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

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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; Hagmann *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.

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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 land-use 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/ifor.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