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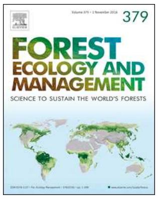

Detecting the influence of climate and humans on pine forests across the dry valleys of eastern Nepal's Koshi River basin

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ABSTRACT

Pine forests provide goods and services crucial to more than ten million people living in the middle-mountains (600–4000 m) of Nepal. These critically important forests are already often overexploited and could be at risk from future climate change. In order to investigate the combined effects of climate and human disturbances on the growth of pine forests, we established a new network of tree-ring sites in six *Pinus wallichiana* and four *P. roxburghii* forests across the dry inner valleys of eastern Nepal's Koshi River watershed. We produced measurements of total annual ring widths, and detrended individual tree-ring series with 67% cubic splines to produce site-level chronologies. The Koshi tree-ring chronologies were compared against local records of mean monthly temperature and total monthly rainfall to identify the main climatic factor(s) limiting pine growth. We also employed a relative growth change method to estimate growth releases and suppressions in ring-width series as indicators of disturbances. At all sites, trees are relatively young (median age was 102 years) and variations in ring-width provide estimates of tree growth over only the past century. Ring-width chronologies from the Koshi have a weak common signal strength in comparison to trees from the same species obtained from sites in the central Himalaya, and the climate-growth response of Koshi pines appears to be governed primarily by moisture balance during winter. Disturbance events evident in pine ring-width data are largely asynchronous, which suggests these forest have been historically perturbed by human influences rather than large-scale climatic or ecological influences. The sacred forest at Sikri contained the oldest living trees (118 years), had the lowest number of disturbance events, and preserved a stronger common signal, which provided additional evidence of the effects of humans on other pine forests in the Koshi basin. Based on our findings, we suggest that modeling the future growth and distribution of pine trees in eastern Nepal should consider winter moisture. Furthermore, management strategies to better conserve pine forests in eastern Nepal should incorporate the two competing influences of climate and human activities on tree growth.

1. Introduction

Pine forests provide key ecosystem services and resources to more than ten million people living in the middle-mountains (600–4000 m) of Nepal (Central Bureau of Statistics, 2012; Shrestha et al., 2007). These mid-mountain forests help mitigate climate change, reduce soil erosion and stabilize slopes (Schreier et al., 1994; Lammeranner et al., 2005; Baral et al., 2009; Shrestha et al., 2013; Dhital et al., 2013; Pandey et al., 2014; Birch et al., 2014), and serve as important sources of timber and firewood for local people (Adhikari et al., 2004; Thoms, 2008). Furthermore, non-timber forest products such as pine resins are important sources of income generation for rural communities (Kanel and Niraula, 2004; KC and Stainback, 2012). The pines also have medicinal values and local people use them as stimulants and anti-pathogens (Kaushik et al., 2013; Sharma et al., 2018). Most pine forests in Nepal are categorized as community forests where thinning, pruning, regulated cattle grazing and controlled harvesting of forest products primarily timber, fuelwood and fodder are practiced (Department of Forest Research and Survery, 2006; cited in Dangal et al., 2017), but these pine forests are often overexploited. In addition, due to observed and anticipated future change in mean and extreme climates (Agarwal et al., 2014, 2016; Karki et al., 2017; Shrestha et al., 2017a; Rajbhandari et al., 2017, 2018; Talchabhadel et al., 2018), the pine forests growing in the relatively dry river valleys of Nepal might be negatively affected (Allen et al., 2010; Williams et al., 2012).

Most studies of pine forests in Nepal have focused on estimating biomass and carbon sequestration (Applegate and Gilmour, 1988; Shrestha et al., 2013; Dangal et al., 2017; Luintel et al., 2018), the

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economic value of forest products (Birch et al., 2014; Chand et al., 2015; Gauli and Hauser, 2011), and the extent of human disturbances (Mahat et al., 1987; Panta et al., 2008). Little is known about climate's influence on the growth of pine trees in Nepal, but understanding the principal climatic factor that limits tree growth is key to appropriately model the future growth and distribution of any tree species (Pearson and Dawson, 2003; Austin and Van Niel, 2011; Elsen and Tingley, 2015; Moran-Ordonez et al., 2017). So far, only tree-ring analysis has been applied to investigate the tree-climate relationships in Nepal, and many of the extant dendroclimatic studies are focused on high elevation (> 3000 m) tree species such as *Abies spectabilis*, *Picea smithiana* and *Betula utilis* (Suzuki, 1990; Bhattacharyya et al., 1992; Cook et al., 2003; Bräuning 2004; Sano et al., 2005; Dawadi et al., 2013; Thapa et al., 2013; Liang et al., 2014; Gaire et al., 2017a; Kharal et al., 2017; Panthi et al., 2017; Rayback et al., 2017; Tiwari et al., 2017; Sigdel et al., 2018b). Two studies have specifically targeted low elevation (< 3000 m) *P. roxburghii* forests but these analyses were based on single sites in western and central Nepal (Aryal et al., 2018; Sigdel et al., 2018a). A few studies have also evaluated the influence of climate on the growth of *P. wallichiana* at higher elevations in western Nepal (Bräuning, 2004; Gaire et al., 2019), but it is not known what climatic factors affect this species' growth at lower elevations. Furthermore, the growth of relatively accessible pine forests might also be affected by human activities, but earlier studies have not attempted to estimate human effects on the growth of pine forests. Quantifying the effects of human disturbance on tree growth may help evaluate the impacts of current and past human actions on forest growth, which would help guide forest managers in the country to develop sustainable forest conservation plans.

Because varying patterns of wide and narrow rings reflect the climatic conditions under which trees grow and disturbances they experience over their life spans (Fritts, 1976; Cook, 1987), tree-ring measurements can provide baseline data to study the combined effects of climate and humans on forest growth (Druckenbrod et al., 2013; Rydval et al., 2016; Trotsiuk et al., 2018). In this study, we present a new network of pine tree-ring sites across the dry valleys of eastern Nepal's Koshi River watershed to examine the influence of climate and human activities on the growth of *P. wallichiana* and *P. roxburghii* forests. Because the inner valleys of the Koshi River catchment are dry compared to central and western Nepal, we test whether it is possible to apply tree-ring analysis to determine the principal climatic factor limiting growth of pine trees under relatively adverse environmental conditions. Furthermore, because low-elevation pines in the Koshi basin are subject to human management and exploitation, we also examine growth releases and suppression to evaluate the effects of human disturbance on the dry forests of eastern Nepal.

2. Materials and methods

2.1. Study area, tree distribution, and sampling sites

The current study was carried out amongst the inner valleys of Koshi River watershed, which is the easternmost river basin in Nepal (Fig. 1). The Koshi River originates from the Tibetan Plateau in the north, flows down the Himalayas, and then finally merges into the Ganges in the south. The river occupies the largest watershed in Nepal and is the third largest tributary of the Ganges River. With most of its population distributed in rural areas, the Koshi watershed is heavily populated in the plains and middle mountains and scattered in the higher mountains (Central Bureau of Statistics, 2012). Having an extreme elevational gradient of more than 8 km (Shrestha et al., 2017a), the Koshi basin hosts a wide range of bioclimatic zones ranging from tropical in the southern plains to alpine and tundra in the northern high altitudes (Karki et al., 2015). As a whole, the climate of Nepal, including the Koshi basin, is heavily influenced by the South Asian monsoon during summer, which delivers roughly 80% of total annual rainfall (Nayava, 1980).

The inner valleys of the Koshi River and its major tributaries are particularly dry, and so provide suitable habitat for *P. roxburghii* and *P. wallichiana* forests (Stainton, 1972; Ohsawa et al., 1986). Within the basin, *P. roxburghii* is most common on dry, south-facing slopes in the river valleys of Tamor, Arun, and Dudhkoshi rivers (major tributaries of the Koshi River), whereas *P. wallichiana* are concentrated in the Solu-khumbu-Everest region (Stainton, 1972; Ohsawa et al., 1986). Across Nepal, the vertical distribution ranges of *P. roxburghii* and *P. wallichiana* are 800–2500 m and 1800–4000 m respectively (Stainton, 1972).

We collected tree-ring samples from ten forest sites in eight districts in the middle-mountains of the Koshi River watershed (Fig. 1, Table 1). The elevation of these forest sites ranged from 825 m (at Hattisude) to 3090 m (at Junbesi). The six *P. roxburghii* sites were located at relatively low elevations (average altitude, 1140 m) with subtropical climates while the *P. wallichaina* sites were located at relatively high elevations (average altitude, 2400 m) in warm temperate climates. The *P. roxburghii* sites were monodominant stands, but the *P. wallichiana* forests, except for Sikri, had several other coexisting species including *Tsuga dumosa* and *Rhododendron spp*. Our field team trekked for one to two days after traveling an equal number of days by Jeep from Kathmandu to reach the sampling sites. All sampled forests are natural (not plantations), close to human settlements, and community managed. At all *P. roxburghii* sites, we noted trees with peeled bark to extract resins. Sites also served as grazing lands for cattle (goats and buffaloes), which were particularly common in *P. wallichiana* forests. We also saw evidence of cut stumps and stacks of logged trees at most sites as pine timber is a common construction material here and elsewhere in Nepal.

2.2. Sample collection, ring-width measurement, and chronology development

We collected 641 core samples from six *Pinus roxburghii* and four *P. wallichiana* forests across the Koshi watershed during the summers of 2016 and 2017 (Table 1, Fig. 1). Haglöfs AB increment borers were used to extract core samples at breast height, and attempts were made to collect two cores from a tree at opposite directions. In those few instances when rugged terrain did not allow us to extract the second core, only one core was collected. The core samples were transferred to the laboratory where they were air dried and then sanded with progressively finer grit sandpapers for clear visualization of ring boundaries under the microscope (Stokes and Smiley, 1968).

For each ring, the calendar year of formation was determined by comparing the patterns of wide and narrow rings across all samples within a site using skeleton plots (Stokes and Smiley, 1968). Ring-width measurements were then generated using a Velmex measurement system. After measurements were produced, the accuracy of cross dating were tested using the computer program COFECHA (Holmes, 1983). To remove the growth trend from each tree-ring width series, we fit a 67% cubic spline and computed ring-width index (the ratio of ring width to spline value; Cook and Peters, 1981). Standardizing ring-width measurements in this manner removes the age-size related growth trend and maximize common signal in the final chronology (Cook and Peters, 1981). For closed-canopy forests like the Koshi pines, spline detrending is recommended over other methods because of its improved ability to estimate and remove competition effects (Cook and Kairiukstis, 1990). All detrended series from each site were averaged to develop a site-level chronology. The standardization procedure and site average chronology building were performed using program ARSTAN (Cook et al., 2017). ARSTAN also computes several common statistical measures to describe the characteristics of tree growth including the all-series correlation (Rbar), the Expressed Population Signal (EPS), and the Signal to Noise Ratio (SNR) (Fritts, 1976; Wigley et al., 1984).

2.3. Detecting climate signals in the Koshi pine chronologies

In order to detect the primary climate variable that limits the

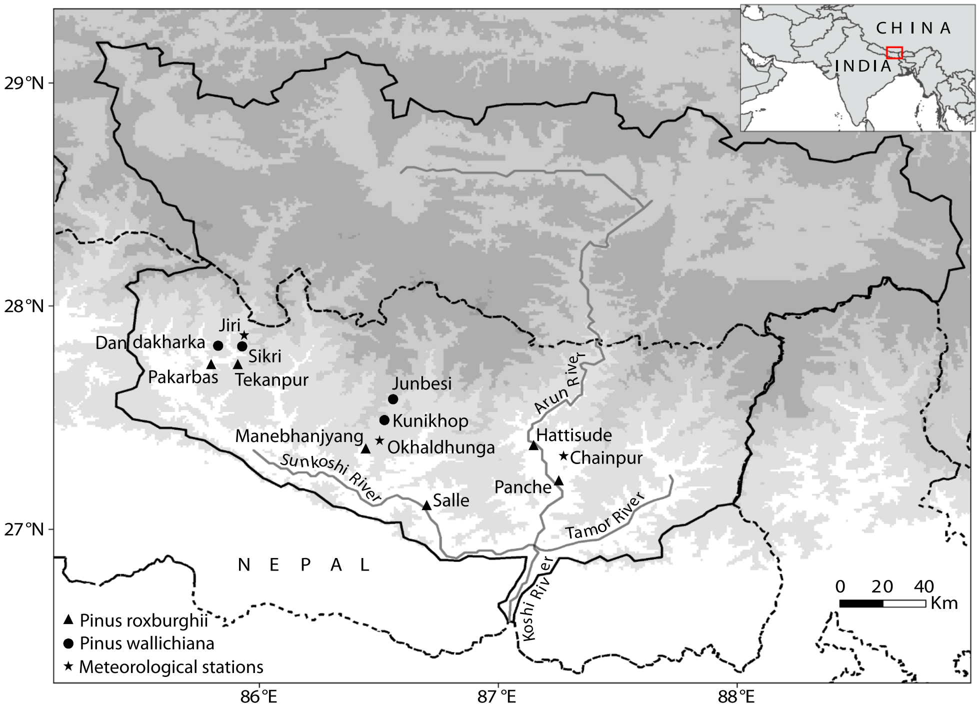

Fig. 1. Map of the Koshi River watershed showing the locations of *Pinus roxburghii* (triangles) and *Pinus wallichiana* (circles) tree-ring sites and meteorological stations (stars) used to examine tree-climate relationships. The solid line represents the catchment boundary of the Koshi River, the dashed-dot line represents Nepal's borders, and the gray lines represent the major river tributaries of the Koshi River.

Table 1
Metadata table describing the details of tree-ring sampling sites in eastern Nepal's Koshi River watershed. Forest sites are ordered by longitude from west to east.

Site name	Species	Location/District	No of trees (cores)	Lat (DD)	Lon (DD)	Elevation (m)	Slope	Aspect	Collection date
Pakarbas (pkw)	*Pinus roxburghii*	Ramechhap	40 (80)	27.24	85.79	1210	20	N	June 2016
Dandakharka (ddk)	*P. wallichiana*	Dolakha	32 (64)	27.50	86.02	1820	22	SW	June 2016
Tekanpur (tkp)	*P. roxburghii*	Ramechhap	30 (60)	27.40	86.09	1130	22	N	June 2017
Sikri (skr)	*P. wallichiana*	Dolakha	16 (32)	27.43	86.23	1750	10	NE	June 2016
Manebhanjyang (mbj)	*P. roxburghii*	Okhaldhunga	34 (69)	27.22	86.44	1513	55	SW	June 2016
Kunikhop (kkp)	*P. wallichiana*	Solukhumbu	30 (60)	27.49	86.52	2950	35	NW	June 2017
Junbesi (jbs)	*P. wallichiana*	Solukhumbu	30 (60)	27.58	86.56	3090	25	W	June 2017
Salle (sal)	*P. roxburghii*	Udaypur	36 (72)	26.97	86.70	1330	57	SW	June 2016
Hattisude (hsd)	*P. roxburghii*	Sankhuwasabha	35 (70)	27.14	87.14	825	18	NW	June 2016
Panche (pnc)	*P. roxburghii*	Dhankuta	37 (74)	27.10	87.25	834	35	N	June 2016

growth of pine trees, we computed Pearson correlation coefficients between each ring-width chronology and climate data from weather stations close to the respective forest site (Table 2). Meteorological stations in Nepal are sparse and were established only recently compared to those in western countries. Because climate data in Nepal are not freely available, we purchased mean monthly temperature and total monthly rainfall data from 14 stations close to the sampling sites from the Nepal Government's Department of Hydrology and Meteorology in Kathmandu. Climate records that were shorter than 31 years were not used even if the corresponding stations were nearby to the sampling sites. Our analysis gave emphasis to rainfall data from Jiri (spanning the period 1961 to 2016), Okhaldhunga (1948 to 2016) and Chainpur (1947 to 2016), and temperature data from Jiri (1965 to 2016) and Okhaldhunga (1977 to 2016). There were a small number of years with missing values (0–6% of total measurements), which we filled with the monthly means of the entire period for each station (Battipaglia et al., 2008). According to the modified Koppen-Geiger climate classification, the sampled forest sites fall under temperate climates with dry winters and hot/warm summers (Karki et al., 2015). The median monthly rainfall is less than 25 mm during November-January and about 600 mm during rainy season (June-September) across the stations (Fig. 2). June-August are the hottest months with temperature measuring between 20 and 25 degrees C while January is the coldest month with mild temperatures between 6 and 11 degrees C (Fig. 2).

Correlation coefficients between tree growth and local climate were computed using the program SEASCORR (Meko et al., 2011). This

Table 2
Metadata table outlining the general features of climate records from weather stations close to tree-ring sampling sites in the Koshi River basin. All climate data were purchased from Nepal's Department of Hydrology and Meteorology in Kathmandu.

Station name	Climate variable	First year	Last year	Span (years)	Lat (DD)	Lon (DD)	Elevation (m)	Corresponding tree-ring site(s)
Jiri	Precipitation	1961	2016	56	27.63	86.23	2003	ddk, skr
	Temperature	1965	2016	52				ddk, skr, sal
Okhaldhunga	Precipitation	1948	2016	69	27.32	86.05	1720	jbs, kkp, sal
	Temperature	1977	2016	40				jbs, kkp, hsd
Chainpur	Precipitation	1947	2016	70	27.28	87.03	1329	hsd
	Temperature	1987	2016	30				

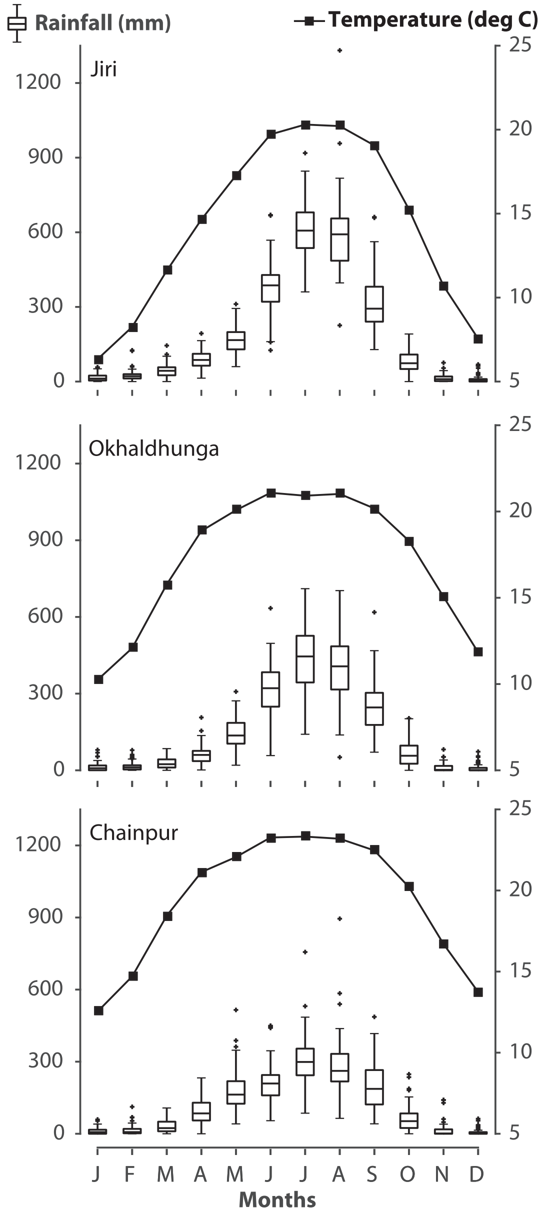

Fig. 2. Climate diagrams demonstrating the total monthly precipitation and mean monthly temperature from meteorological stations at Jiri, Okhaldhunga, and Chainpur used to detect climate signals in tree-ring chronologies.

program performs both monthly as well as seasonal correlation tests by computing simple and partial correlation coefficients between a tree-ring chronology and monthly temperature and precipitation. Significance levels are estimated by Monte Carlo simulations of synthetic tree-ring chronologies. Because the sampled forests were located in the dry valleys of the Koshi basin, we assumed moisture would be the likely dominant factor and therefore chose precipitation as the primary climate variable and temperature as the secondary climate variable. We compared tree growth with climate records from September of the previous year to October of the growth year. The periods of comparison between tree-ring and climate data were short, which might have affected the results as it is difficult to get reliable correlations when the overlapping periods between the two types of data are relatively brief.

2.4. Detecting disturbance events in the Koshi pine forests

Because the sampled forests are affected by management practices and exploited for resources, it is plausible that tree growth might be influenced by those disturbances. We estimated the occurrence of disturbance events within the Koshi pine forests using the radial-growth averaging method (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997). In this approach, disturbances are identified as a relative growth change between the preceding and the subsequent 10-year means of ring widths in every tree-ring series. Nowacki and Abrams (1997) defined moderate (major) disturbance as growth change greater than 25% (50%) between two consecutive 10-year running means for five continuous years. Positive and negative growth changes that met the criteria above were considered to be releases or suppressions, respectively. This relative growth change technique has been widely used to detect growth releases and suppression in each series as indicators of human disturbances in different forest types and tree species globally (Brienen and Zuidema, 2006; Camarero et al., 2011; Schongart et al., 2015; Bretfeld et al., 2015; Omelko et al., 2016; Vitali et al., 2016; Piraino et al., 2017; Camarero et al., 2018). Averaging all cores for each tree might affect the result but we employed the common practice of detecting growth releases and suppressions at the core level. We used TRADER, an R package, to estimate percentage growth change and identify release events in each ring-width series across all sites (Altman et al., 2014). Because the program is designed to detect only release events, we wrote MATLAB code to identify suppression events using the same percentage growth change estimated by TRADER. A disturbance event, for the purpose of this study, was defined as any major suppression or release event that exceeds the 50% growth change criteria.

3. Results

3.1. Cross dating and characteristics of the Koshi pine tree-ring widths

Out of the ten sampled forest sites, we were able to successfully cross-date specimens from all four *P. wallichiana* sites and two of six *P. roxburghii* sites (Table 3). The *P. roxburghii* samples were particularly challenging to cross-date due to the frequent occurrence of false and indeterminate ring boundaries (Fig. 3). Under normal conditions, conifer trees produce distinct light-colored earlywood cells during the early growing season and dark-colored latewood cells at the end of the growing season, making clear boundaries between the rings of consecutive years (Fig. 3a, Fritts, 1976). When climate conditions during the growing season becomes stressful, trees produce latewood-like cells, called false latewood, that have an indistinct boundary, as opposed to true latewood bands that have sharp boundaries with the following year's earlywood cells (Fig. 3b,c; Copenheaver et al., 2006; De Micco et al., 2016; Fritts, 1976; Hoffer and Tardif, 2009). These false rings were more frequent and inconsistent between neighboring trees at four *P. roxburghii* sites (Pakarbas, Tekanpur, Manebhanjyang and Panche), which created major challenges to differentiate between true and false ring boundaries (Fig. 3c). Several samples also had indeterminate boundaries which created extra difficulties in the dating of *P. roxburghii* sites (Fig. 3d). Because of these challenges, we were not able to cross-date samples from those four sites, and therefore did not incorporate them in further analyses. Two *P. roxburghii* sites (Salle and Hattisude) had relatively few and consistent patterns of false latewood bands, so we were able to cross-date specimens from those two sites (Fig. 3b). False-ring boundaries were much less common in samples from *P. wallichiana* sites, so the dating of that species was much more effective. On average, even at the dateable sites we were forced to discard about 13% of collected series due to these challenges.

We measured total tree-ring widths for only those six dated sites. The median value of mean inter-series correlation, which explains the degree of coherence across the samples in a stand, was 0.45 with highest value observed at Sikri (Table 3). We also made additional tests of our assigned dating by making cross-comparisons between all six Koshi chronologies as well as five pine chronologies collected previously (nepa040, nepa005, nepa008, nepa033, nepa007) from central and western Nepal (Cook et al., 2003). We were able to cross-date

Table 3
Table summarizing the ring-width characteristics of *Pinus roxburghii* and *P. wallichiana* chronologies developed from the Koshi River watershed.

	Sites					
	Dandakharka (ddk)	Sikri (skr)	Kunikhop (kkp)	Junbesi (jbs)	Salle (sal)	Hattisdude (hsd)
Chronology span (years)	1917–2015 (99)	1898–2015 (1 1 8)	1936–2016 (81)	1913–2016 (1 0 4)	1910–2015 (1 0 6)	1925–2015 (91)
Number of cores (trees)	59 (32)	26 (14)	31 (18)	50 (30)	61 (33)	58 (34)
Average ring-width	0.416	0.334	0.409	0.379	0.367	0.341
Series intercorrelation	0.461	0.493	0.44	0.441	0.461	0.447
Common period analysis	1977–2012	1953–2012	1963–2015	1948–2015	1968–2015	1965–2011
Correlation within trees	0.509	0.505	0.365	0.29	0.439	0.499
Correlation between trees	0.214	0.209	0.143	0.155	0.18	0.173
Correlation among all series (Rbar)	0.22	0.225	0.148	0.157	0.184	0.178
EPS	0.928	0.853	0.862	0.87	0.925	0.909
SNR	12.943	5.801	6.237	7.716	12.381	9.964

samples from neighboring sites only if they were less than 10 km apart (Fig. 4). For example, the paired chronologies at Dandakharka and Sikri and Junbesi and Kunikhop exhibited positive and significant correlations ($r = 0.39$ & 0.42, $p < 0.01$). Similarly, a pair of previously collected *P. roxburghii* chronologies (nepa007 and nepa033) from the hills surrounding Kathmandu also correlate well with each other ($r = 0.4$, $p < 0.01$). There were a very few years where reduced tree growth was common to most of the Koshi sites, and those marker years were used to cross-date individual series within each stand (Fig. 5). For example, all four chronologies of *P. wallichiana* had narrow rings in 1950, 1955, 1964, 1972, and 1985. In addition, the narrowest ring-width indices in all *P. wallichiana* sites were during 1999–2001. The two *P. roxburghii* chronologies at Salle and Hattisude had narrow rings only in 1955, with no other marker years in common with each other or any *P. wallichiana* chronology.

The median length of the Koshi pine chronologies is 102 years, with the oldest tree located at Sikri and spanning 118 years (Table 3; Fig. 5). All six chronologies exceeded the EPS threshold criteria of 0.85, which helps determine whether the number of core samples is adequate to describe the shared common signal at the stand level (Wigley et al., 1984). The average annual growth rate ranged from 0.34 to 0.41 mm/year, with a median growth rate of 0.37 mm/year across the sites. The median Rbar, which explains the strength of common environmental signal shared across all series, is 0.19. The two *P. wallichiana* sites (Dandakharka and Sikri) had Rbar values equal to 0.22, while rest of the sites were below 0.18 (Table 3). The SNR, which indicates the strength of common signal, ranged from 5.8 at Sikri to 12.9 at Dandakharka.

3.2. Climate signals in the Koshi pine chronologies

At most sites, monthly and seasonal correlation analyses showed that pine tree-ring chronologies had significant and positive correlations with rainfall, and significant negative correlations with temperature during winter months (Fig. 6). Ring-width chronologies at each site had a significant positive correlation with at least one 3-month season of rainfall ending between the previous October and current February. There were however, differences in the magnitude, sign, and specific months of significant correlations between tree growth and precipitation across the sites. In addition, tree growth at Dandakharka, Sikri, and Salle also had significant negative correlations with monthly rainfall in May, August and October. Similarly, tree growth at Dandakharka and Kunikhop were also correlated negatively with spring and summer rainfall. Three out of six chronologies (Sikri, Kunikhop and Salle) had significant negative correlations with winter temperatures. Like precipitation, there were some differences in the particular months or seasons of significant correlations between tree growth and temperature across all sites. For example, Junbesi and Salle chronologies correlated negatively with March temperature while Sikri and Salle chronologies correlated negatively with spring and summer temperatures.

3.3. Disturbances in the Koshi pine forests

We estimated growth releases and suppressions in tree-ring width measurements as indicators of disturbance events for all six forest sites across the Koshi basin (Fig. 7). Disturbance events (releases or suppressions) occurred almost all over the entire span of each chronology.

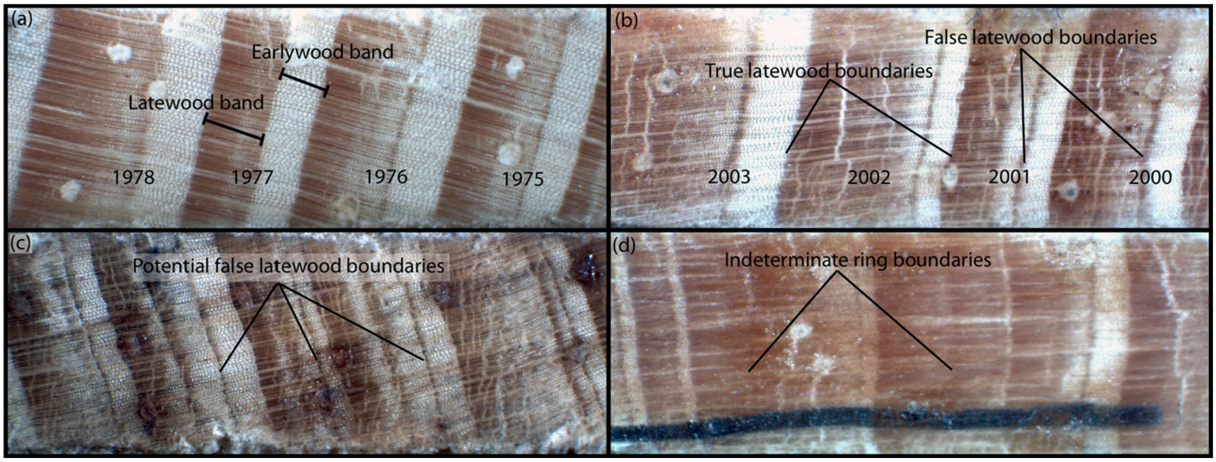

Fig. 3. Wood sections of *P. roxburghii* showing clear and complete earlywood and latewood bands (a), identified false ring boundaries (b), challenging potential false latewood boundaries (c) and indeterminate ring boundaries (d).

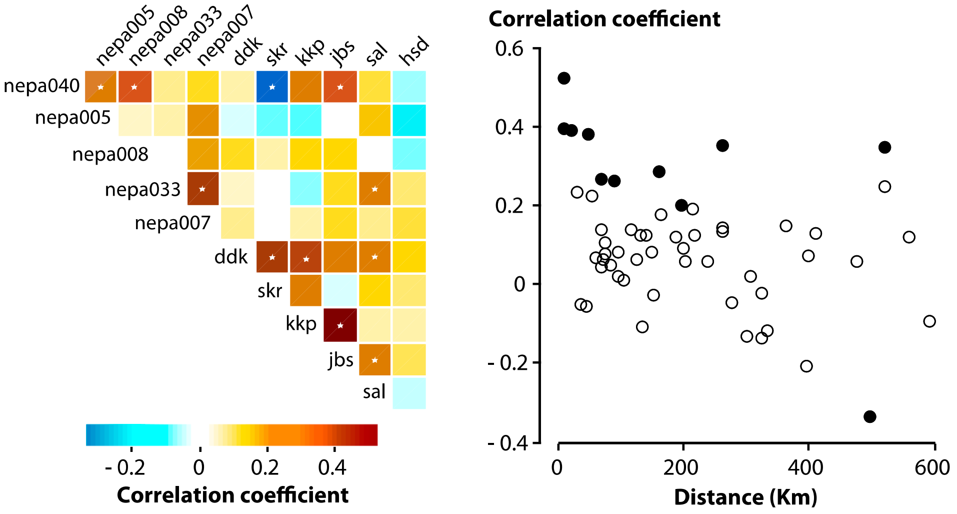

Fig. 4. (a) Matrix of between-chronology correlations for all pairs of pine records including the current Koshi chronologies and previous collections from elsewhere across Nepal. Left and top (right and bottom) sides of the matrix represent chronologies from western (eastern) Nepal. Correlations are calculated for the maximum period of overlap between each pair of chronologies. (b) Scatterplot showing the fading coherence among the pine chronologies with increasing distance. White stars on left panel and filled circles on right panel represent significant correlation coefficients at the 0.01 level.

The *P. roxburghii* forest at Hattisude and *P. wallichiana* forest at Sikri respectively had highest (35) and lowest (18) number of total disturbance events. Except for Junbesi and Hattisude, most chronologies exhibited more suppression events than release events over their entire lengths. The occurrence of continuous release events over multiple years was rare across all sites, with only Hattisude showing growth releases for five continuous years during 1982–1986. In contrast, continuous suppression events for multiple years were much more common. For example, Dandakharka, Salle and Hattisude showed suppression events that lasted for five or more years during 1989–1995, 1986–1993 and 1993–1997 respectively. Except for a very few cases, neither suppression nor release events were synchronized in time across the six sites. Overall, less than 15% of trees were affected either negatively or positively in any one year with few exceptions. For example, 20.6% and 33.3% of trees at Kunikhop and Salle experienced peak suppression events in 1962 and 1937 respectively. In addition, 100% of samples at Sikri showed release in 1913, but that extreme value is due to the fact that only one tree is old enough to include that year.

4. Discussion

4.1. *Cross dating and ring-width characteristics of the Koshi pine chronologies*

From our cross-dating procedures, we learned it is difficult but possible to develop ring-width chronologies of pine trees growing in dry river valleys of the Koshi watershed. Assigning exact dates to the growth rings from *P. roxburghii* trees was particularly challenging due to the frequent occurrence of false and indeterminate ring boundaries. Individual series within each stand matched against each other for all four *P. wallichiana* and two *P. roxburghii* sites. There were several years of reduced growth common across *P. wallichina* forests but marker years were not common between the two *P. roxburghii* sites or between two species. Several pairs of nearby chronologies did match against each other, but poor matches between more distant chronologies indicates the challenges inherent to the large-scale dating of these species in eastern Nepal. This lack of synchrony among the chronologies over short distances might be due to the strong spatial heterogeneity in climate. For example, based on monthly rainfall data from 14 stations across the middle-mountains of the Koshi basin, we found that winter precipitation changes quickly as a function of distance in the study area (Fig. 8).

The Koshi ring-width chronologies provided robust estimates of forest growth and common variance over the past century, as indicated by EPS value greater than 0.85 for all sites (Wigley et al., 1984). All Koshi pine forests are young and have weak common signals compared to those of pines and other species elsewhere in Nepal (Bhattacharyya et al., 1992; Thapa et al., 2017; Aryal et al., 2018; Sigdel et al., 2018a; Gaire et al., 2019), which we interpret as evidence of the strong human use of these forests. Sikri, which is a religiously protected forest, has the oldest living trees and relatively high values of Rbar compared to the other sites. The SNR is low but comparable to several other studies across the central Himalayas (Thapa et al., 2013; Kharal et al., 2017; Gaire et al., 2017b). As part of the forest management practices, community forests in Nepal are regularly thinned by cutting old-appearing trees for improved growth of the rest of the trees as well as to meet local timber demand (Dangal et al., 2017; Rana et al., 2017). Furthermore, the annual growth rate of both pine species is very low compared to pine trees in central and western Nepal (Aryal et al., 2018; Sigdel et al., 2018a) as well as other species across the country with much greater ages (Kharal et al., 2017; Panthi et al., 2017), which suggest these Koshi trees are growing under stress conditions created by climate, humans, or a combination of both factors.

4.2. *Climatic influences in the growth of Koshi pine trees*

Despite subtle differences in climate signals between the sites, overall, moisture supply during winter is the primary factor limiting growth of pine trees at most of the sites in the Koshi River basin as indicated by common positive correlations with winter rainfall and negative correlations with winter temperatures. Because winter is the driest season (Fig. 2), which contributes only 2% of total annual rainfall in the region, small variations in winter moisture supply could be a crucial resource for the overall growth of these pine trees. In other forests, winter rainfall is known to replenish soil moisture balance that can be used by plants during the early growing season (Fritts, 1976; Cleaveland et al., 2003; St. George and Ault, 2014). Rainfall prior to growing season can control the growth of trees in places where temperatures are warm throughout the year for photosynthesis to occur for much longer time in evergreen needles (Fritts, 1976; D'Arrigo and Jacoby, 1991; Cleaveland et al., 2003). The mean winter temperatures in the study area (Fig. 2) never drops below the minimum threshold of 6 degrees C required for trees to enter dormancy (Körner and Paulsen, 2004; Alvarez-Uria and Körner, 2007). A warmer winter could enable the early onset of the growing season but we lack information on cambial activity of pines in the region to confirm that effect. The differences in climate signals we observe across our network might be due to differences in topography, altitude, slope, aspect and microclimate (Dittmar et al., 2003; Babst et al., 2013; Gaire et al., 2017b). Such differences could also be due to rapidly changing rainfall pattern over short distance (Fig. 8) also discussed earlier as one of the challenges in cross-dating pine chronologies. Because the correlation analyses in this

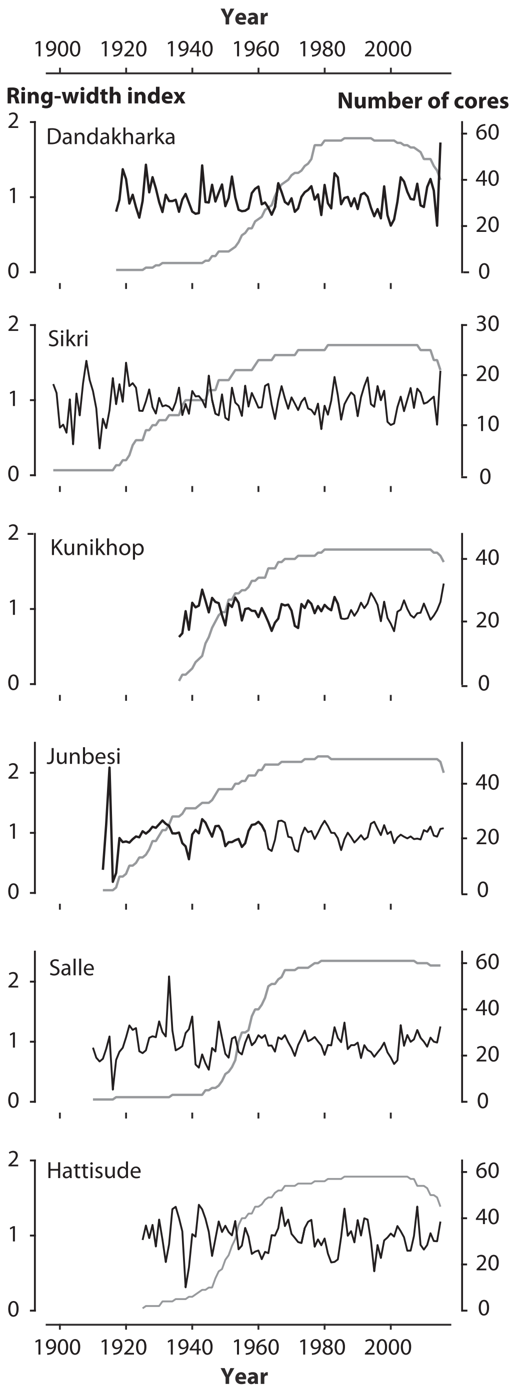

Fig. 5. Tree-ring width chronologies (black lines) and the corresponding number of core samples (grey lines) of *P. wallichiana* (a-d) and *Pinus roxburghii* (e-f) developed at six sites in the Koshi River watershed.

study are based on relatively short periods of overlap between tree-ring chronologies and climate records, we emphasize it is difficult to achieve significant results. Furthermore, human activities might also cause neighboring trees to grow differently irrespective of common climatic control across the stand resulting in weaker correlations with climate.

Our result generally agrees with several studies focused on pine trees across the central Himalaya. Moisture during winter and spring has been reported to limit the growth of *P. roxburghii* in western Nepal (Sigdel et al., 2018a) while only spring moisture was found to be primarily influencing the growth of same species in central Nepal (Aryal et al., 2018). Gaire et al., (2019) also concluded that moisture balance during winter and spring is crucial for the growth of *P. wallichiana*, even though their analysis was based on data from higher elevations compared to the Koshi sites. The climate response of Koshi pine forests is clearly distinct from those of high-altitude tree species including fir, spruce and birch where growth is primarily limited by spring moisture (Dawadi et al., 2013; Thapa et al., 2013; Liang et al., 2014; Gaire et al., 2017a; Panthi et al., 2017; Shrestha et al., 2017b). In addition, compared to other parts of the nation the climate of eastern Nepal remains dry in winter as the westerlies, which deliver cool-season moisture, are confined largely to western Nepal (Shrestha, 2000; Rajbhandari et al., 2018).

4.3. Human disturbances in the Koshi pine forests

Our analysis of release and suppression events during the past hundred years suggests the growths of pine trees in the Koshi River watershed have been historically influenced by human activities. The lack of synchrony in disturbance events, even among close sites, and the overall lower proportion of affected trees compared to the forests elsewhere affected by ecological or climatic agents suggest the identified events are the results of episodic human disturbances specific to each site. Large-scale ecological or climatic disturbances such as insect outbreaks and hurricanes (Büntgen et al., 2009; Fernandes et al., 2018; Trotsiuk et al., 2018) usually affect the growth of a larger proportion of trees within an affected forest. We lack quantitative information on forest exploitation in the Koshi such as number of logged trees, amount of resin tapped, or number of grazing livestock, but during our fieldwork did observe several instances of logging, cattle grazing and resin tapping across the forests. These activities might cause neighboring trees to grow differently, and as a consequence the ring-width chronologies to have weaker common signals. Even though the number of disturbance events depends on the nature of human interventions specific to each forest, both the frequency and intensity of disturbances in this study are fairly comparable to other global studies over similarly long chronologies (Brienen and Zuidema, 2006; Druckenbrod et al., 2013; Parobeková et al., 2016; Rydval et al., 2016; Petritan et al., 2017; Lemus-Lauzon et al., 2018). Sikri, the only religiously protected forest, had the least number of disturbance events, which suggests humans have a discernible effect on the growth of pine forests elsewhere in the Koshi basin.

Growth releases are indicators of canopy openings (Brienen and Zuidema, 2006; Smith and Brennan, 2006; Zhang et al., 2006), which in the case of Koshi pine forests, might be the result of logging. Forest gaps created by intensive logging increases light availability that can enhance the growth of remaining trees at proximity (Figueira et al., 2008). The occurrence of growth suppressions in *P. roxburghii* sites might be due to the combined effects of bark peelings to tap resins (Papadopoulos, 2013; Genova et al., 2014; Chen et al., 2015) and soil compaction by intensive cattle grazing, while growth reductions in the *P. wallichiana* forests might be a consequence of cattle-induced soil compaction (Jones, 2000; Pulido et al., 2018). Growth reductions following resin extractions might be a result of the increased investment of carbohydrates in the production of resins at the expense of tree growth (van der Maaten et al., 2017). Although its effect depends on soil type and tree species, in general, compaction increases soil's strength (bulk density) and decreases the volume of macropores, which limits ability of roots to effectively transport nutrient and water, as a consequence trees might have reduced growth (Corns, 1988).

It is likely that not all disturbance events evident in these data are caused solely by human activities and some events might be a result of climatic change or combined effects of climate and humans (Abiyu et al., 2018). For example, growth indices were lowest during 1999–2001 across all four *P. wallichiana* sites, which coincides with a nation-wide record drought year of 1999 (Sigdel and Ikeda, 2010). Furthermore, based on our analysis of rainfall data from 14 weather stations (not shown), we found that 1998–2001 was one of the driest winter periods in the past five decades across the middle-altitudes in the

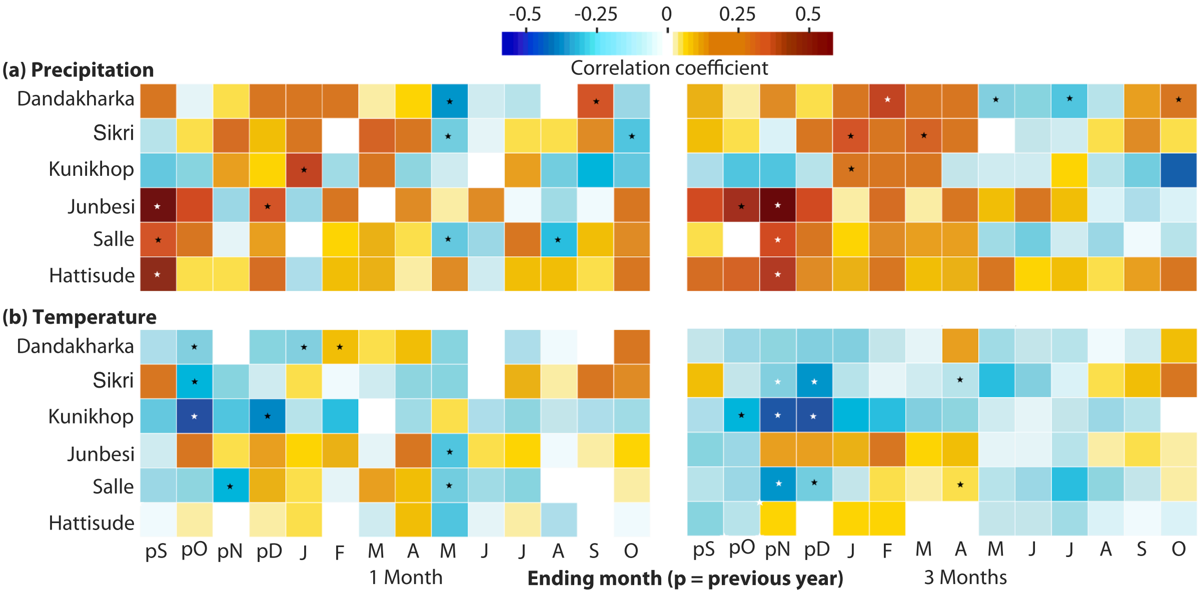

Fig. 6. Color diagram illustrating correlation coefficients between tree-ring width chronologies and local records of climate across the Koshi River watershed. The top panels represent simple correlation coefficients between tree-ring widths and rainfall while the bottom panels represent partial correlations between tree-ring widths and temperature. The left and right panels respectively demonstrate monthly and seasonal (3 months, ending month) correlations. White (black) stars indicate correlation coefficients significant at the 0.01 (0.05) level.

Koshi basin. But, in the same interval, two *P. wallichiana* forests (Kunikhop and Junbesi) experienced growth releases while both *P. roxburghii* forests (Salle and Hattisude) experienced growth suppressions.

5. Conclusions

Pine forests are the primary sources of timber, firewood, and resins to more than three million people living in the middle mountains of eastern Nepal's Koshi River watershed. Based on our analysis of a new network of pine tree-ring width chronologies, we suggest that both climate and human factors have discernible effects on the growth of *Pinus roxburghii* and *P. wallichiana* forests across the Koshi basin. Even though *P. roxburghii* from the Koshi was particularly challenging to cross-date, it is possible to develop annually resolved tree-ring

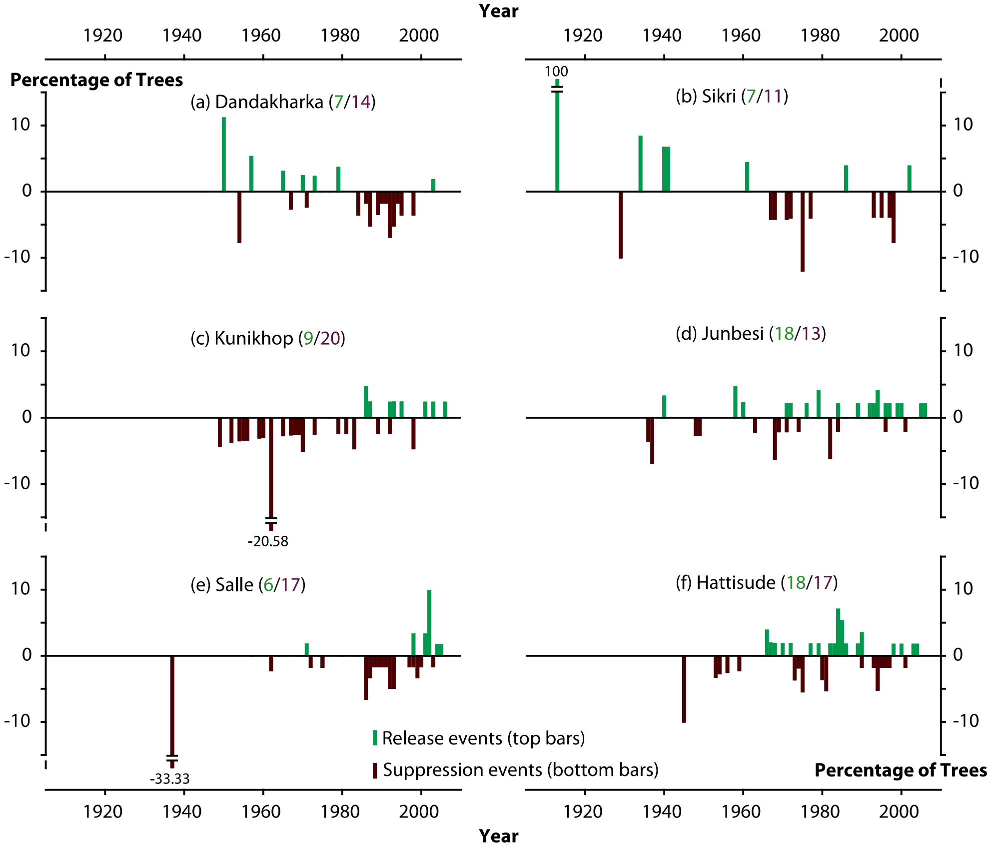

Fig. 7. Bar diagrams showing percentage of trees that experienced disturbances expressed as either growth release or suppression events over time in the forests of *Pinus wallichiana* (a-d) and *Pinus roxburghii* (e-f) across the Koshi River basin. The top green bars represent release events and the bottom brown bars represent suppression events.

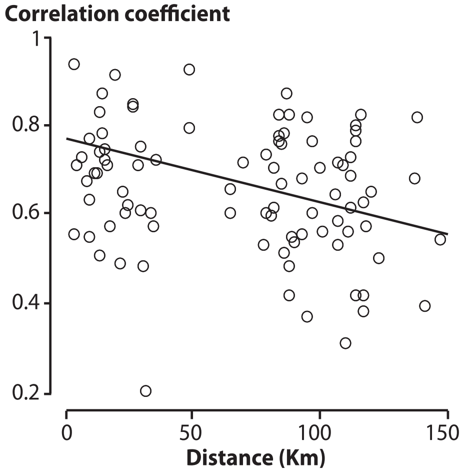

Fig. 8. Distance-correlation plot showing decreasing coherence in winter precipitation with increasing distance among the fourteen meteorological stations at mid-altitudes of the Koshi River watershed. All correlation coefficient values are significant at 0.01 level.

chronologies from both species. Pine forests across the watershed are young and have weak common signals indicating presence of intensive human use in these forests.

Estimation of growth release and suppression events suggested that pine forests across the Koshi watershed have been historically intervened by humans. The higher frequency of single and continuous multiple suppression events than release events, as well as, low annual growth rates of trees indicate that, overall, human activities have negative effects on the growth of the pine forests in the Koshi basin. We hope this knowledge will help stakeholders evaluate their current approaches of forest management and conservation, and make better-informed future decisions. In addition, future research that specifically discriminates between affected and unaffected trees could provide a more complete picture of human disturbances on forests. For example, collection of samples from only resin-tapped trees is recommended to quantify the effects of resin tapping on the growth of *P. roxburghii*. Structured survey questions to the local community forest user groups and the district forest offices would help produce quantitative information on management practices and resource exploitation specific to each site, and enable researchers to better isolate human influences on tree growth.

The growth of pine trees across the Koshi River basin is limited by moisture availability during winter. Because the ring-width chronology at the protected forest at Sikri has a similar climate signal compared to the rest of the sites, we are more confident that winter moisture is important to the growth of Koshi pine forests. This information may be helpful to understand future growth and distribution of pine trees under a changing climate, which could contribute to evidence-based conservation strategies to protect pine forests in eastern Nepal. So far, no attempt has been made to model potential tree distribution movements with climate change in Nepal but studies elsewhere, including the Tibetan Plateau and the Alps (Song et al., 2004; Austin and Van Niel, 2011; Dullinger et al., 2012), have primarily linked tree distribution to summer precipitation. Even though summer is the wettest season in Nepal, it may be important to consider winter moisture to more accurately model future growth and distribution of Koshi pine trees. It is not certain whether rainfall in the watershed will increase or decrease in the coming decades, but the Koshi basin will experience significant warming, particularly during winter in the near future (Agarwal et al., 2014, 2016; Rajbhandari et al., 2017, 2018). This projected rise in winter temperature is likely to enhance winter drought through increased evapotranspiration (Vicente-Serrano et al., 2010; Trenberth et al., 2014). The growth of these critically important pine forests might therefore be further suppressed by future winter drought affecting eastern Nepal.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.03.013.

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