forest fires, Labour opportunity cost, Incentive-based management, Collective action sustainability

INTRODUCTION

For over four decades, Nepal's community forestry program has set the global standard for decentralised natural resource management, often praised as the "gold standard" for balancing ecological restoration with local livelihoods (Ostrom, 1990; Agrawal and Ostrom, 2001). This shift from state-led to community-driven governance was achieved by devolving a bundle of

rights to local Forest User Groups (FUGs), effectively reversing the "tragedy of the commons" through localised collective action. Historically, this success depended on a subsistence-oriented peasantry with low labour opportunity costs and strong voluntarism. Under these conditions, households assumed the demanding tasks of monitoring, patrolling, and silvicultural management as part of their routine collective duties (Adhikari and Lovett, 2006). The

institutional design aligned labour availability, resource dependence, and collective incentives within a relatively closed, subsistence-based socio-economic system (Ghimire and Lamichhane, 2020; Libois *et al.*, 2022).

However, a critical structural shift has emerged. This study focuses on two core analytical constructs: (i) a “wage incentive gap,” referring to the divergence between rising labour opportunity costs and existing institutional compensation mechanisms, and (ii) a “risk-gap,” referring to the divergence between risk exposure and available risk mitigation or transfer mechanisms. Distributional fairness is treated throughout the study as a cross-cutting interpretive concern linked to participation, inclusion, and governance, rather than as a standalone analytical construct defined *ex ante* and guiding the empirical analysis. Ecological improvements, including increased forest biomass, have raised both the value of forest resources and their exposure to fire risk, while institutional arrangements have not adapted to changing socio-economic conditions such as labour scarcity and market integration (Shrestha *et al.*, 2025). At the same time, outmigration and livelihood diversification have reduced the availability of local labour, weakening the voluntaristic base of collective action (Poudyal *et al.*, 2023; Laudari *et al.*, 2024). As a result, participation in fire management is increasingly shaped by wage expectations and risk considerations rather than norm-based obligations. This study examines how these two constructs shape participation in community-based fire management within selected cases.

A fundamental driver of this transition is the reordering of rural labour economies. In the past, the implicit wage for forest management was derived from subsistence benefits such as fuelwood and fodder (Ghimire and

Lamichhane, 2020; Libois *et al.*, 2022). As rural households diversify income sources, with remittances contributing over 25 per cent of national GDP (Sunam, 2020), labour allocation has shifted toward higher-return wage opportunities. This has reduced the residual labour available for collective forest management. Households now evaluate participation in fire management against prevailing wage rates, making unpaid labour economically unattractive. The erosion of subsistence-based incentives has therefore created a clear mismatch between institutional expectations and household decision-making.

This mismatch is best understood as a wage incentive gap, where existing institutional arrangements fail to compensate for rising opportunity costs of labour. Non-participation reflects rational labour allocation rather than declining social cohesion. Evidence from community forests shows that users increasingly prefer to pay fines instead of contributing labour, indicating a shift toward monetised decision-making. Within this study, the wage incentive gap is operationalised through comparisons between prevailing wage rates, project-based incentives, and stated willingness to participate under different incentive conditions. At the same time, participation is shaped not only by wages but also by risk exposure. Fire management involves significant physical danger, yet existing interventions have largely focused on providing equipment such as fire-swatters and basic protective gear. This study conceptualises a “risk-gap” as the divergence between risk mitigation measures, such as Personal Protective Equipment (PPE), and risk transfer mechanisms, such as insurance, which participants increasingly prioritise. In the absence of insurance or formal safety nets, households face the possibility of severe economic loss from injury or death during firefighting. This implicit risk cost raises the



effective price of labour beyond what daily wages alone can offset, directly influencing participation decisions. In the empirical analysis, this construct is examined through participant perceptions and stated preferences regarding PPE and insurance mechanisms.

Together, the wage incentive gap and the risk-gap define the emerging constraints on collective action in community forest fire management. Addressing these gaps requires moving beyond voluntarism toward structured incentive systems that combine wage payments with risk coverage. In this context, this study addresses three questions: (1) the extent to which wage-based incentives offset rising opportunity costs of labour, (2) how participants perceive and prioritise risk management mechanisms, particularly PPE relative to insurance, and (3) how financial incentives are associated with patterns of participation and perceived equity within Community Forest User Groups (CFUGs).

METHODOLOGY

This study used a convergent mixed methods design to examine incentive-based forest fire management in Nepal’s community forestry. The qualitative component focused

on community perceptions, motivations for participation, and institutional challenges related to fire management, while the quantitative component assessed participation rates, wage incentives, and changes in knowledge levels associated with fire management activities. The convergent design enabled triangulation of findings and strengthened internal validity by comparing results across data sources (Creswell and Plano Clark, 2017). This approach addressed research questions beyond the scope of single-method studies and aligned with established guidance for socio-ecological and policy-oriented research in forestry and natural resource management (Hong *et al.*, 2017). To strengthen data integration, each research question was addressed using both quantitative and qualitative evidence, as shown in Table 1, and integration occurred at the interpretation stage, where findings were compared and used to explain convergences and divergences across data sources.

Study sites

The study was conducted in four purposively selected CFUGs in the Sindhupalchowk and Dolakha districts of Nepal. These sites were selected as critical cases because they

Table 1: Integration of research questions, data sources, and analytical approach

Research Question	Analytical Focus	Quantitative Evidence	Qualitative Evidence
RQ1. Wage incentives and participation	Effect of incentives on labour participation	Willingness to participate with and without incentives; wage comparisons	FGDs and KIIs on motivation, labour allocation, and incentive preferences
RQ2. PPE versus insurance (risk gap)	Risk mitigation and participation behaviour	Survey responses on safety perception and participation motivation	FGDs and KIIs on risk perception, safety concerns, and stated preferences
RQ3. Equity and participation	Inclusion across gender and caste groups	Gender and caste disaggregated participation data	FGDs and KIIs on fairness, inclusion, and access to incentives

represent the intersection of high ecological fire risk and high socio-economic transition. Site selection was based on three criteria: (i) documented exposure to recurrent seasonal forest fires based on local forest office records and community reports, (ii) evidence of high out-migration and reduced local labour availability, and (iii) proximity to local labour markets influencing wage expectations. This purposive sampling allows for an intensive examination of the pilot intervention *“Fostering community-led forest fire management in Himalayan regions of Nepal”*. These criteria provide indicative justification but do not establish that the sites are fully representative of all fire-prone or transitioning regions in Nepal. Figure 1 shows the study sites.

Study participants

The study involved two groups of participants. (1) Community stakeholders: Members of CFUGs involved in the pilot intervention. These participants engaged in fire prevention, forest management operations such as thinning, pruning, and fire line construction, and training on forest fire prevention and response. (2) Institutional stakeholders: Representatives from provincial, district, and local governance bodies responsible for forest fire coordination, monitoring, and policy implementation. These included officials from the provincial Ministry of Forest and Environment, divisional forest offices, district administration, local governments, Federation of Community Forestry Users Nepal (FECOFUN), and CFUG leadership structures.

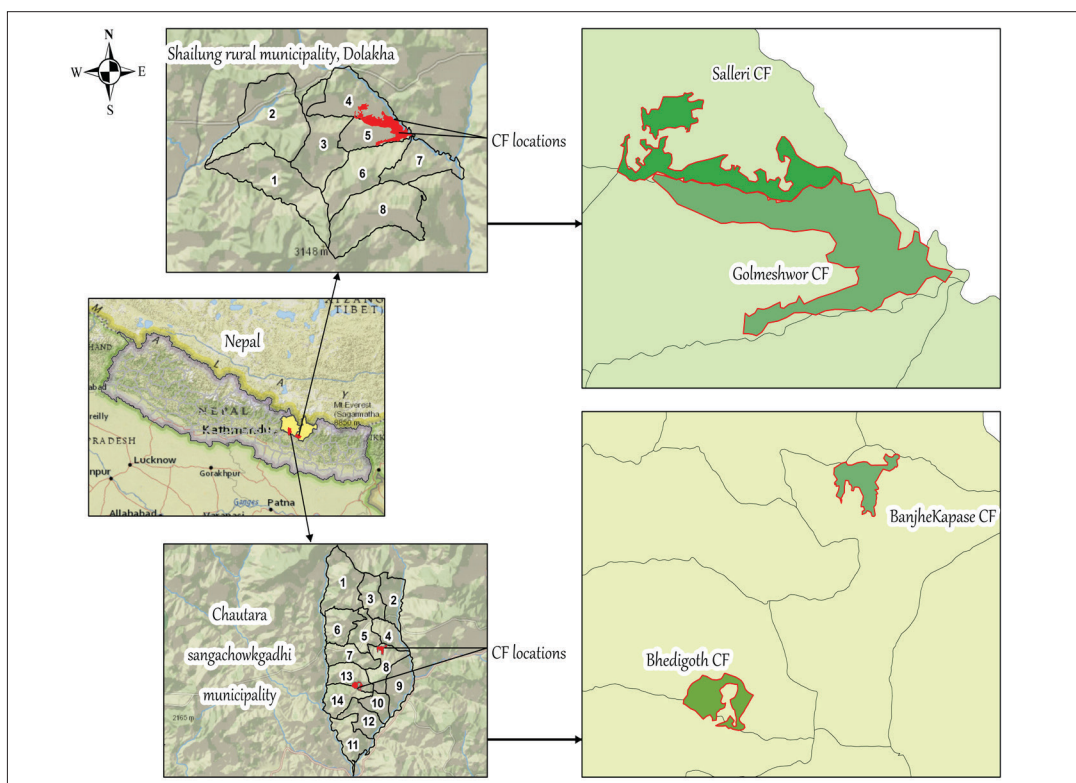


Figure 1: Study sites



CFUGs were selected based on their involvement in the pilot project and exposure to incentive-based fire management measures. Participant selection followed purposive criteria linked to direct participation in fire management activities and decision-making roles. The absence of a counterfactual group and the purposive selection of four CFUG limit causal inference and generalisability. Findings should be interpreted as context-specific insights applicable to similar high out-migration and fire-prone settings. This sampling approach prioritises information-rich cases but may over represent individuals already engaged in intervention, thereby limiting the inclusion of non-participants or dissenting perspectives.

Data collection

Data collection combined focus group discussions (FGDs), Key Informant interviews (KIIs), and semi-structured questionnaire surveys. The study conducted eight FGDs, with two FGDs in each selected CFUG comprising 8-10 participants, to capture site-specific fire risks, local practices,

and experiences with incentives across all intervention areas, while allowing comparison among user subgroups and supporting thematic saturation at the community level. In addition, 24 KIIs were carried out as shown in Table 2, selected based on formal roles, technical responsibilities, and oversight functions, ensuring representation across governance levels and saturation on issues related to institutional capacity, coordination, sustainability, and policy gaps. The quantitative component included 87 semi-structured questionnaire surveys administered to CFUG members engaged in fire prevention activities and training, targeting active participants exposed to wage incentives, equipment provision, and capacity building measures, and enabling assessment of participation levels, perceived opportunity costs, and changes in knowledge associated with incentive-based engagement. The same respondents contributed to both pre- and post-training knowledge assessments. The post-training assessments were administered immediately after completion of the training sessions, capturing short-term knowledge gains rather than long-term retention.

Table 2: Details of key informants

Type of informant	Number
Provincial Ministry of Forest and Environment, Bagmati Province	2
District Administrative Officers	2
Divisional Forest Officers	2
Local Government Staffs	4
FECOFUN members	4
CFUG Chairpersons	4
Forest Fire Response and Prevention Sub-Committee Members	4
Cluster-level Committee Members for Fire Prevention and Response	2
Total	24

Interview procedures and ethics

A semi-structured questionnaire was developed to examine participants' perceptions on wage-based incentives from project implementation sites. The questionnaire was designed based on a review of the literature on different incentive-based mechanisms in community-based fire management and refined through consultation with forestry and economics experts to ensure contextual relevance. The questionnaire included both closed-ended and open-ended questions to capture both qualitative and quantitative insights. In order to make sure the respondents could effectively explain their viewpoints, the interview was conducted in Nepali.

FGDs and KIIs were conducted primarily in the latter half of 2025 A.D. KIIs were selected purposively based on institutional roles and experience in forest fire management. All participants provided informed consent prior to data collection. The study followed standard ethical procedures, including informed consent, voluntary participation and anonymisation of responses. Anonymity was ensured through participant coding, for example, KII 1 to KII 24. Quotes in the results section identify the respondent type (e.g., "CFUG Chairperson, Dolakha" or "DFO Officer, Sindhupalchowk"). Quotations in the results section identify respondent categories without revealing personal identities. Formal institutional ethics approval was not obtained, which is a limitation. However, all participants were informed about the purpose of the study. All KIIs and FGDs were audio-recorded, transcribed verbatim in Nepali, and subsequently translated into English for analysis. During FGD, semi-structured discussion guides were employed to allow the participants to articulate detailed and context-specific insights while maintaining consistency and comparability across sites (Krueger, 2014).

Data analysis

Quantitative data management and analysis

Data were entered in Microsoft Excel 2019 and analysed in R version 4.4.2 (R Core Team, 2025). Survey data were analysed using descriptive statistics, including frequencies and percentages, to summarise participation patterns, perceived opportunity costs, and preferences regarding incentives. The wage premium of 6.1 per cent was calculated by comparing the project wage rate (NPR 800 per day) with the official minimum wage benchmark (NPR 754 per day) issued by MoLESS (2025), using the formula: $[(800 - 754) / 754 \times 100]$. The hourly benchmark was calculated using the official minimum daily wage of NPR 754 divided by the standard 7.5-hour workday commonly applied in national labour guidance and practice ($754/7.5 = 100.53$, rounded to NPR 101). Though this benchmark may not fully reflect local labour market conditions or actual opportunity costs in the study sites. Therefore, the estimated premium should be interpreted as indicative rather than a precise measure of local wage advantage.

Knowledge assessment

A composite knowledge index (0–3) was created by summing binary scores (yes=1; no=0) across three domains: evacuation, tool use, and safety awareness. This approach aligns with established practices for quantifying knowledge outcomes (Cameron and Trivedi, 2010; Deaton, 2019). Changes in knowledge were assessed using a paired non-parametric Wilcoxon signed-rank test, consistent with guidance for repeated-measured data (Siegel and Castellan, 1988; Wilcoxon, 1992). Five pre-training and one post-training observations contained missing values. The paired Wilcoxon signed rank test

was conducted using only complete cases, resulting in a final paired sample size of $N=81$. Indices were defined as:

Pre Knowledge Index = Pre Knowledge Evacuation + Pre Tool Knowledge + Pre Safety Awareness

Post Knowledge Index = Post Knowledge Evacuation + Post Tool Knowledge + Post Safety Awareness

Willingness to participate analysis

The project participants' survey data included two questions measuring respondents' willingness to participate in forest management and fire prevention activities under two conditions: (i) without monetary incentives, assuming access to training and safety materials, and (ii) with wage incentives. Variables were renamed as "willingness without incentives" and "willingness with incentives" for clarity. Responses were recoded into binary values (yes = 1; no = 0), enabling paired comparison across conditions.

The 2*2 contingency table (provided in Appendix 1) was constructed to summarise changes in willingness, capturing four response patterns: willing to willing, willing to unwilling, unwilling to willing, and unwilling to unwilling. McNemar's chi-squared test was applied to evaluate whether wage incentives significantly influenced willingness, with an exact version without continuity correction used to strengthen inference given the sample size and distribution of discordant responses (McNemar, 1947; Agresti, 2019). The McNemar test compares stated willingness under two hypothetical conditions, not observed behaviour before and after an intervention. The second condition includes a bundle of incentives (wages, training, and PPE). Therefore, results should be interpreted as reflecting the combined effect of these elements rather than wages alone.

Qualitative data analysis

Qualitative data from FGDs and KIIs were coded and managed using Taguette (Rampin and Rampin, 2021). The analysis followed a six-stage thematic procedure outlined by Naeem *et al.* (2023) covering data familiarisation, initial coding, theme identification, theme review, theme definition, and reporting.

A hybrid coding strategy was employed. A deductive approach guided by a predefined coding framework (Appendix 2) was first applied followed by iterative refinement through inductive identification of emergent themes. To improve transparency, two researchers independently coded approximately 25 per cent of the transcripts. Coding outputs were subsequently compared, and discrepancies were resolved through iterative discussion until consensus was reached. Although formal inter-coder reliability statistics were not calculated, this reconciliation process strengthened consistency in code application. Final themes were generated through repeated comparison across codes, transcripts, and data sources, with continuous refinement to ensure internal coherence between codes and higher-order themes. Illustrative excerpts from FGDs and KIIs were used to validate theme construction by explicitly linking empirical statements to corresponding codes and thematic categories.

Stakeholder engagement was further differentiated into direct and indirect forms to capture variation in levels of participation and involvement across actors. Consistency checks were conducted throughout the analytical process to maintain alignment between raw data, codes, and emergent themes. Given the qualitative-dominant design, findings are interpreted as explanatory and perception-based, without inference

of causal relationships. While dominant patterns indicated broad support for incentive-based approaches to forest fire management, divergent perspectives were also identified. A subset of respondents raised concerns regarding potential dependency on wage-based incentives, possible erosion of voluntary participation, and unequal distribution of benefits. These contrasting views were retained to ensure a balanced and comprehensive interpretation of stakeholder perceptions.

RESULTS

Wage incentives and community participation in forest fire management

Participation in forest fire management increased following the introduction of wages, relative to earlier seasons when activities relied primarily on voluntary labour by a small group of regular participants. During the intervention period, approximately 20 individuals per CFUG engaged daily during the pre-fire season, based on the reports from FGDs and KIIs rather than systematic baseline records. As no consistent pre-intervention participation counts were available, this comparison should be interpreted as perception-based rather than a direct before-and-after measurement. The daily wage provided for forest fire management across the four CFUGs is uniform at NPR 800 per day. When compared to the prevailing labour daily wage rate (NPR 754), the incentive for forest fire management work was 6.1 per cent higher. However, the incentive structure changes when adjusted for actual labour time. Field observations show that fire management work requires approximately 6 hours per day on average. Based on this, the effective hourly wage under the project is NPR 133, compared

to the statutory hourly benchmark of NPR 101 derived from national labour standards. This results in an effective hourly wage premium of 32.01 per cent. This difference highlights that the incentive strength is more accurately reflected at the hourly level rather than the daily rate. The total number of paid workdays also varies across CFUGs, with Golmeshwor recording 28 days, Salleri 26 days, Bhedigoth 23 days, and BanjheKapase 32 days.

FGDs documented changes in participation patterns. FGDs confirmed that the wage incentive reduced the burden of choosing between household subsistence and forest protection. For poorer households dependent on casual labour, respondents described the wage incentive as an important factor shaping their willingness to participate. One participant noted, “If I receive the wages for the forest management works, then I can contribute daily. It’s easier and less labour-intensive in comparison to our prevailing daily labour work in the construction of houses and so on.” (FGD, Golmeshwor CFUG).

Key informant interviews confirmed that wages increased participation during the project year, but raised concerns about continuity:

“We managed to pay wages this year with donor support, but without a regular budget, we cannot guarantee it in the future.” (KII, Bhedigoth CFUG)

Provision and coverage of Personal Protective Equipment (PPE) and its role in voluntary participation

Across four CFUGs, 40 PPE sets were distributed, averaging 10 per group, covering 45 per cent of active fire management participants. This estimate is based on an

approximate total of 20-22 active participants per CFUG reported during the intervention period, yielding an estimated denominator of 80-88 individuals across sites. As participation varied across days and activities, this coverage rate should be interpreted as indicative rather than exact.

FGDs indicate that PPE improved perceived safety and confidence among participants. A participant noted:

“Before we used to go in with only leaf twigs and branches. With jackets and helmets, we feel safer, even if not everyone has them.” (FGD, BanjheKapase CFUG)

Some FGD participants also emphasised the need for insurance for fire responders, noting, “We cannot predict the impact of fires, and fire behaviour is very tricky; only those who are involved in the response activities know how dangerous the fires are in a real-life scenario. So, these PPEs don’t motivate us to engage in forest fire response activities. If there were a provision of insurance mechanisms, if there were any accident in the field, we can feel secure that the insurance can make or sustain our livelihood.”

Key informants noted that while PPEs are important for safety, they alone do not drive participation. One of the key informants stated:

“PPE is essential, but it is not enough to motivate participation on its own. Without wages or other support, the gear alone will not sustain community participation.” (KII, District Forest Office, Sindhupalchowk)

Training participation, and changes in knowledge practices and roles in community fire response

Training significantly increased participant knowledge related to forest fire prevention and response. The pre-training knowledge index ranged from 0 to 3, with a median value of 2 and a mean of 1.93. These scores reflect a partial understanding of evacuation procedures, tool operation, and safety principles. Five observations were excluded due to missing values. After training, the distribution shifted upward. The post-training knowledge index had a median of 3 and a mean of 2.78. 75 per cent of participants attained the maximum possible score. Only one post-training observation contained missing data. The Wilcoxon signed rank test confirmed a statistically significant increase in knowledge scores ($W = 1445.5$, $p = 2.295e-10$). These results indicate short-term improvement in reported knowledge and core competencies across participants immediately following the training sessions.

Qualitative findings from FGDs align with the observed quantitative gains. Participants described a shift from informal and experience-based fire response toward more structured and safety-oriented practices. One participant reported:

“Before, we thought fire was only about beating flames with green branches. Now we learned the importance of PPEs and how to use the forest fire tools.” (FGD, BanjheKapase CFUG)

While post-training scores indicate immediate gains in knowledge and confidence, KIIs

further contextualise the durability of observed knowledge gains. One key informant stated, “One training is not enough. People forget, and new members join every year.” (KII, Forest Fire Response and Prevention Sub-Committee Members). These findings signal the limits of one-time capacity building in maintaining the value of unpaid volunteer labour over time.

Training activities reached 87 participants across four CFUGs. Table 3 presents participation by gender and caste/ethnic

group. Women accounted for 55.17 per cent of trainees. Dalit participation remained low at 19.54 per cent. Dalit participation at 19.54 per cent should be interpreted with caution, as no consistent benchmark on overall CFUG membership composition or ward-level population shares was available for comparison. Participation levels varied across sites, with some CFUGs showing higher representation. There, this figure reflects sample composition rather than a definitive measure of underrepresentation.

Table 3: Training participation by CFUG, gender, and caste group

CFUG Name	Total Participants	Women (%)	Dalit (%)	Janajati (%)	Other Castes (%)
Golmeshwor CFUG	21	7(33.33)	2 (9.52)	1 (4.76)	18 (85.71)
Salleri CFUG	22	15(68.18)	0 (0.00)	14 (63.63)	8(36.36)
Bhedigoth CFUG	21	13 (61.9)	15 (71.42)	0 (0.00)	6(28.57)
BanjheKapase CFUG	23	13(56.5)	0 (0.00)	14(60.8)	9 (39.1)
Total/Average	87	48 (55.17)	17 (19.54)	29 (33.33)	41 (47.12)

Despite overall gains, qualitative data highlight differences in how knowledge is translated into roles during fire response. Women participants reported increased confidence but limited leadership during active fire response:

“The training was useful, but during fire events, men still take the lead. We are expected to watch from behind.” (FGD, Bhedigoth CFUG).

Additional examples from FGDs indicate that women were often assigned supportive roles such as carrying water, managing logistics, or observing from safer locations, while decision-making during active fire suppression, such as directing fire lines or coordinating response teams, was typically led by men.

Impact of incentives on community participation in forest fire management

The project participants’ responses showed limited willingness to engage in forest fire management on a voluntary basis. When the same respondents assessed participation under conditions including formal training, personal protective equipment, and daily wages, willingness increased sharply. McNemar chi-squared analysis of paired responses confirmed a significant shift in perceptions ($\chi^2 = 23$, $df = 1$, $p = 1.62 \times 10^{-6}$). No respondents shifted from willing participation under the non-incentive condition to unwilling participation under the bundled-incentive condition, while 23 respondents shifted from unwilling

to willing participation. Figure 2 showcases the changes in willingness as per Gender, Education level, and types of occupation the stakeholders are engaged in.

FGDs and KII reinforced these patterns. Participants identified wages and material support as primary motivators. Discussions indicated that earlier reliance on unpaid labour limited participation to a small group of committed individuals, whereas the introduction of wages expanded engagement across age and gender groups. One participant noted, “When we worked for free, only a few elders came. With wages, more youth and women are also willing to join.” (FGD Participant, Salleri CFUG).

Another participant emphasised the symbolic value of incentives, stating, “Volunteering felt like an obligation, but with payment, we feel respected.” (FGD Participant, Golmeshwor CFUG).

At the same time, concerns related to fairness and equity emerged across multiple sites. Participants reported that access to wage-based work and distribution of protective equipment were not always perceived as transparent and inclusive. As one respondent observed, “The same families get chosen for wage work each time. Others are ignored.” These perceptions indicate that while incentives increased willingness to participate overall, their distribution shaped how such

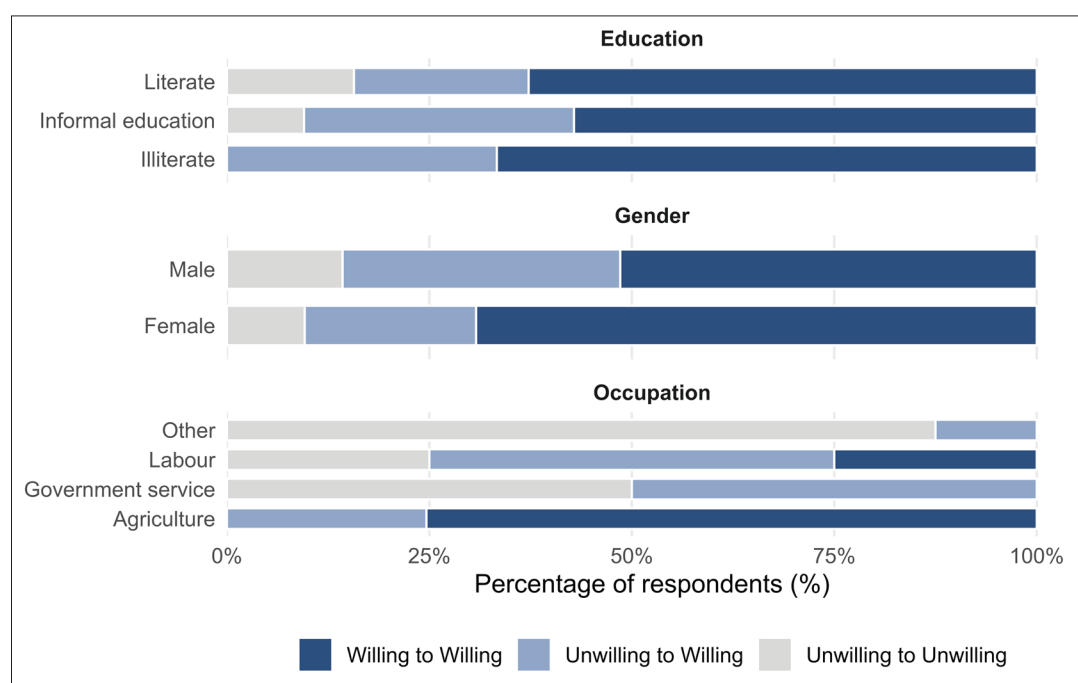


Figure 2: Proportion of respondents indicating willingness to participate under two stated conditions (without incentives and with bundled incentives). Subgroup breakdowns are shown by gender (Male $n = 35$; Female $n = 52$), education level, and occupation categories. The figure displays proportions based on the total number of respondents within each subgroup and illustrates changes in stated willingness rather than actual participation behaviour or longitudinal transitions. Sample sizes for each subgroup category are presented directly within the figure panels.

programs were evaluated at the community level. Questions regarding the sustainability of incentive-based fire management were also prominent. Participants expressed uncertainty about the continuation of wages and external support, and several linked future participations to the reliability of funding mechanisms. One focus group participant stated, “This year we had support, but what about next year. If wages stop, people will stop coming.” (FGD, Banjhekapase CFUG). Others pointed to internal CFUG financing as a possible pathway for continuity, noting, “We cannot always depend on donors. If our CFUG fund pays, then maybe it will last.” (FGD, Golmeshwor CFUG).

Institutional and policy dimensions of incentive-based forest fire management

KIIs provided additional insights into the institutional and policy dimensions, highlighting the three main dimensions: institutional sustainability, governance and equity, and policy gaps.

Institutional sustainability

Leaders emphasised the difficulty of maintaining wage payments without external resources. While acknowledging their effectiveness, they highlighted the limits of CFUG funds.

- “Wages attract people, but our community fund is too small to cover this every year.” (KII, CFUG Chairperson, Bhedigoth CFUG)
- “Unless government allocates a budget for fire control, we cannot sustain wage payments.” (KII, CFUG Secretary, Salleri CFUG)

- “Our forests do not have the provision for timber harvesting and trade as the timber value of pine species is not good in the current market, and we cannot adopt any other agroforestry practices as division forest officers prevent us from doing so. As another option to gain quick incentives, the conversion of pine forests into other mixed forests and the adoption of agroforestry practices could be considered.” (KII, Forest fire Cluster member)

Governance and equity

Local government officials and DFO representatives raised concerns about transparency in distributing wages and PPE. They stressed the need for clear criteria to avoid elite capture.

- “Payments are helpful, but if leaders select only their relatives, the community spirit is damaged.” (KII, District Forest Officer)
- “Incentives must be linked to fair rotation and inclusion of women and marginalised households.” (KII, Shailung rural municipality officer)

Policy gaps

Informants repeatedly noted that while Nepal’s community forestry policy framework recognises voluntary contributions, it does not formally address paid labour for fire management. This gap undermines the institutionalisation of incentive models.

- “Policies talk about volunteer mobilisation, but they do not mention how labour can be valued or paid.” (KII, District Forest Officer)

- “We need clear guidelines so that community funds, donor support, and government programs can work together.” (KII, Provincial Government Officer)

DISCUSSION

Changing volunteerism under rising opportunity costs

Community forestry in Nepal originated within subsistence-based livelihoods, where households relied on fuelwood, fodder, bedding materials, and timber. These dependencies aligned household welfare with forest protection, generating incentives for local rule-making and unpaid collective labour. Low labour opportunity costs, limited market integration, and dense social networks sustained reciprocal norms, enabling voluntary collective management over extended periods (Nuberg *et al.*, 2019; Ghimire and Lamichhane, 2020; Cadman *et al.*, 2023). Volunteer labour was effectively compensated through access to forest products rather than monetary payments.

Findings from the four studied CFUGs indicate a localised adjustment in participation incentives rather than a broader system-wide transition. In the studied CFUGs, willingness to engage in forest fire management without financial compensation has declined as labour opportunity costs rise due to income diversification, seasonal migration, and expanding wage labour markets (Poudyal *et al.*, 2023; Laudari *et al.*, 2024). This interpretation is based on stated preferences and qualitative accounts, not observed behavioural change over time. This reduction in unpaid participation reflects

economic reallocation of labour rather than declining environmental preferences. Moral and cultural attachment to forests persists; however, intrinsic motivations appear insufficient, based on the respondents' perceptions, to offset forgone income during peak fire seasons. This aligns with political economy analyses of common-pool resources, which caution against attributing declining participation solely to weakening social norms (Nightingale, 2017; Ojha *et al.*, 2020).

Participatory governance and local empowerment enhance intrinsic motivation, but labour-intensive forest management increasingly requires extrinsic incentives to sustain engagement under changing economic conditions (Palmer *et al.*, 2020; Charnley, 2023). This study does not empirically test motivational crowding effects; therefore, any reference to such dynamics remains theoretical. Poorly designed financial incentives risk undermining intrinsic motivation, reducing participation once payments end (Oniki *et al.*, 2023; Li *et al.*, 2024). Rising labour scarcity and the physical demands of forestry work increase reliance on hired labour and simplified management practices, with potential implications for long-term sustainability (Jurjonas *et al.*, 2023). Within these study sites, these dynamics suggest a mismatch between institutional expectations of unpaid labour and current livelihood strategies. Remunerating volunteer labour reflects broader economic processes that shape participation and inequality while enabling continued engagement among marginalised groups (Smith *et al.*, 2020). Overall, the findings point to an emerging gap between policy assumptions of voluntary labour and observed participation constraints in high out-migration contexts.

Wage incentives and recognition of labour value

Introducing wage-based incentives was associated with higher stated willingness to participate, indicating that forest fire management competes directly with alternative income-generating activities. The effective hourly wage premium of over 30 per cent suggests that participants perceive compensation as offsetting opportunity costs rather than symbolic payments. Evaluating incentives on an hourly basis improves labour valuation and allows robust comparisons for hazardous, time-intensive tasks (Farina *et al.*, 2021). This inference is drawn from stated willingness and reported labour patterns, not from longitudinal participation data.

Reframing fire management as paid labour aligns participation with household economic strategies, internalising labour costs previously externalised under volunteer-based governance. This addresses chronic under-provision of collective fire protection and aligns with institutional economic theories emphasising incentive compatibility in sustaining public goods (Ostrom, 2010). However, this study does not establish causal effects on sustained participation or long-term institutional outcomes. Evidence from respondents highlights that wages alone are insufficient where risk exposure remains high. Similar patterns were observed in Asia and African community forestry systems when livelihood portfolios expanded, intrinsic motivation alone was insufficient for labour-intensive and risky activities such as fire suppression (Baynes *et al.*, 2015).

Participants consistently emphasised the absence of insurance mechanisms as a constraint on participation despite wage provision. Fire management entails both income and risk dimensions; wages

compensate time but not exposure to physical harm. Evidence from fire suppression and prescribed burning shows that financial incentives increase participation, but risk and liability concerns strongly influence engagement (Watts *et al.*, 2019; Abri, 2022). From a policy perspective, these findings suggest that wage incentives need to be complemented by a risk-sharing mechanism to address both income and safety considerations.

Material and human capital inputs as complementary incentives

PPE improved perceived safety but did not independently drive participation. PPE reduces physical risk but does not offset economic risk from foregone wages or injury. Findings indicate that PPE functions as a supporting input rather than a primary motivator of engagement. Different literature shows that task acceptance increases when PPE is paired with income security, emphasising the need for integrated safety and economic incentives (Wadsworth and Walters, 2019; Abikenova *et al.*, 2024).

Training significantly improved fire management knowledge and preparedness, with post-training gains confirming short-term human capital effectiveness. These gains reflect immediate post-training assessment and do not indicate long-term retention. Qualitative evidence suggests that knowledge depreciates over time, and participant turnover erodes cumulative capacity. One-off training alone does not sustain labour supply for recurrent, high-risk collective action. Sustained human capital development requires repeated training combined with incentive mechanisms. Initial training improves knowledge, skills, and performance but is insufficient to overcome reluctance or perceived risk (Muardi *et al.*, 2022; Ojeda *et*

al., 2025). Social capital and organisational commitment often influence performance more strongly than training alone, highlighting the importance of community relationships and collective engagement (McCaffrey, 2015; Kristanti *et al.*, 2025). The combined evidence from this study suggests that isolated interventions, such as one-time training or PPE provision, are insufficient. Instead, integrated approaches that combine repeated training, financial incentives, and risk coverage are more consistent with observed participation patterns.

Governance, equity, and financial sustainability

Concerns over unequal access to wages and PPE emerged across CFUGs. Perceived inequity undermines trust and threatens institutional legitimacy, even when overall participation rises (Ojha *et al.*, 2009; Turner *et al.*, 2016). Transparent allocation rules, rotation mechanisms, and public disclosure are essential to prevent elite capture. Persistent gender and caste disparities during fire response indicate that human capital gains alone do not translate into equitable role allocation (Agarwal, 2010; Nightingale, 2011). In resource management contexts, inequity and elite capture concentrate benefits, undermining stakeholder support and legitimacy (Turner *et al.*, 2016; Liang and Ma, 2020). Findings from qualitative data highlight that distributional fairness directly shapes community acceptance of incentive-based approaches. Perceived inequity creates governance risks that may limit long-term effectiveness.

Financial sustainability constrains wage-based fire management. CFUGs with limited timber revenue and restricted land-use options often cannot sustain wage payments

without external support. The pilot nature of the intervention further limits inference on long-term financial viability. Dependence on short-term donor funding generates participation volatility and undermines institutional continuity (Ojha *et al.*, 2016). Forests with low commercial value limit long-term financial self-reliance, affecting regular management and adaptation to market-oriented practices (Dhungana *et al.*, 2024). Policy discussions emerging from these findings point towards the need for institutional mechanisms such as co-financing models, integration with municipal budgets, or pooled fire management funds to ensure continuity beyond short-term projects.

Recalibrating volunteerism rather than replacing it

Preferences for wage-based participation reflect rising labour opportunity costs rather than rejection of collective responsibility. Intrinsic motivations persist alongside economic considerations. Incentives appear to modify participation conditions rather than replace existing attachment to forest stewardship. The findings suggest that hybrid models, combining voluntary engagement with targeted incentives for high-risk tasks, are more aligned with current socio-economic conditions in the study sites.

Concerns from forest officials about the erosion of volunteer spirit highlight a governance challenge. The evidence from this study does not demonstrate displacement of intrinsic motivation but indicates changing participation constraints. Fire management remains a high-risk public good; expecting sustained, unpaid provision under changing economic conditions may not align with current labour dynamics.

CONCLUSION: TOWARDS AN INVENTIVE-COMPATIBLE STEWARDSHIP MODEL

The study indicates that Nepal's community forestry program is undergoing a structural transformation driven by rising labour opportunity costs and diversified livelihoods, rendering reliance on unpaid volunteer labour for fire management increasingly unsustainable. Findings from the four studied CFUGs suggest that incentive-based approaches play an important role in sustaining participation in forest fire management under changing socio-economic conditions. While technical training and PPE enhance skills and safety, they do not address economic risks from injury, highlighting the need for bundled interventions that combine skill development, protective equipment, and group insurance to ensure high-risk fire management is accessible, particularly for marginalised households. The evidence indicates that incentives influence stated willingness and perceived participation dynamics, but does not establish causal effects on long-term behavioural change or institutional outcomes. Introducing monetary incentives raises governance concerns, including elite capture and biased allocation, making transparent selection, rotation mechanisms, and targeted inclusion of women and Dalit members essential to maintain legitimacy and equitable participation. Overall, the findings suggest that integrating economic incentives into community forest fire management warrants further investigation across broader, more diverse contexts. The result supports adaptation, rather than substitution of voluntarism through structured and transparent incentive systems, consistent with the empirical evidence from this pilot study.

POLICY RECOMMENDATIONS

The following recommendations are forward-looking and informed by the findings of this pilot study.

- To support CFUG resilience under changing labour markets, policies may consider recognising the economic value of community labour, allowing CFUGs to allocate internal funds toward performance-based incentives for high-risk tasks.
- Technical training and PPE could be complemented by group accident insurance to address perceived risk exposure and improve participation conditions.
- Municipal-level pooled “Fire Resilience Funds” may offer a potential mechanism to support seasonal wage payments and reduce reliance on short-term external funding.
- Transparent incentive protocols, including rotation systems and inclusive participation criteria, are suggested as important considerations to reduce risks of elite capture and improve equity.

ACKNOWLEDGEMENT

The author team thanks the ForestAction Nepal “Fostering Community Led Forest Fire Management in the Himalayan Region of Nepal” Project team for their support in field data collection and for facilitating connections with key stakeholders across the study sites.

Funding Statement: This research was conducted as part of the pilot project “Fostering Community-led Forest Fire Management in High Altitude Regions of Nepal,” which was generously funded by the

Australian Himalayan Foundation (AHF) and the Australian Government Department of Foreign Affairs and Trade (DFAT) under the Direct Aid Programme (DAP).

Declaration of the use of AI: The authors used ChatGPT to improve the writing quality. The content was reviewed and edited by the author, who takes full responsibility for the accuracy and integrity of the publication.

Declaration of competing interest: The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper.

REFERENCES

- Abikenova, S., Kulmagambetova, E., Daumova, G., & Abdrakhmanova, N. (2024). Safe work and personal protective equipment in an economic context. *International Journal of Safety and Security Engineering*, 14, 75–84. <https://doi.org/10.18280/ijss.140108>
- Abri, I. (2022). Evaluating incentive-driven policies to reduce social losses associated with wildfire risk misinformation. *Forests*, 13(12), Article 2071. <https://doi.org/10.3390/f13122071>
- Adhikari, B., & Lovett, J. C. (2006). Institutions and collective action: Does heterogeneity matter in community-based resource management? *The Journal of Development Studies*, 42(3), 426–445. <https://doi.org/10.1080/00220380600576201>
- Agarwal, B. (2010). Gender and green governance: The political economy of women's presence within and beyond community forestry. *South Asia Economic Journal*, 12(2), 349–354. <https://doi.org/10.1177/139156141101200211>
- Agrawal, A., & Ostrom, E. (2001). Collective action, property rights, and decentralisation in resource use in India and Nepal. *Politics and Society*, 29(4), 485–514. <https://doi.org/10.1177/0032329201029004002>
- Agresti, A. (2019). *An introduction to categorical data analysis* (3rd ed.). Wiley.
- Baynes, J., Herbohn, J., Smith, C., Fisher, R., & Bray, D. (2015). Key factors which influence the success of community forestry in developing countries. *Global Environmental Change*, 35, 226–238. <https://doi.org/10.1016/j.gloenvcha.2015.09.011>
- Cadman, T., Maraseni, T., Koju, U., Shrestha, A., & Karki, S. (2023). Forest governance in Nepal concerning sustainable community forest management and red panda conservation. *Land*, 12(2), Article 493. <https://doi.org/10.3390/land12020493>
- Cameron, A. C., & Trivedi, P. K. (2010). *Microeconometrics using Stata* (Rev. ed.). Stata Press.
- Charnley, S. (2023). Livelihood investments as incentives for community forestry in Africa. *World Development*, 168, Article 106260. <https://doi.org/10.1016/j.worlddev.2023.106260>
- Creswell, J. W., & Plano Clark, V. L. (2017). *Designing and conducting mixed methods research* (3rd ed.). Sage.
- Deaton, A. (2019). *The analysis of household surveys: A microeconomic approach to development policy* (Reissue ed.). Johns Hopkins University Press.
- Dhungana, N., Lee, C., Khadka, C., Adhikari, S., Pudasaini, N., & Ghimire, P. (2024). Evaluating community forest user groups' (CFUGs) performance in managing community forests: A case study in central Nepal. *Sustainability*, 16(11), Article 4471. <https://doi.org/10.3390/su16114471>
- Farina, E., Green, C., & McVicar, D. (2021). Are estimates of non-standard employment wage penalties robust to different wage measures? The case of zero hours contracts in the UK. *Industrial Relations*, 60, 345–368. <https://doi.org/10.1111/irel.12284>
- Ghimire, P., & Lamichhane, U. (2020). Community based forest management in Nepal: Current status, successes and challenges. *Grassroots Journal of Natural Resources*, 3, 16–29. <https://doi.org/10.33002/nr2581.6853.03022>

- Hong, Q., Pluye, P., Bujold, M., & Wassef, M. (2017). Convergent and sequential synthesis designs: Implications for conducting and reporting systematic reviews of qualitative and quantitative evidence. *Systematic Reviews*, 6, Article 61. <https://doi.org/10.1186/s13643-017-0454-2>
- Jurjonas, M., Pérez, L., Robson, J., & Noble, A. (2023). Intergenerational perceptions of the collective action challenges facing Mexican community forests. *Land Use Policy*, 134, Article 106913. <https://doi.org/10.1016/j.landusepol.2023.106913>
- Kristanti, M., Wardoyo, D., & Witjaksono, A. (2025). The influence of training, social capital, and commitment on employee performance: A study at the Fire and Rescue Department of Surabaya City. *Journal of Economics, Finance and Management Studies*, 8(1), 1–10. <https://doi.org/10.47191/jefms/v8-i1-55>
- Krueger, R. A. (2014). *Focus groups: A practical guide for applied research*. Sage Publications.
- Laudari, H., Sapkota, L., Maraseni, T., Subedi, P., Pariyar, S., Kaini, T. R., Lopchan, S. B., Weston, C., & Volkova, L. (2024). Community forestry in a changing context: A perspective from Nepal's mid-hill. *Land Use Policy*, 137, Article 107018. <https://doi.org/10.1016/j.landusepol.2023.107018>
- Li, H., Liu, H., & Chang, W. (2024). Extrinsic motivation vs. intrinsic motivation: Key factors influencing farmers' land quality protection behavior in China. *Environmental Management*, 75, 1520–1537. <https://doi.org/10.1007/s00267-024-02088-9>
- Liang, J., & Ma, H. (2021). Interpersonal injustice and perceived legitimacy of authority: The role of institutional trust and informational justice. *Journal of Community and Applied Social Psychology*, 31(2), 184–197. <https://doi.org/10.1002/casp.2492>
- Libois, F., Baland, J., Delbart, N., & Pattanayak, S. (2022). *Community forest management: The story behind a success story in Nepal* [Working paper]. Paris School of Economics.
- McCaffrey, S. (2015). Community wildfire preparedness: A global state-of-the-knowledge summary of social science research. *Current Forestry Reports*, 1, 81–90. <https://doi.org/10.1007/s40725-015-0015-7>
- McNemar, Q. (1947). Note on the sampling error of the difference between correlated proportions or percentages. *Psychometrika*, 12, 153–157. <https://doi.org/10.1007/BF02295996>
- Ministry of Labour, Employment and Social Security. (2025). *Press release related to remuneration*. Government of Nepal. <https://moless.gov.np/content/13291/press-release-related-press-release-remuneration-remained/>
- Muardi, J., Rohmawan, K., & Nurminingsih. (2022). The effect of discipline and training on performance of employees at the Fire and Rescue Service in City Administration of Central Jakarta. *Journal of Management, Accounting, General Finance and International Economic Issues*, 1(12), 83–92. <https://doi.org/10.55047/marginal.v1i2.137>
- Naem, M., Ozuem, W., Howell, K., & Ranfagni, S. (2023). A step-by-step process of thematic analysis to develop a conceptual model in qualitative research. *International Journal of Qualitative Methods*, 22, 1–18. <https://doi.org/10.1177/16094069231205789>
- Nightingale, A. J. (2011). Bounding difference: Intersectionality and the material production of gender, caste, class and environment in Nepal. *Geoforum*, 42, 153–162. <https://doi.org/10.1016/j.geoforum.2010.03.004>
- Nightingale, A. J. (2017). Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, 84, 11–20. <https://doi.org/10.1016/j.geoforum.2017.05.011>
- Nuberg, I., Shrestha, K., & Bartlett, A. (2019). Pathways to forest wealth in Nepal. *Australian Forestry*, 82, 106–120. <https://doi.org/10.1080/00049158.2019.1614805>
- Ojeda, K., & Sánchez Trujillo, M. (2025). Human capacity strengthening for firefighters: A scoping review. *Multidisciplinary Reviews*, 9(1), Article e2026028. <https://doi.org/10.31893/multirev.2026028>
- Ojha, H. R., Ghimire, S., Pain, A., Nightingale, A., Khatri, D. B., & Dhungana, H. (2016). Policy without politics: Technocratic control of climate change adaptation policy making in Nepal. *Climate Policy*, 16(4), 415–433. <https://doi.org/10.1080/14693062.2014.1003775>

- Ojha, H., Persha, L., & Chhatre, A. (2009). *Community forestry in Nepal: A policy innovation for local livelihoods*. International Food Policy Research Institute.
- Ojha, H., Regmi, U., Shrestha, K. K., Paudel, N. S., Amatya, S. M., Zwi, A. B., Nuberg, I., Cedamon, E., & Banjade, M. R. (2020). Improving science-policy interface: Lessons from the policy lab methodology in Nepal's community forest governance. *Forest Policy and Economics*, 114, Article 101997. <https://doi.org/10.1016/j.forpol.2019.101997>
- Oniki, S., Berhe, M., Negash, T., & Etsay, H. (2023). Do economic incentives crowd out motivation for communal land conservation in Ethiopia? *Forest Policy and Economics*, 150, Article 102948. <https://doi.org/10.1016/j.forpol.2023.102948>
- Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press.
- Ostrom, E. (2010). Beyond markets and states: Polycentric governance of complex economic systems. *American Economic Review*, 100, 641–672. <https://doi.org/10.1257/aer.100.3.641>
- Palmer, C., Souza, G., Laray, E., Viana, V., & Hall, A. (2020). Participatory policies and intrinsic motivation to conserve forest commons. *Nature Sustainability*, 3, 620–627. <https://doi.org/10.1038/s41893-020-0531-8>
- Poudyal, B., Khatri, D., Paudel, D., Marquardt, K., & Khatri, S. (2023). Examining forest transition and collective action in Nepal's community forestry. *Land Use Policy*, 134, Article 106872. <https://doi.org/10.1016/j.landusepol.2023.106872>
- R Core Team. (2025). *R: A language and environment for statistical computing* (Version 4.4.2) [Computer software]. R Foundation for Statistical Computing. <https://www.r-project.org/>
- Rampin, R., & Rampin, V. (2021). Taguette: Open-source qualitative data analysis. *Journal of Open Source Software*, 6, Article 3522. <https://doi.org/10.21105/joss.03522>
- Shrestha, M., Karki, R., Bohara, M., & Karna, B. (2025). *The awareness-action gap in community forest fire management: Insights from high-altitude Nepal* [Preprint]. SSRN. <https://doi.org/10.2139/ssrn.5390637>
- Siegel, S., & Castellan, N. J. (1988). *Nonparametric statistics for the behavioral sciences* (2nd ed.). McGraw-Hill.
- Smith, M., Fadel, B., O'Loughlen, A., & Hazeldine, S. (2020). Volunteering hierarchies in the Global South: Remuneration and livelihoods. *Voluntas*, 33, 93–106. <https://doi.org/10.1007/s11266-020-00254-1>
- Sunam, R. (2020). *Transnational labour migration, livelihoods and agrarian change in Nepal: The remittance village*. Routledge.
- Turner, R. A., Addison, J., Arias, A., Bergseth, B. J., Marshall, N. A., Morrison, T. H., & Tobin, R. C. (2016). Trust, confidence, and equity affect the legitimacy of natural resource governance. *Ecology and Society*, 21(3), 18. <https://doi.org/10.5751/ES-08542-210318>
- Wadsworth, E., & Walters, D. (2019). *Safety and health at the heart of the future of work: Building on 100 years of experience*. International Labour Office.
- Watts, J. D., Tacconi, L., Hapsari, N., Irawan, S., Sloan, S., & Widiastomo, T. (2019). Incentivizing compliance: Evaluating the effectiveness of targeted village incentives for reducing burning in Indonesia. *Forest Policy and Economics*, 108, Article 101956. <https://doi.org/10.1016/j.forpol.2019.101956>
- Wilcoxon, F. (1992). Individual comparisons by ranking methods. In S. Kotz & N. L. Johnson (Eds.), *Breakthroughs in statistics* (pp. 196–202). Springer. https://doi.org/10.1007/978-1-4612-4380-9_16

Forest fire policy efforts in Nepal: Present status and future vision

Kanchan Ojha^{1,*}, Ankit Koirala^{2,3}

¹*Environmental Science Graduate Program, Oregon State University, Corvallis, Oregon, USA*

²*Department of Agricultural Economics and Agribusiness Management,
Agriculture and Forestry University, Nepal*

³*Forest Engineering, Resources and Management, College of Forestry,
Oregon State University, Corvallis, Oregon, USA*

*Corresponding author: ojhak@oregonstate.edu

Abstract

In Nepal, forest fires are a growing environmental and socioeconomic disaster fuelled by complex socio-ecological forces, land-use dynamics, and climate change. Nepal's governance response remains fragmented and largely reactive, despite the increasing frequency and intensity of fires. This paper provides a policy review of Nepal's forest fire governance landscape by analysing 18 primary government instruments comprising Acts, Rules, Strategies, Guidelines, Plans, and Policies across federal, provincial, and local governance levels, alongside peer-reviewed and grey literature. The review provides the development of Nepal's institutional and legislative frameworks, from early conservation laws to modern climate adaptation and community forestry instruments, by evaluating each for its institutional mandates, implementation efficacy, and provisions related to forest fires. The results show that Nepal's governance system is vast in scope but is limited by dispersed institutional responsibilities, persistent underfunding, poor interagency coordination, and unequal implementation capacity across the country's federal structure. Nepal's sole comprehensive and specialised policy tool for managing forest fires, the Forest Fire Management Strategy 2010 has been recently upgraded with the release of the Forest Fire Preparedness and Response National Action Plan 2026. Nepal's Community Forest User Groups are among the most significant governance assets for local fire prevention, though their capacity remains inconsistent. The paper concludes with recommendations for consolidating Nepal's governance framework through a unified legal instrument, dedicated financing, strengthened community engagement, technology-enabled monitoring, and cross-border collaboration with neighboring Himalayan countries.

Keywords: Forest fire, Fire governance, Policy review, Nepal forestry, Forest fire legislation

INTRODUCTION

Fire is a fundamental ecological process that supports diverse ecosystem functions such as resprouting, serotiny, and germination rate in response to heat and smoke exposure in plants (Keeley *et al.*, 2011) and social values of fires, such as management of agriculture, forestry & wildlife, and urban areas, along with infrastructure protection (Bowman *et*

al., 2011). Although fire naturally shapes many landscapes and is a common land-management tool, contemporary forest fires have intensified due to increased dryness, anthropogenic climate change, land-use patterns and past management practices (Abatzoglou and Williams, 2016; GoN, 2021; Wolters *et al.*, 2017) with rising temperatures, shifting precipitation patterns, and prolonged drought which is further altering fire regimes

worldwide, leading to more frequent and severe forest fires (Bisht and Singh, 2025; Chuvieco *et al.*, 2014; Halofsky *et al.*, 2020; Moritz *et al.*, 2014).

Uncontrolled forest fires remain a major cause of forest degradation in Nepal, hindering natural regeneration, destroying timber and non-timber forest products (NTFPs), and threatening biodiversity. The scale of this challenge is reflected in fire data of 2016, where fire frequency and burned area surged by 33 per cent and 42 per cent, respectively, compared to the preceding period (Bhujel *et al.*, 2017), while 2021 recorded an unprecedented 6,536 fire incidents nationwide (GoN, 2021). Together, these figures point to an intensifying crisis and raise serious questions about the adequacy of Nepal's current fire management and prevention frameworks.

Why study forest fires in Nepal?

Fires are increasing in intensity worldwide, and Nepal is also not left alone to deal with this global issue. Studies have shown increased fire incidents and burned areas in the Chure and Middle Hill regions of Nepal (K. P. Joshi *et al.*, 2025), as well as the destruction of forest areas and biodiversity throughout the country (Ranabhat *et al.*, 2022). Research further highlights critical deficiencies in scientific infrastructure, technical capacity, training, and funding needed to understand and manage forest fires across Nepal and the broader Eastern Himalayan region (Wang *et al.*, 2021). Compounding this, a robust Random Forest Modeling analysis identified 11.1 per cent of Nepal's land area, including the Chure region, Terai, the southwestern region, and the Middle Mountain region, as very high fire-risk zones, underscoring the extent to which fire-vulnerable areas remain neglected in policy prioritisation (Sapkota *et al.*, 2025a).

Despite this escalating risk, Nepal's forest fire governance has historically rested on a single dedicated policy instrument: the Forest Fire Management Strategy 2010. This strategy guided forest fire management in the country for over a decade, yet with less than 0.5 per cent of the budget allocated to fire management, its implementation remained severely constrained (Pandey *et al.*, 2022). While awareness-raising initiatives such as celebration of forest fire management week, public dissemination (on media) of fire-related information, and distribution of fire-fighting tools have been undertaken under this framework, the strategy was never revisited to reflect the rapidly changing national and international context, or the growing socio-economic and ecological consequences of forest fires, including threats to carbon trading commitments and forest cover maintenance goals (Pandey *et al.*, 2022).

A significant policy shift occurred in 2026 with the introduction of the Forest Fire Preparedness and Response National Action Plan 2026, marking the first major expansion of Nepal's dedicated forest fire policy architecture in 15 years. This development creates a timely and critical opportunity to assess the broader governance landscape, examining what has existed, what has changed, and what remains unaddressed.

Research problem and knowledge gap

Despite the growing severity of forest fire incidents in Nepal, a critical gap exists in the literature, as no comprehensive and systematic policy review has been catalogued and critically evaluated for the full spectrum of legislative, institutional, and strategic instruments governing forest fire management across Nepal's federal structure. Existing studies either focus narrowly on ecological drivers and

fire behaviour (Bhujel *et al.*, 2017; Hamal *et al.*, 2022) or provide fragmented assessments of individual policy instruments (Pandey *et al.*, 2022). The status of knowledge on how Nepal's evolving policy landscape, spanning conservation law, disaster risk reduction frameworks, community forest guidelines, and climate adaptation plans, collectively addresses forest fire risk remains unclear and understudied. We wanted to know: What legislative, strategic, and institutional instruments govern forest fire management in Nepal, how have they evolved, and how effectively are they implemented? This paper attempts to fill this gap by providing a critical analysis of Nepal's forest fire governance landscape, explicitly mapping policy strengths, weaknesses, and implementation challenges. The paper aims to a) document the range of policies, laws and strategies relevant to forest fire management in Nepal, b) identify strengths, gaps and inconsistencies in the current policy framework, and c) propose directions for future policy reform.

Trends and major forest fire events

Over the past two decades, Nepal has witnessed a marked rise in forest fire frequency, burned area, and fire severity, particularly during the dry pre-monsoon season from March to May (Bhujel *et al.*, 2017; Hamal *et al.*, 2022). Satellite-based analyses and historical fire records indicate a steady upward trajectory in both the number of incidents and the total area affected, with particularly severe forest fire seasons recorded in 2016 and 2021 (Bhujel *et al.*, 2017; Pokharel *et al.*, 2023). There is an upward trend in the yearly fire count from 1748 fires in 2013 to 5216 fires in 2024, as shown in Figure 1 (GoN, 2026).

The 2016 forest fire season recorded a 33 per cent increase in incidents and a 42 per cent rise in burned area compared to the 2000-2015 average, resulting in 140 days of active burning, extensive loss of forest resources, and several human casualties (Bhujel *et al.*, 2017, 2022). Similarly, in spring 2021, Nepal experienced a record-breaking fire season, with 6536 active

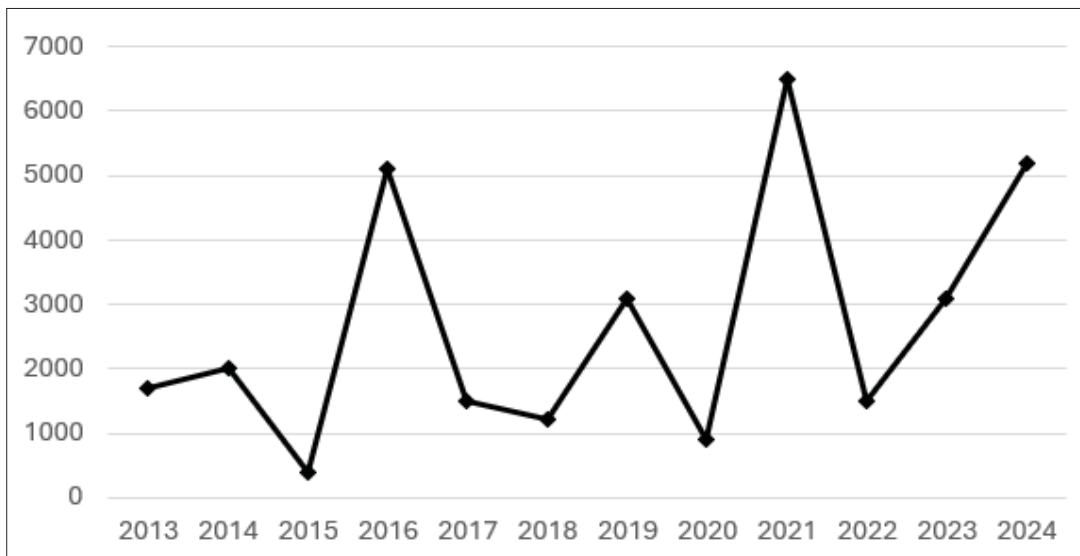


Figure 1: Yearly forest fire counts in Nepal

(Data source: <https://nepal.spatialapps.net/NepalForestFire/FireStats>)

fires detected at a rate nearly ten times higher than the 2002-2020 average, largely driven by prolonged drought and increasing climate variability (Pokharel *et al.*, 2023).

Forest fire activity in Nepal typically occurs from March to May, with high atmospheric temperatures, dry conditions, and extended winters creating favourable circumstances for ignition and spread (Parajuli *et al.*, 2015). The severity of these fires depends largely on fire weather, fuel load, and physiographic conditions. Once the monsoon establishes, typically by mid-June, fire activity gradually subsides (Matin *et al.*, 2017). Forest fires are mostly human-induced and occur during dry seasons, complicating suppression efforts due to Nepal's mountainous terrain; broadleaf deciduous forests in lower regions and needle-leaf forests in higher elevations are most affected (Joshi *et al.*, 2025; Matin *et al.*, 2017). High-risk zones are primarily concentrated in the Mid-Western Development Region, whereas the Eastern Region experienced relatively low fire risk due to higher precipitation levels. The biggest concentration of extremely high-risk forest fire areas is found

in the Province of Lumbini, while the districts of Parsa and Surkhet are also in the most at-risk zone, with more than 50 per cent of their land at high risk (Sapkota *et al.*, 2025a).

Similarly, studies conducted by Mishra *et al.* (2023) show that Nepal's forest fire occurrence and burned area have increased steadily since 2001, with the pre-monsoon season accounting for the majority of incidents. Advanced modelling techniques such as maximum entropy (MaxEnt) and deep neural networks (DNNs) have revealed important spatial patterns of fire vulnerability, with DNNs offering improved predictive performance and supporting more targeted forest fire management interventions.

Collectively, these trends expose a growing vulnerability of Nepal's forests to climate-related fire hazards. The rising frequency and intensity of forest fires highlight the urgent need for better fire management strategies, enhanced monitoring systems, and climate adaptation policies to protect Nepal's forest ecosystems and rural communities.

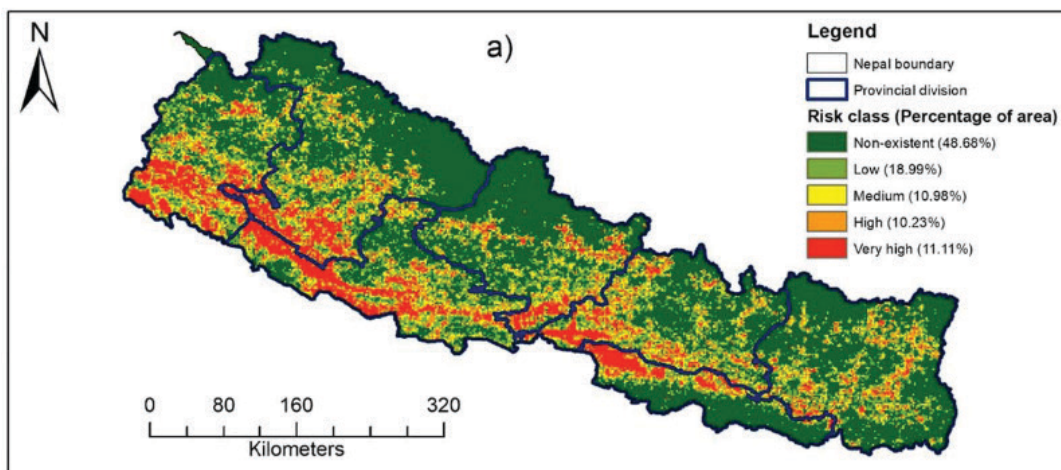


Figure 2: Forest fire risk map of Nepal based on the validated Random Forest model

(Image source: Sapkota *et al.*, 2025a)

Drivers: climatic, anthropogenic, and forest management practices

Forest fires in Nepal are driven by climatic, anthropogenic, and forest management factors, each contributing uniquely to the frequency, intensity, and spatial distribution of fire events (GoN, 2021). Climatic drivers are particularly influential, with rising temperatures, prolonged droughts, and reduced precipitation significantly increasing fire risk (Bhujel *et al.*, 2021; Hamal *et al.*, 2022; Mansoor *et al.*, 2022). Studies have shown that ambient temperatures above 30°C and annual precipitation below 2400 mm are strongly associated with higher fire incidences, especially during the pre-monsoon season when nearly 90 per cent of fires occur (Bhujel *et al.*, 2021; Hamal *et al.*, 2022). Additionally, low humidity and dry soil conditions further enhance the flammability of forest fuels. El Niño is another driver of forest fires in Nepal, as it creates dry, warm conditions that increase fire risk, mainly during the pre-monsoon season (Hamal *et al.*, 2022). The El Niño hinders westerly moisture transport, causes moisture divergence, thereby exacerbating drought conditions, and creates favourable conditions for large-scale forest fires by providing more forest fuels (Hamal *et al.*, 2022; Pokharel *et al.*, 2023). Anthropogenic factors are equally critical, as the majority of forest fires are human-induced (KC *et al.*, 2017). Activities such as agricultural burning, land clearing, and carelessness near roads and settlements are major ignition sources (Mishra *et al.*, 2023) (Table 1). Forests located within 500 meters of roads and settlements are particularly vulnerable, highlighting the impact of human proximity and infrastructure development on fire risk with 89 per cent fire occurring during the pre-monsoon season (Ahmad and Saran, 2024; Bhujel *et al.*, 2021; Mishra *et al.*, 2023; Parajuli *et al.*, 2022).

Table 1: Major causes of forest fires in Eastern Himalaya, including Nepal (Source: Wang *et al.*, 2021)

Fire category	Causes of forest fires
Accidental	Uncontrolled burning Campfires Roadside workers
Negligence	Debris or charcoal burning NTFP* collectors smokers/passers by
Deliberate	Agriculture burning/shifting cultivation Soil fertility fuel wood collectors poachers/ hunters NTFP collectors burning of grass by grazers

*Non-timber forest products

Forest management practices play an important role in shaping the typical frequency, intensity, duration, aerial extent and seasonality of forest fire disturbance in a particular ecosystem, commonly known as fire regimes. Fire management strategies such as prescribed burning, mechanical thinning and restoration of active fire regime can lower the fire intensity and severity by decreasing fuel availability and promoting heterogeneous forest structure (Furlaud *et al.*, 2023). While Community-Based Forest Management (CBFM) has improved forest cover, it can inadvertently increase fire risk by allowing fuel loads to accumulate if not properly managed. The effectiveness of fire prevention depends on the strength of local government, Community Forest User Groups (CFUGs), and the Divisional Forest Office (DFO), as well as on the implementation of fire lines and the availability of firefighting resources (Gautam & Shapkota, 2024; Oli *et al.*, 2025; Tiwari *et al.*, 2022). Studies have

shown that interaction and good governance between central and local authorities significantly impact forest fire management (Brottes Panjaitan *et al.*, 2019). Similarly, Sapkota *et al.* (2015) found that in fire-prone areas such as the Siwalik, social capital and enforceable forest fire management rules emerge as key determinants of community participation in collective fire management. However, effective fire mitigation is hampered by significant institutional and regulatory deficiencies, including a lack of funding, a lack of specialised firefighting teams, and inadequate integration of climate risk into management plans. (Bhujel *et al.*, 2021). To address these issues and mitigate the growing threat of forest fires in Nepal, a comprehensive strategy that incorporates climate projections, strengthens community involvement, and improves policy implementation is needed (Bhujel *et al.*, 2021; Hamal *et al.*, 2022; Pokharel *et al.*, 2023; Tiwari *et al.*, 2022).

Impacts: ecological, economic, health, and social dimensions

Forest fires in Nepal have profound and multifaceted impacts, spanning ecological, economic, health, and social dimensions. Ecologically, forest fires are a major driver of forest degradation, resulting in the annual burning of approximately 172,040 hectares of forest, the damage of 7.07 million tons of biomass, and the release of 3.3 million tons of carbon each year (Bhujel *et al.*, 2022). These fires disrupt plant community assemblages, reduce species diversity, and hinder the regeneration of woody species, particularly in the Terai, Mid-hill, and Mountain ecological zones (Sapkota *et al.*, 2025b). The loss of biodiversity and ecosystem services, such as watershed protection and soil conservation, is significant, and the increased carbon emissions contribute to both local air

pollution and global climate change (Bhujel *et al.*, 2022; Kuikel *et al.*, 2025). Dahal *et al.* (2025) estimated that forest fire could release more than 1 could release more than 170 million tons of soil organic carbon and 325 million tons of above-ground wood carbon, along with the loss of biodiversity in Nepal. Increasing forest fire incidence is likely to affect Sustainable Development Goal (SDG) 13 (Climate Action) and SDG 15 (Life on Land) through impacts on air quality, ecosystem and soil health.

Economically, the consequences of forest fires are substantial. In the year 2023/24, forest fires caused an estimated economic loss of approximately NPR 87 crore (about USD 6.6 million), the largest loss in recent years in Nepal (Figure 3). According to a report from the National Disaster Risk Reduction and Management Authority (NDRRMA) (GoN, 2025b), over the past six years, there were 19,593 fire incidents that caused 593 fatalities. Studies have found that proximity to the nearest forest fire reduced firm revenue in recreational businesses in Oregon, USA, a pattern shaped by market access dynamics (Koirala *et al.*, 2025). Forest fires also reduce property values, with a 0.61 per cent decrease in residential property values for each unit increase in fire radiative power and a 4.48 per cent decline for every additional fire incident in Nepal (Paudel, 2022).

The health effects of forest fires are equally worrying. Fires significantly worsen air quality, especially in urban areas like Kathmandu, where PM_{2.5} levels can remain above safe limits for extended periods, increasing the risk of respiratory and cardiovascular problems (Bhujel *et al.*, 2022). In March and April 2021, forest fires affected air quality in the Kathmandu Valley (Khadgi *et al.*, 2024). From 2007 to 2021, at least 71 people lost their lives, with many others

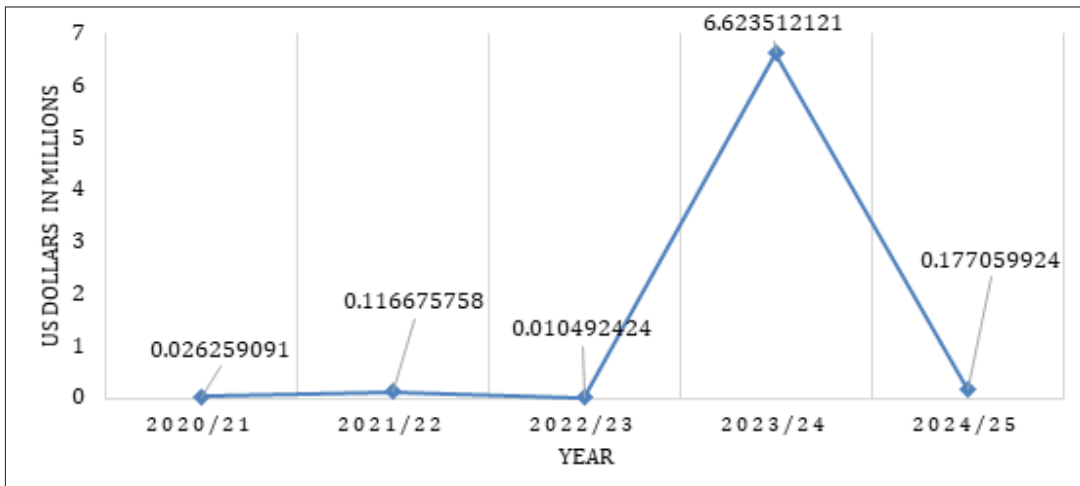


Figure 3: Economic loss (in USD) due to forest fire in Nepal 2018-2024 (Data Source: NDRMA Report, 2025)

experiencing injuries and health issues (Bhujel *et al.*, 2022). Socially, forest fires disrupt education by lowering school completion rates, especially among vulnerable and minority groups, and worsen food insecurity and economic hardship, particularly in rural areas (Paudel, 2022, 2023). The combined effects of these issues highlight the urgent need for integrated fire management and mitigation strategies that focus on ecological restoration, economic stability, public health, and social equality.

METHODS

This study employs a policy review of forest fire management strategies to examine Nepal's forest fire governance landscape. The review followed a structured search and inclusion process across three categories of source materials: 1) primary legislative and policy documents, including Acts, Rules, Strategies, Guidelines, and Plans issued by the Government of Nepal, 2) peer-reviewed academic literature retrieved, and 3) grey literature, including government reports, international organization assessments,

and national planning documents. In total, 17 primary government instruments were included, comprising 6 Acts, 2 Rules, 2 Guidelines, 3 Strategies, 3 Plans, and 1 Policy-alongside peer-reviewed articles that provided contextual and empirical grounding for the analysis.

Policy documents were identified through a systematic search of official government repositories (the Government of Nepal legislative database and Ministry of Forests and Environment publications) and verified against secondary academic sources. Inclusion criteria required that documents: (a) contain explicit provisions or references relevant to forest fire management, prevention, preparedness, or response; and (b) were enacted, amended, or remain operational within Nepal's current federal governance structure.

RESULTS

This section presents the findings of the policy review, organised around the key legislative, strategic, and institutional instruments

governing forest fire management in Nepal. The review spans federal, provincial, and local governance levels, tracing the evolution of Nepal's forest fire policy landscape from early conservation legislation to recent climate adaptation and community forestry frameworks.

Review and critical analysis of forest fire policies in Nepal

Nepal's forest fire governance has developed incrementally across multiple policy domains, resulting in a landscape that is broad in scope but uneven in implementation. The following review examines each major instrument for its forest fire-relevant provisions, institutional mandates, and practical effectiveness, drawing on peer-reviewed literature and government sources to assess both achievements and persistent gaps.

National fire management policies in Nepal

Nepal's forest fire governance is relatively young, having developed mainly in an incremental and reactive way, with evidence

indicating fire control largely depends on ad hoc response and fragmented activities rather than being backed by a coherent national framework (Pandey *et al.*, 2022). The 2010 Forest Fire Management Strategy represents the country's only forest fire-specific policy document; however, it lacks strong legal anchoring, sustained financing, operational impact on the ground, and systematic updating. The integration of forest fire into the disaster risk reduction era, notably through the Disaster Risk Reduction and Management Act (2017), not only expanded the institutional responsibility but also introduced coordination challenges between disaster authorities and forest-sector agencies. The federal Forest Act (2019) further decentralises responsibility to provincial and local governments and community institutions; however, it provides limited, clear guidance on forest fire risk governance. Overall, Nepal's forest fire policy landscape remains fragmented, heavily reliant on subsidiary guidelines, and constrained by uneven implementation capacity across governance levels.

Year	Instrument	Type	Scope/forest fire-relevant provisions	Lead / responsible agency	Remarks
1973	National Parks and Wildlife Conservation Act (NPWCA)	Act	Core legal framework for protected areas; regulates activities in parks/reserves and enables rules for management that cover threats like fires within PAs.	Department of National Parks & Wildlife Conservation (DNPWC), Ministry of Forests & Environment (MoFE).	Conservation-oriented legislation where forest fire is treated implicitly as a management threat rather than as a distinct hazard; strong regulatory authority within protected areas but limited operational guidance on fire prevention and suppression.
1974	National Parks and Wildlife Conservation Rules	Rules	Operationalises NPWCA provisions for management and enforcement inside protected areas; complements Acts' controls relevant to ignition and control within PAs.	DNPWC / MoFE.	Provides administrative and enforcement mechanisms under NPWCA, enabling park authorities to act during fire events; however, forest fire management remains secondary to biodiversity protection objectives.
2002	Nepal Biodiversity Strategy	Strategy	Identifies forest fires as a major human-induced driver of biodiversity loss in Nepal		The Strategy emphasises the urgent need for improved fire prevention, community awareness, and coordinated fire management across institutions to safeguard Nepal's ecosystems.
2010 (2066)	Forest Fire Management Strategy	National strategy	Nepal's only comprehensive forest fire-specific strategy: prevention (fuel management, fire lines), preparedness, detection, suppression, community awareness, training, and planning guidance.	MoFSC (now MoFE); Department of Forests and Soil Conservation; CFUGs as implementers.	Nepal's first and only forest fire-dedicated national framework, emphasising community engagement and prevention; implementation has been uneven due to limited funding, weak institutional anchoring, and lack of periodic updating.

Year	Instrument	Type	Scope/forest fire-relevant provisions	Lead / responsible agency	Remarks
2014 (guidelines updated; widely used post-2014)	Community Forestry Development Program Guidelines	Guidelines	Embeds fire protection activities in CF plans (fire line construction, workshops/training, extension on forest fire control); integrates CFUG responsibilities for prevention/response.	Department of Forests & Soil Conservation; CFUGs.	Operationalises forest fire prevention at the community level by mainstreaming fire control into forest operational plans; effectiveness depends heavily on CFUG capacity, local leadership, and external technical support.
2017 (2074)	Disaster Risk Reduction and Management (DRRM) Act	Act	Establishes the national DRRM system (Council, Authority, committees) across all hazards, including forest fires; assigns multi-tier responsibilities for prevention, preparedness, response and recovery.	National Council & NDRRMA; federal, provincial, and local DRRM committees.	Marks a critical shift by formally recognising forest fires as a multi-hazard disaster risk; however, coordination between disaster authorities and forest-sector institutions remains a persistent challenge.
2018	National Policy for Disaster Risk Reduction & Strategic Plan of Action (2018-2030)	Policy & plan	National DRR policy umbrella that covers forest fire as part of multi-hazard risk reduction; frames roles across government tiers and planning cycles.	MoHA/ NDRRMA with sector ministries incl. MoFE; provincial & local governments.	Provides a unifying policy umbrella that integrates forest fire into national risk reduction planning; sectoral mainstreaming has progressed slowly, with limited translation into forest-specific operational protocols.
2019	DRRM Rules (supporting the 2017 Act)	Rules	Implements of DRRM Act-procedures and coordination for hazard management including forest fire early warning, preparedness, and response mechanisms.	NDRRMA; sectoral ministries; provincial & local DRRM bodies.	Clarifies procedural roles and coordination mechanisms for forest fire response across governance levels; effectiveness is contingent on local government capacity and interoperability with forest agencies.

Year	Instrument	Type	Scope/forest fire-relevant provisions	Lead / responsible agency	Remarks
2019 (2076)	Forest Act, 2019	Act	Modernises forest governance (national, community, protected, leasehold, private forests); establishes funds and responsibilities for conservation/management with implications for fire prevention, response, and CFUG duties; recognizes setting up of fire in the national forest or to do any act that may cause fire as an offence.	MoFE; Dept. of Forests & Soil Conservation; provincial ministries; local governments; CFUGs.	Modernises forest governance by categorising forest into different types: government managed, community, collaborative, leasehold and private forest with corresponding governance arrangements and rights; under federalism and strengthens institutional responsibilities relevant to forest fire management; yet, explicit forest fire provisions remain limited, relying instead on subsidiary guidelines and strategies.
2024 (amendment)	Amendment to NPWCA (Section 5A addition)	Amendment	Adds authority to designate “highly sensitive” areas within PAs; affects how risky activities and emergency responses (incl. fires) are managed inside protected areas.	DNPWC/ MoFE.	Introduces spatial risk differentiation within protected areas, potentially enabling more targeted fire management; practical implications for emergency response and inter-agency coordination are still emerging.
2025	Community Forestry Guidelines	Guidelines	As stated in Appendix 5, 2.1 toward forest conservations, CFUGs perform forest control, construction of fire breaks and fire line, conduct workshops and disseminate information regarding forest fire like newspaper, street acts, radio program. CFUGs can provide immediate financial relief for the loss due to a forest fire	CFUGs	Forest fire is identified as one of the big challenges for the SDGs in the Community Forestry Guidelines, 2025. The activity evaluation regarding the forest fire is incorporated in evaluation form of DFO

Environmental and climate legislation

Environment Protection Act

The Environment Protection Act (EPA), originally enacted in 1997 and significantly amended in 2019, is one of Nepal's key environmental laws; however, it clearly does not directly mention forest fire as an environmental threat. The 2019 amendment added a dedicated chapter on climate change (Chapter 4), including provisions on adaptation planning at both national and local levels (Article 24), and risk management (Article 26), which could, in theory, be broadly interpreted to cover forest fire as a climate-related risk. The Act does not include specific language, regulations, or formal policies regarding forest fire. This legislative silence creates a significant gap, leaving forest fire management fragmented across sector-specific policies rather than rooted in a clear and enforceable legal foundation.

National Climate Change Policy

Unlike the EPA, Nepal's National Climate Change Policy, first issued in 2011 and revised in 2019, incorporates forest fire into the national governance agenda. The policy explicitly recognises forest fires as a climate change impact and commits to developing strategies and policies for forest fire preparedness and response, including monitoring, forecasting, and early warning systems for forest fire hazards (GoN, 2019a). It is also based on Nepal's international agreements under the Paris Agreement, the Sustainable Development Goals, and the Sendai Framework for Disaster Risk Reduction.

Disaster risk reduction legislation

Natural Calamity Relief Act

The Natural Calamity Relief Act of 1982 is Nepal's first legal framework for organised disaster response and laid the foundation for the country's disaster management (GoN, 1982). The explicit inclusion of fire in this Act is important, as it was the first legal recognition in Nepal that fire, including forest fire, required a formal state response system. However, despite its historical significance, the Act's treatment of fire was generic and did not differentiate among structural fires, forest fires, or forest-specific management rules. Fire was recognised as a disaster requiring relief, but not as a hazard requiring proactive management. The Natural Calamity Relief Act was eventually replaced by the Disaster Risk Reduction and Management Act of 2017, which aimed to address many of these issues within a more modern legislative framework.

Disaster Risk Reduction and Management Act

The Disaster Risk Reduction and Management Act (DRRMA) of 2017 signifies a major shift in Nepal's disaster governance by replacing the four-decade-old Natural Calamity Relief Act with a comprehensive, constitutionally based legal framework. The Act explicitly recognises fire as a disaster category, reaffirming its statutory status within Nepal's disaster management system. The DRRMA 2017 was specifically designed to cover the entire disaster management cycle, from risk reduction and preparedness to response and recovery (GoN, 2017, 2019b). Although the DRRMA provides essential

institutional support for forest fire response, it lacks a dedicated, prevention-focused, and ecologically informed governance structure necessary to address the rising forest fire crisis.

National Disaster Risk Reduction Strategic Action Plan

The National Disaster Risk Reduction Strategic Plan of Action (DRRNSPA) 2018-2030 is Nepal's most detailed operational commitment to disaster risk reduction (GoN, 2018). It is one of the first national planning tools to explicitly address forest fire as a key hazard requiring structured governance. The plan recognises Nepal's high vulnerability to various natural disasters, with forest fires identified as a major recurring hazard, especially in the Terai, mid-hills, and mountainous regions. The plan proposes specific forest fire strategies, including establishing a real-time fire monitoring system, developing community awareness and information kits, strengthening early warning systems and community preparedness training, improving firefighting equipment and communication between agencies, and integrating forest fire risk reduction into building codes, settlement planning, and industrial policies (GoN, 2018). Despite these ambitious goals, implementation has been inconsistent: forest fire risk reduction activities lack secure funding and are not fully integrated into provincial and local institutions. The plan's strategic initiatives have yet to be fully operationalised through dedicated annual budgets, technical capacity development, and monitoring systems (Joshi *et al.*, 2024; Pandey *et al.*, 2022). The DRRNSPA 2018-2030 marks an important step forward in Nepal's forest fire management efforts, but its transformative potential depends on sustained political will,

inter-agency coordination, and adequate resource allocation.

Specific forestry & fire-related policies and strategies

Forest Fire Management Strategy

The Forest Fire Management Strategy (FFMS) of 2010, developed by the then Ministry of Forests and Soil Conservation (MoFSC), remains the only comprehensive policy specifically dedicated to forest fire management in Nepal. Its main goal is to reduce losses of life, property, biodiversity, and ecosystem functions through proper forest fire management, ultimately aiming to increase forest productivity (GoN, 2010). The Strategy is organised around four key pillars: strengthening and updating policies, laws, and institutional frameworks; expanding education, awareness, capacity building, and technological progress; promoting community-based fire management and supporting research; and improving coordination, collaboration, international partnerships, and infrastructure. Operationally, the Strategy seeks to establish and reinforce the policy and institutional foundations necessary for effective forest fire management; involve local communities, civil society organisations, and both government and non-governmental bodies in fire prevention and control; develop robust communication and information systems to support disaster mitigation; promote responsible fire use for ecosystem management and community livelihoods; and create conditions that enable the mobilisation of financial, technical, and other resources from national and international donors, including bilateral, multilateral, and other partners, to address challenges posed by uncontrolled and cross-border

fires and their climate and environmental impacts. It prioritised participatory forest fire management, public awareness campaigns, legal reforms, and capacity building for both government and community institutions.

Despite these ambitious commitments, implementation has fallen short of the Strategy's stated vision, with FFMS 2010's achievements lacking in preventive measures and only satisfactory in remedial efforts, with forest fire management provisions remaining scattered across multiple sectoral agencies. This fragmentation hampers policy coordination and integration (Pandey *et al.*, 2022). FFMS 2010 remains as a strategy whose transformative potential has been limited by chronic underfunding, weak inter-agency coordination, and the absence of a dedicated governance structure to drive its implementation (Joshi *et al.*, 2024).

Redd+ Strategy and Safeguards

Nepal's National REDD+ Strategy, finalised by the Ministry of Forests and Environment (MoFE) in 2018 under the United Nations Framework Convention on Climate Change (UNFCCC), represents a significant policy effort to address forest fires as a major threat to Nepal's forest carbon stocks (MoFE, 2018). The strategy explicitly recognises forest fire as one of nine primary causes of deforestation and forest degradation in Nepal, making forest fire an acknowledged and measurable threat to Nepal's emission reduction commitments. Quantitatively, fires have caused about 13 per cent of tree cover loss in Nepal from 2001 to 2023, burning approximately 40,000 hectares of forest each year, with most fire incidents and affected areas recorded between March and May (GoN, 2024, p.10). Strategically, the REDD+ framework emphasises strengthening the fire

control capabilities of DFOs, Protected Area Management Authorities, and CBFM groups through developing specific management plans, allocating dedicated financial and human resources, enhancing monitoring systems, adopting advanced technologies, and improving insurance mechanisms (MoFE, 2018). While the REDD+ Strategy marks a meaningful step in integrating forest fire into Nepal's international climate commitments and emissions-reduction efforts, its focus on fire governance largely centres on carbon accounting and emissions targets rather than on prevention, preparedness, and ecosystem management. Therefore, the REDD+ Strategy offers an important technical and institutional push for forest fire governance, but it is not a replacement for a dedicated, prevention-focused policy framework needed to address Nepal's rising fire crisis (Joshi *et al.*, 2024; Pandey *et al.*, 2022).

Recent initiatives and policy reforms

Recent policy reforms in Nepal demonstrate a clear shift toward institutionalising forest fire management within the broader framework of sustainable forest governance. In alignment with the National Forest Policy 2018 and operationalised through the National Forest Integrated Strategic Plan 2025-2043 (GoN, 2025), forest fire management has been mainstreamed into forest and environmental laws, management plans, and operational guidelines. The reforms mandate the formulation and implementation of federal and provincial forest fire management strategies, annual fire control plans at the DFO level, and the integration of fire risk identification into forest management operational plans. Importantly, fire risk modelling based on fuel load assessments has been introduced as a scientific basis for planning, reflecting a transition from reactive

suppression to risk-informed, and preventive management. These measures are further supported by institutional provisions for Special Forest Fire Fighting Teams at the district level and the establishment of Quick Response Teams involving forest officials, security forces, local governments, and CFUGs.

In addition, policy reforms emphasise fuel load reduction, participatory governance, and technology-enabled monitoring. Provisions for controlled burning, systematic management of slash materials and undergrowth, expansion of fire lines, and utilisation of biomass for commercial purposes (e.g., pellets and briquettes) indicate an integrated approach that links fire risk reduction with forest-based enterprise development. The reforms also prioritise modern technologies, including GIS, remote sensing, LiDAR, satellite imagery, and drones, to support fire risk mapping and early warning systems. The development of a forest fire disaster command system strengthened inter-agency coordination, and integration with disaster management committees further institutionalised multi-level governance mechanisms. Collectively, these initiatives reflect a policy transition toward a preventive, science-based, and community-engaged forest fire management regime aimed at enhancing climate resilience, biodiversity conservation, and sustainable forest productivity in Nepal (GoN, 2018, 2024).

National Adaptation Plan (NAP)

As noted in the National Adaptation Plan (2021-2050), Nepal is one of the most climate-vulnerable countries in the world due to its mountainous geography, ecological complexity, and high levels of poverty and dependence on natural resources. Forest fires are among the climate hazards that will

likely increase in frequency and severity (GoN, 2021). This will also threaten forests, biodiversity, and watershed conservation as damage and destruction from forest fires increase (GoN, 2021).

Nepal's National Adaptation Plan (NAP) 2021 identifies forest fires as a rapidly intensifying climate risk driven by rising temperatures, prolonged dry spells, and increasing drought conditions. The plan prioritises three core objectives: strengthening policy and regulatory frameworks for fire management; enhancing institutional and technological capacities of forest agencies; and improving the resilience of forest ecosystems and forest-dependent communities. Key actions include revising fire management strategies, developing a nationwide early warning system, mapping fire-prone districts, operationalising Joint Rapid Response Teams, and implementing fuel-load management practices. Additional measures such as constructing fire lines, expanding outreach and education programs, and equipping DFOs with modern firefighting tools aim to reduce fire incidence by 50 per cent by 2030 and minimise ecosystem and biodiversity losses by 2035. Collectively, these interventions position NAP 2021 as a comprehensive framework for climate-responsive forest fire management in Nepal.

Forest Fire Preparedness and Response National Action Plan

The recent Forest Fire Preparedness and Response National Action Plan, 2082 (2026), issued by the NDRRMA under the Ministry of Home Affairs (NDRRMA, 2026) marks a meaningful shift in the trajectory of forest fire preparedness and response. Grounded in MODIS satellite data spanning 2013 to 2025, the plan operationalises a district-level risk classification framework and provides

an evidence base that prior instruments lacked. Structurally, the plan organises its response across seven thematic action areas: public awareness, fuel management, weather-based early warning, technology-assisted monitoring, inter-agency coordination, rescue and response, and research and assigns responsibilities across federal, provincial, and local tiers, with supporting roles for civil society and the private sector.

While the plan offers a more coordinated and data-driven approach than its predecessor, its success will ultimately depend on how well it bridges the institutional gap between the forestry and disaster management sectors and whether it receives the ongoing political and financial support that forest fire governance in Nepal has historically lacked.

DISCUSSION

Critical analysis of Nepal's legislative approaches

Nepal's forest fire governance landscape exhibits notable strengths, including a long-standing community forestry model, the recognition of forest fire issues across multiple national policies, and a decentralised governance structure that empowers local actors. However, these strengths are undermined by persistent weaknesses, including fragmented institutional responsibilities, limited enforcement capacity, inadequate technical and financial resources, and weak coordination among government agencies. Critical gaps remain, particularly the absence of a comprehensive forest fire law, insufficient integration of fire risk into climate adaptation and land-use planning, and weak monitoring and data systems. As noted by Wang *et al.* (2021), the lack of a dedicated policy framework is one of the

most significant barriers to effective forest fire management in Nepal. Implementation challenges, including political instability, limited and inconsistent funding, capacity constraints at local and provincial levels, and substantial data and knowledge gaps, further impede progress toward a more coherent and effective forest fire governance system.

Future directions and policy recommendations

Nepal's forest fire governance framework remains fragmented and largely reactive, underscoring the need for a consolidated, forward-looking approach. Establishing a dedicated forest fire Management Act or an equivalent comprehensive framework would unify dispersed legal provisions, clarify institutional mandates across forestry, environment, disaster management, and local governments, and strengthen enforcement. Improved coordination, potentially through a national forest fire Coordination Unit, should be complemented by formalised multi-stakeholder engagement with the MoFE, including CFUGs, NGOs, and provincial and local authorities. Strengthening CBFM remains central, requiring updated operational plans, targeted training, and the integration of scientific tools such as satellite detection, early-warning systems, and real-time monitoring, which could be included with indigenous knowledge and local practices. Sustainable financing, including increased national budget allocations and provincial forest fire funds, is essential to support preparedness, awareness campaigns, and technological upgrades. Given Nepal's shared ecological vulnerabilities with its neighbours, cross-border collaboration on monitoring and response should also be prioritised. Finally, mainstreaming forest fire risk into climate adaptation planning and

land-use regulation will provide the structural coherence needed for long-term resilience. Collectively, these measures offer a realistic and actionable pathway toward more adaptive and effective forest fire governance in Nepal.

CONCLUSION

Nepal's forest fire policy framework has evolved incrementally across conservation, forestry, disaster risk reduction, biodiversity, and climate policy domains. Early legislation, such as the National Parks and Wildlife Conservation Act (1973) and the Forest Act (1993), treated fire primarily as a prohibited activity or as a secondary management concern within broader conservation objectives. Although these instruments established regulatory authority, they did not conceptualise forest fire as a distinct, systemic, and climate-driven hazard. The Forest Fire Management Strategy (2010) marked the first comprehensive, forest fire-specific framework, emphasising prevention, preparedness, community engagement, and inter-agency coordination. However, uneven implementation, limited financing, and weak institutional anchoring constrained its sustained impact.

Subsequent disaster risk reduction legislation, including the Disaster Risk Reduction and Management Act (2017) and the National DRR Strategic Action Plan (2018-2030), reframed forest fire as a multi-hazard disaster risk, expanding responsibilities across federal, provincial, and local levels. Similarly, sectoral instruments such as the REDD+ Strategy (2018) and the updated Forest Act (2019) acknowledged forest fires as drivers of deforestation and forest degradation, yet continued to rely on subsidiary guidelines for operational specificity. Community Forestry Guidelines (2014; 2025) further

mainstreamed forest fire prevention through fire-line construction, participatory hazard mapping, awareness campaigns, and localised response mechanisms, reinforcing the central role of CFUGs. The most recent policy advancement towards forest fire preparedness and response is the Forest Fire Preparedness and Response National Action Plan in 2026. Nevertheless, forest fire policy remains institutionally dispersed, with coordination gaps and variable implementation capacity under Nepal's federal structure.

Recent reforms indicate a gradual transition toward institutionalising preventive and science-based forest fire management. Integration of fire risk modelling, fuel-load management, rapid-response teams, and technology-enabled monitoring (e.g., GIS and satellite-based detection systems) reflects a movement toward risk-informed approaches. The National Adaptation Plan (2021-2025) consolidates this trajectory by explicitly identifying forest fire as a climate-induced hazard and prioritising early warning systems, ecosystem-based management, institutional strengthening, and community resilience. Its measurable targets, such as reducing fire incidence and minimising ecosystem loss, signal a policy shift from reactive suppression toward proactive, climate-responsive adaptation.

Collectively, Nepal's evolving policy landscape demonstrates growing recognition of forest fire as a complex socio-ecological and climate risk. Despite the expansion of legal and strategic instruments, the framework remains fragmented, with overlapping mandates and implementation constraints that limit coherence and effectiveness. Achieving integrated and proactive forest fire management will require strengthened inter-sectoral coordination, sustained

financing, periodic policy updating, and clearer alignment between forest-sector institutions and disaster management authorities. A consolidated, forward-looking forest fire framework, embedded within climate adaptation planning and grounded in community-based implementation, remains critical to enhancing Nepal's preparedness amid accelerating climate change.

In summary, Nepal's forest fire governance is fragmented across multiple sectoral laws and agencies without a unified, prevention-focused legal framework. Second, the Forest Fire Management Strategy (2010) the only dedicated policy instrument, but it has suffered from chronic underfunding, weak inter-agency coordination, and insufficient periodic updating. Third, CBFM through CFUGs is one of Nepal's most significant governance assets for local-level fire prevention, but community capacity and technical support remain inconsistent. Fourth, forest fire is an increasingly climate-driven hazard in Nepal, yet its integration into climate adaptation planning and land-use regulation is still partial and needs strengthening. Fifth, Nepal's federal restructuring has created new institutional layers for forest fire governance at provincial and local levels, but coordination mechanisms between these levels and the central government remain underdeveloped. Sixth, significant data and monitoring gaps persist, limiting evidence-based decision-making at all governance levels. These findings collectively underscore the urgent need for an integrated, proactive, and adequately resourced forest fire governance regime in Nepal.

Declaration regarding the use of AI:

The authors used Claude during the editing process to improve the language and readability.

ACKNOWLEDGMENTS

The authors would like to thank the editors and reviewers of this journal for taking the time to provide us with helpful feedback that helped shape the article.

REFERENCES

- Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on forest fire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42), 11770–11775. <https://doi.org/10.1073/pnas.1607171113>
- Ahmad, L., & Saran, S. (2024). Anthropogenic evidences as precursors to forest fire trigger in Western Himalayan Region. *Environment, Development and Sustainability*, 26(7), 16827–16846. <https://doi.org/10.1007/s10668-023-03312-y>
- Bhujel, K. B., Byanju, R., Gautam, A., Sapkota, R., & Khadka, U. (2021). Fire drivers affecting forest fire occurrences in the tropical mixed broad-leaved forests of Nepal. *Applied Environmental Research*, 43, 84–99. <https://doi.org/10.35762/AER.2021.43.4.7>
- Bhujel, K. B., Maskey-Byanju, R., & Gautam, A. P. (2017). Forest fire dynamics in Nepal from 2000–2016. *Nepal Journal of Environmental Science*, 5, 1–8.
- Bhujel, K. B., Sapkota, R. P., & Khadka, U. R. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Bisht, S., & Singh, H. (2025). Advancing forest fire management practices: Policies and strategies. In H. Singh & N. Kumar (Eds.), *Forest fire and climate change: Insights into science* (pp. 279–293). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-89967-6_15

- Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., DeFries, R., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Mack, M., Moritz, M. A., Pyne, S., Roos, C. I., Scott, A. C., Sodhi, N. S., & Swetnam, T. W. (2011). The human dimension of fire regimes on Earth. *Journal of Biogeography*, 38(12), 2223–2236. <https://doi.org/10.1111/j.1365-2699.2011.02595.x>
- Brottestes Panjaitan, R., Sumartono, Sarwono, & Saleh, C. (2019). The role of central government and local government and the moderating effect of good governance on forest fire policy in Indonesia. *Benchmarking: An International Journal*, 26(1), 147–159. <https://doi.org/10.1108/BIJ-12-2017-0336>
- Chuvieco, E., Martínez, S., Román, M. V., Hantson, S., & Pettinari, M. L. (2014). Integration of ecological and socio-economic factors to assess global vulnerability to forest fire. *Global Ecology and Biogeography*, 23(2), 245–258. <https://doi.org/10.1111/geb.12095>
- Dahal, K., Talchabhadel, R., Pradhan, P., Parajuli, S., Shrestha, D., Chhetri, R., Gautam, A. P., Tamrakar, R., Gurung, S., & Kumar, S. (2025). Nepal's carbon stock and biodiversity are under threat from climate exacerbated forest fires. *Information Geography*, 1(1), 100003. <https://doi.org/10.1016/j.infgeo.2025.100003>
- Furlaud, J. M., Williamson, G. J., & Bowman, D. M. J. S. (2023). Mechanical treatments and prescribed burning can reintroduce low-severity fire in southern Australian temperate sclerophyll forests. *Journal of Environmental Management*, 344, 118301. <https://doi.org/10.1016/j.jenvman.2023.118301>
- Gautam, J., & Sapkota, J. (2024). Community based fire management in Madi Khola Watershed, Nepal. *International Journal of All Research Education and Scientific Methods*, 12, 2455–6211.
- Government of Nepal. (1982). *Natural calamity relief act*. Government of Nepal.
- Government of Nepal. (2010). *Forest fire management strategy*. Ministry of Forest and Soil Conservation.
- Government of Nepal. (2017). *Disaster risk reduction and management act*. <https://faolex.fao.org/docs/pdf/NEP228597.pdf>
- Government of Nepal. (2018). *National disaster risk reduction strategic action plan (2018–2030)*. <https://dpnet.org.np/resource-detail/26?v=1>
- Government of Nepal. (2019a). *National climate change policy 2019*. Ministry of Forest and Environment.
- Government of Nepal. (2019b). *Disaster risk reduction and management rules*. <https://faolex.fao.org/docs/pdf/NEP228606.pdf>
- Government of Nepal. (2021). *National adaptation plan (NAP) 2021–2050*. Ministry of Forests and Environment.
- Government of Nepal. (2024). *National REDD+ strategy (2025–2034)*. https://redd.unfccc.int/media/national_strategy_2025_2034_redd_plus_nepal.pdf
- Government of Nepal. (2025a). *National forest integrated strategic plan (2025–2043)*. https://climate-laws.org/documents/national-forest-integrated-strategic-plan-2025-2043_f8f9
- Government of Nepal. (2025b). वन डढेलो नयिन्त्रण पूर्वतयारी तथा पतकिय राष्ट्रिय कार्ययोजना २०८२ [National action plan for forest fire control preparedness and response 2082 BS]. National Disaster Risk Reduction and Management Authority.
- Government of Nepal. (2026). *Forest fire detection and monitoring system in Nepal*. <https://nepal.spatialapps.net/NepalForestFire/FireStats>
- Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing forest fire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, 16(1), 4. <https://doi.org/10.1186/s42408-019-0062-8>
- Hamal, K., Ghimire, S., Khadka, A., Dawadi, B., & Sharma, S. (2022). Interannual variability of spring fire in southern Nepal. *Atmospheric Science Letters*, 23. <https://doi.org/10.1002/asl.1096>
- Joshi, G. R., Rijal, K., Bhandari, R., Sapkota, R. P., & Dhital, N. B. (2024). A review of implementation of policy instruments on forest fire in Nepal. *Journal of Forest and Environmental Science*, 40(3), 167–179. <https://doi.org/10.7747/JFES.2024.40.3.167>

- Joshi, K. P., Giri, S., Kuinkel, D., Kuikel, S., Devkota, R., Pradhananga, D., Marahatta, S., & Pokharel, B. (2025). Forest fire dynamics in Nepal: Regional trends and socio-ecological drivers. *Trees, Forests and People*, 21, 100942. <https://doi.org/10.1016/j.tfp.2025.100942>
- KC, K. B., Heyojoo, B. P., Karna, Y. K., Sharma, S. P., & Panthi, S. (2017). Incidences of forest fire hazard and its effects on forest cover change in Chitwan National Park, Nepal. *Clarion: International Multidisciplinary Journal*, 6(1), 1–7. <https://doi.org/10.5958/2277-937X.2017.00001.6>
- Keeley, J. E., Pausas, J. G., Rundel, P. W., Bond, W. J., & Bradstock, R. A. (2011). Fire as an evolutionary pressure shaping plant traits. *Trends in Plant Science*, 16(8), 406–411. <https://doi.org/10.1016/j.tplants.2011.04.002>
- Khadgi, J., Kafle, K., Thapa, G., Khaitu, S., Sarangi, C., Cohen, D., & Kafle, H. (2024). Concentration of particulate matter and atmospheric pollutants in the residential area of Kathmandu Valley: A case study of March–April 2021 forest fire events. *Environmental Pollution*, 363, 125280. <https://doi.org/10.1016/j.envpol.2024.125280>
- Koirala, A., Susaeta, A., Chen, Y., & Lewin, P. (2025, July). *Economic impact of megafires on recreational business in Oregon* [Poster presentation]. AAEE & WAEA Joint Annual Meeting, Denver, CO, United States.
- Kuikel, S., Paudel, H. K., Kuinkel, D., Joshi, K. P., Sapkota, S., Malakar, N., Wang, S.-Y. S., & Pokharel, B. (2025). Impact of forest fire smoke on air pollution-related premature mortality in rapidly growing Kathmandu Valley. *Atmospheric Environment: X*, 26, 100334. <https://doi.org/10.1016/j.aecoa.2025.100334>
- Mansoor, S., Farooq, I., Kachroo, M. M., Mahmoud, A. E. D., Fawzy, M., Popescu, S. M., Alyemeni, M. N., Sonne, C., Rinklebe, J., & Ahmad, P. (2022). Elevation in forest fire frequencies with respect to the climate change. *Journal of Environmental Management*, 301, 113769. <https://doi.org/10.1016/j.jenvman.2021.113769>
- Matin, M. A., Chitale, V. S., Murthy, M. S. R., Uddin, K., Bajracharya, B., & Pradhan, S. (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(4), 276–286. <https://doi.org/10.1071/WF16056>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19(1), 3. <https://doi.org/10.1186/s42408-022-00162-3>
- Ministry of Forests and Environment. (2018). *Nepal national REDD+ strategy (2018–2022)*. Government of Nepal. <https://www.forestcarbonpartnership.org/system/files/documents/Nepal%20National%20REDD%2B%20Strategy.pdf>
- Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with forest fire. *Nature*, 515(7525), 58–66. <https://doi.org/10.1038/nature13946>
- National Disaster Risk Reduction and Management Authority. (2026). *Forest fire preparedness and response national action plan, 2082* [National action plan]. Government of Nepal.
- Oli, J., Rai, N., Sharma, R., & Baral, N. (2025). Forest fire trends and management practices in the hills of Nepal. *GIS Journal*, 5(1), 189–202. <https://doi.org/10.57599/gisoj.2025.5.1.189>
- Pandey, H. P., Pokhrel, N. P., Thapa, P., Paudel, N. S., & Maraseni, T. N. (2022). Status and practical implications of forest fire management in Nepal. *Journal of Forest and Livelihood*, 21(1), 32–45. <https://doi.org/10.3126/jfl.v21i1.56583>
- Parajuli, A., Chand, D. B., Rayamajhi, B., Khanal, R., Baral, S., Malla, Y., & Poudel, S. (2015, September 7–11). Spatial and temporal distribution of forest fires in Nepal [Paper presentation]. *XIV World Forestry Congress*, Durban, South Africa.

- Parajuli, A., Gautam, A. P., Sharma, S., Lamichhane, P., Sharma, G., Bist, B. S., Aryal, U., & Basnet, R. (2022). A strategy for involving community forest managers in effective forest fire management in Nepal. *Banko Janakari*, 32(1), 41–51. <https://doi.org/10.3126/banko.v32i1.45476>
- Paudel, J. (2022). Environmental disasters and property values: Evidence from Nepal's forest fires. *Land Economics*, 98(1), 115–131. <https://doi.org/10.3368/le.98.1.110519-0159R2>
- Paudel, J. (2023). Do environmental disasters affect human capital? The threat of forest fires. *Economics of Education Review*, 97, 102463. <https://doi.org/10.1016/j.econedurev.2023.102463>
- Pokharel, B., Sharma, S., Stuienvolt-Allen, J., Wang, S.-Y. S., LaPlante, M., Gillies, R. R., Khanal, S., Wehner, M., Rhoades, A., Hamal, K., Hatchett, B., Liu, W.-Y., Mukherjee, S., & Aryal, D. (2023). Amplified drought trends in Nepal increase the potential for Himalayan forest fires. *Climatic Change*, 176(2). <https://doi.org/10.1007/s10584-023-03495-3>
- Ranabhat, S., Pokhrel, A., Neupane, A., Singh, B., & Gahatraj, S. (2022). Forest fire risk assessment and proposal for fire stations in different geographical regions of Central Nepal. *Journal of Forest and Livelihood*, 21(1), 46–59. <https://doi.org/10.3126/jfl.v21i1.56585>
- Sapkota, L. M., Shrestha, R. P., Jourdain, D., & Shivakoti, G. P. (2015). Factors affecting collective action for forest fire management: A comparative study of community forest user groups in Central Siwalik, Nepal. *Environmental Management*, 55(1), 171–186. <https://doi.org/10.1007/s00267-014-0404-x>
- Sapkota, R. P., Dhital, N., Shrestha, A., Khadka, U., Pokhrel, C., Joshi, G., & Rijal, K. (2025b). Forest fire impacts plant community assemblage in different ecological zones of central Himalaya, Nepal. *Global Ecology and Conservation*, 58, e03443. <https://doi.org/10.1016/j.gecco.2025.e03443>
- Sapkota, S., Joshi, K. P., Kuikel, S., Kuinkel, D., Bhandari, B., Wu, Y., Bing, H., Marahatta, S., Aryal, D., Wang, S.-Y. S., & Pokharel, B. (2025a). Advancing forest fire prediction in Nepal using machine learning algorithms. *Environmental Research Communications*, 7(5), 055003. <https://doi.org/10.1088/2515-7620/add2db>
- Tiwari, S., Paudel, N. S., Sze, J., & Karki, R. (2022). Unravelling the local dynamics of increasing fires in community forests of mid-hills of Nepal. *Journal of Forest and Livelihood*, 21(1), 60–71. <https://doi.org/10.3126/jfl.v21i1.56587>
- Wang, S. W., Lim, C.-H., & Lee, W.-K. (2021). A review of forest fire and policy response for resilient adaptation under changing climate in the Eastern Himalayan region. *Forest Science and Technology*, 17(4), 180–188. <https://doi.org/10.1080/21580103.2021.1979108>
- Wolters, E. A., Steel, B. S., Weston, D., & Brunson, M. (2017). Determinants of residential Firewise behaviors in Central Oregon. *The Social Science Journal*, 54(2), 168–178. <https://doi.org/10.1016/j.soscij.2016.12.004>

Institutional fragmentation and forest fire management in federal Nepal: Bridging the governance gap through incident management systems

Alan Hill¹, Manish Shrestha^{2*}

¹*Institute of Forestry, Hetauda Campus, Tribhuvan University, Kirtipur, Nepal*

²*ForestAction Nepal, Ashram Road, Bagdol, Lalitpur, Bagmati, Nepal*

*Corresponding author: manish.shrestha1979@gmail.com

Abstract

Nepal is facing an increasing forest fire crisis, with more than 34,725 incidents recorded from 2008 to 2021, leading to approximately 800 deaths and NPR 22 billion in economic losses. Although forests cover 46 per cent of the country, management efforts are greatly hindered by institutional fragmentation following Nepal's 2015 shift to federalism. This paper explores how constitutional ambiguities, especially overlapping mandates in Schedules 5, 6, 7, and 9, along with conflicting laws such as the Local Government Operation Act (2017) and the Forest Act (2019), create diagonal accountability and jurisdictional disputes. We contend that these structural gaps lead to at least six layers of administration between policy formulation and operational response, causing ad hoc coordination during critical fire periods. By examining successful Incident Management System (IMS) models from the United States and Australia, this study proposes a step-by-step approach to incorporate Nepal's Community Forest User Groups (CFUGs) into a standardised, expertise-based command structure. Launching pilot programs at the municipal level can help Nepal move ahead of top-down legislative delays and foster "ground-level" operational unity. This analysis presents a scalable model for disaster governance in emerging federal states facing challenges related to decentralised resource management.

Keywords: Forest Fire, Emergency response, Legislative conflict, Coordination mechanism, Forest governance

INTRODUCTION

Forest fires are a key driver of forest degradation in Nepal, with approximately 75 per cent of incidents attributed to human negligence (Bajracharya, 2002; Pandey and Bhattarai, 2025). More than 78 per cent of forest fires occur between March and May, coinciding with the dry season (FAO, 2000; Martin *et al.*, 2017; Mishra *et al.*, 2023), when farmers commonly burn crop residues and prevailing environmental conditions significantly increase fire risk. Despite forests

covering around 46 per cent of Nepal's total land area (FRTC, 2024), the country lacks adequate training, equipment, and most importantly, a coordinated approach to forest fire management. These challenges are compounded by severe resource constraints and institutional gaps.

Nepal's transition to federalism in 2015 has neither sufficiently resolved pre-existing issues nor simplified the administrative complexities that continue to hinder emergency response capabilities across the

three levels of government. This situation reflects the problem of "accepting too many different systems and responsibilities at any one level, which can lead to unanticipated complexity that overpowers performance" (Somlai *et al.*, 2018). The complexity is further intensified by constitutional ambiguity. Although the national government has made several attempts through periodic plans to enhance decentralisation, "the Constitution does not provide an elaboration of the organisational structure for local government decentralisation," leaving essential coordination mechanisms underdeveloped (Bahl *et al.*, 2020).

The relationship between institutional fragmentation and the effectiveness of disaster response is well-documented. Research consistently shows that unclear jurisdictional boundaries, overlapping mandates, and insufficient inter-agency coordination significantly hinder emergency response capabilities (Comfort and Kapucu, 2006; Kapucu, 2009; Shrestha *et al.*, 2025). Forest fires pose particular coordination challenges, as they often cross administrative boundaries, may require resources from multiple agencies, and necessitate rapid decision-making under conditions of uncertainty. Unlike floods or earthquakes, which typically trigger immediate centralised emergency responses, forest fires often start small and escalate gradually. They can occur at multiple locations simultaneously, each characterised by different levels of escalation. This situation creates ambiguity regarding response priorities and resource mobilisation (McLennan and Handmer, 2012). The gradual escalation means that institutional gaps such as unclear command structures, inadequate information-sharing arrangements, and fragmented resource allocation systems can have increasingly severe consequences as fires

intensify. In Nepal, these universal challenges are exacerbated by the relatively new federal arrangements and the lack of clearly defined coordination mechanisms specifically designed for forest fire management across all levels of government.

Effective federal systems address the fragmentation of disaster response by establishing institutional mechanisms that clarify roles, define command structures, and facilitate coordination across jurisdictions. Successful federal disaster management systems typically incorporate clearly defined yet flexible jurisdictional authority, enabling rapid scaling of response levels. This often includes standardised communication procedures, interoperable systems that facilitate information sharing among key agencies, and unified command structures that integrate diverse participant organisations while preserving their specific expertise and resources (Waugh and Streib, 2006). Examples of such frameworks are the United States' National Incident Management System and Australia's Australasian Inter-Service Incident Management System. These systems provide standardised approaches that accommodate the complexities of federal governance while maintaining operational unity during emergencies (Buck *et al.*, 2006). Their effectiveness does not stem from the elimination of jurisdictional boundaries, but rather from the establishment of bridging mechanisms such as unified command, liaison officers, and mutual assistance agreements, that enable multiple agencies to coordinate their actions while operating within their respective authorities. In contrast, Nepal's current institutional landscape lacks these bridging mechanisms, resulting in a situation in which different levels of government tend to operate largely independently during forest fire events.

NEPAL'S FOREST FIRE CRISIS

Scale and impact

Recent data indicate significant annual fluctuations in the number of fire incidents. The 2024 fire season was particularly severe, with more than 6,712 incidents, compared to 1,909 in 2022 (NASA FIRMS, 2025). Between 2008 and 2024, forest fires resulted in approximately 800 fatalities and injured around 2,600 people (Dahal, 2024). However, casualty figures can vary widely due to inconsistent reporting systems across different administrative levels. Between 2008 and 2021, approximately 34,725 forest fire incidents were recorded nationwide (Bhujel *et al.*, 2022), resulting in economic losses estimated at NPR 22 billion (Dahal, 2024).

Seasonal patterns

Human activities are the primary cause of forest fire ignitions. Approximately 89 per cent of these fires occur during the dry season, which lasts from March to May (Matin *et al.*, 2017). More broadly, between 78 per cent and 89 per cent of all forest fires are recorded from March through mid to late May each year (Matin *et al.*, 2017; FAO, 2000; Mishra *et al.*, 2023). This pattern may be further exacerbated by climate change, as evidenced by Nepal's average annual temperature increase of approximately 0.056°C (DHM, 2017), which is closely aligned with the global average increase of about 0.06°C (Lindsey and Dahlman, 2025).

ADMINISTRATIVE COMPLEXITY AND GOVERNANCE CHALLENGES

Pre-federal administrative framework

Before 2015, Nepal operated under a centralised system consisting of 75 districts

organised into 14 zones, a structure established in 1962 under King Mahendra (Bahl *et al.*, 2020). Chief District Officers (CDOs) held significant power as the administrative heads of these districts, often referred to as "kings of the district" during the Panchayat era (1962-1990). They wielded extensive authority over district-level governance, including forest management (Bahl *et al.*, 2020).

While this centralised approach may have provided clearer administrative structures compared to the current federal system, forest management already faced institutional tensions at that time. The Panchayat Forest Rules of 1978 introduced a dual system in which the central Department of Forests maintained technical oversight, whereas village Panchayats held management authority over designated forests. This arrangement led to conflicts between political and technical authority, foreshadowing the current complexities related to jurisdiction (Ojha *et al.*, 2014).

Federal transition and new complexities

Nepal's 2015 Constitution fundamentally restructured governance by establishing three tiers of government, each with overlapping responsibilities for forest management (Bahl *et al.*, 2020). The Constitution allocated 22 exclusive powers to local governments and assigned 15 concurrent powers among federal, provincial, and local levels. This arrangement has created coordination challenges that directly affect the effectiveness of forest fire management.

The administrative reorganisation expanded the original 75 districts to 77, with the districts of Nawalparasi and Rukum each being divided in 2017 (Bahl *et al.*, 2020).

More importantly, the constitutional framework established overlapping jurisdictions, which have likely complicated the coordination of forest fire management efforts. Part 17 of the Constitution established District Assemblies in all 77 administrative districts, comprising leaders from municipal and rural municipalities. Although these assemblies are recognised in the Constitution, they serve as an additional administrative layer rather than a fourth tier of government (Bahl *et al.*, 2020).

The constitutional framework creates significant jurisdictional ambiguities for forest management through overlapping power distributions (Bahl *et al.*, 2020):

- **Schedule 5** assigns the Federal Government authority over national forest policies, national parks, wildlife reserves, and wetlands
- **Schedule 6** places forest management under provincial authority
- **Schedule 7** designates inter-provincial forest resources as shared federal-provincial responsibility
- **Schedule 9** establishes forests as a three-tier concurrent responsibility

These constitutional ambiguities are further complicated by conflicting legislative frameworks that obscure the scope of management authority during forest fire emergencies. The Local Government Operation Act of 2017 empowers rural municipalities to "protect, use, manage, monitor, regulate, as well as formulate and implement laws" for forest resources within their jurisdictions (Dahal *et al.*, 2021). However, these provisions conflict with national forest legislation, as the Forest Act retains oversight with Divisional Forest Officers (DFOs). This creates uncertainty

regarding management authority during fire emergencies and limits local involvement in coordinating pre-season preparation and prevention measures.

The constitutional requirement for provincial and local governments to develop their own forest legislation has introduced additional implementation challenges. Several provincial governments have enacted forest regulations consistent with their constitutional mandates, including Koshi Province's Forest Regulation 2023 (Dahal, 2024) and Bagmati Province's Sustainable Forest Management Procedure 2023 (MOFE Bagmati, 2023). However, due to the overlapping jurisdictional structures mentioned above, these regulations often lack clear operational guidelines for exercising their powers (Charmakar *et al.*, 2024). The ambiguity in constitutional schedules means that provincially developed forest legislation frequently conflicts with or duplicates federal frameworks, leading to legal uncertainty about which tier holds ultimate authority during emergency responses.

Moreover, severe capacity constraints and inadequate financial resources at the provincial and local levels mean that, even where forest legislation exists, these bodies may lack the technical expertise, trained personnel, and budgetary allocations necessary to implement their forest management responsibilities effectively (Acharya and Zafarullah, 2020). This combination of legislative ambiguity and resource scarcity results in forest management authority being theoretically devolved but practically unexercised at sub-national levels.

Disaster management institutional fragmentation

The Disaster Risk Reduction and Management Act of 2017 establishes a complex, multi-tiered structure for disaster

management, which complicates coordination in the context of forest fire response. The Act creates disaster management bodies at the national, provincial, district, and local levels, each assigned specific yet partially overlapping responsibilities (GoN, 2017).

- The **National Council** provides policy guidance to provincial and local levels
- The **Executive Committee** approves disaster response policies and coordinates across federal, provincial, district, and local levels
- The **National Disaster Risk Reduction and Management Authority (NDRRMA)** functions as the central resource agency and coordinates search, rescue, and relief operations
- **Provincial Disaster Management Executive Committees** coordinate between the federal and local levels while implementing disaster response at the provincial level
- **District Disaster Management Committees**, chaired by CDOs, implement disaster response at the district level and coordinate with local levels
- **Local Disaster Management Committees**, chaired by village/municipal leaders, implement local disaster plans
- **Security Agencies** mobilise for disaster response under CDO orders

This institutional arrangement results in at least six administrative layers between policy formulation and operational response during forest fire emergencies. Coordination mechanisms between the disaster management hierarchy and the fragmented forest governance structure remain unclear. District Disaster Management Committees, chaired by CDOs, are supposed to coordinate emergency responses across

administrative boundaries. However, these committees face the challenge of navigating the distinct jurisdictional authorities of forestry departments, provincial governments, local municipalities, and protected area management agencies. Each of these entities operates under various constitutional schedules and legislative frameworks governing forest management, complicating coordination.

Departmental fragmentation

The government of Nepal has established 84 Division Forest Offices that operate under provincial governments rather than the federal Department of Forests and Soil Conservation (Pokharel *et al.*, 2020). In addition, the Department of National Parks and Wildlife Conservation (DNPWC) manages 21 protected areas, which include 13 national parks, 6 conservation areas, 1 wildlife reserve, and 1 hunting reserve. This department operates under the federal government and is independent of district and division office boundaries (Adhikari *et al.*, 2014).

The CDOs, appointed by the federal government, coordinate disaster responses through District Administration Offices. These offices are accountable to the federal government rather than provincial or local authorities (DRCN, 2020). At the same time, DFOs operate under provincial direction but must inform CDOs about forest-related disasters, such as forest fires. This creates a situation of "diagonal accountability," in which Division Forest Offices are required to respond to multiple authorities across different levels of government.

This structural contradiction is highlighted by the fact that, although the Constitution allocates authority over community forests to local governments, the reorganised forest

administration permits DFOs (under provincial governments) to approve local government recommendations. This arrangement effectively undermines the constitutional intent and diminishes local autonomy (Pokharel *et al.*, 2020). Moreover, the presence of critical departments with misaligned administrative boundaries creates jurisdictional ambiguity, complicating emergency coordination efforts during forest fire emergencies. This situation reflects broader trends of re-centralisation within Nepal's supposedly federal forest governance structure (Basnyat *et al.*, 2020). The fragmentation in governance forces forest officers to navigate competing directives from federal disaster management authorities, provincial forest directorates, and local governments, each claiming legitimate authority under different constitutional schedules. As a result, governance during the initial phase of federal implementation becomes ambiguous (Bhusal and Breen, 2024).

Community forest management complexity

Nepal's community forestry program comprises more than 23,026 Community Forest User Groups (CFUGs) that manage more than 2.4 million hectares (CFSC, 2024). Since the implementation of federalism, all three levels of government impose taxes on CFUGs (Dahal *et al.*, 2021), resulting in financial burdens and administrative confusion. This undermines the autonomy of CFUGs and increases the risk posed by forest fires due to fragmented forest management.

The Local Government Operation Act (2017) assigns responsibilities for environmental conservation and forest resource management to local governments, thereby creating an expectation that community forestry will be

overseen by these local authorities (Dahal *et al.*, 2021). However, the Forest Act (2019) maintains operational control with DFOs, who are responsible for approving the operational plans of community forests and monitoring CFUGs (Dahal *et al.*, 2021). This creates dual and often conflicting accountability structures, requiring CFUGs to navigate both the authority of local governments (empowered by constitutional concurrent powers under Schedule 9) and the oversight of provincial forestry departments exercised through the DFOs. Such complexity can hinder effective coordination during forest fire emergencies when quick and unified command structures are crucial.

Currently, nearly all individuals involved in forest fire management, including CFUG members, lack adequate training, knowledge, and experience in fire suppression techniques. Insufficient understanding of suppression methods, limited access to firefighting equipment and personal protective equipment (PPE), and poor communication systems contribute to coordination failures during emergencies (Pandey and Bhattarai, 2025). These capacity gaps at the community level exacerbate the broader challenges of intergovernmental coordination.

POLICY FRAMEWORK GAPS AND LEGISLATIVE CONTRADICTIONS

Dispersed policy framework

Nepal lacks a clear, unified policy framework for forest fire management, as relevant legal provisions are scattered across at least seven major pieces of legislation and lack coherent coordination mechanisms. The National Forest Fire Management Strategy (2010) is the only document that explicitly addresses forest fire management. However, despite their importance, the implementation of preventive

measures has seen limited progress and has not been integrated into the post-2015 federal structure (Matin *et al.*, 2017).

The NDRRMA, established in 2017, was intended to coordinate disaster responses but has struggled to establish clear hierarchies during fire emergencies (GoN, 2017). Currently, the coordination role seems to be maintained by the Ministry of Home Affairs. Additionally, the NDRRMA is severely under-resourced and lacks staff with critical experience in forest fire management.

In 2024, a draft Forest Fire Risk Reduction and Management National Strategy and Action Plan (2079–2087 BS) was developed to align with the National Disaster Risk Reduction and Management Action Plan (2018–2030). However, changes in staff at the end of 2024 resulted in the replacement of key positions, including the Executive Head and Under Secretary of the Forest Fire, Fire, and Environment Branch at the NDRRMA. On July 1, 2025, a meeting was held to review and revise Nepal's Forest Fire Strategy 2010. For this review, the original comprehensive document available in 2024 appears to have been replaced by a version that is significantly reduced in scope and detail.

Legislative implementation gaps

More than 30 local-level acts and regulations have been enacted; however, their effective implementation is hindered by technical issues, coordination gaps among central ministries, and ongoing intervention by central agencies (Acharya and Zafarullah, 2020). The political changes and transition to federalism have led to new forest legislation at both the federal and provincial levels. These changes resulted in adjustments to governance and benefit-sharing models, which evoked uncertainty during emergencies (Charmakar *et al.*, 2024).

Even five years after Nepal's constitutional transition, essential framework legislation remains incomplete. The enabling laws for provincial public service commissions have been delayed, and the civil service legislation is stalled (Bahl *et al.*, 2020). These legislative gaps create operational obscurities that impede coordination during forest fire emergencies, where clear chains of command and responsibility are crucial.

OPERATIONAL CHALLENGES AND COORDINATION FAILURES

Resource constraints and command structure deficiencies

For the two main agencies involved in forest fire management, resources are severely limited. For the fiscal year 2022/23, the NDRRMA received only NPR 5 million (approximately USD \$36,000), while the Ministry of Forests allocated a mere NPR 22 million (around USD \$160,000) for forest fire management throughout all of Nepal (Dahal, 2024; Prasad and Khanal, 2023; Shrestha, 2023). This indicates a significant lack of prioritisation for fire management by the national government.

Current emergency protocols highlight the absence of a coordinated incident management system. When local capacity is exceeded, CDOs request assistance from the armed forces through the Ministry of Home Affairs. However, once the armed forces are deployed, they take command of the situation, despite often having limited experience, training, or equipment for forest fire management. This can lead to problems in the command structure during critical response periods, particularly given the documented inadequacies of existing coordination mechanisms.

Intergovernmental coordination failures

Despite constitutional mechanisms mandating cooperation, coexistence, and coordination between levels of government, Nepal's three tiers of government struggle to collaborate effectively through intergovernmental structures (Acharya and Zafarullah, 2020). Since 2015, the Inter-Provincial Council has convened only three times, with the most recent meeting held in 2019 (Bahl *et al.*, 2020).

Poor intergovernmental relations and conflicts between the three tiers of government have become major obstacles to the successful implementation of federalism in Nepal (Subedi, 2023). This lack of coordination is also evident in other sectors, where federal, provincial, and local authorities struggle to establish unified approaches to shared responsibilities (Bahl *et al.*, 2020).

Despite various efforts, the vastness of forest areas, coupled with resource constraints, and inadequate coordination have resulted in little to no reduction in forest fire incidents and the damage they cause. These incidents highlight the urgent need for effective policies, legal frameworks, and institutional measures to prevent and control forest fires. Achieving this requires concerted efforts by governments at all levels, as well as the active involvement of local communities.

INTERNATIONAL EXPERIENCE: FEDERAL FOREST FIRE COORDINATION

United States: Incident command system development

The United States developed its Incident Command System (ICS) in response to catastrophic forest fires in Southern

California during the 1970s. Coordination failures among multiple agencies resulted in ineffective responses to these disasters (GFMC, 2009). The ICS addresses the complexities of jurisdiction by implementing unified command structures, standardised resource procedures, and scalable organisational frameworks that operate beyond typical administrative boundaries during emergencies (FAO, 2010).

The federal structure of the United States distributes responsibilities among federal agencies, such as the Forest Service and the Bureau of Land Management, as well as state agencies and local fire departments. This setup created coordination challenges similar to those faced in Nepal. The implementation of ICS successfully bridged these jurisdictional gaps by establishing predetermined roles and responsibilities that activate during emergencies, enabling a cohesive response that transcends ordinary administrative limitations.

Australia: Multi-jurisdictional coordination - example NSW

The Australian government comprises the national government, state and territory governments, as well as local governments across all states and territories. Fire management typically operates within two main frameworks in each state: urban fire services and rural fire services (RFS), which often work together during incidents. Rural fire services frequently rely on a substantial number of volunteers.

In New South Wales (NSW), which experiences summer wildfires almost every year, the RFS maintains a central administration in Sydney that oversees and coordinates efforts, particularly during simultaneous fire incidents (NSW RFS,

2024). The state is divided into 44 RFS districts, which are grouped into seven Area Commands, with approximately 124 local control centres managing brigade responses. This organisational structure prioritises local responses, escalating to higher levels only when additional resources are needed. Timely situation reports keep all levels informed and prepared to respond to escalating incidents.

Under the Rural Fire Act 1997, the Rural Fire Service, the NSW National Parks and Wildlife Service (NPWS) and the Forestry Corporation of NSW are designated as fire authorities (Australian Emergency Law, 2020; NSW Government, 1997). They respond to fires within the areas they manage and collaborate as incidents develop further. NSW operates three response levels:

- **Level 1** - Resolved using local resources only, with a Fire Captain or Crew Leader in charge (typically the first arriving Officer).
- **Level 2** - More complex incidents requiring resources beyond the initial response, or the establishment of sectorisation or functional sections due to size, risk, or potential consequences. An appropriately qualified Incident Controller (IC) leads these operations, with management potentially shared between multiple fire authorities.
- **Level 3** - Highly complex incidents requiring significant resources and structure, with the IC typically appointed by the Commissioner (NSW RFS, 2025).

Once declared, all personnel work as a unified team regardless of their employing organisation. The IC and Incident Management Team (IMT) operate within the Australasian Inter-Service Incident Management System (AIIMS), the Incident

Management System (IMS) utilised by the RFS (NSW RFS, 2025). AIIMS is an integral component of emergency management doctrine for the fire and emergency services sector in Australia, enabling agencies to coordinate an integrated and effective response to incidents (AFAC, 2017). The response structure's size and complexity directly match the incident's requirements.

KEY LESSONS FOR NEPAL

International experience highlights several critical success factors, including clearly defined roles that cross administrative boundaries, standardised training and procedures, personnel assignments within an IMS based on knowledge and experience rather than rank, position, or organisation. Additionally, effective mutual aid and resource-sharing mechanisms, along with unified command structures that preserve authority while accommodating multiple stakeholders, are essential for success.

Toward an incident management system for Nepal

Addressing critical coordination issues

Nepal's 2022 draft strategy review identified five critical incident management issues that IMS implementation could systematically address (GoN/MoHA, 2022):

1. **Inter-agency coordination:** IMS would establish predetermined protocols that activate during emergencies, creating formal collaboration mechanisms between all government spheres
2. **Integration into disaster management:** IMS provides the structural frameworks needed to integrate forest fire management into NDRRMA coordination systems

3. **Proactive management:** Pre-incident planning would identify high-risk areas and establish response protocols before fires occur
4. **Incident command systems:** Clear command hierarchies with qualified incident commanders based on expertise rather than institutional hierarchy
5. **Structured command systems:** Standardised organisational structures ensuring consistent coordination regardless of incident location

An IMS would create predefined coordination protocols that activate during forest fires and potentially other emergencies. This system would establish formal mechanisms for collaboration among all levels of government, including specific units such as the Armed Forces. Instead of relying on ad hoc coordination efforts during emergencies, the IMS would provide standardised procedures for information sharing, resource allocation, and joint decision-making among agencies operating across different administrative boundaries.

The system would establish liaison positions and communication protocols to facilitate real-time coordination among federal, provincial, and local agencies while preserving each agency's existing authorities within a unified command structure. CFUGs could be formally integrated as first-response teams, with clear reporting lines to DFOs and local emergency coordinators.

Implementation pathway

Recognising Nepal's political and administrative realities (Acharya and Zaffarullah, 2020; Bahl *et al.*, 2020; Subedi, 2023), IMS implementation should follow a phased approach:

Phase 1: Policy framework development- Create a cohesive national policy that clearly defines the roles of various government levels while addressing any constitutional jurisdictional ambiguities regarding responsibilities. The development of this policy should involve all relevant stakeholders, including federal ministries, provincial governments, local authorities, and representatives from CFUGs. This approach will ensure that IMS implementation fosters consensus rather than imposing external frameworks on existing institutions.

Phase 2: Pilot implementation - Test procedures should be conducted in selected districts that represent various jurisdictional arrangements, including areas with significant community forests, protected areas, and the need for multi-provincial coordination. The pilot districts should represent diverse jurisdictional configurations and include these essential features.

Phase 3: Training and capacity development - Develop standardised training programs to enhance IMS skills across various agencies, while incorporating CFUGs as primary first-response teams. It would be beneficial to seek IMS training from experienced international providers specialising in forest fire management. Special emphasis should be placed on training CFUGs, given their vital role in community-level forest management and early response capabilities.

Phase 4: Resource and technology integration - Implement coordinated resource management systems to enable effective resource sharing during emergencies. This includes standardised equipment specifications, communication systems, and procedures for tracking resources.

Phase 5: Evaluation and refinement- Systematic evaluation should focus on

measurable improvements in coordination effectiveness, response times, and incident outcomes compared to historical performance.

CONCLUSION

Nepal's transition to federalism has complicated forest fire management due to overlapping jurisdictions, fragmented structures, and poor coordination. The complexity of the constitutional framework, along with resource constraints and unclear accountability, hinder effective fire prevention and response. Nevertheless, international examples demonstrate that federal systems can manage emergencies effectively by implementing an IMS. Introducing an IMS in Nepal could provide a standardised command structure that is currently lacking in its administrative framework.

To address these coordination issues, Nepal should focus on developing a "system of systems" approach in a few key municipalities and provinces. This method would preserve successful community-based forest management while integrating it into a coordinated emergency response framework. Ultimately, effective fire management in Nepal requires clarifying roles and responsibilities, harmonising legislation, and establishing coordination mechanisms among various government levels. Without policy reforms that define clear communication and a unified command, Nepal's forests will remain vulnerable, despite ongoing investments in conservation programs.

REFERENCES

- Acharya, K. K., & Zafarullah, H. (2020). Institutionalising federalism in Nepal: Operationalising obstacles, procrastinated progress. *Public Administration and Policy*, 23(2), 125–139. <https://doi.org/10.1108/PAP-03-2020-0013>
- Adhikari, S., Kingi, T., & Ganesh, S. (2014). Incentives for community participation in the governance and management of common property resources: The case of community forest management in Nepal. *Forest Policy and Economics*, 44, 1–9. <https://doi.org/10.1016/j.forpol.2014.04.003>
- Australian Emergency Law. (2020, February 29). Coordinating firefighting with NSW RFS, FC and NPWS. <https://australianemergencylaw.com/2020/02/29/coordinating-firefighting-with-nsw-rfs-fc-and-npws/>
- Australian Fire and Emergency Service Authorities Council. (2017). *AIIMS 2017 manual*. Australian Fire and Emergency Service Authorities Council. <https://www.afac.com.au/marketplace/9be97a80-5025-4ab7-b4ce-4fe7e68ec573>
- Bahl, R. W., Timofeev, A., & Yilmaz, S. (2020). *Implementing federalism: The case of Nepal* (ICePP Working Paper No. 20-10). International Center for Public Policy, Andrew Young School of Policy Studies, Georgia State University. <https://icepp.gsu.edu/files/2020/06/paper2010.pdf>
- Bajracharya, D. (2002). Forest fire situation in Nepal. *International Forest Fire News*, 26, 84–86. <https://dnpnet.org.np/uploads/files/Forest%20Fire%202022-03-20%2010-33-22.pdf>
- Basnyat, B., Treue, T., Pokharel, R. K., Baral, S., & Rumba, Y. B. (2020). Re-centralisation through fake scientificness: The case of community forestry in Nepal. *Forest Policy and Economics*, 115, Article 102147. <https://doi.org/10.1016/j.forpol.2020.102147>
- Bhujel, K. B., Sapkota, R. P., & Khadka, U. R. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Bhusal, T., & Breen, M. G. (2024). A study of the first five-year tenure (2017–2022) of provincial governments in Nepal. *Asian Politics and Policy*, 16(4), 524–547. <https://doi.org/10.1111/aspp.12767>

- Buck, D. A., Trainor, J. E., & Aguirre, B. E. (2006). A critical evaluation of the incident command system and NIMS. *Journal of Homeland Security and Emergency Management*, 3(3), Article 1. <https://doi.org/10.2202/1547-7355.1252>
- Community Forest Study Center. (2024). *Community forest bulletin* (Vol. 20). Community Forest Study Center.
- Charmakar, S., Kimengsi, J. N., & Giessen, L. (2024). Linking institutional change mechanisms with forest management outcomes: Evidence from community forestry in Nepal. *Ecology and Society*, 29(3), 1–35. <https://doi.org/10.5751/ES-15085-290301>
- Comfort, L. K., & Kapucu, N. (2006). Inter-organizational coordination in extreme events: The World Trade Center attacks, September 11, 2001. *Natural Hazards*, 39(2), 309–327. <https://doi.org/10.1007/s11069-006-0030-x>
- Dahal, B. (2024, April 15). Prepare to fight forest fires. *Rising Nepal Daily*. <https://risingnepaldaily.com/news/41587>
- Dahal, B., Joshi, R., Poudel, B., & Panta, M. (2021). Community forestry governance in federal system of Nepal. *Journal of Policy and Governance*, 1(1), 30–45. <https://doi.org/10.33002/jpg010103>
- Democracy Resource Center Nepal. (2020). *The interrelationship between three levels of governments in Nepal's federal structure: A study report* (DRCN Periodic Report No. 9). https://www.democracyresource.org/wp-content/uploads/2020/10/Inter-Government-Relation-EngVer_13October2020.pdf
- Department of Hydrology and Meteorology. (2017). *Observed climate trend analysis in the districts and physiographic regions of Nepal (1971–2014)*. Government of Nepal. https://www.dhm.gov.np/uploads/dhm/climateService/Observed_Climate_Trend_Analysis_Report_2017.pdf
- Food and Agriculture Organization of the United Nations. (2000). *Global forest fire assessment 1990–2000* (Forest Resources Assessment Programme Working Paper No. 55). <https://www.fao.org/3/ad653e/ad653e00.htm>
- Food and Agriculture Organization of the United Nations. (2010). *Wildland fire management handbook for trainers*. <https://www.fao.org/4/i1363e/i1363e01.pdf>
- Forest Research and Training Centre. (2024). *National land cover monitoring system of Nepal, 2020–2022*. Government of Nepal. https://frtc.gov.np/uploads/files/NLCMS_Report_Final.pdf
- Global Fire Monitoring Centre. (2009). *Use of incident command systems in fire management* [Symposium proceedings]. International Symposium on Use of Incident Command Systems in Fire Management, 2009 Pan Asia Forest Fire Symposium. <https://gfmcc.org/wp-content/uploads/Pan-Asia-proceeding-ICSfinal.pdf>
- Government of Nepal. (2017). *Disaster risk reduction and management act, 2074 (2017)*. Ministry of Home Affairs. <https://www.dpnep.org.np/public/resource-detail/1119>
- Government of Nepal. (2022). *Forest fire risk reduction and management national strategy and action plan (2079–2087 BS) [2022–2030 CE]*. National Disaster Risk Reduction and Management Authority, Ministry of Home Affairs.
- Kapucu, N. (2009). Interorganizational coordination in complex environments of disasters: The evolution of intergovernmental disaster response systems. *Journal of Homeland Security and Emergency Management*, 6(1), Article 47. <https://doi.org/10.2202/1547-7355.1498>
- Lindsey, R., & Dahlman, L. (2025). *Climate change: Global temperature*. NOAA Climate.gov. <https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature>
- Matin, M. A., Chitale, V. S., Murthy, M. S. R., Uddin, K., Bajracharya, B., & Pradhan, S. (2017). Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information systems and historical fire data. *International Journal of Wildland Fire*, 26(4), 276–286. <https://doi.org/10.1071/WF16056>

- McLennan, B., & Handmer, J. (2012). Reframing responsibility-sharing for bushfire risk management in Australia after Black Saturday. *Environmental Hazards*, 11(1), 1–15. <https://doi.org/10.1080/17477891.2011.608835>
- Ministry of Forest and Environment, Bagmati Province. (2023). *Sustainable forest management procedure 2079 (2023)*. Government of Nepal. <https://mofe.bagmati.gov.np/content/192/sustainable-forest-management-procedure-2079>
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19, Article 3. <https://doi.org/10.1186/s42408-022-00162-3>
- NASA Fire Information for Resource Management System (FIRMS). (2025). MODIS Collection 6.1 active fire detections [Data set]. NASA EOSDIS. <https://firms.modaps.eosdis.nasa.gov>
- NSW Government. (1997). *Rural Fires Act 1997* (NSW). https://classic.austlii.edu.au/au/legis/nsw/consol_act/rfa1997138/
- NSW Rural Fire Service. (2024). *Structure*. <https://admin.rfs.nsw.gov.au/about-us/structure>
- NSW Rural Fire Service. (2025). *Incident management: General*. <https://www.rfs.nsw.gov.au/resources/publications/operational-procedures-and-guidelines/foundational/incident-management-general>
- Ojha, H. R., Banjade, M. R., Sunam, R. K., Bhattarai, B., Jana, S., Goutam, K. R., & Dhungana, S. (2014). Can authority change through deliberative politics? Lessons from four decades of participatory forest policy reform in Nepal. *Forest Policy and Economics*, 46, 1–9. <https://doi.org/10.1016/j.forpol.2014.04.005>
- Pandey, P. R., & Bhattarai, K. (2025, June 9). Rethinking forest fire management in Nepal: Lessons from Bagmati Province. *Spotlight Nepal*. <https://www.spotlightnepal.com/2025/06/09/rethinking-forest-fire-management-nepal-lessons-bagmati-province/>
- Pokharel, K., Karki, R., Ojha, H. R., Gentle, P., Acharya, D., Banjade, M., & Paudel, D. (2020). State-community relations and deliberative politics within federal forest governance in Nepal. *International Forestry Review*, 22(3), 370–381. <https://doi.org/10.1505/146554820830405609>
- Prasad, R. J., & Khanal, S. (2023, May 13). More pre-monsoon forest fires in Nepal. *Nepali Times*. <https://nepalitimes.com/here-now/more-pre-monsoon-forest-fires-in-nepal>
- Shrestha, M., Karki, R., Bohara, M., & Karna, B. (2025). *The awareness-action gap in community forest fire management: Insights from high-altitude Nepal* [Preprint]. SSRN. <https://doi.org/10.2139/ssrn.5390637>
- Shrestha, S. (2023, May 16). What is flaring Nepal's issue of forest fires? *Nepal Economic Forum*. <https://nepaleconomicforum.org/what-is-flaring-nepals-issue-of-forest-fires/>
- Somlai, I. G., Karakatsoulis, J., Gardner, W., Gautam, A. P., Sharma, S. P., & Adhikari, B. (2018). Forest governance in Nepal: Rationale for centralised forest and wildfire management. *Journal of Management and Development Studies*, 28, 16–35. <https://doi.org/10.3126/jmds.v28i0.24956>
- Subedi, G. (2023). Intergovernmental interaction in federal Nepal and challenges in the transitional period. *Journal of Multidisciplinary Research*, 2(1), 49–60. <https://nepjol.info/index.php/ijmr/article/download/53620/40121>
- Wagh, W. L., & Streib, G. (2006). Collaboration and leadership for effective emergency management. *Public Administration Review*, 66(S1), 131–140. <https://doi.org/10.1111/j.1540-6210.2006.00673.x>

Anticipatory forest-fire risk governance in Nepal

Basundhara Bhattarai^{1,2}, Kenisha Shrestha^{1,*}, Priyanka Gurung¹,
Prativa Sapkota^{1,3,4}, Hemant Ojha^{1,5}

¹*Institute for Study and Development Worldwide (IFSD), Parramatta, Sydney,
NSW 2150, Australia*

²*Western Sydney University, Hawkesbury Campus, Richmond, Australia*

³*Fire Risk, Research and Community Preparedness, Country Fire Authority,
Burwood East, Victoria, 3151, Australia*

⁴*School of Agriculture, Food and Ecosystem Sciences, University of Melbourne, Parkville,
Victoria, 3010, Australia*

⁵*Australian National University (ANU), Canberra, ACT 2600, Australia*

*Corresponding author: K.shrestha@ifsd.com.au

Abstract

Nepal's pre-monsoon forest fires are becoming increasingly frequent, widespread and socially consequential, damaging lives and livelihoods. However, responses remain largely reactive. These risks are compounded by institutional fragmentation and policy gaps that prevent timely and coordinated action. Drawing on disaster risk reduction principles, this perspective proposes an anticipatory approach to fire risk governance, emphasising the importance of community forestry institutions. In doing so, it combines empirical insights from Nepal with operational lessons from New South Wales and Victoria, Australia. Both cases highlight how forecast-based fire danger ratings function as decision triggers for agencies and communities. The Victorian case also illustrates how such triggers are embedded in the broader governance system. Together, these cases demonstrate that anticipatory governance is not about the forecast system alone, but about the systematic linkage of information to decision-making and behavioural response.

Keywords: Forest fire, Anticipatory governance, Disaster risk reduction, Fire preparedness, Nepal

INTRODUCTION

Nepal has been experiencing recurrent dry-season forest fires in both the Hill and Terai regions, with impacts on air quality, livelihoods, and public safety. The persistence and spatial extent of these fires indicate a systemic risk. Forest fires typically peak during the pre-monsoon period (February-May) and are increasingly driven by rising temperatures, prolonged dry periods, land-use change, and expanding exposure at the forest-settlement interface, thereby reducing the effectiveness of response-focused approaches (NASA Earth

Observatory, 2021; Nepali Times, 2023). To make matters worse, response capacity, especially at the local level, remains limited. Fire response tends to remain reactive, with limited emphasis on proactive and systemic risk management. Internationally, forest fires are increasingly recognised as a disaster risk with cascading effects across health, livelihoods, infrastructure, and ecosystems (UNDRR, 2015; UNDRR, 2023). Australia has a long history of governance reform to manage fire risks in one of the most fire-prone continents on the planet.

In this perspective paper, we examine anticipatory forest fire risk in Nepal through a systems lens, analysing how institutional fragmentation and governance gaps constrain effective forest fire risk management, and how anticipatory governance can strengthen coordination, preparedness, and early action across levels of government. To do this, we also draw on insights from the state of New South Wales in Australia. This perspective uses the “boiling pot” analogy to analyse forest fire risks in Nepal, where rising temperatures, increased fuel loads, frequent ignitions, and expanding exposure are building simultaneously.

FOREST FIRE RISK AS A “BOILING POT”

The “boiling pot” metaphor effectively illustrates how multiple factors can combine to push a system past a critical point. Just as a pot boil only when heat, fuel, and pressure are sustained, Nepal’s forest fire situation is becoming more threatening. Rising temperatures and prolonged dry periods increase heat; land management shifts lead to fuel accumulation; human activities frequently cause ignitions; and expanding settlements, roads, and infrastructure along forest edges increase exposure. When these elements converge, the risk of rapid, severe fires escalates significantly, potentially overwhelming local response capabilities.

Disaster risk reduction (DRR) frameworks emphasise managing risk before it becomes a disaster by focusing on understanding risk, strengthening risk governance, investing in risk reduction, and enhancing preparedness for effective response and recovery (UNDRR, 2015). In forest fire contexts, this implies anticipatory action through predefined, trigger-based measures linked to forecasts and observed conditions (e.g., fire danger

ratings, fuel dryness, wind events) that activate prevention measures, resource positioning, restrictions on high-risk activities, and readiness of incident management structures. This involves monitoring and acting on changing fire risk conditions before escalation occurs. Without such anticipatory governance, Nepal risks being trapped into a recurring cycle of emergency mobilisation, short-term containment of fires that limits immediate spread but does not reduce underlying risk and recurring losses, effectively a ‘pot’ that boils over each year and becomes progressively harder to manage.

Scientific evidence and lived experience point in the same direction: baseline fire risk conditions are shifting. Hotter days, longer dry spells, erratic pre-monsoon rainfall and stronger wind events are changing how quickly forests dry and how aggressively fires spread (Barik and Roy, 2023). At the same time, rural out-migration and changing farming practices can leave more fuel in the landscape, as grasslands are not grazed as before, terraces are not maintained, and forest floors accumulate dry leaf litter (Moreira *et al.*, 2020). As roads, power lines and settlements expand along forest edges, the likelihood of ignition rises precisely where exposure is greatest. Nepal does not need to become as dry as Australia to face forest fire (known as bushfire in the Australian context) dynamics; it only needs more heat, more fuel, and more people and assets in harm’s way. As elaborated below, this convergence is already underway, and the “boiling pot” is no longer a future risk but a present and intensifying reality.

DRIVERS OF ESCALATING FOREST FIRE RISK IN NEPAL

The escalation of forest fire risk in Nepal is not driven by a single factor but by the interaction of multiple reinforcing

drivers. These include climatic, ecological, institutional, and socio-economic drivers, and they are increasingly aligned, intensifying both the likelihood and the impacts of fire.

Weather and climate signals

The pre-monsoon period in Nepal is characterised by low humidity, rising temperatures, and unpredictable winds that can rapidly increase fire spread potential. Satellite-based analyses have documented extreme fire seasons, including 2016 and 2021, when drought conditions contributed to unusually high hotspot counts and smoke impacts (NASA Earth Observatory, 2021). For example, in 2021, the National Aeronautics and Space Administration (NASA) reported that Nepal received roughly a quarter of normal rainfall between January and April, and that the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor detected tens of thousands of hotspots early in the season, with smoke contributing to hazardous air quality and disruptions (NASA Earth Observatory, 2021). These conditions are consistent with broader regional trends. The Intergovernmental Panel on Climate Change (IPCC)’s Sixth Assessment Report concludes with high confidence that the Hindu Kush Himalaya (HKH) has warmed faster than the global average and that compound hot-and-dry events, which elevate fire weather, are projected to intensify across South Asia (IPCC, 2022). Region-specific assessments by the International Centre for Integrated Mountain Development (ICIMOD) reach similar conclusions, projecting longer dry seasons and an increased frequency of extreme heat across the cryosphere-monsoon transition zones where Nepal’s most fire-prone forests are located (Wester *et al.*, 2019). While any single season has multiple contributing causes, the direction

of risk towards hotter and potentially longer fire seasons is clear, aligns with regional climate risk projections for the HKH region, and warrants precautionary governance.

Fuels, forest condition and land management

Nepal’s success in forest regeneration, largely through community forestry, has environmental benefits, but it can also increase available biomass that can burn if forests are under-managed for fuel loads. Empirical analyses underscore the magnitude: between 2001 and 2020, more than 172,000 hectares of Nepal’s forest burned, with biomass losses exceeding 7 million tonnes (Bhujel *et al.*, 2022). Additional evidence from vulnerability mapping shows that 78-89 per cent of the burned area occurs between March-May, and that fire frequency has trended upward by roughly 0.6 per cent per year (Mishra *et al.*, 2023; Matin *et al.*, 2017). Commentary and reporting in Nepal increasingly link rising fire impacts to fuel accumulation in protected and regenerating forests, compounded by reduced everyday use and stewardship in some places due to labour scarcity and rural out-migration (Nepali Times, 2023). Recent policy analysis similarly argues that insufficient and delayed forest management, together with weakened community-level collective action, has allowed fuels to build and small ignitions to escalate (ForestAction, 2025a). In the “boiling pot” analogy, fuels represent the contents of the pot, where greater accumulation without active management leads to more severe outcomes when conditions align.

Ignitions and incentives

Many forest fires have proximate human ignition sources: escaped agricultural burning,

roadside fires, carelessness during forest product collection, or deliberate lighting linked to grazing and access. However, focusing only on these immediate human causes risks overlooking the underlying structural issue. Across Nepal, changing rural livelihoods, out-migration, declining livestock rearing, and regulatory constraints on forest use and timber harvesting have reduced everyday forest-community interaction and weakened collective forest management practices (Tiwari *et al.*, 2022; Poudyal *et al.*, 2023). While these changes have contributed to forest regeneration and the expansion of forest cover, they have also reduced biomass extraction and landscape management in many community forests, creating conditions that increase forest fire risk. Additionally, Nepal lacks consistent incentive systems and enforceable, locally legitimate rules that reduce preventable ignitions on the highest-risk days. A risk-governance approach shifts the question from who started the fire to under what conditions ignitions are most likely to become damaging fires, and what rules, communication systems, and enforcement capacities exist to suppress that transition.

Exposure and the forest-settlement interface

Roads, power infrastructure, and expanding settlements increase both the probability of ignition and the consequences of fire. For instance, the spatial risk modelling for the Terai Arc Landscape, shows that human ignition pressure and exposure converge precisely where transport corridors and settlement edges meet regenerating forest, producing localised hotspots that are poorly captured by district-level statistics (Parajuli *et al.*, 2022). Nepal now has several operational and near-real-time information systems

that can support exposure-aware planning, including the Government of Nepal's Forest Fire Detection and Monitoring System and associated interfaces that report fire statistics and locations, and regional systems developed with ICIMOD's SERVIR-HKH programme that integrate MODIS/VIIRS detections and provide outlook indices (DoFSC, 2026; SERVIR-HKH/ICIMOD, 2020). However, these systems only reduce risk if they inform action. When danger is elevated, agencies and communities need pre-defined and trigger-based actions that include resource staging, patrols, restrictions, and readiness of incident management teams, rather than passive observation. However, translating information into action remains constrained by fragmented institutional mandates, weak command-and-control arrangements, and unclear coordination across forest agencies, disaster authorities, and local governments, often resulting in delayed and uneven responses.

These drivers clearly show that forest fire risk in Nepal is not only increasing but also becoming more complex and interconnected. Forest fire is best understood as a livelihood shock that also creates long-tail ecological and economic impacts. Fire interrupts the seasonal calendar that supports rural households: fodder and bedding collection, grazing routes, leaf litter for compost, access to fuelwood and timber, and income from non-timber forest products (NTFPs). Severe fires can erase years of investment in regeneration and protection by community forest user groups (CFUGs) and can damage the watershed functions on which agriculture depends. Burned slopes can erode rapidly with the first heavy rains, contributing to sedimentation, irrigation disruption and downstream flood risk, illustrating how fire can cascade into other hazards rather than competing with

them (UNDRR, 2015). A substantial body of geomorphological evidence shows that forest fire-induced changes in soil hydrophobicity, vegetation cover and surface roughness can increase post-fire erosion and debris-flow hazard by one to several orders of magnitude, with effects persisting for years (Shakesby, 2011). For Nepal's steep mid-hill terrain, where fire seasons immediately precede the monsoon, this temporal coupling makes post-fire watershed risk a foreseeable and therefore manageable component of fire governance rather than a separate problem.

FOREST FIRE RISK AS A GROWING LIVELIHOOD CRISIS IN NEPAL

Forest fires in Nepal are not only an environmental hazard but also a multidimensional livelihood crisis with far-reaching social, economic, and health impacts. The consequences extend well beyond burned areas, affecting public health, labour productivity, equity, and governance systems.

Smoke, health, and productivity losses

Smoke turns local fires into a national-scale public health and economic issue. During dry seasons, smoke has driven unhealthy air quality, flight disruptions and school closures (Kuikel *et al.*, 2024). Health impacts are difficult to quantify precisely in Nepal due to limited monitoring coverage and attribution challenges, but the mechanism is well established: increased pollution levels elevate respiratory and cardiovascular risks and reduce labour productivity. A critical review of forest fire-smoke epidemiology found consistent associations between landscape fires and respiratory exacerbations, with growing evidence of cardiovascular and perinatal

effects (Reid *et al.*, 2016). A subsequent global multi-city analysis attributed an estimated 33,500 deaths per year to short-term exposure to forest fire pollution with PM 2.5 (microscopic airborne particulate matter considered highly toxic to human health) across 749 locations (Chen *et al.*, 2021). For Nepal specifically, the Lancet Countdown estimates that ambient air pollution, of which dry-season biomass burning is a substantial seasonal contributor, reduces life expectancy by roughly 3.4 years (Lancet Countdown, 2024). Treating fire as only an environmental or forestry issue thus underestimates its cross-sectoral costs.

Equity and inclusion issues

Fire risk is unevenly distributed, as women, older people, and low-income households often have fewer options to avoid smoke exposure or relocate temporarily and face greater care burdens during crises. Similarly, many households living near forests remains highly dependent on forests for livelihoods such as firewood, fodder, grazing, and non-timber forest products, making them disproportionately exposed to fire impacts while also having fewer livelihood alternatives and limited recovery capacity. Historically marginalised groups, including Dalit communities in many local contexts, can be over-represented in hazardous response labour while under-represented in decision-making and in access to compensation or recovery support. Additionally, people with disabilities face greater challenges during evacuation, response, and recovery, yet these dimensions remain weakly integrated into forest fire preparedness and response systems in Nepal. Comparative work on Nepali community forestry shows that the meaningful inclusion of women in user group executive positions is associated with measurable improvements

in rule compliance and forest conditions (Agarwal, 2009). Intersectional analyses further demonstrate that caste, class, and gender jointly shape who decides, who labours, and who benefits in everyday forest management (Nightingale, 2011). Fire risk decisions such as when to patrol, who to alert, where to invest in fuel reduction, and how to compensate losses reproduce these inequities unless explicitly designed not to. This pattern mirrors broader evidence that community-based forest governance can deliver major gains yet still faces challenges of elite capture and inequitable benefit sharing without deliberate inclusion measures (Gurung *et al.*, 2011; Cadman *et al.*, 2023). A risk governance approach should therefore adopt an explicit equity lens for preparedness and response planning, ensuring that the needs, capacities, and safety of vulnerable and forest-dependent groups are integrated into fire governance systems, consistent with international DRR guidance (UNDRR, 2015).

ANTICIPATORY RISK GOVERNANCE FOR READINESS

While many fires are human ignited, the deeper determinant of disaster outcomes is governance. This encompasses how Nepal organises institutional incentives, authority, information flows, and capacity across the prevention-preparedness-response-recovery cycle. Anticipatory governance means acting on forecasts and observed risk, rather than waiting for flames to overwhelm local capacity. It requires (i) clear institutional responsibilities across forest agencies, disaster management authorities, and local governments; (ii) predictable financing for prevention and preparedness; (iii) operational protocols for escalation and inter-agency coordination; and (iv) public communication

systems that translate technical risk into simple, trusted triggers for action (UNDRR, 2015; UNDRR, 2023). Without these elements, awareness campaigns and ad hoc enforcement are unlikely to shift outcomes at scale.

Translating early warning into early action

Nepal already receives near-real-time hotspot detections from global systems (e.g., NASA FIRMS) and has national and regional monitoring platforms that provide alerts and outlook indices (NASA FIRMS, 2026; SERVIR-HKH/ICIMOD, 2020; DoFSC, 2026). However, the missing link is institutionalising what happens *after* an alert is issued: Who verifies it? Who issues public warnings? What restrictions apply? Which resources are pre-positioned? Which CFUGs or communities receive support for patrols and fuel management? Without clear answers to these questions, early warning does not translate into early action. Anticipatory action requires that these steps be defined before the season, exercised, and resourced. Otherwise, information becomes a dashboard rather than a life and livelihood protecting system. The forecast-based financing (FbF) literature offers a transferable template: pre-agreed triggers tied to weather, and exposure forecasts release pre-positioned funds and authorise pre-defined actions hours to days before a hazard escalates, shifting the cost curve from response to readiness (Coughlan de Perez *et al.*, 2015). Embedding such triggers into Nepal's disaster financing, administered via the National Disaster Risk Reduction and Management Authority (NDRRMA), and matched to municipal preparedness plans, would convert existing fire danger information into binding operational decisions.

Financing prevention and preparedness

Nepal's fire response often relies on emergency mobilisation and short-term transfers of basic equipment. This approach is structurally expensive and inefficient because it pays repeatedly for response while underinvesting in the measures that reduce incident numbers and severity. Policy analysis has called for dedicated institutional arrangements and decentralised approaches that empower CFUGs and local governments, while strengthening coordination with security forces and disaster agencies (ForestAction, 2025a). However, despite being well positioned to support prevention and response through local resources and coordination, local governments often remain weakly accountable in forest fire management due to overlapping mandates in Nepal's forest governance system. While Division Forest Offices (DFOs) at the provincial level retain formal oversight responsibilities for forests, they often operate with limited budgets and human resources, underscoring the need for clearer institutional arrangements that support local governments through DFOs' technical oversight and coordination functions.

Strengthening community forestry for fire risk reduction

Community forestry is a globally recognised strength of Nepal's forest sector, providing local institutions and social capital that can enable prevention and rapid first response. However, its effectiveness in reducing fire risk depends on adequate support, coordination, and safeguards. Federal restructuring has created overlapping mandates and coordination challenges among local governments, DFOs, and CFUGs,

contributing to 'passive' forest management and heightened hazards (ForestAction, 2025b). Anticipatory fire governance should therefore treat CFUGs as core risk reduction partners, supported by technical services, training, and resources, while also strengthening inclusive decision-making and safeguards against elite capture, so that the burdens and benefits of fire management are shared fairly (Cadman *et al.*, 2023; Gurung *et al.*, 2011). A risk lens forces practical questions about where damaging fire is likely, who and what are exposed, who is most vulnerable, what capacities exist, and how prevention, preparedness, response, and recovery (PPRR) connect. Insights from bushfire management in New South Wales (NSW), Australia, offer instructive operational example of how a jurisdiction can translate these questions into everyday systems, while also showing that even well-developed systems must continually adapt to climate-driven extremes.

OPERATIONAL LESSONS FROM NEW SOUTH WALES (NSW), AUSTRALIA

Experience from NSW, Australia, provides instructive examples of how anticipatory risk governance can be translated into practice through forecasts, institutional coordination, and public communication that support timely and pre-defined action.

Fire danger ratings and triggers

NSW uses publicly communicated fire danger ratings to translate complex weather-fuel conditions into simple categories that are tied to recommended actions and, on severe days, legal restrictions (NSW RFS, 2024). These ratings serve as shared anticipatory triggers for both households and agencies.

This system supports two critical functions: (i) community decision-making (e.g., prepare, avoid travel, or leave early), and (ii) agency operational readiness through pre-positioning resources, staffing incident management teams, and activating coordination arrangements before fire escalation. Since 2022, the four level Australian Fire Danger Rating System (Moderate, High, Extreme, Catastrophic) has unified what was previously a patchwork of state level scales. Post-implementation evaluations in NSW emphasise that simplicity and consistency rather than technical sophistication are what make ratings actionable for households and agencies (AFAC, 2022; McCoy and Field, 2022).

Consistent incident management

NSW applies a common incident management language and role structure so that, when a fire escalates, coordination can scale quickly without re-inventing who does what. For Nepal, the transferable point is modest but important: anticipatory governance works best when roles, authority, information flows, and requests for support are organised in a shared way across community, municipal, provincial, and federal levels before a crisis intensifies. Without such common structures, coordination delays can undermine early action. Detailed design choices, institutional fit and sequencing for an Incident Management System in Nepal are addressed in the complementary paper (Hill and Shrestha, 2026) and are not repeated here.

Communicating risk requiring early decisions

NSW guidance explicitly states that on the highest danger days (“Catastrophic”), the safest option is to leave fire risk areas well before any fire starts because homes may not

withstand fires and help may not be available (NSW RFS, 2024). This form of direct communication is critical to anticipatory risk governance because it links high risk conditions to early protective decisions. It is an uncomfortable message, but it shifts the focus from promising suppression everywhere to managing exposure and vulnerability through timely action. Nepal’s rugged terrain, limited access, and constraints on specialised suppression resources make a similar realism essential, particularly for remote settlements and high value watersheds where rapid response is difficult.

STRENGTHENING ANTICIPATORY FIRE RISK GOVERNANCE: LESSONS FROM VICTORIA, AUSTRALIA

Victoria’s fire governance system has co-evolved through successive cycles of fire events, public inquiries, and policy reforms, transitioning from a largely reactive firefighting model to a more anticipatory approach of fire management (Dwyer *et al.*, 2025). The evolution demonstrates that anticipatory fire governance is not simply the result of a single reform, but how it emerges gradually drawing on institutional learning, system-wide coordination, and adaptation at multiple levels.

At the core of the anticipatory system is the forecast-based decision-making, as illustrated in the NSW case. The Australian Fire Danger Rating System (AFDRS) is an official forecast system that translates weather and fuel conditions into publicly available fire risk categories expressed as ‘Fire Danger Ratings’, to guide both agency preparedness and communities’ protective action (AFAC, 2022; Kenny *et al.*, 2024). These risk categories do not only function as the information tool but as an anticipatory governance mechanism,

connecting weather and fuel conditions to behavioural guidance, operational readiness, and regulatory controls including restrictions based on the pre-defined triggers (AFAC, 2022). Together, these ratings act as the shared reference to align decisions across households, emergency services and government agencies. Prior to adopting a nationally consistent system the AFDRS, Victoria relied on the McArthur system. The transition marked a shift from an empirically derived index to a comprehensive science-based system that integrates diverse environmental, behavioural, and spatial factors into fire risk assessment (Hollis *et al.*, 2024). This highlights that anticipatory fire governance is not merely a technical improvement in forecast system, but a shift in how fire risk is understood and acted upon.

Operation of the forecast system is deeply embedded in a broader governance structure, characterised by a multi-level coordination, adaptive institutional reform, and risk informed planning (Dwyer *et al.*, 2025), recognising that isolated sectoral responses are insufficient for an effective forest fire governance. Coordination across levels, is central to essential decision-support in Victoria, for planning and preparedness enabling prioritisation of resources, infrastructure protection and fuel management in high fire risk areas. These insights can be relevant to Nepal, in realising that the challenges are not the absence of fire risk information but the lack of a system that facilitates linking information to coordinated anticipatory action across multiple governance levels.

The Victorian case also highlights the that even within a well-established system of anticipatory fire risk governance, understanding community preparedness and behaviour are still challenging. Evidence

from different fire events including 2009 Black Saturday bushfires illustrates persistent challenges in timely decision making, inadequate preparedness and reactive responses (Whittaker *et al.*, 2013). More studies also emphasise that providing early warning does not necessarily guarantee the early action, signalling the importance of comprehensive understanding of behavioural insights, communication strategies and decision-support mechanisms within the governance systems.

BUILDING AN ANTICIPATORY FIRE RISK SYSTEM UNDER FEDERALISM: OPPORTUNITIES FOR ACTION

Nepal's community forestry system is a foundational asset for fire risk reduction, but it cannot be asked to carry a growing hazard without systematic support. Many CFUGs already cut basic fire lines, organise patrols and respond to small ignitions; however, out-migration and ageing membership reduce available labour, and limited access to protective gear, tools, training, insurance, and communications constrains safe and effective response. Under federalism, overlapping mandates among local governments, DFOs and CFUGs can also delay decisions and dilute accountability (ForestAction, 2025b; Hill and Shrestha, 2026). Any effective approach must therefore recognise both the strengths and the capacity limits of community institutions and focus on how multi-level governance can enable them.

Federalism makes anticipatory fire governance both more complex and more necessary. Fires do not respect administrative boundaries, yet authority and budgets do. Hill and Shrestha (2026) analyses the constitutional and legislative sources of role confusion in detail; we therefore focus on risk governance

implications. Preparedness cannot depend on improvised negotiation once smoke is already in the sky. A practical way forward is to define (and resource) complementary roles that are activated before the crisis through pre-agreed preparedness levels linked to forecast danger. In broad terms, municipalities lead local risk mapping, preparedness planning, volunteer support, water points and public communication; provinces provide training systems, logistics, surge capacity and cross-municipality coordination; and the federal level sets minimum standards, maintains national early warning infrastructure, enables mutual aid, and integrates fire risk into disaster-risk financing and accountability mechanisms.

Decision support is the connective element of anticipatory governance. Nepal's monitoring systems already integrate satellite detections and provide incident reporting and outlook information (SERVIR-HKH/ICIMOD, 2020; DoFSC, 2026). The next step is to formalise an end-to-end chain from forecast to action. This could include: (i) a Nepal adapted fire danger rating or readiness index communicated in plain language; (ii) standard operating procedures that specify what municipalities, forest offices and CFUGs do at each level (e.g., patrols, restrictions on open burning, staffing of response teams); (iii) escalation rules for requesting provincial or federal support; and (iv) routine post-season evaluation using consistent incident data capturing livelihood and health impacts as well.

First, Nepal can treat large forest fires as a core disaster-risk governance issue rather than a seasonal forestry problem by establishing a clear national framework that defines PPRR responsibilities across forest agencies, disaster authorities and all three levels of government. Such a framework should

include standing coordination arrangements that are activated by risk levels (not ad hoc crisis negotiation), minimum standards for planning and capability, and predictable financing for prevention and preparedness. This includes support for community-level fuel management and fire lines, equipment maintenance, communications, training, and post-season learning so that investment shifts from repeated emergency mobilisation towards sustained readiness.

Second, anticipatory action requires shared triggers that convert risk information into routine decisions. Building on existing monitoring and outlook tools, Nepal could co-design a simple, nationally consistent preparedness-level system (or fire danger rating/readiness index) communicated in plain language and explicitly tied to actions at each level. These actions may include patrols, restrictions on high risk burning, pre-positioning of resources, staffing arrangements, and clear escalation rules for requesting provincial or federal support. Standard operating procedures should specify who verifies alerts, who issues public warnings, and what actions are authorised and funded at each preparedness level; and routine incident reporting, seasonal summaries and after-action reviews should track livelihood and health impacts alongside burned area so that budgeting reflects the true costs of fire.

Third, capability must be built where fires start. Municipalities and CFUGs should be supported as front-line risk-reduction partners through training, basic protective equipment, communications, and safe operational guidance that prioritises responder protection and avoids hazardous "heroic" suppression. This should be complemented by a scalable coordination doctrine and role clarity to enable smooth support as incidents become more complex (detailed incident-

management system design is addressed in the companion paper). Equity should be made operational by specifying inclusive representation in preparedness planning, fair access to training and equipment, and safeguards so marginalised groups are not disproportionately assigned the most dangerous tasks.

Finally, preparedness will not reduce losses if combustible forest fuels continue to accumulate. Locally appropriate landscape and fuel management options that are designed with community acceptance and safety in mind, should be prioritised, particularly considering the financial and technical limitations faced by local communities. In many areas, indigenous knowledge systems and locally available resources can support prevention and early responses. However, increasingly severe forest fires can also place communities and frontline responders at significant risk, highlighting the need for stronger institutional support, training, protective equipment, and access to more specialised tools and operational capacities. Additionally, targeted learning partnerships can further help Nepal adapt proven elements of public warning and operational readiness to its federal and community forestry context.

CONCLUSION

Nepal's forest fire risk is no longer a seasonal issue, but a systemic governance challenge driven by the convergence of rising heat, fuel accumulation, human ignitions, and expanding exposure. The paper shows that the core gap is not the absence of information or local institutions, but the failure to convert these into timely, coordinated, and anticipatory action. Without such a shift, reactive response will continue to

produce escalating livelihood, health, and environmental losses.

The main opportunity is to build an end-to-end anticipatory fire risk system that links monitoring to action through clear roles, shared triggers, predictable preparedness financing, and practical coordination across all levels of government. Priority recommendations include strengthening community forestry institutions as supported local partners, establishing standard operating procedures and escalation arrangements, investing in locally appropriate fuel management and responder safety, and adapting relevant lessons from NSW to Nepal's federal and community forestry context.

Anticipatory fire governance is not a technical upgrade but rather a fundamental shift in how the state understands and manages risks. Without this shift, forest fires will continue to be treated as isolated seasonal events, even as their impacts become increasingly national in scale. With it, Nepal has a credible pathway to reduce losses, protect vulnerable communities, and align its forest and disaster governance systems with the realities of a changing climate.

Declaration of the use of AI: During the preparation of this manuscript, the authors used ChatGPT-4 to gather factual information and support editing for grammar and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the article.

REFERENCES

Australasian Fire and Emergency Service Authorities Council. (2022). *The Australian fire danger rating system*. <https://afdrs.com.au/>

- Agarwal, B. (2009). Gender and forest conservation: The impact of women's participation in community forest governance. *Ecological Economics*, 68(11), 2785–2799. <https://doi.org/10.1016/j.ecolecon.2009.04.025>
- Barik, A., & Baidya Roy, S. (2023). Climate change strongly affects future fire weather danger in Indian forests. *Communications Earth & Environment*, 4, 452. <https://doi.org/10.1038/s43247-023-01112-w>
- Bhujel, K. B., Sapkota, R. P., & Khadka, U. R. (2022). Temporal and spatial distribution of forest fires and their environmental and socio-economic implications in Nepal. *Journal of Forest and Livelihood*, 21(1), 1–13. <https://doi.org/10.3126/jfl.v21i1.56575>
- Cadman, T., Maraseni, T., Koju, U. A., Shrestha, A., & Karki, S. (2023). Forest governance in Nepal concerning sustainable community forest management and red panda conservation. *Land*, 12(2), 493. <https://doi.org/10.3390/land12020493>
- Chen, G., Guo, Y., Yue, X., Tong, S., Gasparrini, A., Bell, M. L., Armstrong, B., Schwartz, J., Jaakkola, J. J. K., Zanobetti, A., Lavigne, E., Nascimento Saldiva, P. H., Kan, H., Royé, D., Milojevic, A., Overcenco, A., Urban, A., Schneider, A., Entezari, A., ... Li, S. (2021). Mortality risk attributable to wildfire-related PM2.5 pollution: A global time series study in 749 locations. *The Lancet Planetary Health*, 5(9), e579–e587. [https://doi.org/10.1016/S2542-5196\(21\)00200-X](https://doi.org/10.1016/S2542-5196(21)00200-X)
- Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Jongman, B., Klose, T., & Suarez, P. (2015). Forecast-based financing: An approach for catalyzing humanitarian action based on extreme weather and climate forecasts. *Natural Hazards and Earth System Sciences*, 15(4), 895–904. <https://doi.org/10.5194/nhess-15-895-2015>
- Department of Forests and Soil Conservation. (2026). *Forest fire detection and monitoring system in Nepal* [Web portal]. Government of Nepal, Ministry of Forests and Environment.
- Dwyer, G., Marjoribanks, T., Morgan, F., & Farmer, J. (2025). Bushfire public inquiries: From recommendations to hybrid emergency management arrangements. *Australian Journal of Public Administration*, 84(2), 403–441.
- ForestAction Nepal. (2025a). *Strengthening forest fire management in Nepal* (Policy Brief No. 52). ForestAction Nepal.
- ForestAction Nepal. (2025b). *Fostering collaboration between community forestry and local government in Nepal* (Policy Brief No. 51). ForestAction Nepal.
- Gurung, A., Karki, R., & Bista, R. (2011). Community based forest management in Nepal: Opportunities and challenges. *Resources and Environment*, 1(1), 26–31.
- Hill, A., & Shrestha, M. (2026). Institutional fragmentation and forest fire management in federal Nepal: Bridging the governance gap through incident management systems. *Journal of Forest and Livelihood*. [Companion paper, this issue].
- Hollis, J. J., Matthews, S., Anderson, W. R., Cruz, M. G., Fox-Hughes, P., Grootemaat, S., ... & Sauvage, S. (2024). A framework for defining fire danger to support fire management operations in Australia. *International Journal of Wildland Fire*, 33(3), WF23141.
- Intergovernmental Panel on Climate Change. (2022). Asia. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the IPCC* (pp. 1457–1579). Cambridge University Press. <https://doi.org/10.1017/9781009325844.012>
- Kenny, B. J., Matthews, S., Sauvage, S., Grootemaat, S., Hollis, J. J., & Fox-Hughes, P. (2024). Australian fire danger rating system: Implementing fire behaviour calculations to forecast fire danger in a research prototype. *International Journal of Wildland Fire*, 33(4).
- Kuikel, S., Pokharel, B., & Bhattarai, N. (2024). The effect of wildfires on air quality in Kathmandu, Nepal. *Environmental Advances*, 15, 100493. <https://doi.org/10.1016/j.envadv.2024.100493>
- Lancet Countdown on Health and Climate Change. (2024). *The 2024 report of the Lancet Countdown on health and climate change — Nepal country profile*. Lancet Countdown on Health and Climate Change.

- Matin, M. A., Chitale, V. S., Murthy, M. S. R., Uddin, K., Bajracharya, B., & Pradhan, S. (2017). Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information systems and historical fire data. *International Journal of Wildland Fire*, 26(4), 276–286. <https://doi.org/10.1071/WF16056>
- McCoy, L., & Field, D. (2022). Lessons from the NSW RFS trial of the Australian fire danger rating system. *Australian Journal of Emergency Management*, 37(4).
- Mishra, B., Panthi, S., Poudel, S., & Ghimire, B. R. (2023). Forest fire pattern and vulnerability mapping using deep learning in Nepal. *Fire Ecology*, 19, Article 3. <https://doi.org/10.1186/s42408-022-00162-3>
- Moreira, F., Ascoli, D., Safford, H., Adams, M. A., Moreno, J. M., Pereira, J. M. C., Catry, F. X., Armesto, J., Bond, W., & González, M. E. (2020). Wildfire management in Mediterranean-type regions: Paradigm change needed. *Environmental Research Letters*, 15(1), 011001. <https://doi.org/10.1088/1748-9326/ab541e>
- NASA Earth Observatory. (2021, April 15). A fierce fire season in Nepal. NASA. <https://earthobservatory.nasa.gov/images/148185/a-fierce-fire-season-in-nepal>
- NASA Land, Atmosphere Near real-time Capability for EOS. (2026). *Fire information for resource management system (FIRMS)* [Database]. NASA LANCE.
- Nepali Times. (2023, May 13). More pre-monsoon forest fires in Nepal. *Nepali Times*.
- Nightingale, A. J. (2011). Bounding difference: Intersectionality and the material production of gender, caste, class, and environment in Nepal. *Geoforum*, 42(2), 153–162. <https://doi.org/10.1016/j.geoforum.2010.03.004>
- NSW Rural Fire Service. (2024). *Fire danger ratings and total fire bans in NSW*. <https://www.rfs.nsw.gov.au/fire-information/fdr-and-tobans>
- Parajuli, A., Gautam, A. P., Sharma, S. P., Lamichhane, P., Sharma, G., Bist, B. S., Aryal, U., & Basnet, R. (2022). A strategy for involving community forest managers in effective forest fire management in Nepal. *Banko Janakari*, 32(1), 41–51. <https://doi.org/10.3126/banko.v32i1.45476>
- Poudyal, B. H., Khatri, D. B., Paudel, D., Marquardt, K., & Khatri, S. (2023). Examining forest transition and collective action in Nepal's community forestry. *Land Use Policy*, 134, 106872. <https://doi.org/10.1016/j.landusepol.2023.106872>
- Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, 124(9), 1334–1343. <https://doi.org/10.1289/ehp.1409277>
- SERVIR-HKH/ICIMOD. (2020). *Forest fire detection and monitoring system in Nepal*. International Centre for Integrated Mountain Development.
- Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews*, 105(3–4), 71–100. <https://doi.org/10.1016/j.earscirev.2011.01.001>
- Tiwari, S., Paudel, N. S., Sze, J., & Karki, R. (2022). Unravelling the local dynamics of increasing fires in community forests of mid-hills of Nepal. *Journal of Forest and Livelihood*, 21(1), 60–71. <https://doi.org/10.3126/jfl.v21i1.56587>
- United Nations Office for Disaster Risk Reduction. (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030*. UNDRR.
- United Nations Office for Disaster Risk Reduction. (2023). *Report of the midterm review of the implementation of the Sendai Framework for Disaster Risk Reduction 2015–2030*. UNDRR.
- Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.). (2019). *The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people*. Springer. <https://doi.org/10.1007/978-3-319-92288-1>
- Whittaker, J., Haynes, K., Handmer, J., & McLennan, J. (2013). Community safety during the 2009 Australian 'Black Saturday' bushfires: An analysis of household preparedness and response. *International Journal of Wildland Fire*, 22(6), 841–849.



AUSTRALIAN
HIMALAYAN
FOUNDATION

