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Scott St. George
University of Minnesota Twin Cities

D. K. Kharal
Department of Forest Research and Survey

Narayan Gaire
Tribhuvan University

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U.K. Thapa
University of Minnesota, USA

S. St. George
University of Minnesota, USA

D.K. Kharal
Government of Nepal, Nepal

N.P. Gaire
Tribhuvan University, Nepal

Abstract

The climate of Nepal has changed rapidly over the recent decades, but most instrumental records of weather and hydrology only extend back to the 1980s. Tree rings can provide a longer perspective on recent environmental changes, and since the early 2000s, a new round of field initiatives by international researchers and Nepali scientists have more than doubled the size of the country's tree-ring network. In this paper, we present a comprehensive analysis of the current tree-ring width network for Nepal, and use this network to estimate changes in forest growth nation-wide during the last four centuries. Ring-width chronologies in Nepal have been developed from 11 tree species, and half of the records span at least 290 years. The Nepal tree-ring width network provides a robust estimate of annual forest growth over roughly the last four centuries, but prior to this point, our mean ring-width composite fluctuates wildly due to low sample replication. Over the last four centuries, two major events are prominent in the all-Nepal composite: (i) a prolonged and widespread growth suppression during the early 1800s; and (ii) heightened growth during the most recent decade. The early 19th century decline in tree growth coincides with two major Indonesian eruptions, and suggests that short-term disturbances related to climate extremes can exert a lasting influence on the vigor of Nepal's forests. Growth increases since AD 2000 are mainly apparent in high-elevation fir, which may be a consequence of the observed trend towards warmer temperatures, particularly during winter. This synthesis effort should be useful to establish baselines for tree-ring data in Nepal and provide a broader context to evaluate the sensitivity or behavior of this proxy in the central Himalayas.

Keywords

Dendrochronology, dendroclimatology, Himalayas, paleoclimate, Nepal, tree rings

I Introduction

Nepal's climate has changed significantly over the recent decades. The Nepal Himalaya has warmed rapidly since the 1970s, with the

Corresponding author:
U.K. Thapa, Department of Geography, Environment and Society, University of Minnesota, 267 19th Avenue South, Minneapolis, MN 55455, USA.
Email: thapa037@umn.edu

increase in temperature being even more pronounced at higher elevations (Shrestha and Aryal, 2011; Shrestha et al., 1999; Stocker et al., 2013). Over the same interval, precipitation has become both more intense and sporadic, with the region experiencing fewer rainy days on average (Karki et al., 2017; Shrestha et al., 2000, 2017). During the past three decades, roughly a third of the country's rivers produced increased flow during spring and winter seasons, likely reflecting the enhanced contribution from snowmelt due to warming (Gautam and Acharya, 2012). But most climate observations in Nepal are available only back to the 1980s, and this brief perspective makes it more difficult to gauge both the rate and potential causes of recent changes.

To address this deficiency, several biological or geological proxies have been used to reconstruct Holocene climates in the Nepal Himalaya, including pollen (e.g. Schlütz and Zech, 2004), glacial moraines (Gayer et al., 2006; Owen, 2009), lake sediments (Fujii and Sakai, 2002), and tree rings (e.g. Cook et al., 2003; Sano et al., 2005; Thapa et al., 2015). Tree-ring data from Nepal have been used as surrogates to reconstruct seasonal temperatures at local (Sano et al., 2005; Thapa et al., 2015), regional (Cook et al., 2003; Cook and Krusic, 2008), and sub-continental to continental scales (Cook et al., 2008, 2010, 2013a), as well as local summer drought severity (Sano et al., 2011) and spring precipitation (Gaire et al., 2017a). Dendrochronological methods have also been applied to assess treeline shifts in response to warming temperatures in central Nepal (Gaire et al., 2014, 2017) and to date archeological sites in the Mustang region (Schmidt, 1993; Schmidt et al., 1999). Cook et al. (2003) conducted a comprehensive sampling campaign in the 1990s to collect tree-ring specimens from sites across the country, but, since that time, a new round of field initiatives by international researchers (e.g. Bräuning, 2004; Liang et al., 2014) and Nepali scientists (e.g. Dawadi et al., 2013; Kharal et al., 2017; Thapa et al., 2013) have more than doubled the size of the country's tree-ring network. But because these recent studies have adopted a variety of different approaches to remove age–size trends from ring-width data and compile stand-level composites (called 'chronologies'; Fritts, 1976), it is not appropriate to combine those published series to yield a reliable estimate of past variations in tree growth across Nepal. Gaire et al. (2013) recently reviewed the history of dendrochronology in Nepal and summarized the current status of the national tree-ring network, but their summary only reported the number of collections obtained from particular tree species or geographic regions and did not include a reanalysis of the original tree-ring data.

In this paper, we present a comprehensive analysis of the current tree-ring width network for Nepal, and use this network to estimate mean changes in forest growth across the country during the past four centuries. First, we summarize the development of tree-ring width collections from Nepal, and describe their distribution by tree genera, elevation, and region. Second, we evaluate the fundamental characteristics of common signal in Nepalese tree-ring chronologies, including the quality of the common signal shared amongst all trees at a given site, the variability in strength of that signal through time and the presence of shared growth anomalies including locally absent rings. Third, after applying the same method of age–size standardization to all records, we develop a four-century-long growth index of mean tree-ring widths across Nepalese forest and report two major growth excursions during that interval. Because we apply the same pre-processing to all tree-ring width data in our network, we are better able to evaluate long-term growth trends without the conflating influence of inconsistent standardization methods. Finally, we conclude by highlighting the potential applications of dendrochronology to studies of environmental change in Nepal.

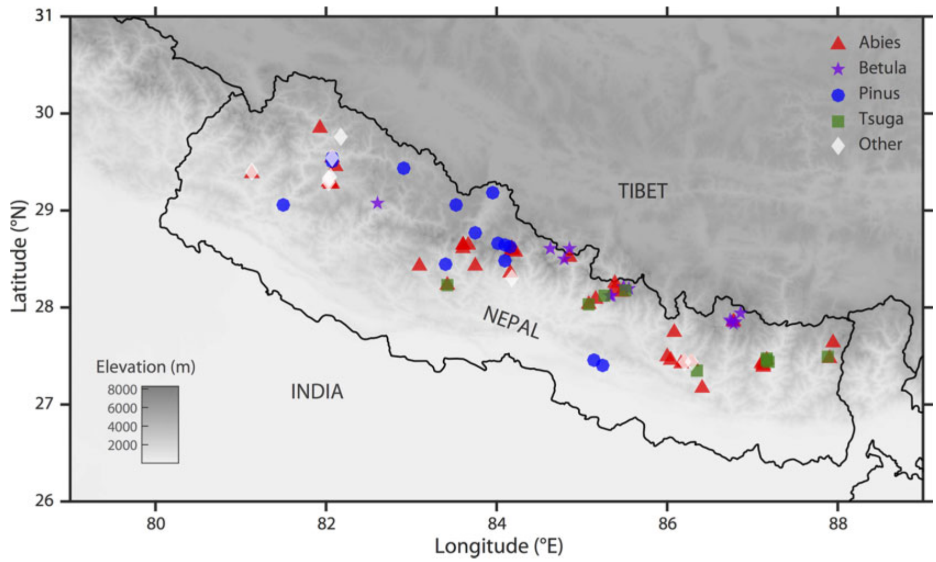

Figure 1. The current network of known tree-ring width data from Nepal, classified by tree genera. This compilation includes data archived at the International Tree Ring Data Bank (Grissino-Mayer and Fritts, 1997) and privately held records reported in the published literature.

II Development and structure of the Nepalese tree-ring width network

Based on our survey of the literature and public databases, we estimate the Nepalese tree-ring width network currently includes more than 80 individual records (ring-width measurements made on core samples from dozens of trees or more at a single location; Figure 1). The network is primarily the result of three major pulses of field collections in the late 1970s, the 1990s, and the recent decade (Figure 2(a)). The first collections were made by Rudolf Zuber in 1979–1980 while working under the direction of Fritz Schweingruber from the Swiss Forest Research Center in Birmensdorf. Zuber collected 13 records from central and western Nepal, with the tree-ring measurements for these samples being generated later by Amalava Bhattacharyya, Edward Cook, and Paul Krusic (Bhattacharyya et al., 1992; Cook et al., 2003). In the early 1980s, Eizi Suzuki from Japan's Kagoshima University developed three records from western Nepal (Suzuki, 1990). Following Suzuki's collections, no sampling was conducted in Nepal for the next decade until Edward Cook and Paul Krusic from Columbia University made several trips over six consecutive years collecting tree-core samples during the 1990s (Cook et al., 2003). During the same period several non-Nepalese investigators, including Burghart Schmidt, Achim Bräuning, and Masaki Sano, also developed records from Nepal (Bräuning, 2004; Sano et al., 2005; Schmidt, 1993; Schmidt et al., 1999). By the end of the 20th century, roughly half of the current network was in place. Finally, due in part to the establishment of the first tree-ring laboratory in Nepal at the Nepal Academy of Science and Technology in Kathmandu, the latest round of tree-ring collections has been led by scientists of Nepalese origin, either based domestically (e.g. Gaire et al., 2013) or working abroad (e.g. Dawadi et al., 2013).

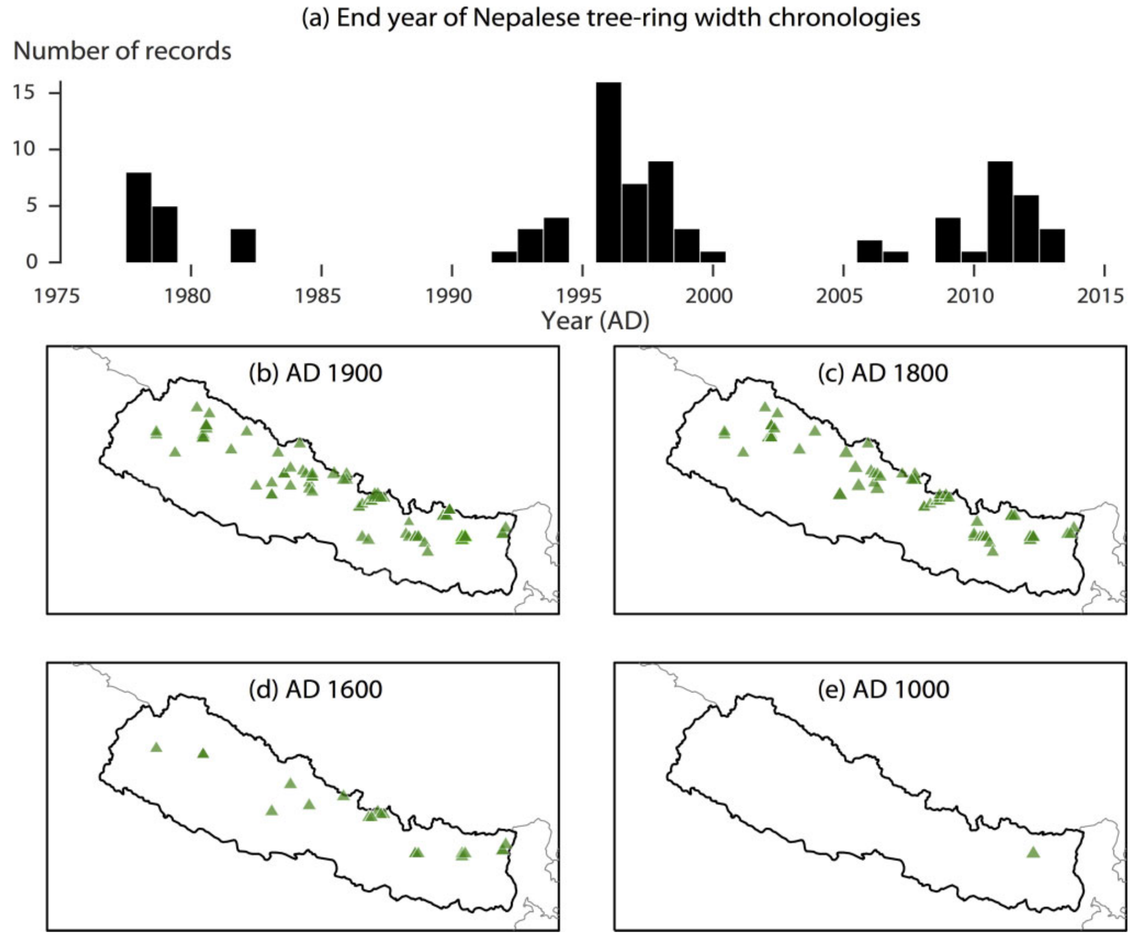

Figure 2. (a) Histogram showing the year of collection for tree-ring width records in Nepal, and maps showing the distribution of tree-ring records (triangles) that extend back to (b) AD 1900, (c) AD 1800, (d) AD 1600, and (e) AD 1000. These plots are based on all 86 tree-ring records established across the nation to date.

The spatial distribution of the Nepalese tree-ring width network is fairly homogenous along the country's east–west dimension (Figure 1). Nearly half (41) of the records are located in central Nepal between 83° and 86°E. In the central region, most collections have been made in Langtang National Park, Manaslu Conservation Area, and the Annapurna Conservation Area (Bhattacharyya et al., 1992; Cook et al., 2003; Dawadi et al., 2013; Gaire et al., 2014; Liang et al., 2014), likely due to these regions' proximity to Kathmandu and their relatively gentle topography as compared to other parts of the country. The Nepalese records span an elevation range of nearly three kilometers between 1320 m and 4150 m (Figure 3), with most collections having been made between 2500 and 3800 m. This elevation range matches the distribution of most of the conifer species including pine, fir, hemlock, and spruce at this elevation along east–west Nepal. A few high-elevation records have been established near the elevational limit of tree growth in Nepal (3900–4200 m) to study treeline dynamics (Gaire et al., 2014) or the

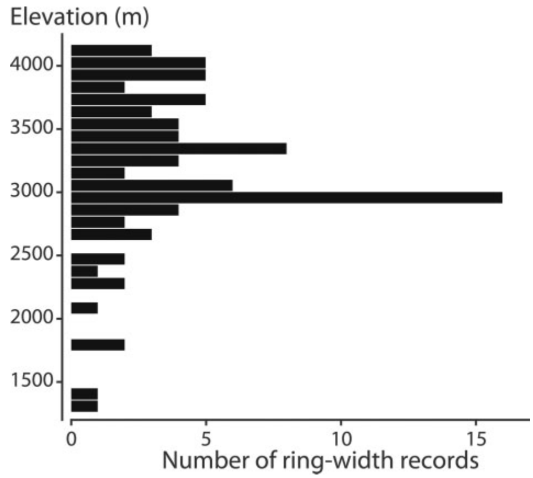

Figure 3. Histogram showing the distribution of all Nepalese tree-ring width records by elevation established to date.

climate relationships of treeline species (Liang et al., 2014). Only 10 ring-width records have been developed at sites below 2500 m, and most of those collections have been made from *Pinus*, which is the most widely distributed conifer genus at lower elevations (Stainton, 1972). Prior dendrochronological investigations of pines, particularly *P. roxburghii* (Bhattacharyya et al., 1992; Cook et al., 2003) have reported that this genus frequently forms false rings (Fritts, 1976), which might pose another obstacle to the development of ring-width records from these particular trees. The only broad-leaved tree species collected below 2500 m is *Populus ciliata*, and only one record has been established from this species.

Overall, ring-width chronologies in Nepal have been developed from nine genera and 11 tree species (Table 1). Nearly half of the total records were collected from *Abies spectabilis* due to its wide east–west distribution across Nepal (Stainton, 1972). Other common species include *Betula utilis*, *Tsuga dumosa*, and *Pinus wallichiana*. Half of the Nepalese records span at least 292 years, and there are 22 records scattered across the country that predate AD 1600 (Figure 2(d)). The longest Nepalese tree-ring width record, which extends back to AD 856, was built from a mid-elevation stand of *Tsuga dumosa* from eastern Nepal (Cook et al., 2003). The exceptional length of that chronology is evidence that the forests of Nepal offer at least some opportunities to construct long, millennial-length records from living trees, instead of being only restricted to long sequences pieced together from historical or subfossil wood.

III Synthesis of the Nepal Himalayan tree-ring network

Following our survey of the published literature, we obtained tree-ring width measurements for 55 locations in Nepal (Table 2), drawing upon data from the public archive maintained by the International Tree-Ring Data Bank (ITRDB, Grissino-Mayer and Fritts, 1997), and new records produced by Nepalese scientists (Gaire et al., 2011, 2014; Kharal et al., 2017; Thapa et al., 2015). The remainder of the Nepal tree-ring width network described earlier in Section II is held privately by individual investigators, and we were not able to include those data in our analysis.

Each set of ring-width measurements was evaluated using the COFECHA software package (Holmes, 1983) to confirm cross-dating accuracy (Fritts, 1976) and to identify cases of locally absent ('missing') rings (Schulman, 1941; St. George et al., 2013). We generated site-level composites (chronologies) via the RCSigFree (courtesy of Dr Edward Cook, Columbia University), and used the signal-free standardization method (Melvin and Briffa, 2008) with age-dependent smoothing (Melvin et al., 2007) to estimate and remove long-term trends related to tree age or size from individual ring-width measurements. The signal-free method uses an iterative approach to produce detrending curves that are 'free' of growth patterns common across the entire set of ring-width measurements at a given

Table 1. Length of the longest ring-width chronologies in Nepal for several major tree species.

Species	Span (years)	Earliest year (AD)	Most recent year (AD)	Reference
Tsuga dumosa	1141	856	1996	Cook et al. (2003)
Pinus wallichiana	694	1303	1996	Cook et al. (2003)
Abies spectabilis	603	603	1997	Cook et al. (2003)
Juniperus recurva	582	1417	1998	Cook et al. (2003)
Betula utilis	458	1552	2009	Dawadi et al. (2013)
Ulmus wallichiana	432	1566	1977	Cook et al. (2003)
Picea smithiana	422	1591	2012	Thapa et al. (2015)
Abies pindrow	363	1650	2012	Thapa et al. (2013)
Pinus roxburghii	297	1683	1979	Bhattacharyya et al. (1992)
Cedrus deodara	265	1714	1978	Bhattacharyya et al. (1992)
Populus sp.	171	1824	1994	Cook et al. (2003)

location, and is intended to preserve more variance at medium and low frequencies relative to traditional detrending approaches (Melvin and Briffa, 2008).

IV Fundamental characteristics of Nepalese tree-ring width records

In this section, we summarize the fundamental characteristics of tree-ring width data from Nepal, beginning by outlining the quality of common signal inherent to individual sets of ring-width measurements. Neighboring trees exhibit similar year-to-year patterns in tree-ring widths because their growth is influenced by common external environmental forcings, which can include climate, disturbance, and competition (Cook, 1987). The clarity of that shared environmental signal is most often estimated by computing the mean correlation between all possible pairs of tree-ring width measurements within the stand (RBAR; Wigley et al., 1984). Over the entire Northern Hemisphere tree-ring width network, the median value of RBAR is 0.4, but for some records, mainly those in the arid American Southwest, this metric may exceed 0.8 or 0.9 (St. George, 2014). The median value of RBAR for the Nepal tree-ring network is 0.35, which is lower than the hemispheric standard but does match the level of agreement reported for other collections from the broader region, including those in the neighboring Himalayas and the Tibetan Plateau (St. George, 2014). There is not any clear spatial pattern in RBAR across the country (Figure 4), but tree-ring width data derived from *Pinus roxburghii* and *P. wallichiana* generally exhibit a stronger common signal than the other major tree species. The five pine chronologies have a median RBAR of 0.43, and two of the five highest RBAR values are associated with *P. wallichiana* from mid-elevation (3000 m) sites in central Nepal. Because in many cases those ring-width records with strong between-tree agreement are also the most skillful predictors for climate reconstruction, this result indicates *Pinus* species from Nepal's lower to mid-elevation forests may be particularly well-suited to be potential paleoclimatic proxies.

In terms of temporal coverage, the Nepal tree-ring width network provides a robust estimate of annual forest growth over roughly the past four centuries. Six chronologies maintain an Expressed Population Signal (EPS; Wigley et al., 1984) greater than 0.85 back to AD 1600 (Fig 5(b)). Earlier in the 16th century, five chronologies or fewer satisfy this criterion, and the mean ring-width index (computed as the average of all chronologies; Figure 5(a)) and mean RBAR values (Figure

Table 2. Metadata table outlining the general characteristics of tree-ring width records assembled from the public archive (International Tree Ring Data Bank; Grissino-Mayer and Fritts, 1997) and the respective investigators. Records are ordered by longitude from east to west. Unless noted by a specific citation, records were obtained from the World Data Center for Paleoclimatology (WDC-Paleo).

Site code	Species	Site name	Lat (degree N)	Lon (degree E)	Elevation (m)	Reference
nepa021	ABSB	Ghunsa	27.63	87.95	3740	WDC-Paleo
nepa027	ABSB	Lamite Bhajyung	27.48	87.9	3267	WDC-Paleo
nepa042	TSDU	Yalung khola	27.5	87.88	3033	WDC-Paleo
nepa004	TSDU	Above hatiya	27.43	87.18	2940	Cook et al. (2003)
nepa012	TSDU	Budorouke	27.45	87.17	2970	Cook et al. (2003)
nepa030	TSDU	Lukuchi Khola	27.47	87.17	2880	Cook et al. (2003)
nepa011	ABSB	Budorouke	27.45	87.17	2970	Cook et al. (2003)
nepa026	ABSB	Kauma Karka	27.38	87.13	2900	Cook et al. (2003)
nepa036	ABSB	Rachel's Death	27.43	87.12	3630	Cook et al. (2003)
nepa032	ABSB	Mumbuk	27.4	87.12	3200	Cook et al. (2003)
nepa034	ABSB	Nehe Karka	27.42	87.1	3250	Cook et al. (2003)
bhw032	BEUT	Sagarmatha	27.95	86.85	4100	Gaire et al. (2017b)
bhw033	ABSB	Sagarmatha	27.85	86.78	4100	Gaire et al. (2017b)
nepa013	ABSB	Chardung	27.17	86.42	3300	Cook et al. (2003)
nepa041	TSDU	Tragdobuk	27.35	86.35	2950	Cook et al. (2003)
nepa009	ABSB	Bhulepokhari	27.43	86.28	3600	Cook et al. (2003)
nepa010	JURE	Bhulepokhari	27.43	86.28	3600	Cook et al. (2003)
nepa018	JURE	Dobini danda	27.43	86.2	3500	Cook et al. (2003)
nepa017	ABSB	Dobini Danda	27.43	86.2	3500	Cook et al. (2003)
nepa014	ABSB	Chardung Danda	27.42	86.17	3000	Cook et al. (2003)
nepa002	ABSB	Kalinchowk gebirge	27.75	86.08	3720	WDC-Paleo
nepa022	ABSB	Kalinchowk	27.45	86.05	3720	Bhattacharyya et al. (1992)
nepa028	ABSB	Lamjura	27.5	86	3020	WDC-Paleo
bhw008	ABSB	Langtang NP	28.25	85.38	2729	Gaire et al. (2011)
nepa029	TSDU	Langtang	28.12	85.27	2670	Cook et al. (2003)
nepa007	PIRO	Bhaktapur	27.4	85.25	1320	WDC-Paleo
nepa033	PIRO	Nagarjun	27.45	85.15	1420	WDC-Paleo
nepa039	TSDU	Banal-Salme	28.03	85.07	2910	Cook et al. (2003)
nepa038	ABSB	Banal-Salme	28.03	85.07	3115	Cook et al. (2003)
bhw011	ABSB	Manaslu	28.52	84.86	3690	Gaire et al. (2014)
nepa006	PPCI	Bagarchap	28.3	84.18	2270	WDC-Paleo
bhw027	ABSB	Manang	28.60	84.18	3175	Kharal et al. (2017)
bhw028	ABSB	Manang	28.60	84.174	3375	Kharal et al. (2017)
bhw029	ABSB	Manang	28.59	84.17	3575	Kharal et al. (2017)
nepa031	ABSB	Marsyangdi khola	28.35	84.15	2900	Bhattacharyya et al. (1992)
nepa008	PIWA	Bhratang	28.48	84.1	3095	Cook et al. (2003)
nepa001	ABSB	Ghorepani pass, Annapurna	28.42	83.75	3220	Bhattacharyya et al. (1992)
bhw025	ABSB	Mustang, Pangu Khark	28.65	83.66	3100	Kharal et al. (2014)

(continued)

Table 2. (continued)

Site code	Species	Site name	Lat (degree N)	Lon (degree E)	Elevation (m)	Reference
bhw023	ABSB	Mustang, Titi lower	28.65	83.61	2700	Kharal et al. (2014)
bhw024	ABSB	Mustang, Titi upper	28.64	83.61	2900	Kharal et al. (2014)
bhw026	ABSB	Mustang, Lete upper	28.61	83.61	3300	Kharal et al. (2014)
nepa016	TSDU	Deorali	28.23	83.42	1830	Cook et al. (2003)
nepa015	ABSB	Deorali	28.23	83.42	1830	Cook et al. (2003)
nepa005	PIWA	Alu bari	28.45	83.4	3000	WDC-Paleo
nepa035	ABSB	Pun Hill	28.43	83.1	2950	WDC-Paleo
nepa019	ABSB	GhurchiLehk Recollection	29.28	82.07	3330	Cook et al. (2003)
nepa037	PCSM	Rara Goan	29.35	82.05	3000	WDC-Paleo
nepa020	ABSB	GhurchiLehk	29.3	82.05	3450	Bhattacharyya et al. (1992)
nepa003	ABSB	Above Gheri	29.28	82.05	3450	Cook et al. (2003)
nepa024	PCSM	KatyaKhola-3	29.3	82.02	3480	Cook et al. (2003)
nepa025	ULWA	KatyaKhola	29.32	82.02	2760	Cook et al. (2003)
nepa023	ABSB	Katyakhola-2	29.3	82.02	3330	Cook et al. (2003)
nepa040	PIRO	TilaNala	29.05	81.5	2080	Bhattacharyya et al. (1992)
bhw009	ABPI	Khaptad	29.38	81.13	3000	Thapa et al. (2013)
bhw010	PCSM	Khaptad	29.4	81.13	2700	Thapa et al. (2015)

Note: ABPI: *Abies pindrow* (Royle) Spach; ABSB: *Abie spectabilis* (D.Don) Spach; BEUT: *Betula utilis* D.Don; JURE: *Juniperus recurva* Buch.-Ham. ex D. Don; PCSM: *Picea smithiana* (Wal.) Bois; PIRO: *Pinus roxburghi* Sarg; PIWA: *Pinus walichiana* A.B. Jackson; TSDU: *Tsuga dumosa* (D.Don) Eichl; ULWA: *Ulmus wallichiana* Planch; PPCI: *Populus ciliata* Wall. ex Royle.

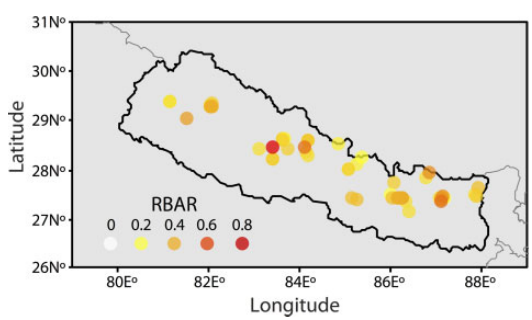

Figure 4. Map showing the strength of common growth signals shared across the forest stand (as measured by the mean between tree correlation, RBAR; Wigley et al., 1984) for each tree-ring width chronology.

5(b)) both fluctuate wildly, which suggests that such a restricted network is not a reliable indicator of tree growth across the country. As a result, we restrict our subsequent analysis to the portion of the Nepal network that spans the period between AD 1600 and 2013. That interval predates by more than a century the country's unification by Prithvi Narayan Shah in AD 1768 (Pradhan, 2009), and encompasses the Rana dynasty, the return of the Shah family to power, and the modern initiation of the Federal Democratic Republic of Nepal in 2008 (Sharma, 2012).

In addition to evaluating the signal quality of tree-ring width chronologies across Nepal, we also identified all occurrences of locally absent rings within the national network. As a consequence of severe environmental stress, often related to drought, wildfire, or insect infestation, trees will occasionally form a discontinuous layer of wood around their stem (Fritts et al., 1965; Glock and Pearson, 1937; Schulman, 1941). All the tree-ring

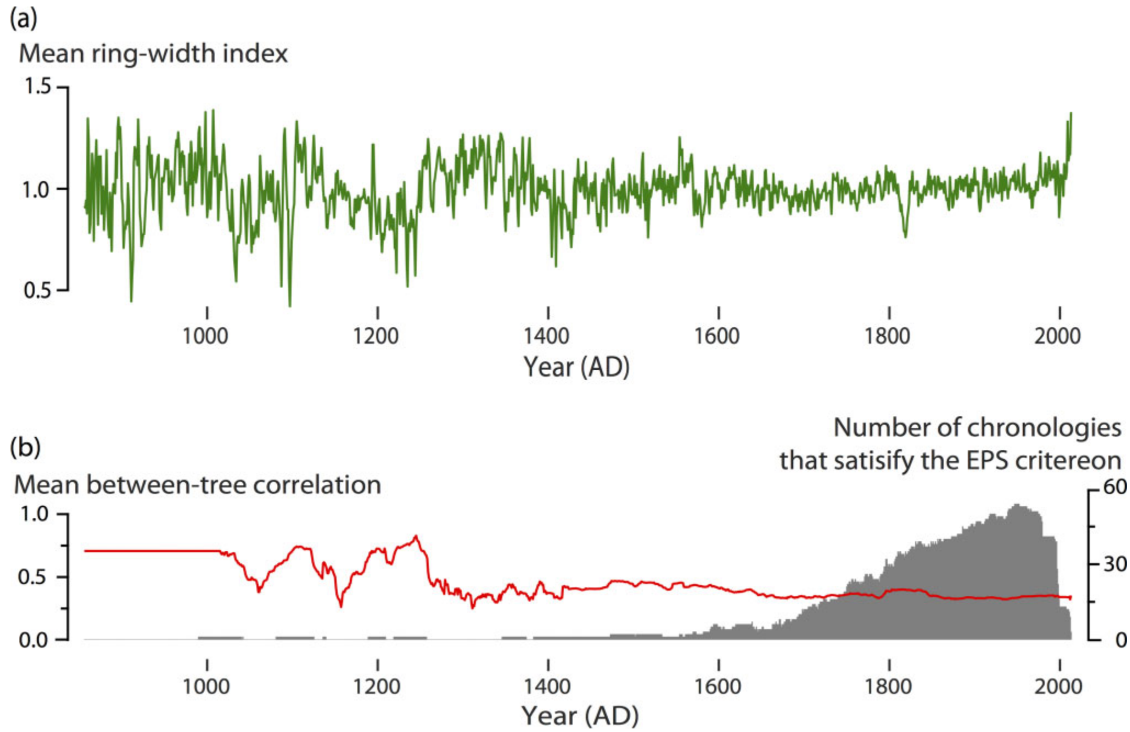

Figure 5. (a) The composite (median) ring-width chronology constructed by combining all 55 tree-ring chronologies from Nepal. (b) The total number of site chronologies that preserve an adequate estimate of the stand-wide signal (grey bars, as measured by the Expressed Population Signal, EPS; Wigley et al., 1984), and time-varying between-tree correlations, RBAR (red line).

data in our synthesis followed the 'Tucson Decadal Format' standard, which uses the number zero to represent locally absent rings (Holmes, 1994). For each site, we computed the total number of absent rings as a percentage of all rings included in that set of measurements. We also calculated the frequency of absent rings for each year by dividing the total number of absent rings across the network by the total number of rings. Across the entire Nepal tree-ring network, the median frequency of absent rings was 0.12% and ranged between 0 (no absent rings present in the record) to 0.55%. There is no obvious spatial pattern in the distribution of absent rings across the country (Figure 6(a)), but these features occur most frequently in low-elevation pines and high-elevation fir (Figure 6(b)). During the past four centuries, absent rings were most common in 1999 (1.6% of all rings), AD 1657 (1.2%), and during the period between AD 1817 and 1820 (1.1–1.4%). Globally, by far the most common cause of geographically widespread absent rings (cases where they occur simultaneously at several locations) is severe moisture stress (St. George et al., 2013; Novak et al., 2016). The high frequency of absent rings in AD 1999 coincides with a record drought in that year across the country (Sigdel and Ikeda, 2010), which suggests that in Nepal locally absent rings might be evidence of shortfalls in moisture supply during the growing season.

V Four centuries of tree growth in the Nepal Himalaya

In order to provide a long-term view of tree growth across the country, we constructed an

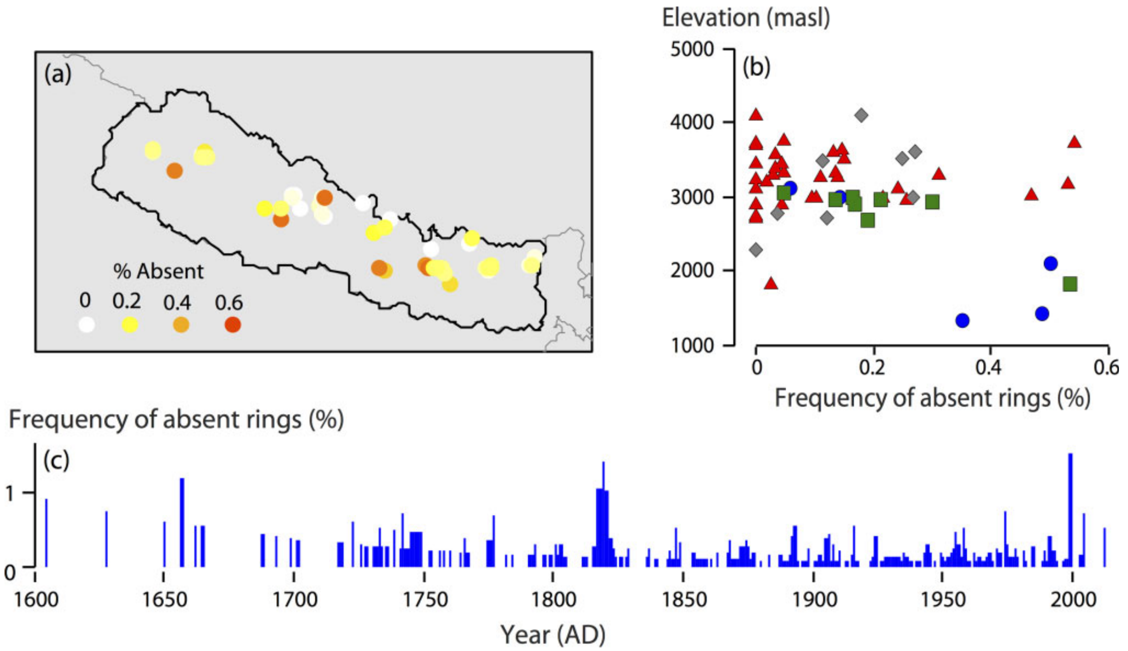

Figure 6. (a) Map showing percentage of locally absent rings within each site chronology across Nepal. (b) Scatterplot comparing the percentage of absent rings (sorted by genera) plotted against elevation. The symbols match the genera described in Figure 1. (c) Percentage of locally absent rings (total number of absent rings divided by the total number of rings) in the Nepalese ring-width network by year.

all-Nepal tree-ring composite by computing the median of the entire set of ring-width chronologies through time (Figure 7(a)). It would also be possible to aggregate tree-ring chronologies by region (Briffa et al., 1998; Yang et al., 2014) or via principle components analysis (Cook et al., 2013a; Liang et al. 2014), but we chose to compute a simple average in order to provide a general overview of growth across the network that was not limited by the length of the shortest series. Across the network, the median between-chronology correlation is 0.17, and the agreement is somewhat stronger in the eastern part of the network (Figure 8), likely because more collections have been made in the areas between Langtang and Kanchenjunga. To avoid the influence of segments with low sample replication and signal quality, each individual chronology was truncated at the year where its EPS value fell below the 0.85 threshold (Wigley et al., 1984) prior to being combined into the all-Nepal median.

Over the past four centuries, two major events are prominent in the all-Nepal composite: (i) a prolonged and widespread growth suppression during the early 1800s; and (ii) heightened growth during the most recent decade. The median ring-width index was below one for each year between AD 1811 and AD 1822, with the lowest growth during this interval occurring in AD 1817 (Figure 7(b)). This extended downturn in tree growth is evident in chronologies from all major tree genera and at all elevations within the network. This period coincides with two major eruptions of Indonesian volcanoes, including the unknown eruption of AD 1809 (Cole-Dai et al., 1997) and the AD 1815 Tambora eruption (Stothers, 1984). The latter event was the third-largest eruption of the past 1500 years (Gao et al., 2008; Oppenheimer, 2003) and was responsible

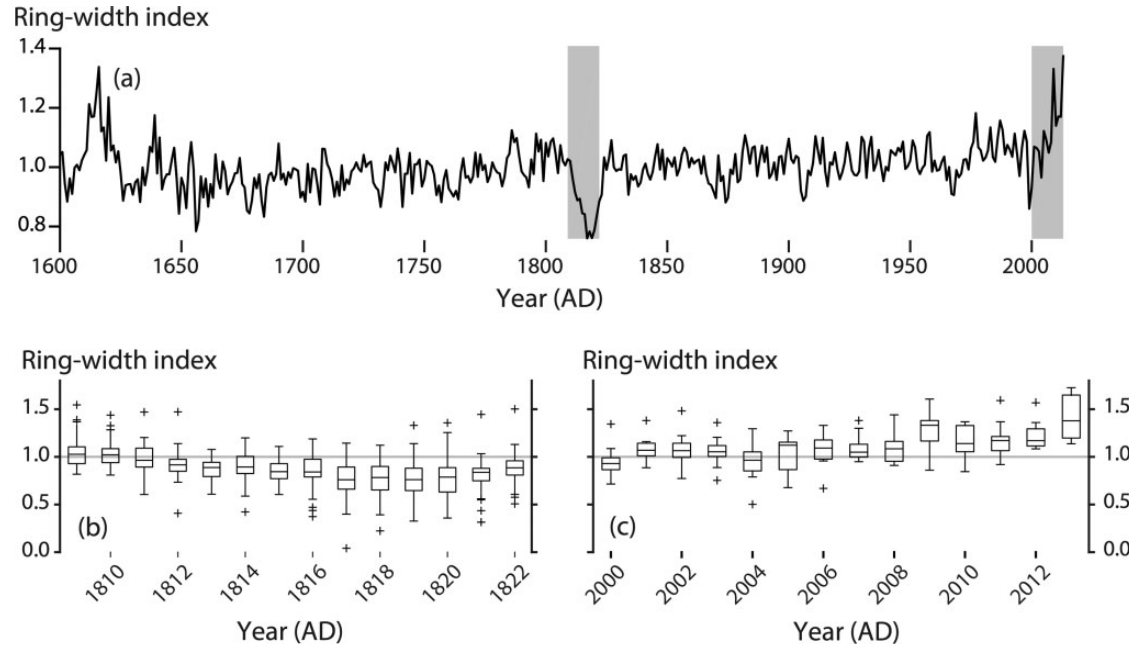

Figure 7. (a) Median ring-width chronology across the Nepal tree-ring network since AD 1600. Box plots illustrating the distribution of tree-ring width indices across all available sites during (b) the early 1800s and (c) the early 21st century.

for the abnormally cold weather observed across much of the Northern Hemisphere during AD 1816 (Cole-Dai et al., 2009). Recent studies have argued that major tropical eruptions can cause the Asian monsoon to fail two or three years after the triggering event (Anchukaitis et al., 2010), and drought estimates based on tree rings show dry conditions extending over much of the region during the AD 1809 to 1822 period (Cook et al., 2010; Figure 9). But because the influence of eruptions on monsoon precipitation is not thought to persist for several consecutive years, even after the very largest events (Anchukaitis et al., 2010), it may be that the early 1800s slowdown in forest growth was the combined product of two or more dry years caused by explosive volcanism that was subsequently amplified and extended by legacy effects imposed by tree physiology (Anderegg et al., 2015). But regardless of the specific cause, the early 1800s growth suppression is evidence that short-term disturbances related to climate extremes can exert a lasting influence on the vigor of Nepal's forests. More optimistically, because there have not yet been any reports of increased tree recruitment following this slowdown in tree-line forests (Gaire et al., 2014, 2017b), this event may not have been sufficiently severe to cause widespread tree mortality.

Our all-Nepal tree-ring index suggests that tree growth has been above average in almost every year since AD 2000 (Figure 7(c)). This apparent trend towards higher ring-widths has coincided with widespread and substantial warming in Nepal's alpine environments (Shrestha and Aryal, 2011; Shrestha et al., 1999), and a concomitant increase in the upper limit of *Abies* (Gaire et al., 2014). Other age–size standardization methods (specifically, negative exponential curves and 30-year cubic smoothing splines) also produced all-Nepal ring-width indices with marked post-2000 growth increases, but examining the tree-ring width

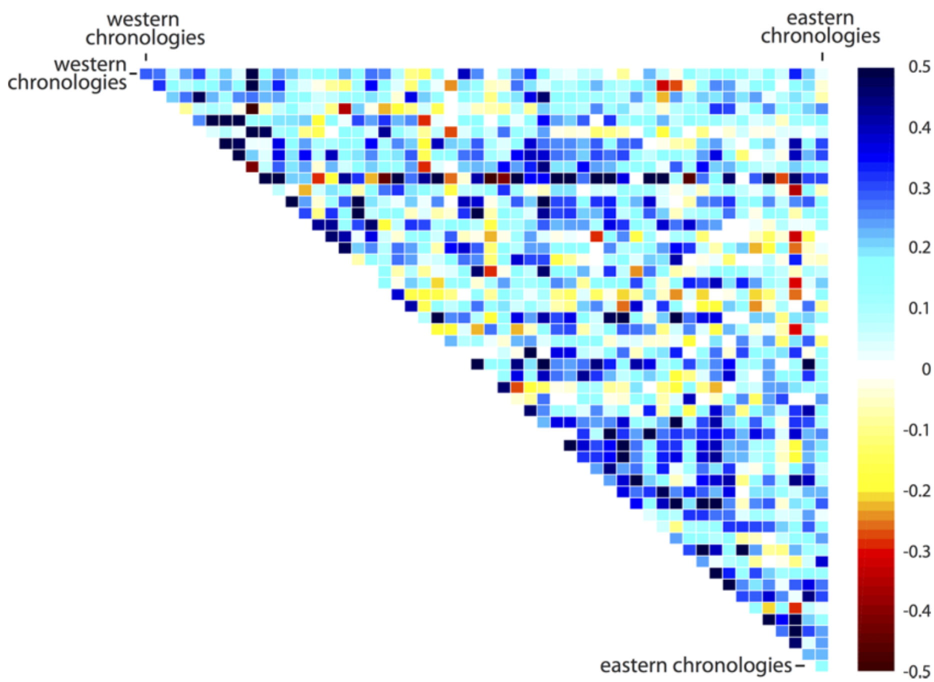

Figure 8. Matrix of between-chronology correlations for all pairs of records within the Nepal tree-ring network. Correlations are calculated for the maximum period of overlap between each pair of chronologies. The portion of each chronology that did not meet the EPS criterion (0.85) was not included in this analysis.

measurements (not detrended) for the 11 *Abies* collections shows only four sites with enhanced growth over the most recent decade (Figure 10). Because this recent spurt of high growth could perhaps be an artifact of our chronology construction, we recommend other methods be applied to evaluate potential enhancement of *Abies* growth at high-elevation sites, such as the installation of dendrometer bands (Deslauriers et al., 2007; McMahon and Parker, 2015) or applying either satellite or ground-based methods to estimate tree biomass and productivity of Himalayan fir (Chave et al., 2014; Donoghue et al., 2007; Popescu, 2007).

VI Priorities for future tree-ring work in Nepal

Our synthesis of the current Nepalese tree-ring width network demonstrates that these data provide a reliable estimate of tree-growth across the country back to approximately AD 1600. Earlier on, there are not a sufficient number of tree-ring records to estimate regional tree growth or serve as paleoclimate surrogates. Longer records are needed to test, for example, whether the warm and dry period that occurred in many parts of the world during AD 900–1400 (Chen et al., 2015; Cook et al., 2004; Goosse et al., 2012; Mann et al., 2009) had any manifestation in Nepal. Those few chronologies that predate AD 1500 demonstrate that old growth forests are still present in Nepal, and samples obtained from archeological sites could also be very useful to extend chronologies back in time. So far, the sole attempt to date archeological timbers in Nepal using tree rings was conducted by the Nepalese Department of Archeology and the German Research Foundation in the early 1990s (Schmidt et al., 1999). That project,

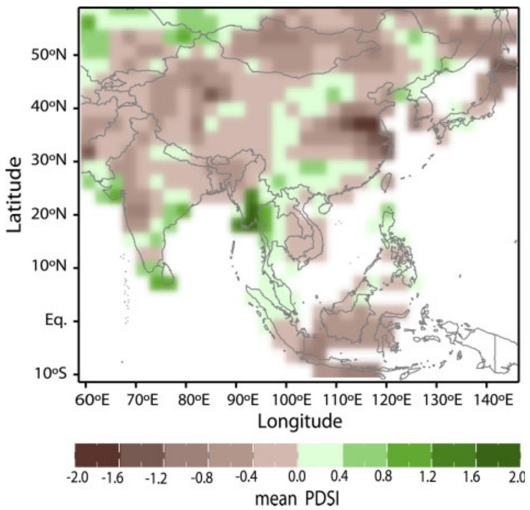

Figure 9. The spatial pattern of Palmer Drought Severity Index (PDSI; Palmer, 1965) across monsoon Asia during the period AD 1809 to 1822. The PDSI values are reconstructed from a large network of moisture-sensitive tree-ring records from the region (Cook et al., 2010), which includes some of the Nepalese records incorporated into our current analysis.

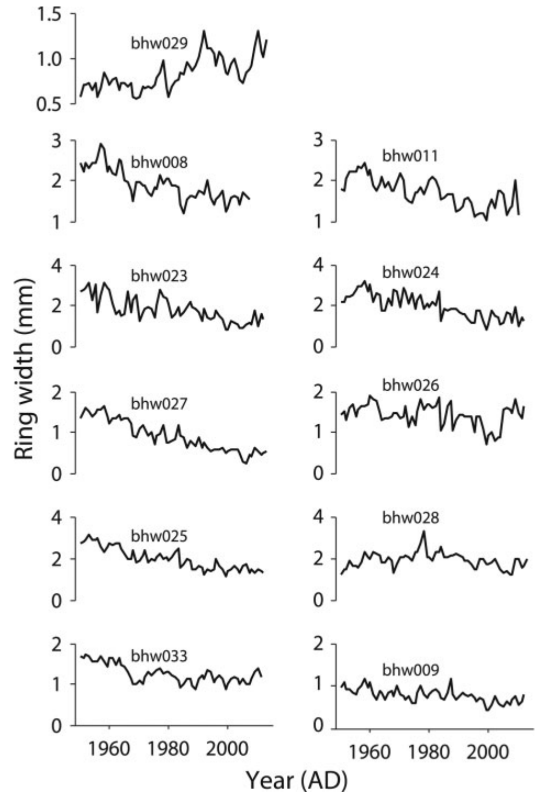

Figure 10. Mean 'raw' ring-width composites for those 11 *Abies* records that post-date AD 2000. In contrast to our other analysis, these chronologies were produced without any standardization to remove trends due to age or size.

which was conducted in the Mustang Valley of central Nepal, began with the collection of wooden artifacts from caves in the Muktinath and southern Mustang valleys, and expanded to include samples from several houses and ruins between Marpha and Dzakot. This suite of archeological specimens from three tree species (*Pinus wallichiana*, *Abies spectabilis*, and *Picea smithania*) yielded a master chronology that extended between AD 1997 and AD 1324. Obtaining timbers from archeological sources like these may be key to the development of longer tree-ring sequences for use in paleoclimatology or paleoecology.

Based on our survey, it is apparent that tree-ring width chronologies from pines have stronger between-tree agreement than other species, and pines also form locally absent rings more commonly. Because these two characteristics are often associated with sensitivity to moisture, this behavior might be evidence that Nepalese pines could serve as proxies for drought or streamflow. Cook et al. (2003) suggested that *P. wallichiana* are primarily moisture-limited and for that reason did not include records from those species within their nation-wide temperature reconstruction. Pines have been successfully used to reconstruct rainfall and streamflow in the adjoining regions, including India (Singh et al., 2009), China (Liu et al., 2005), Pakistan (Cook et al., 2013b), and Mongolia (Liu et al., 2009), but in Nepal, no attempt has been made to reconstruct past hydroclimate using tree rings.

Our study confirms that the high-elevation fir has grown rapidly during the recent-most decade. However, only 11 *Abies* chronologies post-date

AD 2000, and these records were mostly developed from central Nepal. Additional *Abies* collections from treeline forests in the far-western and far-eastern regions of the country are needed to make a robust argument about the recent growth trends of this species. Further collections from other high-elevation species such as hemlock and birch as well as low-elevation pines would also be helpful to determine if *Abies* is currently growing faster than any other species. If we were able to gauge more accurately the rate and causes of the recent growth of Nepalese high-elevation forests, then that would help develop strategies such as assisted migration and restoration (Gray and Hamann, 2013) to conserve these systems that are critical for livestock grazing, wildlife habitat, and tourism (Nepal, 2000; Stevans, 2003).

VII Conclusions

Nearly four decades have passed since Rudolf Zuber collected the first tree-ring samples from Nepal, but in many respects the country remains a frontier area for dendrochronology and its various sub-disciplines (Bhuju, 2016; Cherubini, 2015). Even today, most of the country's tree-ring data have been developed by international scientists, with the pioneering efforts of Ed Cook and Paul Krusic (Cook et al., 2003) making up the largest single contribution to the network. But over the last 10 years most tree-ring studies have been led by foresters and environmental scientists from Nepal, and that work has expanded considerably the geographic coverage and the variety of tree species and forest biomes within the network. The Nepal tree-ring network now encompasses an altitudinal range of nearly 3 kilometers, extending from lower temperate forests near Kathmandu to treeline forests in Sagarmatha (Mt. Everest) National Park, and includes data from nine genera and 11 species. Even though forests in Nepal are an important local resource for timber and fuel (Pandit and Bevilacqua, 2011), half of all tree-ring chronologies in the network extend back at 292 years and 22 records span the past four centuries (and earlier). Taken together, these data provide a much longer perspective on tree-growth trends across the Nepal Himalaya and allow us to evaluate how Nepalese forests have been affected by recent and past environmental changes.

In order to assess tree growth across Nepal, we obtained data for 55 tree-ring width records out of the 86 records we estimate have been collected from the country. After averaging together those chronologies to construct an all-Nepal ring-width index spanning the past four centuries, we identified two prominent and long-lasting growth excursions. The first, which occurred in the early 19th century, shows that forests across Nepal experienced a prolonged downturn in growth that began in 1811 and extended until 1822. This widespread growth suppression, which is evident in all major tree genera and across the entire elevational range of the network, may be the result of one or more volcanically induced monsoon failures (Anchukaitis et al., 2010) whose detrimental influence on tree growth was subsequently amplified by strong legacy effects due to tree physiology (Anderegg et al., 2015). The other prominent growth anomaly is an apparent trend towards wider rings since AD 2000 in high-elevation forests, most of which are located in central Nepal. Although this recent growth spurt does coincide with widespread and substantial warming in Nepal's alpine environments, the techniques used to remove age–size trends from ring-width data can sometimes artificially inflate tree-ring indices near the recent end of the series (Melvin and Briffa, 2008). For that reason, we suggest that in-situ or remotely sensed methods be applied to either corroborate or refute tree-ring evidence for enhanced tree growth in Nepal's highest-elevation forests.

The Nepal tree-ring width network has been used to extend back the temperature record from Kathmandu (Cook et al., 2003) and these data have also been incorporated into efforts to reconstruct drought in Monsoon Asia (Cook et al., 2010) and summer temperatures in East Asia (Cook et al., 2013a). We anticipate that this synthesis will aid the identification of priority targets (both geographic areas and tree species) for future tree-ring collections in Nepal, and provide a broader context to evaluate the characteristics of newly developed tree-ring data. And more broadly, we hope this new assessment will highlight the substantial recent progress made by Nepali scientists and their international collaborators to produce a robust dataset for paleoclimate reconstruction drawn from the forests of the Nepal Himalaya.

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References

Anchukaitis KJ, Buckley BM, Cook ER, et al. (2010) Influence of volcanic eruptions on the climate of the Asian monsoon region. *Geophysical Research Letters* 37: 1–5.

Anderegg WRL, Schwalm C, Biondi F, et al. (2015) Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* 349: 528–532.

Bhattacharyya A, LaMarche, Jr. VC and Hughes MK (1992) Tree-ring chronologies from Nepal. *Tree-Ring Bulletin* 52: 59–66.

Bhuju DR (2016) Nepal tree ring study updates. *Dendrochronologia* 38: 117.

Bräuning A (2004) Tree-ring studies in the Dolpo-Himalya (western Nepal). In: Jansma E, Bräuning A, Gartner H, et al. (eds) *TRACE-Tree Rings in Archaeology, Climatology and Ecology: Proceedings of the DENDROSYMPOSIUM 2003*. Utrecht: Reihe Umwelt, 8–12.

Briffa KR, Schweingruber FH, Jones PD, et al. (1998) Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391: 6678–6678.

Chave J, Rejou-Mechain J, Burguês A, et al. (2014) Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology* 20: 3177–3190.

Chen J, Chen F, Feng S, et al. (2015) Hydroclimatic changes in China and surroundings during the Medieval Climate Anomaly and Little Ice Age: Spatial patterns and possible mechanisms. *Quaternary Science Reviews* 107: 98–111.

Cherubini P (2015) Enigmatic High-Asian tree rings: A postcard from the roof of the world (Kathmandu, Nepal). *Dendrochronologia* 34: 31–32.

Cole-Dai J, Ferris D, Lanciki A, et al. (2009) Cold decade (AD 1810–1819) caused by Tambora (1815) and another (1809) stratospheric volcanic eruption. *Geophysical Research Letters* 36, L22703. doi:10.1029/2009GL040882.

Cole-Dai J, Mosley-Thompson E and Thompson LG (1997) Annually resolved southern hemisphere volcanic history from two Antarctic ice cores. *Journal of Geophysical Research* 102: 761–771.

Cook ER (1987) The decomposition of tree-ring series for environmental studies. *Tree-Ring Bulletin* 47: 37–59.

Cook ER and Krusic PJ (2008) Experimental reconstruction of large-scale summer monsoon drought over India and the Tibetan Plateau using tree rings from "High Asia". *Palaeobotanist* 57: 515–528.

Cook ER, Anchukaitis KJ, Buckley BM, et al. (2010) Asian monsoon failure and megadrought during the last millennium. *Science* 328: 486–489.

Cook ER, Krusic PJ, Anchukaitis KJ, et al. (2013a) Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 CE. *Climate Dynamics* 41: 2957–2972.

Cook ER, Krusic PJ and Jones PD (2003) Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. *International Journal of Climatology* 23: 707–732.

Cook ER, Palmer JG, Ahmed M, et al. (2013b) Five centuries of Upper Indus River flow from tree rings. *Journal of Hydrology* 486: 365–375.

Cook ER, Woodhouse CA, Eakin CM, et al. (2004) Long-term aridity changes in the western United States. *Science* 306: 1015–1018.

Dawadi B, Liang E, Tian L, et al. (2013) Pre-monsoon precipitation signal in tree rings of timberline *Betula utilis* in the central Himalayas. *Quaternary International* 283: 72–77.

Deslauriers A, Sergio R and Tommaso A (2007) Dendrometer and intra-annual tree growth: What kind of information can be inferred? *Dendrochronologia* 25: 113–124.

Donoghue DNM, Watt PJ, Cox NJ, et al. (2007) Remote sensing of species mixtures in conifer plantations using LiDAR height and intensity data. *Remote Sensing of Environment* 110: 509–522.

Fritts HC (1976) *Tree Rings and Climate*. London: Academic Press.

Fritts HC, Smith DG, Cardis JW, et al. (1965) Tree-ring characteristics along a vegetation gradient in northern Arizona. *Ecology* 46: 393–401.

Fujii R and Sakai H (2002) Paleoclimatic changes during the last 2.5 myr recorded in the Kathmandu Basin, Central Nepal Himalayas. *Journal of Asian Earth Science* 20: 255–266.

Gaire NP, Bhuju DR and Koirala M (2013) Dendrochronological studies in Nepal: Current status and future prospects. *Fuuast Journal of Biology* 3: 1–9.

Gaire NP, Bhuju DR, Koirala M, et al. (2017a) Tree-ring based spring precipitation reconstruction in western Nepal Himalaya since AD 1840. *Dendrochronologia* 42: 21–30.

Gaire NP, Dhakal YR, Lekhak HC, et al. (2011) Dynamics of *Abies spectabilis* in relation to climate change at the treeline ecotone in Langtang National Park. *Nepal Journal of Science and Technology* 12: 220–229.

Gaire NP, Koirala M, Bhuju DR, et al. (2014) Treeline dynamics with climate change at central Nepal Himalaya. *Climate of the Past* 10: 1277–1290.

Gaire NP, Koirala M, Bhuju DR, et al. (2017b) Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. *Dendrochronologia* 41: 44–56.

Gao C, Robock A and Ammann C (2008) Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. *Journal of Geophysical Research* 113(D23): D23111. http://doi.org/10.1029/2008JD010239

Gautam MR and Acharya K (2012) Streamflow trends in Nepal. *Hydrological Sciences Journal* 57: 344–357.

Gayer E, Lave J, Pik R, et al. (2006) Monsoonal forcing of Holocene glacier fluctuations in Ganesh Himal (Central Nepal) constrained by cosmogenic ^{3}He exposure ages of garnets. *Earth and Planetary Science Letters* 252: 275–288.

Glock W and Pearson GA (1937) *Principles and Methods of Tree-Ring Analysis*. Washington, DC: Carnegie.

Goosse H, Guiot J, Mann ME, et al. (2012) The medieval climate anomaly in Europe: Comparison of the summer and annual mean signals in two reconstructions and in simulations with data assimilation. *Global and Planetary Change* 84–85: 35–47.

Grissino-Mayer HD and Fritts HC (1997) The International Tree-Ring Data Bank: an enhanced global database serving the global scientific community. *The Holocene* 7(2): 235.

Gray KL and Hamann A (2013) Tracking suitable habitat for tree populations under climate change in western North America. *Climatic Change* 117: 289–303.

Grissino-Mayer Henri D and Fritts HC (1997) The International Tree-Ring Data Bank: An enhanced global database serving the global scientific community. *The Holocene* 7: 235–238.

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43: 69–78.

Holmes RL (1994) *Dendrochronology Program Library – Users Manual*. Tucson, AZ: University of Arizona.

Karki R, Hasson S, Schickhoff U, et al. (2017) Rising precipitation extremes across Nepal. *Climate* 5(1): 4. doi:10.3390/cli5010004.

Kharal DK, Meilby H, Rayamajhi S, et al. (2014) Tree ring variability and climate response of Abies spectabilis along an elevation gradient in Mustang, Nepal. *Banko Janakari* 24: 3–13.

Kharal DK, Thapa UK, St. George S, et al. (2017) Tree-climate relations along an elevational transect in Manang valley, central Nepal. *Dendrochronologia* 41: 57–64.

Liang E, Dawadi B, Pederson N, et al. (2014) Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? *Ecology* 95: 2453–2465.

Liu Y, Bao G, Song H, et al. (2009) Precipitation reconstruction from Hailar pine (*Pinus sylvestris* var. *mongolica*) tree rings in the Hailar region, Inner Mongolia, China back to 1865 AD. *Paleogeography, Paleoclimatology, Paleoecology* 282: 81–87.

Liu Y, Cai Q, Shi J, et al. (2005) Seasonal precipitation in the south-central Helan Mountain region, China, reconstructed from tree-ring width for the past 224 years. *Canadian Journal of Forest Research* 35: 2403–2412.

McMahon SM and Parker GG (2015) A general model of intra-annual tree growth using dendrometer bands. *Ecology and Evolution* 5: 243–254.

Mann ME, Zhang Z, Rutherford S, et al. (2009) Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326: 1256–1260.

Melvin TM and Briffa KR (2008) A "signal-free" approach to dendroclimatic standardisation. *Dendrochronologia* 26: 71–86.

Melvin TM, Briffa KR, Nicolussi K, et al. (2007) Time-varying-response smoothing. *Dendrochronologia* 25: 65–69.

Nepal SK (2000) Tourism in protected areas: The Nepalese Himalaya. *Annals of Tourism Research* 27: 661–681.

Novak K, Luis MD, Saz MA, et al. (2016) Missing rings in *Pinus halepensis*: The missing link to relate the tree-ring records to extreme climatic events. *Frontier in Plant Science* 7: 1–11.

Oppenheimer C (2003) Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography* 2: 230–259.

Owen LA (2009) Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet. *Quaternary Science Reviews* 28: 2150–2164.

Palmer WC (1965) *Meteorological Drought*. Research Paper, vol. 45. U.S. Weather Bureau.

Pandit R and Bevilacqua E (2011) Forest users and environmental impacts of community forestry in the hills of Nepal. *Forest Policy and Economics* 13: 345–352.

Popescu SC (2007) Estimating biomass of individual pine trees using airborne lidar. *Biomass and Bioenergy* 31: 646–655.

Pradhan K (2009) *The Gorkha Conquests*. Kathmandu: Himal Books.

Sano M, Furuta F, Kobayashi O, et al. (2005) Temperature variations since the mid-18th century for western Nepal, as reconstructed from tree-ring width and density of *Abies spectabilis*. *Dendrochronologia* 23: 83–92.

Sano M, Ramesh R, Sheshshayee M, et al. (2011) Increasing aridity over the past 223 years in the Nepal Himalaya inferred from a tree-ring δ18O chronology. *The Holocene* 22: 809–817.

Schlütz F and Zech W (2004) Palynological investigations on vegetation and climate change in the Late Quaternary of Lake Rukche area, Gorkha Himal, Central Nepal. *Vegetation History and Archeobotany* 13: 81–90.

Schmidt B (1993) Dendrochronological research in south Mustang. *Ancient Nepal* 130–133: 20–33.

Schmidt B, Wazny T, Malla K, et al. (1999) Chronologies for historical dating in high Asia/Nepal. In: Wimmer R and Vetter RE (eds) *Tree-Ring Analysis: Biological, Methodological and Environmental Aspects*. Wallingford: CAB International, 205–211.

Schulman E (1941) Some propositions in tree-ring analysis. *Ecology* 22: 193–195.

Schwartz MW, Iverson LR, Prasad AM, et al. (2006) Predicting extinctions as a result of climate change. *Ecology* 87: 1611–1615.

Sharma J (2012) Social science engagement and political interregnum in Nepal. *Economic and Political Weekly* XLVII: 1–8.

Shrestha AB and Aryal R (2011) Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change* 11: 65–77.

Shrestha AB, Bajracharya SR, Sharma AR, et al. (2017) Observed trends and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010. *International Journal of Climatology* 37: 1066–1083.

Shrestha AB, Wake CP, Dibb JE, et al. (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology* 20: 317–327.

Shrestha AB, Wake CP, Mayewski PA, et al. (1999) Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *Journal of Climate* 12: 2775–2786.

Sigdel M and Ikeda M (2010) Spatial and temporal analysis of drought in Nepal using standardized precipitation index and its relationship with climate indices. *Journal of Hydrology and Meteorology* 7: 59–74.

Singh J, Yadav RR and Wilmking M (2009) A 694-year tree-ring based rainfall reconstruction from Himachal Pradesh, India. *Climate Dynamics* 33: 1149–1158.

St. George S (2014) An overview of tree-ring width records across the Northern Hemisphere. *Quaternary Science Reviews* 95: 132–150.

St. George S, Ault TR and Torbenson MCA (2013) The rarity of absent growth rings in Northern Hemisphere forests outside the American Southwest. *Geophysical Research Letters* 40: 3727–3731.

Stainton JDA (1972) *Forests of Nepal*. New York: Hafner Publishing Company.

Stevans S (2003) Tourism and deforestation in the Mt. Everest region of Nepal. *The Geographical Journal* 169: 255–277.

Stocker TF, Qin D, Plattner GK, et al. (eds) (2013) *The Physical Science Basis*. Cambridge: Cambridge University Press, 4–29.

Stothers RB (1984) The great Tambora eruption in 1815 and its aftermath. *Science* 224: 1191–1198.

Suzuki E (1990) Dendrochronology in coniferous forests around Lake Rara, west Nepal. *The Botanical Magazine Tokyo* 103: 297–312.

Thapa UK, Shah SK, Gaire NP, et al. (2013) Influence of climate on radial growth of *Abies pindrow* in western Nepal Himalaya. *Banko Janakari* 23: 14–19.

Thapa UK, Shah SK, Gaire NP, et al. (2015) Spring temperatures in the far-western Nepal Himalaya since AD 1640 reconstructed from *Picea smithiana* tree-ring widths. *Climate Dynamics* 45: 2069–2081.

Wigley TML, Briffa KR and Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Applied Meteorology and Climatology* 23: 201–213.

Yang B, Qin C, Wang J, et al. (2014) A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences* 25: 2903–2908.