Dendrochronologia 44 (2017) 193–202

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Growth variable-specific moisture and temperature limitations in co-occurring alpine tree and shrub species, central Himalayas, Nepal

S.A. Rayback[a,*], K.B. Shrestha[b,d], A. Hofgaard[c]

[a] Department of Geography, University of Vermont, 207 Old Mill Building, 94, University Place, Burlington, VT 05405, USA
[b] Department of Biology, University of Bergen, Post Box 7803, NO-5020 Bergen, Norway
[c] Norwegian Institute for Nature Research, Post Box 5685 Sluppen, NO-7485 Trondheim, Norway
[d] UiB Global, Jekteviksbakken 31, PO Box 7800, NO-5020 Bergen, Norway

ARTICLE INFO

Keywords:
Abies spectabilis
Cassiope fastigiata
Dendroecology
Forest-tundra ecotone
Himalayas

ABSTRACT

Trees and shrubs found in the forest-tundra ecotone (FTE) are considered to be highly sensitive to climate change, but their response to climatic drivers is only partially understood. We use dendrochronological techniques to develop growth chronologies for co-occurring tree (*Abies spectabilis*, radial growth and height) and dwarf shrub (*Cassiope fastigiata*, stem elongation and leaf number) species in central Himalaya, Nepal, in order to identify and compare climate drivers of growth (temperature, precipitation, moisture (SPEI)). Our results reveal growth variable-specific responses characterized by a predominant response to previous year and non-growing season climate, and to length of the monsoon season. Tree radial growth was significantly correlated with temperature during previous summer and non-growing season months, and moisture in the late monsoon (September). Tree height increment correlated with late-monsoon temperature and moisture in the previous post-monsoon. Shrub stem elongation mainly correlated with temperature and moisture conditions in previous-year pre-monsoon (May), while leaf production correlated with moisture in previous pre-monsoon and monsoon periods, and precipitation in the late-monsoon. These results contribute new evidence that mid-latitude FTE tree and shrub species and individual growth variables are limited by unique climate drivers operational at different periods during and outside the monsoon season. Within the context of rising temperatures and increased precipitation variability in the Himalayas, moisture may become a more frequent stressor on tree and shrub growth. Consideration of climate and site variable interactions at alpine sites is important to detecting subtleties of growth response. Dendroecological studies of co-occurring tree and shrub species help to identify concomitant and disparate growth responses to climate drivers and in turn, provide information and insight into FTE changes in the Himalayas and elsewhere.

1. Introduction

High elevation mountains are sensitive to climate change (Rangwala and Miller, 2012) and recent evidence suggests elevation-dependent warming in mountain regions on a global scale (Mountain Research Initiative EDW Working Group, 2015). In the Nepal Himalayas, recent studies indicate changing climatological conditions over the past several decades including rising temperatures (Shrestha et al., 1999; Kattel and Yao, 2013; Shrestha et al., 2012; Salerno et al., 2015), variable precipitation patterns (Shrestha et al., 1999; Xu et al., 2009; Yao et al., 2012; Shrestha et al., 2012; Salerno et al., 2015) and a weakening Indian monsoon (Wu et al., 2003; Thompson et al., 2006; Wang and Ding, 2006; Zhou et al., 2008). The effect of these climatic changes upon the vegetation is not well quantified, including understanding of primary drivers, synergistic interactions with other environmental variables, feedbacks with the atmosphere and hydrosphere, and related effects on ecosystem services.

Trees and shrubs found at the forest-tundra ecotone (hereafter FTE) are considered to be highly sensitive to climate change (Tranquillini, 1979; Körner and Paulsen, 2004; Hofgaard et al., 2009; Hallinger et al., 2010) and thus, understanding their response to a changing climatological context in the Himalayas has been the subject of recent research (Gaire et al., 2014; Schickhoff et al., 2015; Shrestha et al., 2015; Chhertri and Cairns, 2016; Suwal et al., 2016; Bhuju, 2016). In the last decade, the number of dendroclimatological and dendroecological studies of tree species found in the Himalayas and the Tibetan Plateau has increased (Cook et al., 2003; Sano et al., 2005; Cook et al., 2010; Liang et al., 2014). Research on alpine shrubs in the Himalayas and

* Corresponding author.
E-mail address: srayback@uvm.edu (S.A. Rayback).

http://dx.doi.org/10.1016/j.dendro.2017.06.001
Received 28 March 2017; Received in revised form 30 May 2017; Accepted 1 June 2017
Available online 10 June 2017
1125-7865/

elsewhere also continues to expand (Bär et al., 2008; Hallinger et al., 2010; Myers-Smith et al., 2011; Rayback et al., 2012a; Liang et al., 2012; Li et al., 2013; Myers-Smith et al., 2015), extending the reach of dendrochronological techniques into tree-less environments and initiating the beginning of a spatially-continuous network of proxies across vegetation communities. Understanding the response of co-occurring tree and shrub species to climate, now and in the future, may help to elucidate the physiological mechanisms controlling local and landscape-scale transitions from forest to shrub tundra.

Research on trees and shrubs in the Himalayas and Tibetan Plateau has yielded heterogeneous results in terms of climate drivers. In some cases, and in line with ecological theory (Körner and Paulsen, 2004; Wieser and Tausz, 2007), temperature is considered the primary limitation on growth (Yadav and Bhattacharyya, 1992; Bräuning et al., 2004; Li et al., 2013). Alternatively, evidence from other studies points to moisture availability as the limiting factor (Singh et al., 2006; Sano et al., 2010; Borgaonkar et al., 2011; Dawadi et al., 2013; Yang et al., 2013; Liang et al., 2014). Of these studies, none examined the climate drivers of growth of tree and shrub species co-occurring in the FTE.

The objectives of this study were twofold: first, develop growth chronologies for two co-occurring but functionally different woody species, *Abies spectabilis* (two chronologies: annual tree-ring widths and annual height-growth) and *Cassiope fastigiata* (two chronologies: annual stem elongation and number of leaves produced per year) at a high elevation FTE site in the central Himalayas, Nepal, and second, identify and compare the climate drivers of growth in these two species. Based on previous research, we hypothesized that *A. spectabilis* growth would respond to a moisture deficit signal in the pre-monsoon season in the year of growth (Sano et al., 2010) and *C. fastigiata* to a late winter-early spring temperature signal (Liang et al., 2015).

2. Material and methods

2.1. Study site

The study area is located on a mesic, north-facing slope of Langtang Valley (28°05′50″ N, 85°23′30″ E) in the Rasuwa district in the central Himalayas, Nepal (Fig. 1). The valley is situated in the southernmost range of the greater Himalayas with the landscape dominated by rockfall sediments and glacio-fluvial moraine deposits (Heuberger et al., 1984).

Continental and maritime factors influence the climate of Nepal with the central portion of the Himalayas dominated by the southeast monsoon and orographic effects (Putkonen, 2004; Barry, 2008). The mean annual (pre- and monsoon season (MJJAS)) temperature (1900–2008; CRU TS3.23; Harris et al., 2014) is approximately 3.5 °C (9.7 °C) (Fig. 2). The approximate mean temperature of the warmest month (July) is 11.3 °C, and the coldest (January) is −5.4 °C. In the central Himalayas, temperatures rise rapidly in May and June and then quickly decrease in September. Monsoonal precipitation (1900–2008; CRU TS3.23; Harris et al., 2014) between June and September (~771 mm) accounts for approximately 71% of total annual precipitation (~1087 mm) at this site, while snowpack (~21% of annual total) is present from November to March (Fig. 2). Monsoonal precipitation typically lags behind temperature, peaking in July and August. Precipitation in the central Himalayas is altitude-dependent (Putkonen, 2004; Ichiyanagi et al., 2007; Barry, 2008). Measurements by the Tropical Rainfall Measuring Mission (TRMM) satellite show an increase in annual precipitation from the lowlands to 2000 m.a.s.l., then a decline with increasing elevation and latitude (http://disc.sci.gsfc.nasa.gov/daac-bin/tcc.pl; Liang et al., 2014). Precipitation totals are strongly influenced by smaller scale wind patterns, as well as slope aspect (Barry, 2008). Variations in topography over small scales may also influence local climate conditions.

Recent analysis has shown that surface temperatures have increased across the Himalayas by 1.5 °C from 1982 to 2006 (0.06 °C yr^{-1}) and that overall, average precipitation has increased, but with notable seasonal, annual, and geographic variability (Shrestha et al., 2012). There have been significant increases in annual and seasonal temperatures, increases in annual, spring and summer precipitation and declines in fall and winter precipitation in ecoregions in and around the study site (Shrestha et al., 2012).

Evidence of grazing, trampling, logging and burning was apparent in the region, and as the FTE is actively utilized by pastoralists, it was not possible to find sampling sites completely devoid of recent human activity.

2.2. *Abies spectabilis* and *Cassiope fastigiata*

One tree and one shrub species in close spatial proximity were investigated in this study. Distributed from East Nepal to eastern Afghanistan, *Abies spectabilis* (D. Don) Spach (Himalayan silver fir) typically occurs on the southern flank of the Himalayas, forming forests at higher elevations (~2700 to 4000 m.a.s.l.). It is a dominant forest species (mean height: 24–40 m) in the central and western regions of Nepal, but may also occur as stunted individuals at higher elevations (Ghimire and Lekhak, 2007). It is associated with other conifer and broadleaf trees and shrubs on southern (e.g., *Quercus semecarpifolia*) and northern (*Quercus* spp, *Rhododendron campanulatum*, *R. lepidotum*, and *R. anthopogon*) slopes (Ghimire and Lekhak, 2007), as well as *Betula utilis* and *Salix* spp. on more arid sites (Liang et al., 2014). The species grows best on moist and shady, north-facing slopes, preferring acidic and clay soils.

The shrub species, *Cassiope fastigiata* (Wall.) D. Don (Himalayan heather), is an evergreen, dwarf shrub (*Ericaceae*) found on both north- and south-facing slopes and distributed across an altitudinal range of 2800–4500 m.a.s.l. in the southern Himalayas in Nepal, Bhutan, India and Pakistan, as well as in Yunnan, China and Tibet (Polunin and Stainton, 1984). *C. fastigiata* thrives in the more open portion of the FTE with *Rhododendron* species as dominant components and the sparse occurrence of *A. spectabilis* seedlings and saplings. Shrubs may attain a height of 30 cm and are characterized by a decumbent form and stiff, multi-branched stems (Polunin and Stainton, 1984). Plant propagation via layering occurs in *C. fastigiata*, resulting in multiple short stems. The shrub's leaves are ovate (4–6 mm long and 1.5–2 mm wide) with a deep furrow and hyaline margin. As characteristic of the genus *Cassiope*, two alternating sets of opposite leaves form four distinct rows along the stem. Smaller leaves formed in the early and late growing season, bracket larger leaves formed during the summer. This wave-like pattern in leaf lengths was first described by Warming (1908) for the circumpolar heather, *Cassiope tetragona* (L.) D. Don. Callaghan et al. (1989) used the leaf pattern to identify and date individual years of growth for *C. tetragona* and develop chronologies of annual growth. Later, Johnstone and Henry (1997) discovered leaf node scar patterns in adjacent leaf rows were analogous to the wave-like pattern in leaf-lengths and, as leaf scars are visible along the stem for long periods of time, they can be used to develop longer chronologies of annual growth and reproduction (Rayback and Henry, 2006). This technique has also been used to identify and date annual growth in the North American shrub, *C. mertensiana* (Bong) D. Don (Rayback et al., 2012a).

2.3. Field sampling

Abies spectabilis trees and saplings were sampled between the elevations of 3750 and 3960 m.a.s.l. in June 2008 (trees: up to 3910 m a.s.l.). The sampling area encompassed a 100 m wide band perpendicular to the slope covering two kilometers horizontal distance. Location coordinates and the elevation of each sampled tree, sapling and shrub individual were recorded using GPS. Xylem increment cores were collected from mature, dominant trees. Two cores per tree (n = 24 trees) were extracted at a height of 50–80 cm above ground surface with a 5 mm increment borer at 180° to each other and perpendicular to the