




ORIGINAL RESEARCH

Open Access



Climate and humans interact to shape the fire regime of a chir pine (*Pinus roxburghii*) forest in eastern Bhutan

Karma Tenzin^{1*} , Craig R. Nitschke¹, Kathryn J. Allen^{1,4}, Paul J. Krusic², Edward R. Cook³, Thiet V. Nguyen^{1,5} and Patrick J. Baker¹

Abstract

Background Chir pine (*Pinus roxburghii* Sarg.) forests are distributed in the dry valleys of Bhutan Himalaya. In the past, these forests have been heavily influenced by human activities such as grazing, burning, resin tapping, and collection of non-timber forest products. Bhutan's Forest Act of 1969, which shifted forest management from local community control to centralized governmental control, greatly restricted these activities. To understand the implications of the Forest Act on the chir pine forests, we used tree-rings and fire scars to reconstruct the fire history of a chir pine forest in eastern Bhutan. This provided an opportunity to characterize the fire regime before and after the Forest Act of 1969 was implemented and assess the scale and magnitude of changes that have occurred.

Results We developed a 120-year chir pine fire chronology from nine sites within a single forested landscape. Between 1900 and ~1970, fires were small and patchy. When fires occurred, they were limited to one to two sites within the larger study area. After 1970, there was a distinct shift in fire activity, with fires in 1985, 1989, 1996, 2000, and 2013 burning > 90% of sample plots. Fire activity was positively associated with La Niña conditions (wetter, cooler) in the preceding year. This is likely the result of increased accumulation and connectivity of fuels on the forest floor in wetter years.

Conclusions Prior to 1970, the fire regime in the studied chir pine landscape in eastern Bhutan was dominated by patchy, low-intensity fires indicating that the fire regime was fuel limited. After 1970, fires became larger and more frequent. This shift was associated with the enactment of the Bhutan Forest Act in 1969, which regulated grazing and implemented a policy of strict fire exclusion in government-reserved forests. This likely led to a large buildup of fuels, particularly after La Niña years. Historical patterns of grazing and low-intensity fires prior to the Forest Act kept fuel loads low and disconnected. The cessation of most human activities in these forests after 1969 resulted in an increase in fuel loads and connectivity within the landscape. This has greatly reshaped fire regimes in the chir pine forests of eastern Bhutan over the past half century.

Keywords Climate, Dendroecology, El Niño, Fire regime, Fire scars, Himalaya, La Niña

Resumen

Antecedentes Los bosques de pino chir, o pino indio de hoja larga (*Pinus roxburghii* Sarg.) están distribuidos en los valles secos del Himalaya en Bután. En el pasado, estos bosques fueron fuertemente influenciados por actividades

*Correspondence:

Karma Tenzin

tenzink@student.unimelb.edu.au

Full list of author information is available at the end of the article



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

humanas como el pastoreo, fuegos, colección de resinas, y recolección de productos no forestales. La ley forestal de Bután de 1969, que cambió el manejo forestal desde el control comunitario local a uno ejercido por las autoridades gubernamentales centrales, restringió fuertemente esas actividades. Para entender las implicancias de esta ley forestal sobre los bosques de pino chir, usamos los anillos de crecimiento y cicatrices de fuego para reconstruir la historia de fuego en un bosque de pino chir en el este de Bután. Esto proveyó de una oportunidad para caracterizar el régimen de fuegos antes y después que la aplicación de esta ley forestal fuera implementada en 1969, y determinar así la escala y magnitud de los cambios ocurridos.

Resultados Desarrollamos una cronología del pino chir de 120 años en nueve sitios dentro de un paisaje de bosque uniforme. Desde 1900 y hasta 1970, los incendios fueron pequeños y ocurrían en parches. Cuando estos ocurrían, estaban limitados a 1–2 sitios dentro de la gran área de estudios. Después de 1970, hubo un cambio distintivo en la actividad de los incendios, con ocurrencia en los años 1985, 1989, 1996, 2000, y 2013, quemando > 90% de las parcelas de muestreo. La actividad de los incendios fue asociada positivamente con condiciones de la Niña (más húmedas y frías) en el año precedente al evento de incendio. Este es probablemente el resultado de una acumulación incremental y mayor conectividad del combustible en el suelo forestal en años húmedos.

Conclusiones Antes del año 1970, el régimen de fuego en el paisaje de pino chir estudiado en el este de Bután, estaba dominado por fuegos de baja intensidad y que ocurrían en parches, indicando que ese régimen estaba limitado por la disponibilidad del combustible. Luego de 1970, los incendios comenzaron a ser más frecuentes y abarcaban mayores superficies. Este cambio estuvo asociado con la puesta en vigencia de la Ley Forestal de 1969, que regulaba el pastoreo e implementaba una política estricta de exclusión del fuego en reservas forestales gubernamentales. Esto llevó a un gran crecimiento y acumulación de combustibles, particularmente luego de años Niña. Los patrones históricos de pastoreo y baja intensidad de los incendios previos a la puesta en vigencia de la Ley forestal, mantenían la carga de combustibles a niveles bajos y desconectados entre sí dentro de ese paisaje. La implementación de esta ley reconfiguró dramáticamente los regímenes de fuego en los bosques de pino chir en el este de Bután en los últimos 50 años.

Background

Fire regimes vary over space and time and across multiple scales and are influenced by a range of factors (Baisan and Swetnam 1990; Bradstock 2010). At broad biogeographic scales, climate shapes fire regimes (McKenzie et al. 2004; Littell et al. 2009), influencing factors such as fire frequency, intensity, and seasonality (Dale et al. 2001; Beniston 2003). However, at local and regional scales, human activity may be equally important in determining the nature of fire regimes (DeWilde and Chapin 2006). At the local scale, people may reduce fuel loads through prescribed burning, grazing, and firewood collection. They may also increase the number and spatial distribution of ignitions within a landscape (e.g., Nguyen et al. 2023). At regional scales, land-use patterns (e.g., swidden agriculture) and forest policy may influence fire regimes by changing fuel structures and ignition sources through fire management and suppression practices (Liu et al. 2010; Liu and Wimberly 2015; Archibald 2016; Nguyen et al. 2023).

In many parts of the world, the historical use of fire to promote grazing and agriculture has significantly altered fuel loads and patterns, which in turn has impacted fire intensity and spread (Swetnam and Betancourt 1998). In the chir pine (*Pinus roxburghii* Sarg.) forests of Bhutan, a long history of human activity, through grazing, burning,

resin tapping, and lemon grass (*Cymbopogon flexuosus* Steud.) harvesting, has provided essential income, both cash and non-cash, to support rural livelihoods (Choden et al. 2021; Yeshey et al. 2022; Wangchuk et al. 2023). These practices were commonplace in Bhutan for at least 500 years. However, the Bhutanese government nationalized the country's forests under the Forest Act of 1969 (RGOB 1969), transforming land-use management across Bhutan and profoundly altering many aspects of the structure and dynamics of Bhutan's forests (Rosset 1999). Prior to 1969, farmers engaged in shifting cultivation and pasture management practices that included the controlled burning of forest undergrowth (Dorji et al. 2006). However, after the nationalization of forests, the use of forest resources, whether directly (e.g., firewood) or indirectly (e.g., grazing, burning), by local communities was heavily constrained (Dorji et al. 2006).

In other parts of the world, changes in forest policy have had profound consequences on fire regimes. For example, in western North America, the institutionalization of strict fire suppression policies in the early 1900s has led to shifts in forest structure and composition. This has led to a shift from relatively frequent, low severity fires to infrequent, but more intense and severe fires in fuel-limited systems (Steel et al. 2015). In the late 1800s and early 1900s, British colonial

forest management in India promoted fire suppression to protect forest regeneration, but also led to a fundamental alteration of forest structure and composition (Troup 1921). Bhutan's change in forest policy was implemented much more recently than in western North America and India. However, there have been no attempts to understand the potential implications of this national policy shift on the forests and fire regimes of Bhutan. After 55 years, the consequences, if any, of those changes should be apparent.

To understand how the Forest Act of 1969 might have influenced the forests and fire regimes of Bhutan over the past half century, it is necessary to reconstruct the history of fire activity before and after the implementation of the forest policy. Tree rings provide a well-established tool for reconstructing past fire regimes and disentangling various potential drivers such as climate and land-use history. However, only a few studies have attempted to reconstruct fire regimes and their drivers in Asian forests, and these have been largely restricted to high-latitude sites. For example, Bigio et al. (2022) investigated how land-use activities and regional drought have influenced historical fire regimes in Siberia, providing valuable insights into the complex interactions between human activities and climate factors. Hessel et al. (2016) examined the relationship between fire and climate in Mongolia over several centuries, offering a comprehensive perspective on long-term fire dynamics in a changing environment.

Similarly, Saladyga et al. (2013) explored the effects of privatization, drought, and fire exclusion in the Tuul River watershed of Mongolia. The few existing fire studies from Bhutan have focused on understanding contemporary fire frequency, tree regeneration responses, the impact of fire on soil structure (Chhetri 1994; Sangye 2005; Delma 2011), and mapping areas prone to forest fires (Tshering et al. 2020). There is a lack of published research on historical forest fire dynamics in the eastern Himalayan region of Bhutan (Tshering 2006). In Bhutan, documented forest fire records date back to only the early 2000s and have poorly demarcated fire boundaries (DoFPs 2014). These issues limit insights that fire history mapping can have on understanding the various drivers of fire activity in the region. Brown et al. (2011) highlighted the considerable potential for developing long-term fire histories in the Himalayas, while Fulé et al. (2021) emphasized the need to further develop the tree-ring research network in the Himalayas and continental Southeast Asia to permit such studies. Chir pine is one species that has been identified as having potential to produce long-term fire histories that can be used to explore the link among humans, climate variability, and fire occurrence and severity (Brown et al. 2011).

This study aimed to better understand the relationships between fire, human activity, and climate variability in the chir pine forests of eastern Bhutan. This research complements past work conducted in this ecosystem by Brown et al. (2011) and expands the fire history network in the region (see Fulé 2021). Our objectives were to: (1) examine the consequences of the 1969 Forest Act on fire regimes in chir pine forest in eastern; and, (2) determine the relative role of climatic conditions on fire occurrence within these forests.

Methods

Study area

The Kingdom of Bhutan is located on the southern slopes of the Himalayas, situated between China and India (Fig. 1). It covers an area of 38,394 km² and has a steep north–south elevation gradient with elevation increasing from 160 to 7000 m over a distance of ~170 km (National Statistical Bureau 2021). The driving influence of Bhutan's climate is the north Indian monsoon which brings wet, humid conditions in the summer and colder, drier conditions over winter (Stewart et al. 2017). Bhutan has a diversity of climatic conditions however due to its low latitude, its steep elevation gradients, and its complex topography (National Statistical Bureau 2021). The southern plains and foothills (100–2000 masl) are subtropical with heavy rainfall occurring during the summer monsoon, while the valleys of the central region of the inner Himalayan (2000–4000 masl) have a temperate climate and typically receive less rainfall than the surrounding slopes and ridges (Stewart et al. 2017). In many areas of South and Southeast Asia that experience a monsoonal climate, fire is a key disturbance agent that shapes forest dynamics (Baker et al. 2008; Baker and Bunyavejchewin 2009). Within the Asian monsoon region, large areas of forests with grassy understories experience a 4–6-month annual dry season followed by a 3–6-month wet season. These conditions can produce an abundance of understory fuel biomass during the wet season and the necessary climatic conditions to dry the fuels allowing them to efficiently burn in the dry season.

Bhutan's natural forests are still mostly intact with 71% of the land under forest cover (FRMD 2016). Mixed conifer and broadleaved forests are the dominant forest types accounting for 13.5% and 45.9% of the forest area, respectively (FRMD 2016). Forests of chir pine constitute about 3% (98,563 ha) of the total forest area (FRMD 2016) and are associated with a seasonal tropical climate that occurs in dry valleys at lower elevations in Bhutan. Chir pine forests are common across the foothills of the Himalayas, occurring from Afghanistan in the west to Myanmar in the east. They have been heavily impacted by a long history of logging and burning (Kala 2009).

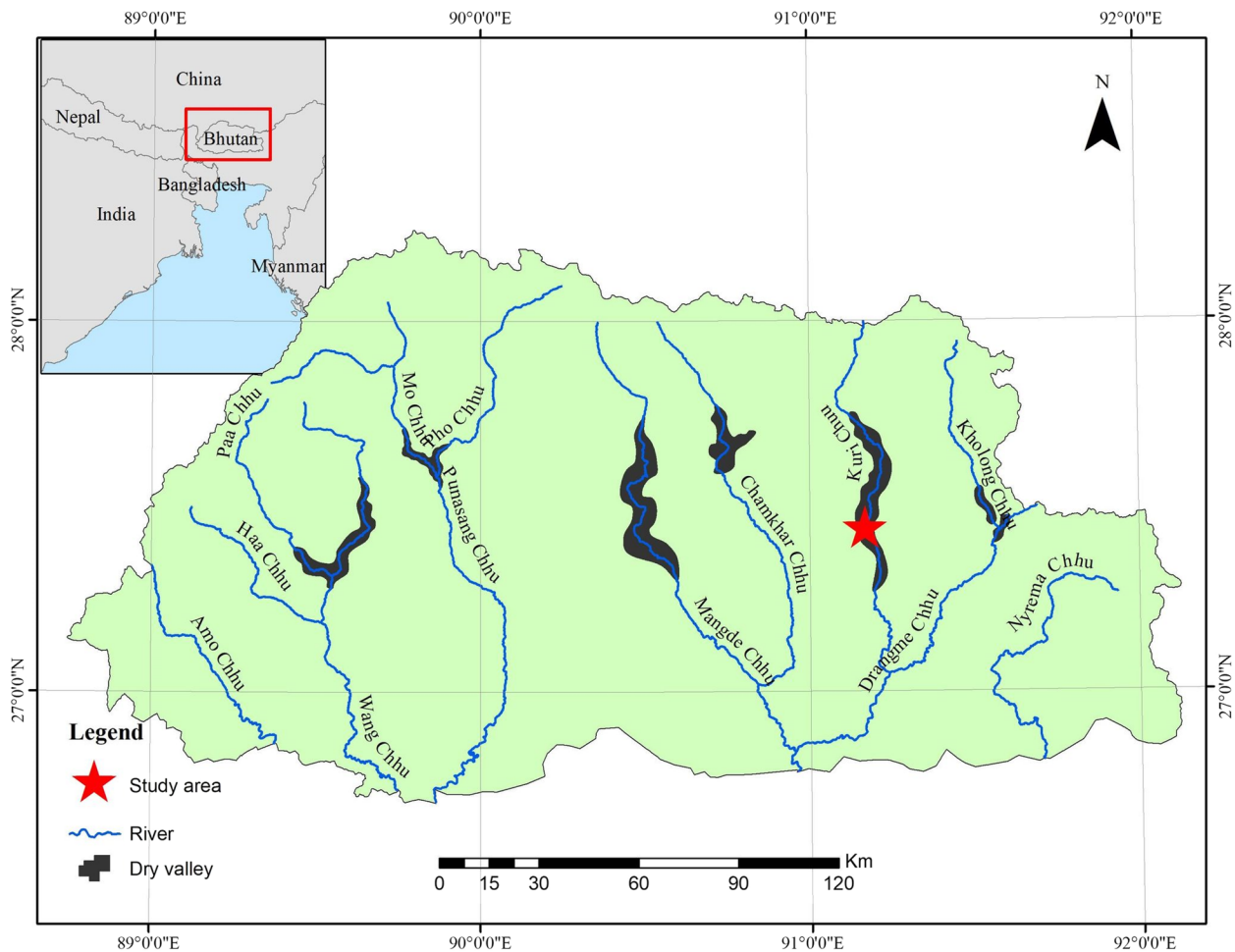


Fig. 1 Map showing the study area along the Kurichu River in eastern Bhutan, and the distribution of similar dry valleys in the Bhutan Himalaya (Ohsawa, 1987)

In this study, we carefully chose an approximately 80-ha area within a chir pine forest in eastern Bhutan for an in-depth analysis of its fire history. This site exhibits typical characteristics commonly found in chir pine forests across the region, including tree density, canopy cover, and a diverse range of tree ages. These attributes were considered when selecting the study site to ensure its representativeness of chir pine forests in eastern Bhutan. The research site was located in a dry valley along the Kurichu river in eastern Bhutan (Fig. 1) that supports both mature and young stands of chir pine (Fig. 2b). The undergrowth consists mostly of C_4 grasses, scattered shrubs, and, in some places, high densities of chir pine seedlings. The study site was located on a steep slope (40–50%) with a northern aspect. Elevation at the study site ranges from 1200 to 1800 m. The area receives most of its rainfall during the summer monsoon (June–September), with total annual precipitation of 770 mm. The mean annual air temperature at the study site is 17.9 °C (1996–2013)

(NCHM 2019). July and August are both the warmest and wettest months, with a mean monthly temperature of 27 °C and mean monthly precipitation of 189 mm, respectively (NCHM 2019). Winters (December–February) are cool (mean monthly temperature = 17.8 °C) and dry (mean monthly precipitation < 7 mm) (Fig. 3).

Field methods

There is anecdotal evidence that the study site has experienced numerous forest fires over time; however, the timing, frequency, and extent of these fires have not been quantified. To characterize fire activity, we established a systematic grid of sample plots across the ~80 ha study site. Three parallel transect lines were placed ~1000 m apart and located along the elevational gradient on the north-facing slope of the Kurichu river basin. Along each transect, three sampling points were established at 200-m intervals. The total area sampled was 9 ha within the 80-ha site. At each sampling point, a 1-ha circular plot



Fig. 2 **A** A live chir pine (*Pinus roxburghii*) with externally visible fire scarring (i.e., a catface formation). Catface refers to the process by which distinct scars or depressions, often resembling the rough and irregular texture of a cat’s face, develop on the surface of trees that have been affected by wildfires. **B** Chir pine forest in the study area. **C** Tree disc sample with multiple fire scars

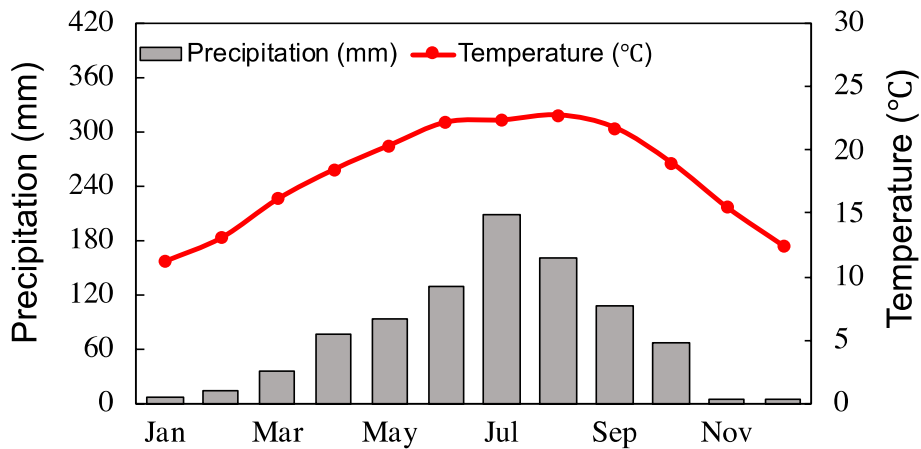


Fig. 3 The climograph for Monggar district (1996–2020) showing mean monthly temperature (line) and precipitation (bars)

(radius=56.4 m) was established from which fire scar samples and tree recruitment data were collected (see Fig. 2a). We extracted two to four cores from all living trees using a standard 5 mm Haglof tree corer. We used a chainsaw to cut either a wedge of wood from live trees with externally visible fire scars or a complete cross section from dead and downed trees. A summary description of transect characteristics is provided in Table 1.

Laboratory methods

All cores and cross sections were prepared using standard dendrochronological techniques (Stokes and Smiley 1996). Using a belt sander, each sample was progressively sanded with increasingly finer grades of sandpaper until distinct annual rings were visible (see Fig. 2c). The cross-sections and cores were then scanned at a resolution of 1200 dpi with an Epson 11000XL scanner and

Table 1 Plot and site characteristics of sampling plots in Eastern Bhutan, 2020

Transect	Plot	Area (ha)	Number of fire-scar trees sampled	Elevation (m)	Slope (%)	Aspect
1	1	1	16	800	40	N
	2	1	6	1000	55	N
	3	1	9	1200	25	N
2	1	1	19	700	55	NW
	2	1	6	1000	50	NW
	3	1	19	1200	65	NW
3	1	1	16	700	30	NW
	2	1	8	1000	45	NW
	3	1	19	1200	30	NW

cross-dated using a locally developed master chronology. The dating of each fire scar sample was further verified against a master chir pine chronology previously developed from the same area (Ugyen Wangchuck Institute for Conservation and Environmental Research, unpublished data). Fire scar locations within the annual rings can be used to determine the season of fire occurrence (Capprio and Swetnam 1995). For fire-scarred samples, a calendar year was assigned to each cross-dated fire scar and the location of a fire scar within a growth ring was recorded. Cambial activity of chir pine commences in mid-March, peaks during the monsoon season (June to August), and then declines until cessation of growth by the end of November. The cambium then remains dormant until the start of the next growing season (Khattak and Abdul 1993). The position of fire scars was categorized as: D (dormant, where the scar was located in the earlywood and latewood boundary), EE (early earlywood), ME (middle earlywood), LE (late earlywood), and L (latewood). These were then grouped into seasonal periods: (1) dry season (D + EE) and (2) wet season (ME + LE + L).

Data sets and analytical methods

We used the Fire History Analysis and Exploration System (FHAES v2.0.2 (Brewer et al. 2016)) to organize the fire scar data for each plot and develop a master chronology to explore potential fire–climate relationships. All fire scar dates were analyzed to calculate the frequency and seasonality of the site's fire regime. We fitted a Weibull function to analyze the distributions of fire intervals and express fire interval statistics in probabilistic terms. For the fire interval analyses, we used a composite of all trees that recorded at least one fire. Breakpoint analysis was used to examine potential structural changes in the cumulative number of fires spanning from 1923 to 2018. To conduct this analysis, we utilized ordinary least squares-based cumulative sum (CUSUM) tests and employed the Bayesian information criterion to

determine the optimal number of breakpoints. The analysis was performed using the R statistical software (v 4.0, R Core Team 2022) with the *strucchange* package developed by Zeileis et al. (2002).

To assess the association between fire and climate, we used superposed epoch analysis (SEA) within the FHAES framework (Brewer et al. 2016). We analyzed NINO 3.4 index values (Rayner et al. 2003) and Southern Oscillation Index (SOI) (Ropelewski and Jones 1987) for the June–July–August (JJA) period from 1901 to 2020, which aligns with the primary months of monsoon rainfall in Bhutan and for IOD, we utilized the values 1901–2020 for JJA from the Frontier Research Systems for Global Change (www.jamstec.go.jp). Additionally, we analyzed the Palmer Drought Severity Index (scPDSI) (Barichivich et al. 2021) which characterizes the dry season conditions from December to March over the same time frame. To conduct the SEA, we created fire event files listing all fire dates and fires that scarred at least 25% of the sampled trees recording fire events (Fulé et al. 2021). We analyzed climatic conditions for the year of the fire and the three preceding years. We assessed the relationship between fire and climate indices based on 1000 bootstrapped values derived from Monte Carlo simulations of randomly selected years to calculate the 95%, 99%, and 99.9% confidence intervals.

Results

The dataset consists of 416 trees from the nine sampling plots of which 118 trees had fire scars. Analysis of fire history data collected from living trees ($n = 113$) and stumps/snags ($n = 5$) revealed evidence of at least one fire in all nine sampling plots (Fig. 4). The tree-ring chronology from the core samples covered the period from 1764 to 2019; the chronology based on fire scar samples covered the period 1800 to 2019, with the earliest fire scar observed in 1923 and the most recent in 2018. Prior to 1923, no fires were recorded, although

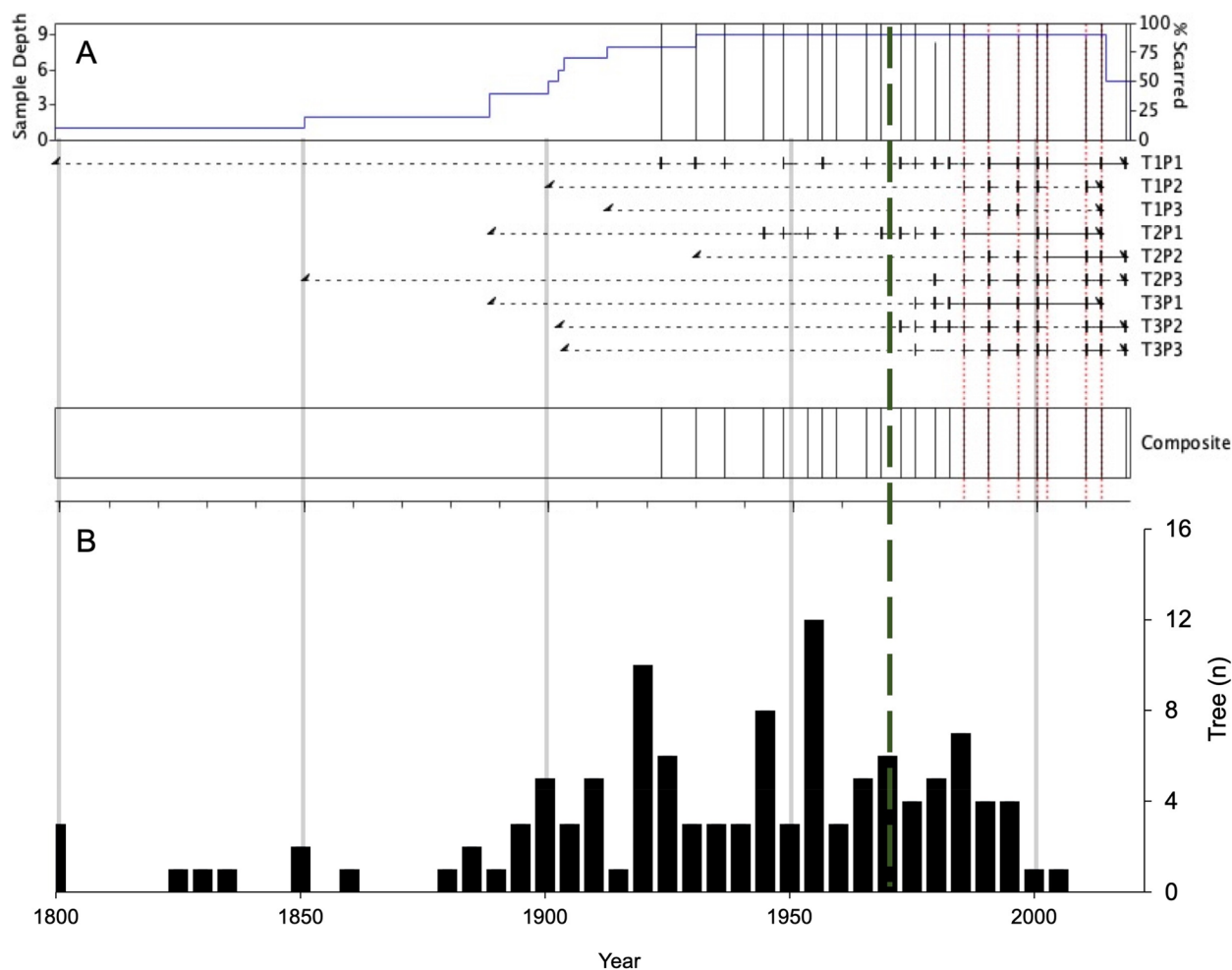


Fig. 4 Fire sample records from 1800–2019 for nine sites from the chir pine forest in eastern Bhutan (fire scars dates from 1923 onwards). **A** The horizontal dotted line represents time spans of fire-scarred trees of each site (composite of three plots). Vertical bold lines indicate fire scars formation on ≥ 1 sampled trees and vertical dashed highlighted red lines indicate common major fire years, that occurred across at least five plots. **B** Tree age-structure (age calculated from fire-scarred samples) bar chart (5-year bins) for all plots combined. The vertical dotted green line shows the timeline of policy change in 1969

28% of the trees in the sampled plots had established before 1920 (Fig. S2/S3). Multiple trees displayed fire scars in the same year, which became more prevalent from the 1970s onward, indicating synchronous fire occurrence across the sample plots. Fire years that impacted multiple sample plots included 1985, 1989, 1996, 2000, 2002, 2010, and 2013 (Fig. 4). These 7 years accounted for more than 50% of all fire scars observed in the study.

In the analysis of the 100-year period from 1920 to 2019, a total of 250 fire scars were recorded. However, the analysis of breakpoints revealed significant shifts in the cumulative number of fire scars, specifically occurring in 1970, 1984, and 1999 ($S = 4.03$, $p < 0.001$, OLS-CUSUM test, Fig. S4). Due to the relatively short

time spans between the breakpoints, we focused on the first breakpoint, which occurred in 1970. From 1920 to 1969, only 13 fire scars were documented (i.e., 0.05% of all fire scars). However, in the subsequent 49-year period (1970–2019), there was an 18-fold increase in the number of fire scars, with 237 fire scars recorded (99.5% of all fire scars) (Fig. S1).

All fire scars occurred in the growth dormancy phase (between the latewood and earlywood) or the early early-wood of the tree ring, which coincided with the dry season (November–March) when fires commonly take place (Chhetri 1994; Dorji 2006). There was no evidence of fires occurring in the monsoon season (June–August). The mean fire return interval across the study site was 4 years (see Table 2). It was evident from the

Table 2 Descriptive statistics of the fire interval data of the study area (All plots) and for each plot (T#P#). T1, T2, T3 are the transects

Composite parameters	T1P1	T1P2	T1P3	T2P1	T2P2	T2P3	T3P1	T3P2	T3P3	All_plots
Mean fire interval	5.94	5.60	-	5.75	5.50	4.88	4.22	4.60	5.38	4.52
Fire frequency	0.17	0.18	-	0.17	0.18	0.21	0.24	0.22	0.19	0.22
Minimum fire interval	2.00	3.00	-	2.00	3.00	2.00	2.00	3.00	2.00	2.00
Maximum fire interval	12.0	10.0	-	15.0	8.00	8.00	8.00	10.0	10.0	8.00
Weibull mean	5.97	5.63	-	5.8	5.52	4.89	4.24	4.62	5.4	4.54
Weibull median	5.71	5.44	-	5.34	5.54	4.82	4.11	4.44	5.19	4.47
Weibull fire frequency	0.18	0.18	-	0.19	0.18	0.21	0.24	0.23	0.19	0.22

(-) referred to data not available

fire reconstructions that a shift from patchy, small-scale fires to widespread fires had occurred over time in the study area (Fig. 6).

Our findings suggest a significant positive correlation between fire occurrence and the NINO 3.4 index from 1923 to 2018 and a significant negative correlation with the SOI (Fig. 5). Results from the SEA analyses indicate that fire years were strongly associated with both the Nino3.4 (JJA) and the SOI (JJA) indices (Fig. 6a, b). This relationship was significant ($p < 0.05$) 1 year after a La Niña event (i.e., 1984, 1988, 1995, 1988, 2001, 2012, 2017). Fire years were not significantly associated with the dry season scPDSI (Fig. 6c) or wet season (JJA) IOD (Fig. 6d). Almost half of the fire years (12 of 22 years from 1923 to 2018) occurred when NINO3.4 was negative (Fig. 5). These results provided new insights into the role of climate variability in influencing fire activity in the study area.

Discussion

Our study provides novel insights into fire regimes and their association with climate variability and human activity in Bhutan. We found that the fire regime in the study area has changed over the past century. Since the 1970s, fires have shifted from patchy, small-scale fires to widespread fires across the study area (see Fig. 5 and Fig. S5). This shift coincided with a sweeping change in forest policy that was legislated and implemented in 1969 and saw an end to the use of fire as a silvopastoral management tool by local farmers and herders. The ban on shifting cultivation has likely had an influence on both ignition sources and fuel availability. Prior to 1970, all recorded fires occurred at only one or two of the nine sampled locations. After 1970, there was a distinct shift in fire extent with at least five fires occurring across nine of the sampling locations within the study landscape. The reduction in the use of fire has likely interacted with ENSO to facilitate the accumulation of contiguous fuel

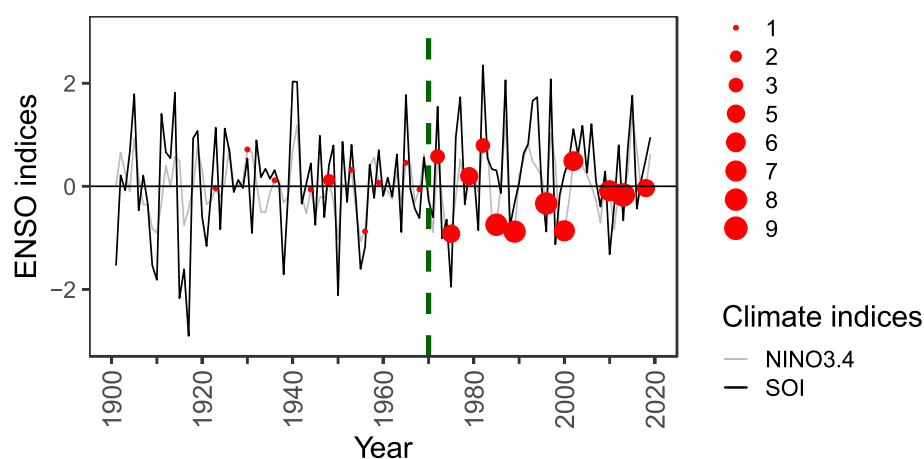


Fig. 5 Time series of reconstructed Niño3.4 and SOI (the SOI index is multiplied by -1 to align the index with the Niño3.4 index) with fire activity. An El Niño event occurs when the sea surface temperature (SST) anomalies exceed $+0.5$ °C, indicating sustained warming. In contrast, a La Niña event is identified when the SST anomalies fall below -0.5 °C, indicating sustained cooling. The SOI index is negatively correlated with SST anomalies and represents the difference in mean sea level pressure between Tahiti and Darwin, Australia. For the SOI, negative values indicate drier conditions and positive values indicate wetter conditions. Red circles are proportional in size to the number of sites burned each year. The lines show the mean annual values for each climate series. The vertical dotted green line shows the timeline of policy change in 1969

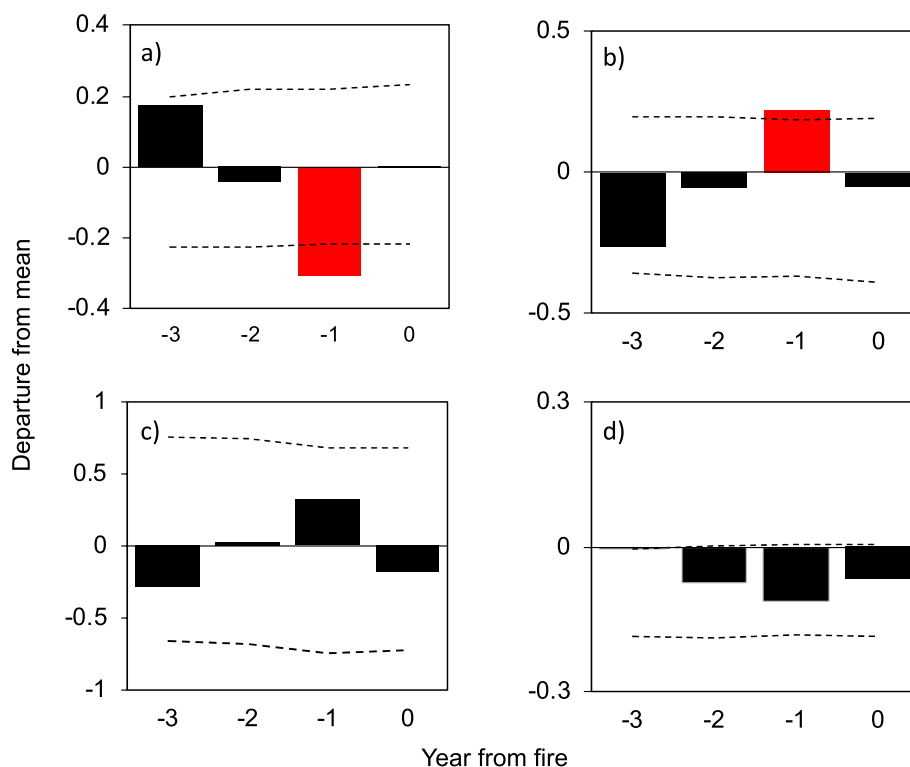


Fig. 6 Superposed epoch analysis of 25% fire and **a** El Niño Southern Oscillation (NINO3.4), **b** SOI, **c** scPDSI, and **d** Indian Ocean Dipole (IOD). Red bars indicate a significant association at the 95% level based on bootstrap sampling. SOI varies inversely with the NINO3.4 index. Typically, years with low NINO3.4 and high SOI values are La Niña years (i.e., wet). Values > 0 indicate dry and warm conditions and values < 0 indicate wet and cool condition

loads that support the occurrence and spread of more frequent fires. The increase in fire occurrence and extent suggests that the landscape has become more connected (see Turner and Romme 1994) as fuel, ignition, and climate switches have become increasingly synchronized since the 1970s leading to a change in the fire regime (see Bradstock 2010).

The chir pine forests of Bhutan are relatively open pine savannas with a ground layer dominated by grasses. Ignition in these forests typically comes from human activities (Dorji 2006; Darabant et al. 2012a, b). The monsoonal climate that dominates the region is characterized by an annual wet and dry season cycle. During wet seasons, typically lasting 3–6 months, sufficient moisture promotes the growth of grassy biomass. During the 4–6 months of the dry season, temperatures steadily increase, and relative humidity steadily decreases. Under these conditions, the grassy biomass cures and the fine fuels on the forest floor dry out and become capable of carrying fire every year. With the onset of the monsoon, the biomass becomes too wet to burn and the fire season ends. Forest fires are therefore strictly limited to the dry season (November–March) across the region (Troup 1921; Bahuguna and Upadhyay 2002; Dorji 2006; Matin

et al. 2017; Fulé et al. 2021). Our fire scar dataset confirmed this pattern for our study site, with 100% of fire scars occurring in the dry season. The pattern of fire suggests that climate, biomass, and human-based ignitions interact to shape fire occurrence in the region with climate acting on intraannual and interannual cycles.

The primary climatic driver of fire activity in the chir pine forests of our study region was the El Niño–Southern Oscillation (ENSO). ENSO can have a modulating influence on the Indian monsoon in many parts of South and Southeast Asia (Sano et al. 2012; Yadav 2011; 2012) and more generally across the region (Cook et al. 2010). This influence impacts hydroclimatic conditions throughout the Asian monsoon region (Cleary and Grill 2004; Lu et al. 2019; Hamal et al. 2022). In Bhutan, La Niña (El Niño) is associated with wet (dry) conditions (Sano et al. 2013). The significant association between La Niña conditions and fire occurrence found in this study suggests that fire activity in this landscape may be fuel limited and that increased rainfall during the wet season of a La Niña year produces higher and more connected fuel loads which are then available to burn in the subsequent dry season. Similar patterns in which antecedent wet conditions are associated with regional fire years have

been described in other parts of the world. For example, Nguyen et al. (2023) identified similar patterns with preceding La Niña conditions associated with fire occurrence in the seasonal tropical forests of central Vietnam. In Northern Australia, increased rainfall during the monsoon period has also led to more and larger fires during the subsequent dry season (Harris et al. 2008).

Kitzberger et al. (2001) showed that ENSO variability synchronized fire activity in North and South America (specifically southwestern US and Patagonia) with a strong association between fire years and antecedent wet years associated with El Niño. These regions experience a similar hydroclimatic pattern to La Niña as Bhutan (i.e., above-average precipitation), which led to increased fuel loads and fuel connectivity. Increases in fuel loads across the landscape can facilitate the occurrence of widespread fires in the dry years that follow La Niña events. This pattern has been described for other strongly seasonal environments dominated by conifer forests. For example, Brown et al. (2008), using a multi-century record of fire activity from Utah (USA), found that antecedent wet conditions followed by dry conditions led to regional fire years. They attributed this effect to greater fine fuel loads and fuel continuity due to increased regional productivity during years with above-average rainfall.

In regions with strong seasonality and moderate total annual precipitation, net primary productivity is typically moisture limited (Pausas 2004). Years with above-average rainfall generally lead to increased biomass production, which, during the subsequent dry season (see Fig. 5), can lead to greater fuel availability and continuity (Pausas 2004; Pausas and Bradstock 2007). Where ignitions are not limited, this can promote the occurrence of frequent fires that burn over extensive areas (van Wilgen et al. 2010). Prior to 1970, however, widespread fires did not occur consistently across our study area, despite some very strong La Niña years (i.e., wet conditions). The high temperatures and low humidity conditions during the annual dry season, which regularly cure grassy biomass, suggest that fuel moisture is not limiting fire spread from year to year. During years with average to below-average rainfall, biomass of fine fuels may have been insufficient to allow for fires to spread over large areas, unless ignitions were ubiquitous. In years with above-average rainfall, biomass of fine fuels would have been much greater allowing for one or a few ignitions to cause widespread fire. The primary factors limiting fire in these forests are therefore fuel availability and ignition sources.

The results suggest that activities, such as grazing or collection of non-timber forest products, in particular lemon grass (*Cymbopogon flexuosus* Steud.), may have reduced ground-layer biomass independently of climate and/or that human population density was sufficiently

low that ignitions were rarer (Guyette et al. 2002). There is no evidence however of a discrete change in local human population density in or around 1970. However, in 1969, the Royal Government of Bhutan passed the Forest Act (RGOB 1969), which placed strict controls on various forest-related activities such as the use of fire, grazing, fuelwood collection, and timber extraction on public forest land. Grazing was restricted, and concerted efforts were made to reduce the size of local cattle populations by introducing high-yielding crossbred cattle. The ban on the use of fires after 1970 promoted shrub encroachment into rangelands which in turn reduced areas available for grazing (Gyamtsho 2002). The timing of the discrete shift in fire activity coincides with the Forest Act of 1969. This suggests that changes in human activities within the forests, interacting with ENSO, have likely influenced fuel loads and fuel connectivity across the study landscape. The shift has changed the fire regime from one that was fuel limited, with fuels disconnected spatially and temporally, promoting infrequent and small fires. Now, the fire regime is driven by ignition limitation, where highly connected fuel loads can support more frequent and widespread fires across the landscape.

Management recommendations

Identifying the key drivers of fire activity is crucial for developing effective fire management strategies that align with local, regional, and national goals. In the case of Bhutan, maintaining the constitutional mandate of 60% forest cover into perpetuity and achieving a carbon-negative economy are essential environmental goals. However, the increasing extent and frequency of fires pose a significant threat by potentially increasing carbon emissions and depleting standing carbon pools in Bhutan's forests (UNDP 2021). Forest management policies that inadvertently contribute to larger and more frequent fires could undermine Bhutan's environmental goals. For chir pine forests in Bhutan, it appears that a national forest policy designed to improve forest management has produced an unintended perverse environmental outcome. Specifically, by removing grazing and planned fire from the forests, the policy has led to the accumulation of high and contiguous fuel loads that has promoted the occurrence of more frequent and widespread fires over the last 50 years.

Forest managers should adopt strategies that prioritize reducing the quantity and connectivity of fuel loads to reduce the risk of future wildfires in chir pine forests. One crucial strategy entails the implementation of controlled local property rights, which should empower local communities to actively participate in the management and conservation of their forests. A shift towards managing these forests as community forests would be

beneficial. Community forest management encompasses regulated activities such as cattle grazing and sustainable collection of non-timber forest products. These activities not only provide livelihood opportunities for communities but also contribute to the overall health and vitality of the forest ecosystem. Furthermore, forest management interventions such as silvicultural thinning and mosaic fuel-reduction burning have considerable potential for mitigating fire risks (Darabant et al. 2012a, b; Vilà-Vilardell et al. 2020). Silvicultural thinning involves the selective removal of specific trees to achieve defined objectives, including the reduction of fuel loads and enhancement of forest resilience (Stephens et al. 2023). In addition, mosaic fuel-reduction burning is a controlled burning practice that can create breaks in fuel continuity, thereby limiting the potential spread of wildfires (Collins et al. 2023).

Recent advances in our understanding of monsoon dynamics can also make significant contributions to our ability to assess and predict changes in monsoon precipitation patterns (Chen et al. 2019). This knowledge can provide insight into how shifts in monsoon behavior may influence fire regimes, potentially enabling the forecasting of years that may promote fuel load development, thereby leading to elevated fire risk in subsequent years. Integrating monsoon dynamics with ENSO cycles could inform the timing of application of fuel management strategies. This approach has the potential to strengthen our capacity to mitigate fire risks and safeguard ecosystems. Together, these strategies underscore the importance of proactive, sustainable, and community-involved forest management practices that can mitigate the vulnerability of chir pine forests to future wildfires and foster their long-term health and resilience.

Conclusions

Dendroecological studies play a vital role in providing long-term historical context about fire regimes. We identified that the fire regime in our study areas has changed since 1970 due to a change in forest policy which altered how people have used the forest. The fire regime is no longer fuel limited but ignition limited. This study offers critical information for forest managers in Bhutan and other eastern Himalayan countries, enabling them to develop strategies that enhance forest resilience to fire and establish monitoring programs to guide long-term planning for sustainable forest management. By managing forest fuels following periods of above average precipitation, the fuel switch can be reestablished which should promote less frequent and extensive fires in landscape. By

incorporating these measures, forest managers in Bhutan could address the challenges posed by increasing fire activity while maintaining its commitment to environmental conservation and sustainable forest management. Expanding this work to other geographic locations and forest types within Bhutan and the broader Himalayan region (India and Nepal) could yield broader insights into how fire regimes have interacted with forest governance, human activities, and climate in the region. These insights can help shape the sustainable management and conservation of similar forest types across the Himalayas.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-024-00275-x>.

Supplementary Material 1.

Acknowledgements

This research was supported by Melbourne International Research Scholarship (MIRS). We thank the Ugyen Wangchuck Institute for Forestry Research and Training (UWIFoRT), Department of Forests and Park Services, Ministry of Energy and Natural Resources, Bhutan, for their technical and logistic support for the fieldwork and laboratory work. We also thank the field crew and staff members of UWIFoRT for their assistance with fieldwork.

Authors' contributions

K.T., C.R.N., K.A., and P.J.B. co-designed the study. K.T. conducted fieldwork, laboratory processes, and tree-ring analysis and wrote the original draft. C.R.N. and K.A. provided validation, visualization, supervision, and reviewed and edited the manuscript. P.J.K., E.R.C., and T.V.N. reviewed and edited the draft. P.J.B. provided overall supervision, funding acquisition, reviewed, and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials

Available on request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

We have no conflicts of interest to disclose.

Author details

¹School of Agriculture, Food, and Ecosystem Sciences, University of Melbourne, 500 Yarra Blvd, Richmond, Victoria, Australia. ²Department of History, Stockholm University, Stockholm, Sweden. ³Tree Ring Laboratory, Lamont Doherty Observatory of Columbia University, Palisades, NY, USA. ⁴School of Geography, Planning, and Spatial Sciences, University of Tasmania, Sandy Bay, TAS, Australia. ⁵Forest Science Institute of South Vietnam, 1 Pham Van Hai Street, Tan Binh District, Ho Chi Minh City, Vietnam.

Received: 1 August 2023 Accepted: 10 April 2024
Published online: 06 May 2024

References

- Archibald, Sally. 2016. Managing the human component of fire regimes: Lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371 (1696): 20150346. <https://doi.org/10.1098/rstb.2015.0346>.
- Baisan, Christopher H., and Thomas W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. *Canadian Journal of Forest Research* 20 (10): 1559–1569. <https://doi.org/10.1139/x90-208>.
- Bahuguna, V.K., and A. Upadhyay. 2002. Forest fires in India: Policy initiatives for community participation. *International Forestry Review* 4 (2): 122–127. <https://doi.org/10.1505/IFOR.4.2.122.17446>.
- Baker, Patrick J., and Bunyavejchewin Sarayudh. 2009. Fire behavior and fire effects across the forest landscape of Continental Southeast Asia. In *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics*, 311–34, 311–34. Berlin, Heidelberg: Springer.
- Baker, Patrick J., Sarayudh Bunyavejchewin, and Andrew P. Robinson. 2008. The impacts of large-scale, low-intensity fires on the forests of continental South-East Asia. *International Journal of Wildland Fire* 17 (6): 782–792. <https://doi.org/10.1071/WF07147>.
- Barichivich, Jonathan., Timothy Osborn, Ian Harris, Gerard van der Schrier, and Philip Jones. 2021. Monitoring global drought using the self-calibrating Palmer Drought Severity Index. [In "State of the Climate in 2020" eds. Dunn RJH, Aldred F, Gobron N, Miller JB & Willett KM (eds.). *Bull Am Meteorol Soc* 102(8): S68–S70. <https://doi.org/10.1175/BAMS-D-21-0098.1>.
- Beniston, Martin. 2003. Climatic change in mountain regions: a review of possible impacts. Climate variability and change in high elevation regions: past, present & future. *Climatic Change*, 5–31. <https://doi.org/10.1023/A:1024458411589>.
- Bigio, Erica R., Thomas W. Swetnam, Christopher H. Baisan, Christopher H. Guiterman, Yegor K. Kisilyakhov, Sergey G. Andreev, Eduard A. Batotsyrenov, and Alexander A. Ayurzhanayev. 2022. The influence of land-use activities and regional drought on historical fire regimes of Buryatia Siberia. *Environmental Research Letters* 17 (5): 054043.
- Bradstock, Ross A. 2010. A biogeographic model of fire regimes in Australia: Current and future implications. *Global Ecology and Biogeography* 19 (2): 145–158. <https://doi.org/10.1111/j.1466-8238.2009.00512.x>.
- Brewer, Peter W., Elaine K. Sutherland, Donald A. Falk. 2016. Fire History Analysis and Exploration System (FHAES) Version 2.0.2 [Computer Software]. <https://doi.org/10.5281/zenodo.34142>
- Brown, Peter M., Emily K. Heyerdahl, Stanley G. Kitchen, and Marc H. Weber. 2008. Climate effects on historical fires (1630–1900) in Utah. *International Journal of Wildland Fire* 17 (1): 28–39.
- Brown, Peter M., Amalava Bhattacharyya, and Santosh K. Shah. 2011. Potential for developing fire histories in chir pine (*Pinus roxburghii*) forests in the Himalayan foothills. *Tree-Ring Research* 67 (1): 57–62. <https://doi.org/10.3959/2009-15.1>.
- Capprio, A. C., and Thomas W. Swetnam. 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California. Pages. 173–179. In *JK Brown, RW Mutch, CW Spoon and RH Wakimoto [Tech. Coor.], Symposium on fire in wilderness and park management: proceedings. USDA For. Ser Gen Tech Rep. INT-GTR-320*.
- Chen, Lin, Qu. Xia, Gang Huang, and Yuanfa Gong. 2019. Projections of East Asian summer monsoon under 1.5 C and 2 C warming goals. *Theoretical and Applied Climatology* 137: 2187–2201.
- Chhetri, Dal B. 1994. Seasonality of forest fires in Bhutan. *International Forest Fire News* 10: 5–9.
- Choden, Kunzang, Craig R. Nitschke, Stephen B. Stewart, and Rodney J. Keenan. 2021. The potential impacts of climate change on the distribution of key tree species and Cordyceps in Bhutan: Implications for ecological functions and rural livelihoods. *Ecological Modelling* 455: 109650. <https://doi.org/10.1016/j.ecolmodel.2021.109650>.
- Cleary, Daniel F.R., and Andrea Grill. 2004. Butterfly response to severe ENSO-induced forest fires in Borneo. *Ecological Entomology* 29 (6): 666–676. <https://doi.org/10.1111/j.0307-6946.2004.00649.x>.
- Collins, L., R. Trouvé, P.J. Baker, B. Cirulus, C.R. Nitschke, R.H. Nolan, L. Smith, and T.D. Penman. 2023. Fuel reduction burning reduces wildfire severity during extreme fire events in south-eastern Australia. *Journal of Environmental Management* 343: 118171. <https://doi.org/10.1016/j.jenvman.2023.118171>.
- Cook, Edward R., Kevin J. Anchukaitis, Brendan M. Buckley, Rosanne D. D'Arrigo, Gordon C. Jacoby, and William E. Wright. 2010. Asian monsoon failure and megadrought during the last millennium. *Science* 328 (5977): 486–489. <https://doi.org/10.1126/science.1185188>.
- Dale, Virginia H., Linda A. Joyce, Steve McNulty, Ronald P. Neilson, Matthew P. Ayres, Michael D. Flannigan, Paul J. Hanson, Lloyd C. Irland, Ariel E. Lugo, Chris J. Peterson, Daniel Simberloff, Frederick J. Swanson, Brian J. Stocks, and B. Michael Wotton. 2001. Climate change and forest disturbances: Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *BioScience* 51 (9): 723–734. [https://doi.org/10.1641/0006-3568\(2001\)051\[0723:CCAFD\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2).
- Darabant, Andras., Prem B. Rai, O Eckmüllner, Georg Gratzler, and Dorji Gyeltshen. 2012. Guidelines for nation-wide thinning of blue pine. Thimphu, Bhutan: Department of Forests and Park Services, Ministry of Agriculture.
- Darabant, Andras., Prem B. Rai, and Dorji. 2012. Fire as a Land management tool in chir pine forests with lemon grass understorey. RNR RDC Jakar, Department of Livestock, Ministry of Agriculture & Forests.
- Delma, Sigyel. 2011. Carbon sequestration in a fire ecosystem in Eastern Bhutan. M.Sc. thesis, University of Natural Resources and Life Sciences, Vienna.
- DeWilde, L.O., and F.S. Chapin. 2006. Human impacts on the fire regime of interior Alaska: Interactions among fuels, ignition sources, and fire suppression. *Ecosystems* 9: 1342–1353.
- DoFPs. 2014. Fire Records (1992–2014). Forest Protection and Enforcement Division, Department of Forests and Park Services, Royal Government of Bhutan.
- Dorji, Lam, Edward L. Webb, and Ganesh P. Shivakoti. 2006. Forest property rights under nationalized forest management in Bhutan. *Environmental Conservation* 33 (2): 141–147. <https://doi.org/10.1017/S0376892906002979>.
- Dorji, Tandin. 2006. Forest fire situation in Bhutan. *International Forest Fire News (IFFN)*; FAO/UNECE: Geneva, Switzerland, 6. 55–63.
- FRMD. 2016. National Forest Inventory Report II: 1–49. Ministry of Agriculture and Forests, DoFPS, Thimphu.
- Fulé, Peter Z., Satish C. Garkoti, and Rajeev L. Semwal. 2021. Frequent burning in chir pine forests, Uttarakhand India. *Fire Ecology* 17 (1): 20. <https://doi.org/10.1186/s42408-021-00106-3>.
- Guyette, Richard P., Rose-Marie. Muzika, and Daniel C. Dey. 2002. Dynamics of an anthropogenic fire regime. *Ecosystems* 5 (5): 472–486. <https://doi.org/10.1007/s10021-002-0115-7>.
- Gyamtsho, Pema. 2002. Condition and potential for improvement of high altitude rangelands. *Journal of Bhutan Studies* 7 (4): 82–98.
- Hamal, Kalpana., Binod Dawadi, Arbindra Khadka, Suresh K Ghimire, and Shankar Sharma. 2022. Interannual variability of spring fire in southern Nepal. *Atmospheric Science Letters*, no. April: 1–13. <https://doi.org/10.1002/asl.1096>.
- Harris, Sandra, D. Nigel Tapper, Ben Orlove Packham, and Neville Nicholls. 2008. The relationship between the monsoonal summer rain and dry-season fire activity of northern Australia. *International Journal of Wildland Fire* 17 (5): 674–684. <https://doi.org/10.1071/WF06160>.
- Hessl, Amy E., Peter Brown, Oyunsanaa Byambasuren, Shawn Cockrell, Caroline Leland, Ed. Cook, Baatarbileg Nachin, Neil Pederson, Thomas Saladyga, and Byambagerel Suran. 2016. Fire and climate in Mongolia (1532–2010 common era). *Geophysical Research Letters* 43 (12): 6519–6527.
- Kala, Chandra Prakash. 2009. Indigenous uses and structure of chir pine forest in Uttaranchal Himalaya, India. *International Journal of Sustainable Development and World Ecology* 11 (2): 205–210. <https://doi.org/10.1080/13504500409469824>.
- Khattak, T.M., and Majeed Abdul. 1993. Seasonal activity of the cambium and radial growth of wood formation in chir pine (*Pinus roxburghii* Sarg.). *Sarhad Journal of Agriculture* 9 (3): 205–208.
- Kitzberger, Thomas, Thomas W. Swetnam, and Thomas T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. *Global Ecology and Biogeography* 10 (3): 315–326. <https://doi.org/10.1046/j.1466-822X.2001.00234.x>.
- Littell, Jeremy S., Donald McKenzie, David L. Peterson, and Anthony L. Westerling. 2009. Climate and wildfires area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications* 19 (4): 1003–21.
- Liu, Zhihua, Hong S. He, Yu. Chang, and Hu. Yuanman. 2010. Analyzing the effectiveness of alternative fuel reductions of a forested landscape in Northeastern China. *Forest Ecology and Management* 259 (7): 1255–1261.

- Liu, Zhihua, and Michael C. Wimberly. 2015. Climatic and landscape influences on fire regimes from 1984 to 2010 in the western United States. *Plos One* 10 (10): 1–20. <https://doi.org/10.1371/journal.pone.0140839>.
- Lu, Bo., Haiyan Li, Wu. Jie, Taixi Zhang, Jing Liu, Bao Liu, Ying Chen, and Jiazila Baishan. 2019. Impact of El Niño and Southern Oscillation on the summer precipitation over Northwest China. *Atmospheric Science Letters* 20 (8): 1–8. <https://doi.org/10.1002/asl.928>.
- Matin, Mir A., Vishwas Sudhir Chitale, Manchiraju S.R., Murthy, Kabir Uddin, Birendra Bajracharya, and Sudip Pradhan. 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>.
- McKenzie, Donald, Ze'ev Gedalof, David L. Peterson, and Philip Mote. 2004. Climatic change, wildfire, and conservation. *Conservation Biology* 18 (4): 890–902. <https://doi.org/10.1111/j.1523-1739.2004.00492.x>.
- National Statistical Bureau [NSB]. 2021. Statistical Year Book of Bhutan 2021. National Statistical Bureau, Thimphu Bhutan.
- NCHM. 2019. Analysis of historical climate and climate change projection for Bhutan. National Center for Hydrology and Meteorology, Royal Government of Bhutan.
- Nguyen, Thiet V., Kathryn J. Allen, Nam C. Le, Cuong Q. Truong, Karma Tenzin, and Patrick J. Baker. 2023. Human-driven fire regime change in the seasonal tropical forests of central Vietnam. *Geophysical Research Letters* 50 (13): e2022GL100687.
- Ohsawa, Masahik. 1987. Life zone ecology of the Bhutan Himalaya. Chiba, Japan: Laboratory of Ecology, Chiba University.
- Pausas, Juli G. 2004. Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean Basin). *Climatic Change* 63: 337–350.
- Pausas, Juli G., and Ross A. Bradstock. 2007. Fire persistence traits of plants along a productivity and disturbance gradient in Mediterranean Shrublands of South-East Australia. *Global Ecology and Biogeography* 16 (3): 330–340. <https://doi.org/10.1111/j.1466-8238.2006.00283.x>.
- Rayner, N. A. A., De E. Parker, E. B. Horton, Chris K. Folland, Lisa V. Alexander, D. P. Rowell, Elizabeth C. Kent, and A. Kaplan. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres* 108 (D14).
- Rosset, J. 1999. Temperate conifer forests of Bhutan: a review of forestry research activities until June, 1998. RNR-RC Jakar, Special publication No 3.
- RGOB. 1969. The Bhutan Forest Act, 1969. Thimphu, Bhutan: Ministry of Trade, Industries and Forests.
- Ropelewski, Chester F., and Phil D. Jones. 1987. An extension of the Tahiti-Darwin southern oscillation index. *Monthly Weather Review* 115 (9): 2161–2165.
- Saladyga, Thomas, Amy Hessel, Baatarbileg Nachin, and Neil Pederson. 2013. Privatization, drought, and fire exclusion in the Tuul River watershed, Mongolia. *Ecosystems* 16: 1139–1151.
- Sangye, M. 2005. *The impact of fire frequency on the regeneration of Pinus roxburghii in Eastern Bhutan*. Vienna: M.Sc. thesis, University of Natural Resources and Life Sciences.
- Sano, Masaki, Phuntsho Tshering, Jiro Komori, Koji Fujita, Xu. Chenxi, and Takeshi Nakatsuka. 2013. May–September precipitation in the Bhutan Himalaya since 1743 as reconstructed from tree ring cellulose $\Delta 18O$. *Journal of Geophysical Research Atmospheres* 118: 8399. <https://doi.org/10.1002/jgrd.50664>.
- Sano, Masaki, Xu. Chenxi, and Takeshi Nakatsuka. 2012. A 300-year Vietnam hydroclimate and ENSO variability record reconstructed from tree ring $\Delta 18O$. *Journal of Geophysical Research Atmospheres* 117 (12): 1–11. <https://doi.org/10.1029/2012JD017749>.
- Steel, Zachary L., Hugh D. Safford, and Joshua H. Viers. 2015. The fire frequency–severity relationship and the legacy of fire suppression in California forests. *Ecosphere* 6 (1): 1–23.
- Stephens, Scott L., Daniel E. Foster, John J. Battles, Alexis A. Bernal, Brandon M. Collins, Rachelle Hedges, Jason J. Moghaddas, Ariel T. Roughton, and Robert A. York. 2023. Forest restoration and fuels reduction work: different pathways for achieving success in the Sierra Nevada. *Ecological Applications* 34: e2932.
- Stewart, Stephen B., Kunzang Choden, Melissa Fedrigo, Stephen H. Roxburgh, Rodney J. Keenan, and Craig R. Nitschke. 2017. The role of topography and the north Indian monsoon on mean monthly climate interpolation within the Himalayan Kingdom of Bhutan. *International Journal of Climatology* 37: 897–909.
- Stokes, M. A., and T. L. Smiley. 1996. *An introduction to tree-ring dating*. Tucson, AZ: University of Arizona Press.
- Swetnam, Thomas W., and Julio L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* 11 (12): 3128–3147. https://doi.org/10.1007/978-90-481-8736-2_32.
- Team, R Core. 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <https://www.R-project.org>.
- Troup. 1921. The silviculture of Indian trees. Published under the authority of His Majesty's Secretary of State for India in Council. Clarendon Press, Oxford. <https://doi.org/10.5962/bhl.title.24363>.
- Tshering, Kinley. 2006. Development of an effective forest fire management strategy for Bhutan. M.Sc. thesis, University of Montana. <https://scholarworks.umt.edu/etd>.
- Tshering, Kinley, Phuntsho Thinley, Mahyat Shafapour Tehrany, Ugyen Thinley, and Farzin Shabani. 2020. A comparison of the qualitative analytic hierarchy process and the quantitative frequency ratio techniques in predicting forest fire-prone areas in Bhutan Using GIS. *Forecasting* 2 (2): 36–58. <https://doi.org/10.3390/forecast2020003>.
- Turner, Monica G., and William H. Romme. 1994. Landscape dynamics in crown fire ecosystems. *Landscape Ecology* 9: 59–77.
- UNDRP. 2021. Assessment of climate risks on forests and biodiversity for National Adaptation Plan (NAP) Formulation Process in Bhutan. Assessment Report August 2021. National Environment Commission, Ministry of Agriculture and Forest.
- Vilà-Vilardell, Lena, William S. Keeton, Dominik Thom, Choki Gyeltshen, Kaka Tshering, and Georg Gratzler. 2020. Climate change effects on wildfire hazards in the wildland-urban-interface – blue pine forests of Bhutan. *Forest Ecology and Management* 461 (January): 117927. <https://doi.org/10.1016/j.foreco.2020.117927>.
- Wangchuk, Sangay, Jennifer Bond, Rik Thwaites, and Max Finlayson. 2023. Exploring human–wildlife conflict and implications for food self-sufficiency in Bhutan. *Sustainability (Switzerland)* 15 (5): 4175. <https://doi.org/10.3390/su15054175>.
- van Wilgen Brian, W., Gregory G. Forsyth, Helen De Klerk, Sonali Das, Sibusisiwe Khuluse, and Peter Schmitz. 2010. Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *Journal of Applied Ecology* 47 (3): 631–638.
- Yadav, R.K. 2012. Why is ENSO influencing Indian northeast monsoon in the recent decades? *International Journal of Climatology* 32 (14): 2163–2180. <https://doi.org/10.1002/joc.2430>.
- Yadav, Ram R. 2011. Tree ring evidence of a 20th century precipitation surge in the monsoon shadow zone of the Western Himalaya India. *Journal of Geophysical Research Atmospheres* 116 (2): 1–10. <https://doi.org/10.1029/2010JD014647>.
- Yeshey, Rebecca M. Ford, Rodney J. Keenan, and Craig R. Nitschke. 2022. Subsistence farmers' understanding of the effects of indirect impacts of human wildlife conflict on their psychosocial well-being in Bhutan. *Sustainability* 14: 14050.
- Zeileis, Achim, Friedrich Leisch, Kurt Hornik, and Christian Kleiber. 2002. Strucchange: An R package for testing for structural change. *Journal of Statistical Software* 7 (2): 1–38.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.