Forest Fires in Tropical Deciduous Forests—A Precursor to Anticipatory Adaptation Framework

Jayshree Das and P. K. Joshi

Abstract Tropical deciduous forests provide habitat to a wide range of life forms and ecosystem services to mankind. Forest fires in these forests have become an environmental threat that challenges the vulnerability of ecosystems and communities in the immediate vicinity. These also contest the adaptation and resilience as they act as carbon sinks. However, at times forest fires in these Tropical deciduous forests become disastrous and such disasters are expected to increase with the predicted climate change scenarios. These uncontrolled fires often bring damage to the resources and services being provided by the forests. To curb the variety of damages due to fire, the implementation of fire management strategies and the identification of responsible factors is important for disaster risk reduction. Fire susceptibility mapping and modeling of the area provides a framework for the anticipatory adaptation and solution toward reducing the impact of forest fire disasters. The framework for susceptibility mapping guides monitoring and assessment of species richness, soil and vegetation interaction, and changes in the usage of non-timber forest products by the local communities. Though the distribution of fire susceptibility is highly dependent on the terrain conditions, the accessibility to the forest products is determined by their availability. This paradigm shift of forest dominant landscapes from the fire risk zones to community interactive landscapes would enhance the adaptation frameworks for the less studied disasters and their dynamics in the climate change scenarios.

Keywords Forest fire · Susceptibility mapping · Modeling · Adaptation

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1 Introduction

According to United Nations, wildfire or forest fire can be described as “any uncontrolled and non-prescribed combustion or burning of plants in a natural setting such as a forest, grassland, bushland or tundra, which consumes the natural fuels and spreads based on environmental conditions (e.g., wind, topography)”. The widespread distribution of fire contributed to the formation of biomes since 400–350 million years ago approximately (Chowdhury and Hassan 2015; Qadir et al. 2021). Fire plays an ecological dynamism in defining biological structure and function, influencing ecosystem, community, and biome (Bui et al. 2017; Mclauchlan et al. 2020). Recurrent fire events have direct positive and negative consequences on the ecosystem which impact biotic components (Chowdhury and Hassan 2015; Nami et al. 2018).

Recent fire events observed globally are due to two primary reasons, the first as a management tool (also known as prescribed fire) (Mclauchlan et al. 2020), and secondly human actions and climatic shifts are moving fire incidences and the frequency is increasing tremendously (Fox et al. 2016). While the former is avoided by forest managers due to ecological consequences (Mclauchlan et al. 2020), later led to snowballing forest fire incidences and large-scale destruction of biological organisms (Eskandari and Miesel 2017; Mclauchlan et al. 2020). Growing human settlement and developmental society has increased the demand for forest products which intensifies these events (de Belém Costa Freitas et al. 2017). Forest fire cascade carbon cycle which provokes climate change and increases the risk for forest ecosystem with increased biomass accumulation, drought condition, and rising temperature (Feurdean et al. 2017; Briones-Herrera et al. 2019). This builds up the need of predicting future forest fire incidences and understand the priorities of ecological factors to maintain the integrity of multi-functional forests.

Alarming fire events in recent days press the need to understand fire behavior with altering climatic variables and human action (Bui et al. 2017; Eskandari and Chuvieco 2015). In this chapter we present a perspective, on how various ecological components regulate forest fire and vice-versa; the importance of modeling toward prediction of future forest fire—an adaptation strategy, to assist in forest management, early warning system, and resource allocation. We present how the coupling of spatial and temporal satellite remote sensing data for factors, and modeling approaches help to understand the site-specific risk of a forest fire. Our overall perspective is understanding the increased intensity of forest fires, the contribution of biota, biophysical and human action toward the recurrent fire, and predicting increased risk of fire frequency, intensity, regimes, and susceptibility. We would also confer a better modeling approach through comparison study between statistical or weighted modeling and machine learning approach (Fig. 1).

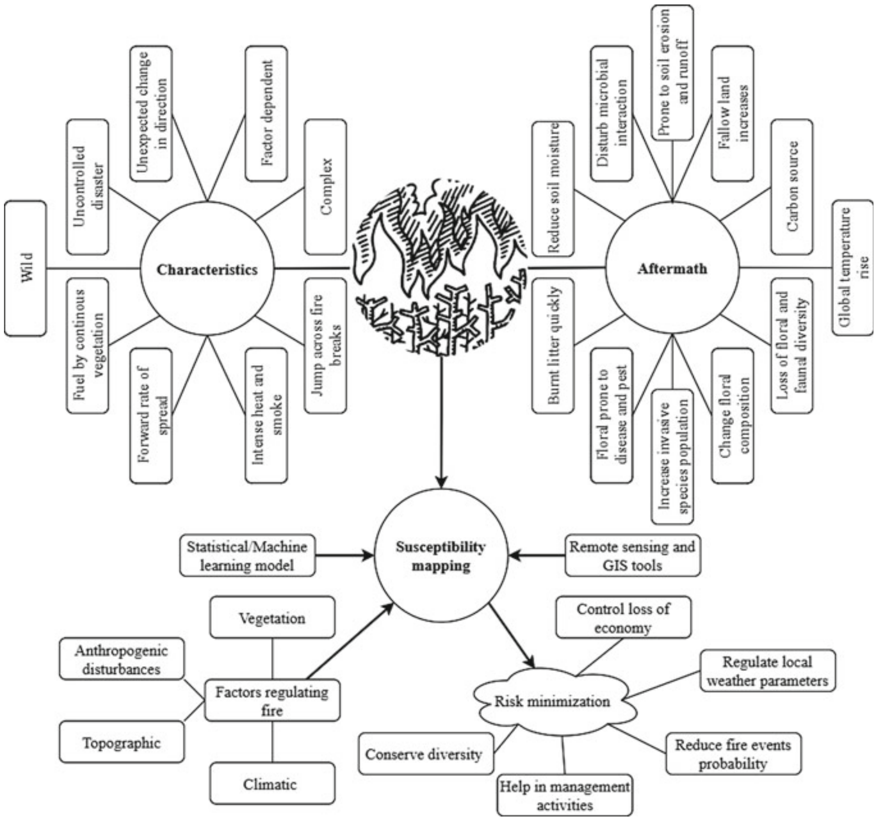

Fig. 1 Forest fire characterization and step to curb the consequences of fire

2 Characterizing Forest Fire Factors

Forest fire is a complex phenomenon that can be well explained from the conceptual model of the "fire regime triangle" (Davis et al. 2017). Nevertheless, fire frequency and intensity are dependent on some fundamental units—fuel supply by predominant forest structure, prevailing topography, climatic condition, and igniting agent (Eskandari and Miesel 2017; Feurdean et al. 2017; Chitale and Behera 2019)—which varies according to spatial and temporal scales. These units are identified as crucial factors to regulate fire actions across the globe.

2.1 Vegetation Composition

Recurrent forest fire events are considered to be the driving force behind the existing structure and composition of biotic communities in terrestrial ecosystems (Mclauchlan et al. 2020). From historical lineages, fire is considered a vital force in the natural selection of biotic communities and other organisms in an ecosystem, landscape, or biome. Studies describe plants have fire-adaptive traits in the evolutionary process like post-fire recruitment, re-sprouting, and fire-resistant or fire promoting (Feurdean et al. 2017; Mclauchlan et al. 2020), which can be recognized from a detailed analysis of phylogeny. Large forest fires occur due to the availability of fuel load produced by existing forest types which is the result of afforestation program, lack of management practices, and migration (Duarte and Teododo 2016; Alcasena Urdíroz et al. 2018; Briones-Herrera et al. 2019). Fuel load management strategy reduces forest fire incidences in vegetation due to fire suppression activities leading to a larger fire in extreme climatic conditions (Fox et al. 2016). A study conducted to understand fuel characteristics in different fire ecosystems shows that tropical forests with heavy fuel loaded moisture restrict ignition more than limited fuel with dry spells (Briones-Herrera et al. 2019). Fuel moisture affects fire as it increases ignition delay time and decreases flame emissivity (Duarte and Teododo 2016).

In tropical forests, fire events can be limited by higher precipitation and fuel moisture (Briones-Herrera et al. 2019). However biotic diversity also affects fire characteristics, broad-leaved deciduous forests have high leaf moisture contributing to a moister microclimate and lower content of flammable volatile compounds, which reduce fire incidences compared to the boreal forest (Feurdean et al. 2017). Fuel dryness connecting active forest increases risk by including multi-variants effects of climate, anthropogenic slash, and burn activity. Understanding the relationship between vegetation structure and composition fuel load production with fire across the globe and future prediction modeling is a difficult task for researchers. The absence of past fire event details makes it tedious to explain the link between fire and vegetation diversity.

2.2 Topography

Fire behavior is quite highly influenced by topography as it is usually static with a time scale (Chowdhury and Hassan 2015). Topography which includes aspect, elevation, and slope, affects fuel and weather change which regulates the spread of forest fire accordingly (de Belém Costa Freitas et al. 2017). A steeper slope accelerates the rate of ignition and fire spread increases toward a higher slope. In the northern hemisphere, the south and southwest aspects provide favorable conditions for fire ignition due to high fuel temperature, lower humidity, and higher sunshine period (Mclauchlan et al. 2020). Lower chances of forest fire in higher elevations are affected by precipitation, wind direction, and speed. Extreme human activities and changing land-use patterns can accelerate a forest fire.

2.3 Climatic Condition

Recent climatic variations as a result of the global climate change phenomenon are extremely conducive to the ignition of fire (Fox et al. 2015; Davis et al. 2017; Briones-Herrera et al. 2019). Climatic variables that affect fire regions show temporal variations ranging from short-duration weather to climatic change over centuries. On a global scale, fire weather index prediction shows around 33–62% of burnable areas by the mid-twenty-first century in comparison to 22% in 2019 (Abatzoglou et al. 2019). Fire season with a widespread fuel load supports recurrent fire events and spreads over a large spatial scale. Large drought spell or rising temperature, wind characteristic, precipitation level, relative humidity, and moisture content in fuel loaded zone provoke or reduce fire intensity over a region (Fox et al. 2015; Yang et al. 2015; Bui et al. 2016). Favorable climate parameters with fuel restricted or fuel limited zone even have reduced fire events. Antecedent rainfall in a forest ecosystem brings a good flush of foliage, widespread deposition of fuel is made available. Climatic conditions within and across an ecosystem describe changes in the type and structure of biotic components with a shift of climate over temporal scale (Chitale and Behera 2019). Fuel-loaded zone with moisture that is not prone to fire, shift to higher fire risk when there is a rise in a dry spell with restricted moisture content. Fire and climate relationship can be summarized from climatic variables like temperature, precipitation, and change in their pattern which affect fuel availability.

2.4 Anthropogenic Intervention

Human interference in the natural ecosystem influences fire incidents by adding greenhouse gases to the atmosphere leads to global warming, changing land-use patterns affect fuel load structure, composition, and continuity, altering frequency and distribution of ignition sources, and intentional ignition for agriculture as a sole motto (Eskandari and Chuvieco 2015). Studies carried out to analyze fire risk show a positive relation between fire occurrence and human influence index (Eskandari and Chuvieco 2015; Marques et al. 2021). Anthropogenic influences had no significant impact on ignition probability, but they did have a significant positive indirect effect on the likelihood of forest fires through fire policy (Xiong et al. 2020).

In many parts of the world known for the ignition of fire due to the natural cause has been replaced by assertive human actions as input. Fire suppression activities increase fuel load and allow interference of invasion into the non-pyrogenic

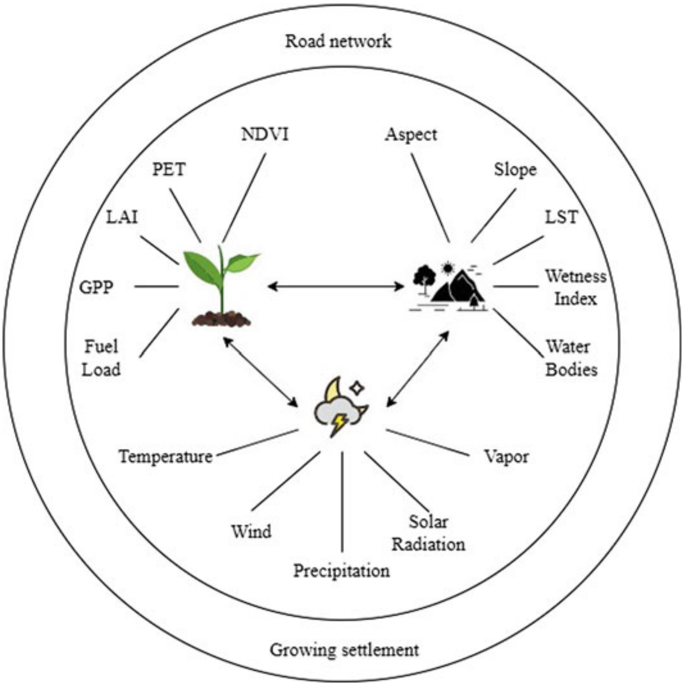

Fig. 2 Factors contributing to forest fire (Inner circle—Natural component, Outer circle—Anthropogenic component)

ecosystem, menacing fire-adaptive ecosystem (Mclauchlan et al. 2020). Anthropogenic impact on the natural ecosystem and climatic change have a greater influence on wildfire, growing duration of fire season (Kauffman and Uhl 1990; Marques et al. 2021). While fuel discontinuity or fuel restriction due to human action reduces fire frequencies accordingly. Land-use change disturbs widespread fuel availability which controls the increase or cut in incidents. It is a major challenge for forest managers to identify anthropogenic influence at multilevel ecosystem organizations with varying socio-economic demands in a region (Fig. 2).

2.5 Changing of Susceptibility in Relation with Factors Contributing

Forest fire incidence, susceptibility, spread, and risk can be understood when ecological and anthropogenic factors relevant to forest fire are known (Adab et al. 2013). Site-specific zonation according to fire susceptibility changes with the change in fire affecting factors. The factors describe fire intensity, severity, the spatial extent of burned area, and lengthening of fire season. Fire prediction studies show a large number of fire events occur in a forest area with a high number of summer days without rain, population size, and topographic features (Boubeta et al. 2015). Different characteristics of fire impact biotic components by affecting establishment, survival, reproduction, and mortality; disturbing ecological interactions (Fox et al. 2015).

3 Ecological Consequences of Forest Fire

Forest fire is a physical force regulating ecosystem and composition at a global spatial scale. From the historical period, it is being evident that forest fire destroys biotic diversity, release captured carbon, and impact climatic condition (Fox et al. 2016). Changing fire susceptibility and frequency interferes with the plant life cycle from the establishment to mortality, developing plant adaptive traits, and introduction of invasive species. Increasing fire activities reduce carbon storage in terrestrial ecosystems and increase global warming making the plant community more prone to fire, changing albedo, and upsurge concentration of GHGs and aerosol. Soil is a relatively large terrestrial carbon pool, nutrient, and microbial source which are highly prone to combustion. Rather than natural components, increasing fire frequency and spread put risk on the socio-economic profile of dwelling communities, disease, and loss of lives (Chowdhury and Hassan 2015).

3.1 Impact on Plant Diversity

Fire and plant diversity are interconnected and directly impact each other. While fuel load and continuity provoke the occurrence of forest fire, post events stimulate ecological succession, development of plant adaptation traits, and provoke global warming by significantly adding up CO_2 to the atmosphere (Eskandari and Chuvieco 2015). This shows fire can alter plant association, disturbing ecological systems. Global warming makes conditions favorable to increase fire frequency and affect flammable species. Fire-plant interaction effects are visible with post-fire species establishment, growth, reproduction, dispersal and seed treatment, crown cover and mortality, and surviving species association (Chitale and Behera 2019). Dry spell with strong wind spread fire over large patch engulfing newer forest not prone to the disaster. Fire suppression encourages plant community establishment and better canopy development. Interaction within plant community and fire has both positive and negative feedback mechanisms. But it is difficult to foresee future climax communities in an ecosystem because of interaction as it varies with changing climate, land fragmentation and encroachment, forest type and structure, invasive species introduction, and prevailing disturbances.

3.2 Impact on Soil Community

Fire may contribute toward soil formation, increasing runoff and erosion which disturb soil nutrients and microbial action in soil (Fox et al. 2016). Recurrent fire incidences, behavior, and spread affect soil structure and composition, altering physiochemical characteristics, organic nutrients, C pool or flux, pyrogenic reaction, and activity of soil biota in comparison to unburnt or control sites. Combustion and pyrolysis destroy upper strata nutrient content while lower layers are also affected by heat flow. Plant communities are the first to show the effect of changing soil characters, further affecting ecosystem structure and function, community. Soil microbial population, biomass content, and mycorrhizal association are infected according to change in fire severity and spread. The effect on the microbial population is persistent over a long period and disturbs the association of microbes within the ecosystem. Recently studies are carried on microbial nutrient content analysis and their association with plant growth, but the focus is needed toward analyzing the synergistic effect of fire and any other disaster like global warming, reduced rainfall, or anthropogenic interference.

4 Susceptibility Modeling and Mapping

Fire prevention and suppression activities followed traditionally proved to be ineffective with Spatio-temporal limitations (Alcasena Urdíroz et al. 2018). Mapping and modeling of forest fire help in the prediction of future incidents, forest managers in taking necessary prevention measures, formulation of fire control policies (Boubeta et al. 2015), and developing fire resilient ecosystems (Alcasena Urdíroz et al. 2018). It focuses on the development of various prediction modes, which explain the challenging pattern of various fire relating variables with a forest fire.

4.1 Fire and Remote Sensing

Using satellite imagery enables researchers to have brief information about a forest fire in remote locations to ecosystems around the globe (Abdollahi et al. 2018). Advancement of temporal and spatial resolution of satellite imagery provides recorded descriptions of recent fire incidences by preparing susceptibility zonation maps (Eugenio et al. 2016). These imageries convey information of geographical coordinates, time, extent, and seasonality which help to analyze the direct links between biotic components and soil properties. Integration of satellite-based remote sensing approach and past ignition records has been proved by researchers to be a successful tool in the prediction of future forest fire events and risk (Abdollahi et al. 2018). It helps to understand the ecological impact, economic damage, and improve strategies toward management planning, fire suppression activities, or fuel treatment (Briones-Herrera et al. 2019). Rather than fire information it also provides precise information about multiple factors regulating ignition, explaining causal-effect relation. Better spatial and temporal resolution and extrapolation of cloud-contaminated images can be deciphered with higher prediction efficiency (Chowdhury and Hassan 2015). Above all aids, the tool is spanning over the past few decades, lacks paleo-ecological facts about the assessment of wildfire regimes and their impact on the ecosystem. The satellite also has other limitations like restricted temporal and spatial extent, characterizing fire intensity, and detecting fire especially active ones. Addressing these challenges would support forest managers and researchers to curb recurrent wildfire and loss of biodiversity.

4.2 Forest Fire and Prediction Modeling

Understanding the need to curb alarming tropical forest fire events, researchers used various modeling approaches to predict future fire events and increased susceptibility of a site with varying ecological factors and anthropogenic interference. Simple to sophisticated modeling approaches are applied to assess forest fires. Some studies were carried out in different regions of the world (Adab et al. 2013; Boubeta et al. 2015; Duarte and Teododo 2016; Bui et al. 2016; Eskandari and Miesel 2017; Bui et al. 2017; Abdollahi et al. 2018; Alcasena Urdíroz et al. 2018; Briones-Herrera et al. 2019; Abedi Gheshlaghi et al. 2020; Bui et al. 2019) to explain factors contributing to forest fire and forecast future risk associated with site-specific. Statistical models fit well with different scales and resolutions of remote sensing data over a large region (Bui et al. 2017). Forest fire susceptibility mapping studies found that modeling using a machine learning approach to be more efficient than weighted models. The application of the machine learning approach generated better results in explaining the complex relationship between forest fire and various factors with higher accuracy (Bui et al. 2016). A study done to assess tropical forest fire susceptibility using Particle Swarm Optimized Neural Fuzzy (PSO-NF) (Bui et al. 2017) was found to perform better than other machine learning algorithms. Kernel logistic modeling was found to be a promising tool for forest fire susceptibility mapping in tropical forest types (Bui et al. 2016). Prediction modeling and mapping of forest fire occurrence from above ground carbon density in different ecoregions could be used for spatial fire occurrence mapping, integrating with GIS tools to estimate fire danger mapping and strategies for proper fuel management (Briones-Herrera et al. 2019). Nevertheless, limitations of remote sensing data over scale and resolution hinder the performance of the machine learning approach and emphasis the development of new prediction modeling to improve prediction accuracy and precision (Fig. 3).

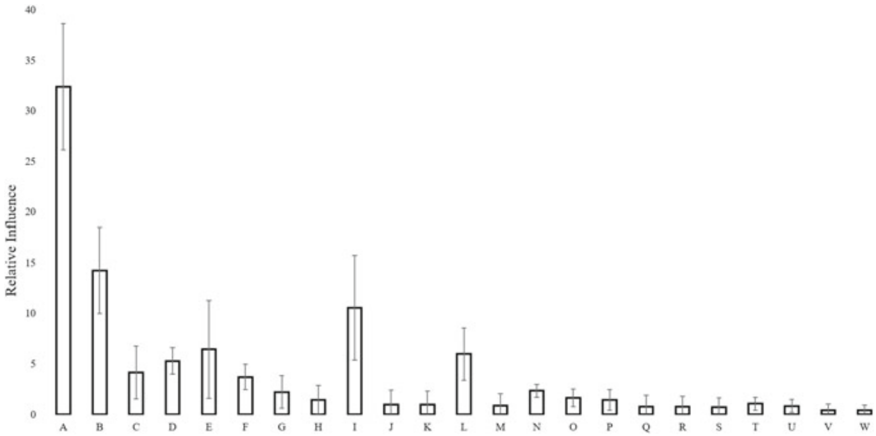

Fig. 3 Relative influence of variables toward the occurrence of forest fire computed using machine learning models (A—Vegetation, B—Temperature, C—Solar radiation, D—Normalized Difference Vegetation Index (NDVI), E—Normalized Difference Water Index (NDWI), F—Elevation, G—Land Surface Temperature (LST), H—Distance from the road, I—Leaf area index (LAI), J—Distance from the settlement, K—Distance from the railway, L—Distance from water, M—Precipitation, N—Wind speed, O—Slope, P—Topographic wetness index (TWI), Q—Aspect)

5 Need of Anticipatory Adaptation Strategy

In general, forest ecosystems have a high capacity for adaptation via community change and natural selection; however, natural processes may be slower than in anthropogenic systems and may not keep up with rapidly changing conditions. Adaptation strategies can either reduce a hazard exposure by containing or controlling it, or decrease susceptibility and increase the capacity to cope, adapt, or benefit from the effects of a hazard (or multiple hazards) through a variety of practices, including those taken before and after impacts are noticed (Devisscher et al. 2016). A proper assessment of risks to ecosystem services, determination of the level of fire vulnerability at the ecosystem and administrative unit, a climate-based early warning system to inform policymakers of high-risk areas, an appropriate incentive and/or penalty scheme to change behavior toward responsible fire use, and sustainable forest management practices in high-risk areas are all characteristics of an anticipatory fire management approach (Kieft et al. 2016). Fire adapted strategies are community-based initiatives that rely on inhabitants to play an integral part in reducing wildfire risk (Steelman 2016). Heterogeneity is also gaining traction as a strategy for enhancing ecosystem resilience. Diversity of vegetative type, stand structure, and successional age classes, as well as patch mosaic burning, have been advocated for biodiversity conservation. Further adaptation strategy is risk management, which employs assessment, mitigation measures, and forest fire inhibition practices to reduce the loss of structures, economic and ecological values of forests due to wildfire (Spies et al. 2014).

A major challenge in encouraging adaptation in fire-prone landscapes is the juxtaposition of a forest ecosystem that is dependent on ephemeral damage and regrowth of biomass, local plant and animal populations, and an anthropogenic system that prefers structural strength, predictability of socio-economic complexities, and potential human protection (Spies et al. 2014). Feedback between the natural and human systems is a crucial barrier to understanding, modeling, and developing adaptive behaviors in fire-prone landscapes. Policies, strategies, and programs may be adopted at different administrative levels to create consistent incentives for action, but institutionalization may take a long time (Steelman 2016).

6 Future Scope

Fire is a complex process in a forest ecosystem regulated by various factors. More carbon in the atmosphere, higher temperatures, less snow, lower humidity, more extreme fire, changing landscapes, more values at risk, more property damage, more fire crews at risk, and more reactive spending are all possible outcomes. Forest fire susceptibility modeling and mapping help to understand how it fits in the present and future socio-ecological conditions and minimize the shift of susceptibility to next higher level with leading changes in climatic parameter or anthropogenic interference.

Our goals should be a predictive forest fire management system that can help to create more socially and ecologically resilient landscapes. Anticipatory fire management would facilitate the identification and implementation of critical actions months before a fire event to minimize the risk of an outbreak. We need policies and practices that are in accordance with the social and ecological realities of such regions where forest fires are anticipated to be a problem. The way forward requires a multi-prolonged, ecosystem-based, and predictive approach is necessary for long-term fire reduction and sustainable forest management. The fundamental premise of anticipatory adaptation is based on preparedness to respond to potential ways in which future forest fire regimes may unfold. This would assist in climate change adaptation and disaster risk reduction in the tropical deciduous forests ecosystem in particular and the adjoining communities at large.

References

Abatzoglou JT, Williams AP, Barbero R (2019) Global emergence of anthropogenic climate change in fire weather indices. Geophys Res Lett 46(1):326–336

Abedi Gheshlaghi H, Feizizadeh B, Blaschke T (2020) GIS-based forest fire risk mapping using the analytical network process and fuzzy logic. J Environ Plann Manag 63(3):481–499

Abdollahi M, Islam T, Gupta A, Hassan QK (2018) An advanced forest fire danger forecasting system: integration of remote sensing and historical sources of ignition data. Remote Sens 10(6):923

Adab H, Kanniah KD, Solaimani K (2013) Modeling forest fire risk in the northeast of Iran using remote sensing and GIS techniques. Nat Hazards 65(3):1723–1743

Alcasena Urdíroz FJ, Ager AA, Salis M, Day MA, Vega García C (2018) Optimizing prescribed fire allocation for managing fire risk in central Catalonia. Sci Total Environ 621:872–885

Boubeta M, Lombardía MJ, Marey-Pérez MF, Morales D (2015) Prediction of forest fires occurrences with area-level Poisson mixed models. J Environ Manage 154:151–158

Briones-Herrera CI, Vega-Nieva DJ, Monjarás-Vega NA, Flores-Medina F, Lopez-Serrano PM, Corral-Rivas JJ, Carrillo-Parra A, Pulgarin-Gámiz MÁ, Alvarado-Celestino E, González-Cabán A, Arellano-Pérez S, Álvarez-González JG, Ruiz-González AD, Jolly WM (2019) Modeling and mapping forest fire occurrence from aboveground carbon density in Mexico. Forests 10(5):402

Bui DT, Le TKT, Nguyen CV, Le DH, Revhaug I (2016) Tropical forest fire susceptibility mapping at the Cat Ba National Park Area, the Hai Phong city (Vietnam) using GIS-based kernel logistic regression. Remote Sens 8(4):1–15

Bui DT, Bui QT, Nguyen QP, Pradhan B, Nampak H, Trinh PT (2017) A hybrid artificial intelligence approach using GIS-based neural-fuzzy inference system and particle swarm optimization for forest fire susceptibility modeling at a tropical area. Agric For Meteorol 233:32–44

Bui DT, Hoang ND, Samui P (2019) Spatial pattern analysis and prediction of forest fire using new machine learning approach of multivariate adaptive regression splines and differential flower pollination optimization: a case study at Lao Cai province (Viet Nam). J Environ Manage 237:476–487

Chitale V, Behera MD (2019) How will forest fires impact the distribution of endemic plants in the Himalayan biodiversity hotspot? Biodivers Conserv 28(8):2259–2273

Chowdhury EH, Hassan QK (2015) Operational perspective of remote sensing-based forest fire danger forecasting systems. ISPRS J Photogramm Remote Sens 104:224–236

Davis R, Yang Z, Yost A, Belongie C, Cohen W (2017) The normal fire environment—modeling environmental suitability for large forest wildfires using past, present, and future climate normals. For Ecol Manage 390:173–186

de Belém Costa Freitas M, Xavier A, Fragoso R (2017) Integration of fire risk in a sustainable forest management model. Forests 8(8):1–20

Devisscher T, Boyd E, Malhi Y (2016) Anticipating future risk in social-ecological systems using fuzzy cognitive mapping: the case of wildfire in the Chiquitania, Bolivia. Ecol Soc 21(4)

Duarte L, Teododo AC (2016) An easy, accurate, and efficient procedure to create forest fire risk maps using the SEXTANTE plugin Modeler. J for Res 27(6):1361–1372

Eskandari S, Chuvieco E (2015) Fire danger assessment in Iran based on geospatial information. Int J Appl Earth Obs Geoinf 42:57–64

Eskandari S, Miesel JR (2017) Comparison of the fuzzy AHP method, the spatial correlation method, and the Dong model to predict the fire high-risk areas in Hyrcanian forests of Iran. Geomat Nat Haz Risk 8(2):933–949

Eugenio FC, dos Santos AR, Fiedler NC, Ribeiro GA, da Silva AG, dos Santos ÁB, Paneto GG, Schettino VR (2016) Applying GIS to develop a model for forest fire risk: a case study in Espírito Santo, Brazil. J Environ Manage 173:65–71

Feurdean A, Veski S, Florescu G, Vannière B, Pfeiffer M, O'Hara RB, Stivrins N, Amon L, Heinsalu A, Vassiljev J, Hickler T (2017) Broadleaf deciduous forest counterbalanced the direct effect of climate on Holocene fire regime in hemiboreal/boreal region (NE Europe). Quatern Sci Rev 169:378–390

Fox DM, Martin N, Carrega P, Andrieu J, Adnès C, Emsellem K, Ganga O, Moebius F, Tortorollo N, Fox EA (2015) Increases in fire risk due to warmer summer temperatures and wildland urban interface changes do not necessarily lead to more fires. Appl Geogr 56:1–12

Fox DM, Laaroussi Y, Malkinson LD, Maselli F, Andrieu J, Bottai L, Wittenberg L (2016) POST-FIRE: a model to map forest fire burn scar and estimate runoff and soil erosion risks. Remote Sens Appl Soc Environ 4:83–91

Kauffman JB, Uhl C (1990) Interactions of anthropogenic activities, fire, and rain forests in the Amazon Basin. In: Fire in the tropical biota. Springer, Berlin, Heidelberg, pp 117–134. https://doi.org/10.1007/978-3-642-75395-4_8
Kieft J, Smith T, Someshwar S, Boer R (2016) Towards anticipatory management of peat fires to enhance local resilience and reduce natural capital depletion. In: Ecosystem-based disaster risk reduction and adaptation in practice. Springer, Cham, pp 361–377. https://doi.org/10.1007/978-3-319-43633-3_16
Marques JF, Alves MB, Silveira CF, e Silva AA, Silva TA, Dos Santos VJ, Calijuri ML (2021) Fires dynamics in the Pantanal: Impacts of anthropogenic activities and climate change. J Environ Manage 299:113586
Mclauchlan KK, Higuera PE, Miesel J, Rogers BM, Schweitzer J, Shuman JK, Tepley AJ, Varner JM, Veblen TT, Adalsteinsson SA, Balch JK (2020) Fire as a fundamental ecological process: research advances and frontiers. J Ecol 108(5):2047–2069
Nami MH, Jaafari A, Fallah M, Nabiuni S (2018) Spatial prediction of wildfire probability in the Hyrcanian ecoregion using evidential belief function model and GIS. Int J Environ Sci Technol 15(2):373–384
Qadir A, Talukdar NR, Uddin MM, Ahmad F, Goparaju L (2021) Predicting forest fire using multispectral satellite measurements in Nepal. Remote Sens Appl Soc Environ 100539
Spies TA, White EM, Kline JD, Fischer AP, Ager A, Bailey J, Bolte J, Koch J, Platt E, Olsen CS, Jacobs D (2014) Examining fire-prone forest landscapes as coupled human and natural systems. Ecol Soc 19(3)
Steelman T (2016) US wildfire governance as social-ecological problem. Ecol Soc 21(4)
Xiong Q, Luo X, Liang P, Xiao Y, Xiao Q, Sun H, Pan K, Wang L, Li L, Pang X (2020) Fire from policy, human interventions, or biophysical factors? Temporal–spatial patterns of forest fire in southwestern China. For Ecol Manage 474:118381
Yang W, Gardelin M, Olsson J, Bosshard T (2015) Multi-variable bias correction: application of forest fire risk in present and future climate in Sweden. Nat Hazard 15(9):2037–2057