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Research Article

Keywords: dendrochronology, fire scars, climate, El Niño, superposed epoch analysis, Himalaya, Pinus roxburghi

Posted Date: August 18th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3222119/v1

Version of Record: A version of this preprint was published at Fire Ecology on May 6th, 2024. See the published version at https://doi.org/10.1186/s42408-024-00275-x.

Climate and humans interact to shape the fire regime of a chir pine forest in eastern Bhutan

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ABSTRACT

Background: Chir pine (*Pinus roxburghii* Sarg.) forests are distributed in the dry valleys of Bhutan Himalaya. These forests are heavily influenced by biotic activities such as grazing, resin tapping and NWFP (non-wood forests produce) collection. Understanding the relationship between past and present climate and the frequency and severity of forest fires is important for assessing the relative importance of potential drivers on fire occurrence and extent. This study aimed to reconstruct the fire history of a forested landscape dominated by chir pine in eastern Bhutan using crossdated fire scars disc samples.

Results: The chir pine fire chronology extended to the early 1900s. Between 1900 and ~1970 fires were typically small and limited to a small number of sites within the larger study area. After 1970 a distinct shift in fire activity occurred 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, which likely contributed to a greater accumulation of fuels on the forest floor.

Conclusions: Historical reconstruction of fire activity from a site in eastern Bhutan highlights the interaction between human activity and climatic conditions. Prior to 1970 fire activity was dominated by patchy, low-intensity fires. After 1970 fires became larger and more damaging. This shift is 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 led to large build-ups of fuels, particularly after La Niña years. The ubiquity of ignition sources and strong rainfall seasonality ensured that fire could occur in most years. However, the change in forest policy and local community activities in the forests altered the amount and connectivity of fuels within the landscape, reshaping the fire regime in the chir pine forests of eastern Bhutan.

Key words: *dendrochronology, fire scars, climate, El Niño, superposed epoch analysis, Himalaya, Pinus roxburghi*

Background

Climate influences the frequency, intensity, and timing of fire (Dale et al. 2001; Beniston 2003). Fire regimes are intimately linked to climate variability (McKenzie et al. 2004; Littell et al. 2009). High-elevation areas, such as the Himalayas, are predicted to increases in temperature and decreases in precipitation under future climate change. This is expected to lead to more frequent and more intense droughts (Cook et al. 2010) in the coming decades (Kumar et al. 2006; Tsering et al. 2010; Singh et al. 2011). With this shift towards a warmer and drier future, fire regimes are predicted to change (Nitschke and Innes 2013). Changes in fire regimes are expected to be characterized by a change in frequency, magnitude, and intensity of fires (Brown et al. 2004; Keeton et al. 2007). Changes in climate and fire regimes are, however, already occurring. The Sixth Assessment Report (AR6) of the IPCC reported that extreme events such as droughts have already increased the frequency and intensity of fires (Portner et al. 2022). To understand how a changing climate may impact future fire regimes, it is important to understand past characteristics of fire regimes.

Drought and temperature, operating at broader scales, are not only the factors that shape fire regimes. At finer scales, topography and fuel influence fire occurrence and intensity (Brown et al., 2004). In many ecosystems, humans also play a significant role in shaping fire regimes. Humans can affect fire regimes through various activities such as land use change, increased source of ignitions, use of fire for management, and fire suppression (Liu and Wimberly 2015; Archibald 2016; Nguyen et al. 2023). The historical use of fire to promote grazing and agriculture also significantly altered fuel loads and patterns, which in turn impacted fire intensity and spread (Swetnam and Betancourt 1998)

Across large areas of South and Southeast Asia that experience strongly seasonal climates, 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 ground-story fuel biomass during the wet season and the necessary climatic conditions to dry the fuels allowing them to efficiently burn in the dry season.

In the dry mountain valleys of Bhutan, the chir pine (*Pinus roxburghii* Sarg.) forests have been heavily influenced by human activities such as grazing, resin tapping, and harvesting of lemon grass (*Cymbopogon flexuosus* Steud.), which provide cash and non-cash income that support rural livelihoods (Choden et al. 2021; Yeshey et al. 2022; Wangchuk et al. 2023). Prior to the nationalization of the forest in 1969 (RGOB 1969), the burning of forest undergrowth was traditionally practiced by farmers engaged in shifting cultivation and pasture management (Dorji et al. 2006).

Tree-ring based fire history studies from Europe and North America have identified that fire activity has varied spatially and temporally in response to local, regional, and global climate drivers (Swetnam and Betancourt 1990). Fire scars found in trees can provide valuable insights into the relationship between fire and climate (Heyerdahl and Alvarado 2003; Yocom et al. 2010). However, few studies have explored the links between fire and climate in the tropics or in Asia. In the western Himalaya, fire activity has been found to be influenced by regional climate and human activities (Bar et al. 2021). 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 that are prone to forest fires (Tshering et al. 2020). There is a lack of published research on historical forest fire dynamics in the eastern Himalayan regions (Tshering 2006). In Bhutan, documented forest fire records only date back to the early 2000s and have poorly demarcated fire boundaries on the ground (DoFPs 2014). These issues limit insights into the various drivers of fire activity in the region. Brown et al. (2011) highlighted the considerable potential to develop 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 between humans, climate variability, and fire occurrence and severity (Brown et al. 2011). In this study we developed a century-long fire reconstruction from a chir pine forest in eastern Bhutan to explore the interactions amongst fire activity, humans, and climate.

METHODS

Field methods

The Kingdom of Bhutan is located on the southern slopes of the Himalayas, situated between China and India (Fig. 1). It covers 38,394 km^2 with a steep north-south elevation gradient in which the elevation goes from 160 to 7000 m over a distance of ~170 kilometers (National Statistical Bureau 2021). Bhutan is characterized by diverse climatic conditions owing to its low latitude, its steep elevation gradients, and its complex topography (National Statistical Bureau 2021).

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 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. However, they have been heavily impacted by a long history of logging and burning (Kala 2009). In this study, we selected an area of ~80 ha of chir pine forest in eastern Bhutan to conduct a detailed analysis of its fire history. This forest is broadly representative of the forest type across the region.

The research site is 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 is 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 mean annual precipitation of 200 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).

[Fig.1]

[Fig. 2]

[Fig. 3]

The chir pine forest at the study site has a history of repeated forest fires. However, the timing, frequency, and extent of these fires are largely unknown. To characterize fire activity within the broader landscape, we established a systematic grid of sample plots across an area of ~80 ha. Three parallel transect lines were placed along an elevational gradient on the north-facing slope of the Kurichu river basin. Three sampling points were established along each transect at 200-metre intervals. The transects were ~1000 meters apart. The total area sampled was 9 ha over a landscape area of approximately 80 ha. At each sampling point, a 1-ha circular plot (radius = 56.4 m) was established in which fire scar samples and tree recruitment data were collected. (see Fig. 2a). We extracted 2-4 cores from all living trees using a standard Haglof tree corer. We used a chainsaw to extract 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.

[Table 1]

Laboratory methods

All cores and fire scar samples were prepared using standard dendrochronological techniques (Stokes and Smiley 1996). Each sample was sanded to a fine finish using a belt sander and increasingly fine 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 crossdated 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). After crossdating of tree rings was completed on fire-scarred samples, dates were assigned to fire scars and the location of fire scars within the growth rings were recorded. Cambial activity of chir pine commences in mid-March, peaks during the monsoon season (June to August), and then declines until cessation by the end of November. The cambium then remains dormant until the start of the next growing season (Khattak and Abdul 1993). Fire scar locations within the annual rings can be used to determine the season of fire occurrence (Capprio and Swetnam, 1995). The position of fire scars was categorized as D (dormant) if 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

All of the fire scar years (and fire seasons) obtained from the fire-scarred samples were recorded in Fire History Analysis and Exploration System (FHAES v2.0.2; (Brewer et al. 2016). We used FHAES to organize the fire scar data for each plot and develop a master chronology to explore potential fire-climate relationships. To identify synchronous fire events across plots, we developed a composite fire chronology for each plot. All fire scar dates were analyzed to calculate the frequency and seasonality of the local fire regime. All fires scars were observed to occur in the growth dormancy phase (between the latewood and earlywood) or the early early-wood of the tree ring, which coincide with the dry season (November – March) when fires commonly take place (Chhetri 1994; Dorji, 2006). We fitted a Weibull function to analyze the distributions of fire intervals and express fire interval statistics in probabilistic terms. In conducting the fire interval analyses, we used a composite of all trees recording at least one fire, which provides a detailed record of fire events.

The El Niño-Southern Oscillation (ENSO) is an atmosphere-ocean phenomenon that occurs every 2-7 years in the Pacific Ocean, altering rainfall patterns and temperatures on a global scale (Betts et al. 2018). ENSO is one of the dominant forcing mechanisms of local hydroclimatic variability in the Himalayan region (Bhutiyani et al. 2010; Yadav 2012; Kumar and Jaswal 2016) and in the East Asian and South Asian summer monsoon regions (Annamalai et al. 2007; Liu et al. 2015; Fan et al. 2021). The impacts of ENSO are more pronounced in semi-arid and arid environments. Different phases of ENSO can have different effects on fire-related processes. The wet phase of ENSO (Nicholls 1991; Holmgren et al. 2006) can facilitate the development of abundant fuel loads, which can increase fuel connectivity and fire intensity. The dry phase of ENSO can produce drier conditions, increasing the rate of fuel drying and the flammability of the fuels (Mariani et al. 2016; Nguyen et al. 2023).

In our study, we utilized superposed epoch analysis (SEA) within the FHAES framework (Brewer et al. 2016) to examine the correlation between fire occurrence and various climatic variables. The climate indices employed for this investigation consisted of the instrumental ENSO indices, which include the NINO 3.4 index (Rayner et al. 2003) and the Southern Oscillation Index (SOI) (Ropelewski and Jones, 1987). We used the NINO 3.4 index values for the June-July-August (JJA) period from 1901 to 2020, which corresponds to the primary months of monsoon rainfall in Bhutan (see Fig. 3). We also used the Palmer Drought Severity (scPDSI) Index (Barichivich et al. 2021) to characterize dry season (December – March) conditions over the same period. We sourced the data from the Royal Netherlands Meteorological Service (http://climexp.knmi.nl). For the IOD, we utilized the values (1901 – 2020) for JJA from the Frontier Research System for Global Change (www.jamstec.go.jp). The data for all climate variables were extracted from the grid cell nearest to our study site (27.25° N, 91.25° E).

We assessed fire-climate association using SEA analysis. We created fire-event files listing: 1) all fire dates; and, 2) those that scarred at least 25% of the sampled trees that recorded fires (Fulé et al. 2021). To determine if there was a relationship between fire occurrence and climate, we analyzed climatic conditions in the year of the fire and the three years that preceded the fire. We used 1000 bootstrapped values derived from Monte Carlo simulation of randomly selected years to provide 95%, 99% and 99.9% confidence intervals. To explore the spatial pattern of climate drivers on fire activity, we compared our fire year records with the SOI and the Nino3.4 index for (JJA months) from 1901-2020.

We used breakpoint analysis 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 as an exploratory tool and employed the Bayesian information criterion to determine the optimal number of breakpoints. Following the methodology outlined by (Zeileis 2005), we constructed a segmented regression model. The entire 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).

Results

The dataset consisted 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 a 28% of the trees in the sampled plots had established before 1920 (Fig. S2/S3). Recording of fire scars began from 1923 onwards. Of note, is the occurrence of multiple trees displaying fire scars in the same year, which became more prevalent from the 1970s onward, indicating synchronous fire scarring across the sample plots. Fire years that involved multiple sample plots included 1985, 1989, 1996, 2000, 2002, 2010, and 2013 (Fig. 4). These seven years account for more the 50% of all fire scars 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 fires 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).

There was no evidence of fires occurring in the monsoon season (June-August). The mean fire return interval pooled across the study site was four years (see Table 2). It was evident from the fire reconstructions that a shift from patchy, small-scale fires to widespread fires has occurred in the study area (Fig. 6).

[Fig. 4]

[Table 2]

Fire occurrence was associated with ENSO variability from 1923 to 2018 (Fig. 5). Results from the SEA analyses indicate that fire years were strongly associated with both indices used here, the Nino3.4 (JJA) and the SOI (JJA) (Fig. 6 a, b). This relationship was evident one year after a La Niña event (*i.e.*, 1984, 1988, 1995, 1988, 2001, 2012, 2017) and was significant ($p < 0.05$) for fires that scarred $\geq 25\%$ of the sampled trees. Fire years were not strongly associated with the dry season scPDSI (Fig. 6c) or wet season (JJA) IOD (Fig. 6d) for eastern Bhutan. Almost half of the fire years (12 of 22 years from 1923 to 2018) occurred when NINO3.4 was negative (Fig. 5).

[Fig. 5]

[Fig. 6]

Discussion

Our study provides novel insights into fire regimes and their association with climate variability and human activities in Bhutan Himalaya. We found that the fire regime in the study area has changed over the past century. Since the 1970s, fires shifted from patchy, small-scale fires to widespread fires across the study area (see Fig. 5 and Fig. S5). This shift coincides 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 reduction in the utilization of fire as a management tool likely interacted with ENSO to generate the accumulation of contiguous fuel loads that facilitated the occurrence of more frequent and extensive fires.

Bradstock (2010) proposed a biogeographic model of fire occurrence in which biomass, its ability to burn, fire weather, and ignition act as hypothetical switches that must be simultaneously activated for fires to occur. In some landscapes, fire may be limited because one or more of these switches is not activated. For example, an ecosystem may have insufficient biomass to carry a fire, the biomass may be too wet to burn, or there may not be an ignition source to start the fire. The chir pine forests of Bhutan are relatively open pine savannas with a ground layer dominated by grasses. The monsoonal climate that dominates the region is characterized by an annual wet and dry season cycle. During wet seasons, 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 susceptible to fire every year. Ignition in these forests typically comes from human activities (Dorji, 2006; Darabant et al. 2012). With the onset of the monsoon, the biomass becomes too wet to burn and the fire season ends. Consequently, forest fires are 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 intra- 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 is largely responsible for modulating the Indian monsoon. The ENSO-monsoon linkage has been identified for many parts of South and Southeast Asia (i.e., Vietnam (Sano et al. 2012), India (Yadav, 2011; Yadav, 2012)) and more generally across the region (Cook et al. 2010). This influences regional hydroclimatic conditions throughout the Asian monsoon region (Cleary and Grill 2004; Lu et al. 2019; Hamal et al. 2022). Sano et al. (2013) explored the influence of ENSO on rainfall in Bhutan and showed that La Niña (El Niño) is associated with wet (dry) conditions across Bhutan. The strong association between La Niña conditions and fire occurrence suggests that fire activity in this landscape may be fuel limited and that an increase in rainfall in the preceding year’s wet season may produce greater 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) have demonstrated similar patterns in which preceding La Nina conditions are associated with fire occurrence in seasonal tropical forests in central Vietnam. In Northern Australia, increased rainfall during the monsoon period 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 leads to increased fuel loads and fuel connectivity.

Increases in fuel loads across the landscape 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, 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 ignition is not limiting, this can lead to fires that burn over large local areas or even regional scales.

We found a discrete shift in fire size around 1970. Prior to 1970, all recorded fires occurred at only one or two of the nine sampling locations. After 1970, there was a distinct shift in fire extent with at least five fires occurring across eight or nine of the sampling locations within the study landscape. According to Bradstock's (2010) model, this suggests that around 1970 all four 'switches' were more regularly activated at the broader landscape scale. The high temperatures and low humidity conditions during the annual dry season regularly cure grassy biomass suggesting that fuel moisture is not limiting fire spread from year to year. The primary factors limiting fire in these forests are therefore fuel availability and ignition sources. The shift from small-scale fires to fires that burn through the entire study landscape likely reflects a changing interaction between these two limiting factors and human activities. In 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. However, prior to 1970 widespread fires did not occur consistently across our study plots, despite some very strong La Niña years (i.e., wet conditions). This suggests that either other activities, such as grazing or collection of non-timber forest products (NTFPs) like lemon grass, reduced ground-layer biomass independently of climate and that human population density was sufficiently low that ignitions were rarer (Guyette et al. 2002).

There is no evidence of a discrete change in the collection of NTFPs, local human population density, or fire suppression activity 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. In particular, grazing was restricted, and concerted efforts were made to reduce the size of local cattle populations by introducing high-yielding crossbred cattle. The abandonment of cattle grazing led to significant increases in grass and shrub biomass (Gyamtsho 2002). This would have created large areas with substantial and well-connected fine fuel loads. While ENSO variability is correlated with fire activity in the study area (Fig. 5), the timing of a discrete shift in fire activity in our study site and the known date (and demonstrated enforcement) of the Forest Act of 1969 suggests that the observed change in the fire regime have likely resulted from changes in human activities in the forests that in interaction with ENSO have influenced fuel loads and fuel connectivity across the study landscape. This has turned a fuel-limited fire regime, where fuels were historically disconnected both spatially and temporal in most years, and fires were infrequent and small, into a fire regime driven by ignition limitation with highly connected fuel loads that support more frequent and widespread fires.

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, influenced by climate change impacts in the region, 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 therefore undermine Bhutan's environmental goals.

In the chir pine forests that we studied; it appears that a national forest policy designed to improve forest management has produced an unintended perverse environmental outcome. Specifically, by removing grazing from the forests, the policy has led to the accumulation of high and contiguous fuel loads that promote the occurrence of more frequent and widespread fires. To mitigate this threat, forest management policies should consider mechanisms aimed at reducing the amount and connectivity of fuel loads. Examples of such strategies include implementing controlled local property rights, which could involve regulated cattle grazing and sustainable non-timber forest product (NTFP) collection. Additionally, management interventions such as silvicultural thinning and mosaic fuel-reduction burning have shown promise in mitigating fire risks (Darabant et al., 2012; Vilà-Vilardell et al., 2020).

Conclusions

Dendroecological studies play a vital role in providing long-term historical context about fire regimes. Such studies offer 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. The shift in the fire regime in the region from a predominately fuel to ignition limited regime provides managers with an understanding of how to switch the fire regime back to its pre 1970 state. 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 and advancing research efforts, forest managers in Bhutan could effectively address the challenges posed by increasing fire activity while maintaining its commitment to environmental conservation and sustainable forest management. Conducting similar studies across the region would provide a better understanding of how fire interacts with human activities and climate in Bhutan and the other broader Himalaya region.

Acknowledgements

This research was support by Melbourne International Research Scholarship (MIRS). We would like to thank the Ugyen Wangchuck Institute for Conservation and Environmental Research (UWICER), Department of Forests and Park Services, Ministry of Agriculture and Forestry, Bhutan for their technical and logistic support for the fieldwork and laboratory work. We also would like to thank the field crew and staff members of UWICER for their assistance with fieldwork.

Author contributions

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.

DATA AVAILABILITY STATEMENT

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.

Reference

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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

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. (-) referred to data not available.

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

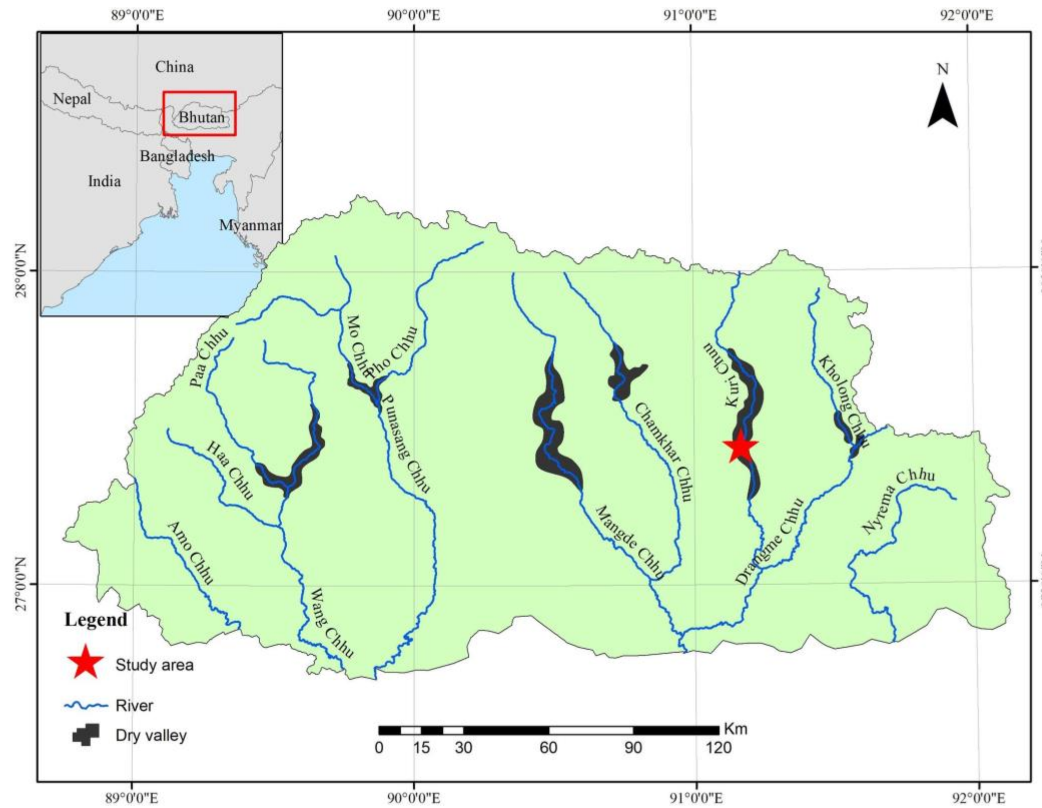

Fig. 1 Map showing the study area along the Kurichu River in eastern Bhutan, and the distribution of similar dry valleys in the Bhutan Himalaya (Ohsawa, 1987)

Fig. 2 A) A live chir pine (*Pinus roxburghii*) with externally visible fire scarring (i.e., a catface formation,) B) chir pine forest in the study area, C) tree disc sample with multiple fire scars.

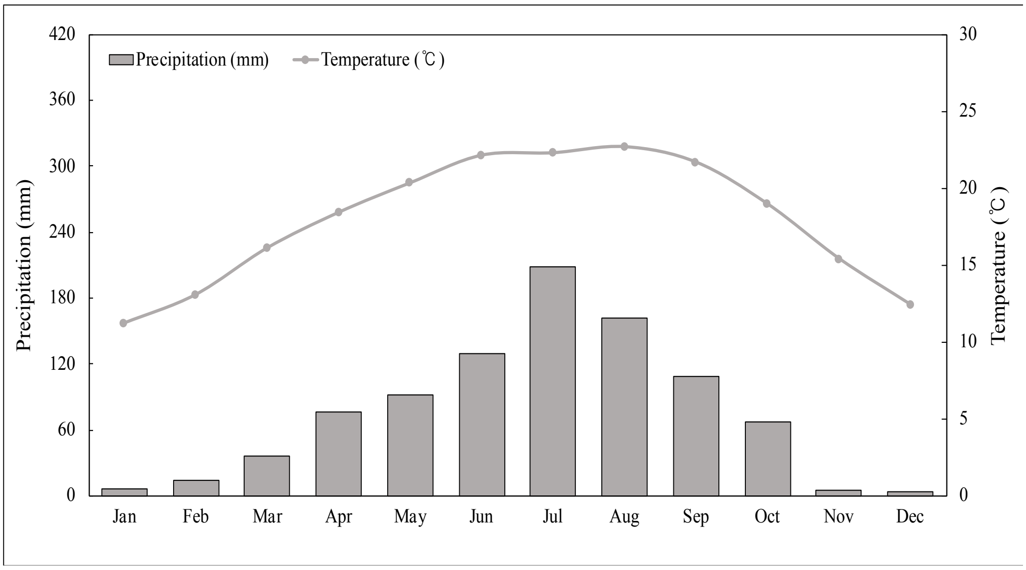

Fig. 3 The climograph for Monggar district (1996-2020) showing mean monthly temperature (line) and precipitation (bars

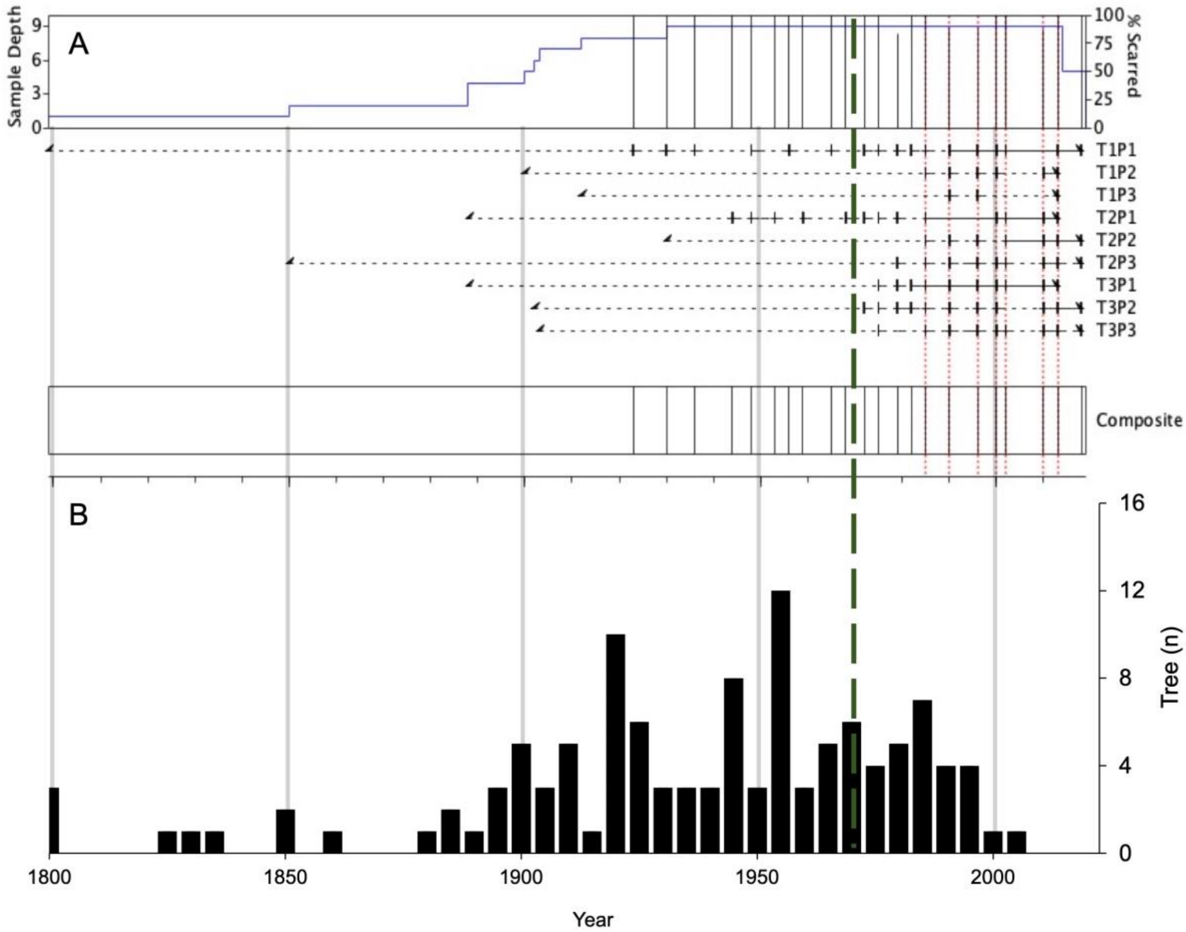

Fig. 4 Fire sample records from 1800-2019 for 9 sites from the chir pine forest in eastern Bhutan (Fire scares dates from 1923 onwards). (A) The horizontal dotted line represents time spans of fire-scarred trees of each site (composite of three plots). Vertical bold lines indicate fire scars formation 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 line shows the timeline of policy change in 1969**.**

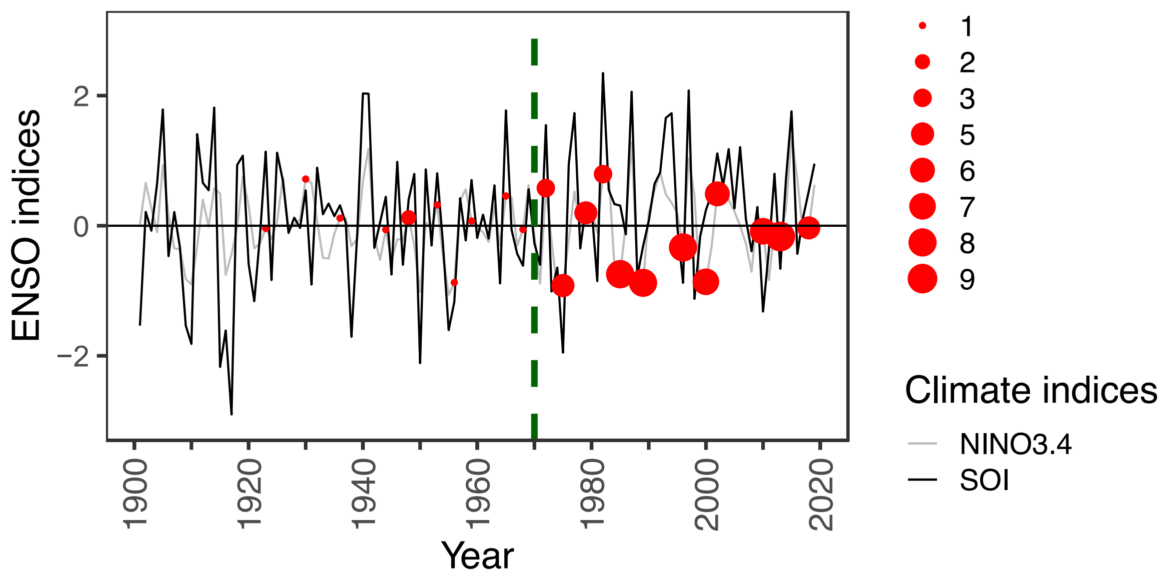

Fig. 5 Time series of reconstructed Niño3.4 and SOI (The SOI index is multiplied by -1 to align the index with the Niño3.4 index) with fire activity. An El Niño event occurs when the sea surface temperature (SST) anomalies exceed +0.5°C, indicating sustained warming. In contrast, a La Niña event is identified 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. 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.

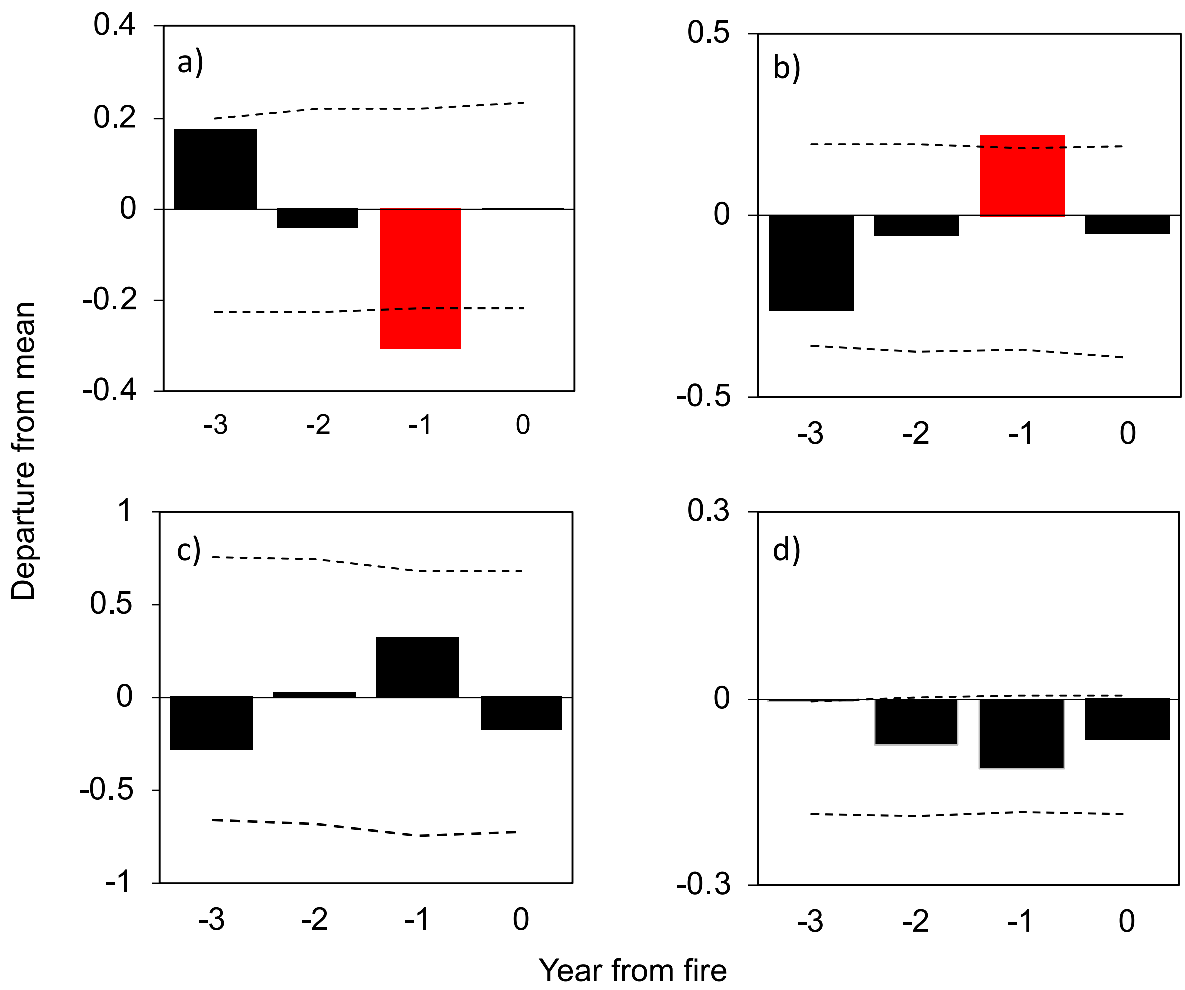

Fig. 6 Superposed Epoch analysis of 25% fire and: (a) El Niño Southern Oscillation (NINO3.4), (b) SOI, (c) scPDSI, and (d) Indian Ocean Dipole (IOD). Red bars indicate a significant association at the 95% level based on bootstrap sampling. SOI varies inversely with the NINO3.4 index. Typically, years 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.

Supplementary Files

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