Chapter 15
Climate Change and Treeline Dynamics in the Himalaya

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Abstract Treelines are sensitive to changing climatic conditions, in particular to temperature increases, and the majority of global alpine treelines has shown a response to recent climate change. High temperature trends in the Himalaya suggest a treeline advance to higher elevations; it is largely unknown, however, how broader-scale climate inputs interact with local-scale factors and processes to govern treeline response patterns. This paper reviews and synthesizes the current state of knowledge regarding sensitivity and response of Himalayan treelines to climate warming, based on extensive field observations, published results in the widely scattered literature and novel data from ongoing research of the present authors.

Palaeoecological studies indicate that the position of Himalayan treeline ecotones has been sensitive to Holocene climate change. After the Pleistocene-Holocene transition, treelines advanced in elevation to a position several hundred metres higher than today under warm-humid conditions and reached uppermost limits in the early Holocene. Decreasing temperatures below early and mid-Holocene levels induced a downward shift of treelines after c. 5.0 kyr BP. The decline of subalpine forests and treeline elevation in the more recent millennia was coincident with weakening monsoonal influence and increasing anthropogenic interferences.

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To assess current treeline dynamics, treeline type, treeline form, seed-based regeneration and growth patterns are evaluated as sensitivity indicators. Anthropogenic treelines are predominant in the Himalaya; upslope movement of these treelines is related to the effects of land-use change. Near-natural treelines, rare nowadays, are usually developed as krummholz treelines which are relatively unresponsive. Strong competition within the krummholz belt and dense dwarf scrub heaths further upslope largely prevents the upward migration of tree species and retards treeline advance to higher elevation. However, intense recruitment of treeline trees within the treeline ecotone and beyond indicates beneficial preconditions for future treeline ascent. Growth patterns of treeline trees are particularly sensitive to higher winter and pre-monsoon temperatures, suggesting that moisture supply in the pre-monsoon season might be an effective control of future treeline dynamics. Modelled upslope range expansions of treeline trees point to potentially favourable bioclimatic conditions for an upward shift of treelines.

Keywords Holocene • Monsoon • Niche modelling • Recruitment • Seedling • Soil moisture • Soil temperature • Tree radial growth • Treeline advance • Treeline form • Treeline type

15.1 Introduction

Impacts of climate change have affected natural and human systems on all continents and across the oceans in recent decades, with emerging evidence of strong and comprehensive impacts on mountain regions of the world (Huber et al. 2005; Körner et al. 2005; Schickhoff 2011; Grover et al. 2015). Subjected to above-average warming, mountain and glacier environments are highly vulnerable and especially sensitive to changes in climate. Cascading, more or less globally consistent effects on physical systems include mountain permafrost degradation, shrinking glaciers, changing snowpacks, and changing water discharge and availability in rivers and streams (IPCC 2014). With regard to mountain biota, substantial evidence has accumulated reinforcing the conclusion that observed changes in plant and animal phenology and growth have occurred in response to higher temperatures (Cook et al. 2012; Peñuelas et al. 2013), and that the distribution of many plant and animal species has shifted upwards in elevation (Lenoir et al. 2008; Gonzalez et al. 2010; Chen et al. 2011; Gottfried et al. 2012; Pauli et al. 2012).

Thus, it is generally assumed that impacts of contemporary climate change also modify patterns and processes in alpine treeline ecotones and ultimately affect the altitudinal position of treelines in mountains of the world (Holtmeier and Broll 2005, 2007; Wieser et al. 2014). This assumption is based on strong general links between thermal deficiency and treeline position that have resulted in a consensus that treeline positions at continental and global scales are thermally limited, with variations induced by specific local site conditions. In the course of a long history of treeline research, correlations between treeline formation and air and soil temperatures have been repeatedly established (e.g. Däniker 1923; Wieser and Tausz 2007; Holtmeier 2009; Richardson and Friedland 2009; Körner 2012; Paulsen and Körner 2014; Weiss et al. 2015). At a global scale, treeline formation and maintenance appear to coincide with a growing season mean air temperature ranging from 5.5 to 7.0 °C and a growing season mean soil temperature of 6.4 ± 0.7 °C (Körner 1998, 2007, 2012; Körner and Paulsen 2004). However, considerable deviations from a global treeline isotherm occur at local scales, suggesting a rather broad error term with regard to a global soil temperature threshold. For instance, we assessed a growing season mean soil temperature of 7.5 ± 0.5 °C at a near-natural treeline in Rolwaling/Nepal (Müller et al. 2016). Mean temperatures which do not exist in nature are obviously rather rough indicators of thermal deficiency at treeline elevations.

Given the repeated climatically caused treeline fluctuations during the Holocene (MacDonald et al. 2000; Reasoner and Tinner 2009; Schwörer et al. 2014) and the general dependency of the upper limit of tree life on heat balance, it seems apparent that climate warming will improve growth conditions of treeline forest stands, generate higher stand densities and induce treelines to advance to higher elevations (Grace et al. 2002; Dullinger et al. 2004; Smith et al. 2009). However, treeline movement to greater elevations is a complex process which is extremely difficult to predict since the sensitivity of global treelines to recent climate change is highly diverse. Observed responses at treelines are quite inconsistent and sometimes contradictory, spanning the entire gradient from static treelines with rather insignificant responses to dynamic treelines substantially migrating upslope (e.g. Camarero and Gutiérrez 2004; Daniels and Veblen 2004; Danby and Hik 2007; Kullman and Öberg 2009; Moiseev et al. 2010; Liang et al. 2011; Kullman 2014; Mathisen et al. 2014; Schickhoff et al. 2015). The variability in the response of treelines to changes in climate is reflected in a recent meta-analysis based on a global dataset of 166 sites for which treeline dynamics had been reported since AD 1900. Fifty-two percent of the sites showed advancing treelines, while 47 % did not reveal any elevational shifts; 1 % experienced treeline recession (Harsch et al. 2009). In old-settled mountain regions, e.g. in the European Alps where pastoral use, logging, mining and other land-use impacts had lowered the treeline during the Holocene, land abandonment and the general decline of human impact are usually the dominant driver for treeline movement to higher elevations (Gehrig-Fasel et al. 2007; Vittoz et al. 2008). However, when substantial treeline advances during the twentieth century are reported, effects of land use and climate change are often hard to disentangle (e.g. Baker and Moseley 2007).

To explain the gradient from complete treeline inertia to rapid upslope migration, the local-scale complexity of abiotic and biotic site factors and their interrelationships have to be considered that collectively result in nonlinear responses to climate. Response variability must be attributed to the interaction of broad-scale climate inputs and fine-scale modulators of treeline patterns (Holtmeier and Broll 2005, 2007, 2009; Batllori and Gutiérrez 2008; Elliott 2011; Malanson et al. 2007, 2011). It is still largely unknown, however, how local-scale site conditions such as abiotic site factors, plant interactions associated with facilitation, competition and feedback systems modify treeline response patterns to region-wide climate controls. The mechanisms of seedling establishment and growth to maturity across the treeline ecotone are of particular interest in this respect (Smith et al. 2003, 2009; Wieser et al. 2014). Different treeline forms (diffuse, abrupt, island, krummholz) obviously show varied responsiveness and may allow inferences on the general mechanisms controlling response patterns (Harsch and Bader 2011), but it is still an open question to what extent treeline form can be used to predict treeline dynamics. In order to analyze how local-scale factors and processes mediate the broader-scale climate inputs and interact and govern sensitivity and response of treelines, complex research approaches at local and landscape scales and in different treeline environments are needed (Holtmeier 2009; Malanson et al. 2011; Wieser et al. 2014).

Recently, the scientific interest in treelines increased considerably since treeline ecotones are potentially promising research objects for detecting and monitoring climate change effects. While European and North American mountains have been a major focus in treeline research programmes, comparatively very few studies have been conducted in the Himalayan mountain system. Information on altitudinal position, physiognomy and treeline-forming tree species is more or less sufficiently documented in the widely scattered literature (Schweinfurth 1957; Champion and Seth 1968; Stainton 1972; Troll 1972; Gupta 1983; Puri et al. 1989; Singh and Singh 1992; Schickhoff 2005; Miehe et al. 2015). However, recent reviews illustrated the deficient state of knowledge of Himalayan treelines, only very scanty information has been published with regard to sensitivity and response to climate change (cf. Schickhoff 2005; Dutta et al. 2014; Schickhoff et al. 2015).

Large warming trends (up to 1.2 °C per decade at higher altitudes) have been observed in the Himalaya in the past 30–40 years (Shrestha and Aryal 2011; Gerlitz et al. 2014; Hasson et al. 2016, Chap. 2 in this volume). Considering the sensitivity of mountain biota and ecosystems in the Himalaya to climate change (Xu et al. 2009; Shrestha et al. 2012; Telwala et al. 2013; Aryal et al. 2014; Anup and Ghimire 2015), substantial effects on Himalayan treeline ecotones are to be expected. Since treeline ecotones in the Himalaya are strongly modified by human impact (Miehe and Miehe 2000; Schickhoff 2005), it is often a challenge to detect a clear climate change signal and to exclude land-use change as a driver of treeline dynamics. Respective research has to concentrate on the few remaining near-natural treeline sites (Fig. 15.1). This paper summarizes the most current knowledge about sensitivity and response patterns of Himalayan treelines to climate change, updating a previous review (Schickhoff et al. 2015) and complementing it by inferring insights from palaeoecological studies.

15.2 Holocene Climatic Changes and Treeline Fluctuations

In view of the direct relationship between thermal conditions and the elevational position of treelines, it is obvious that treeline ecotones have been sensitive to changing climatic conditions in the course of the Holocene and have reflected

Fig. 15.1 Altitudinal zonation of a near-natural north-facing treeline in the central Himalaya: upper subalpine forests of *Abies spectabilis* and *Betula utilis* (leaves still unfolded) give way to *Rhododendron campanulatum* krummholz at c. 4000 m, Rolwaling, Nepal (Schickhoff, 2013-04-15) (Source: Udo Schickhoff)

general long-term climatic trends. It has been documented for many mountain regions of the world, in particular for the European Alps, the Scandes and the Rocky Mountains, that treelines have been fluctuating throughout postglacial times in response to climatic oscillations (Lang 1994; Tinner and Theurillat 2003; Reasoner and Tinner 2009; Körner 2012). Respective information on the Himalaya, however, is still comparatively poor and mainly based on fossil pollen in high-elevation mires and lakes. Complementary plant macrofossil and charcoal studies, missing to date even in the wider region with a few exceptions (e.g. Kaiser et al. 2009; Kramer et al. 2010a), will be valuable in determining the local occurrence of tree taxa at treeline elevations. On the other hand, numerous palaeoclimatic studies have generated insights into changing climatic conditions in South Asia during the Holocene, especially with regard to monsoon variability (e.g. Overpeck et al. 1996; Prasad and Enzel 2006; Clift and Plumb 2008; Cai et al. 2012). Thus, available proxy data allow the inference of a fairly clear pattern of Holocene treeline fluctuations. In the following we review the current knowledge about Holocene climate and subalpine/alpine vegetation changes in order to detect treeline shifts across the Himalayan mountain system in spatial and temporal differentiation.

In general, the reaction of Himalayan treelines to changes in climatic conditions during the Holocene roughly follows the well-established temperate zone response pattern with upslope movement during warmer periods and recession during cooler phases. However, the emerging picture of Holocene treeline fluctuations reveals considerable regional variations throughout the Himalaya which show that factors other than temperature play a significant role. Moisture balance is a crucial control in this respect, largely depending on the monsoon intensity that has changed with spatial and temporal variability on a regional scale (Staubwasser 2006). Other critical factors include soil physical and chemical properties, disturbance regimes (fire, avalanches, other extreme events), individual tolerances and ecological demands of tree species, regeneration, migrational lags and competition from established vegetation (Holtmeier 2009). Despite regional variations, the general course of Himalayan treeline fluctuations during the Holocene is in agreement with studies from other extratropical mountain regions. After the Pleistocene-Holocene transition (c. 11.7 kyr BP), Asian monsoon precipitation increased dramatically (Morrill et al. 2003), resulting in warm and moist climatic conditions. Treelines advanced in elevation to a position several hundred metres higher than today, thus reaching uppermost limits in the early Holocene (Fig. 15.2). Decreasing temperatures below early and mid-Holocene levels induced a general and widespread downward shift of treelines after c. 5.0 kyr BP. The decline of subalpine forests and treeline elevation in the more recent millennia was coincident with weakening monsoonal influence and increasing anthropogenic interferences. However, Holocene treeline history was by no means uniform throughout the entire Himalayan mountain system. Substantial spatial and temporal differences become apparent at regional to local scales.

15.2.1 Hindukush-Karakorum-Himalaya in N Pakistan, W Tibet

Comparatively scanty information is available for the far NW of the mountain system (Hindukush-Karakorum-Himalaya in N Pakistan, adjacent W Tibet). After the transition to warmer conditions and reforestation in the postglacial period (Singh 1963; Agrawal et al. 1989), enhanced precipitation and maximum moist and warm conditions prevailed between 10.7 and c. 7.0 kyr BP (Gasse et al. 1996; Brown et al. 2003). Increased humidity influx into the arid/semiarid mountain region north of the main Himalayan range had been sufficient for the development of closed coniferous forests in the upper montane and subalpine belt as far as the upper Ishkoman Valley, location of the present-day northernmost pine forest (*Pinus wallichiana*) (Schickhoff 2000a). Schlütz (1999) documented a dense *Pinus wallichiana* forest thriving at high elevation in the Rakhiot Valley (Nanga Parbat) at least since 7.9 kyr BP. Reinforced monsoonal rains at 7.2 kyr BP and increasing winter and spring precipitation from the westerlies after 6.3 kyr BP enhanced total precipitation effectiveness (Prasad and Enzel 2006), resulting in the dominance of *Picea*, *Betula* and *Salix* at treeline elevations in the Nanga Parbat area (Schlütz 1999). Miehe et al. (2009a) provided evidence of the local existence of a forest habitat (*Pinus wallichiana*) in the Yasin Valley (E Hindukush) until around 5.7 kyr BP. Climate history and vegetation reconstruction suggest a treeline ascent to higher elevation than

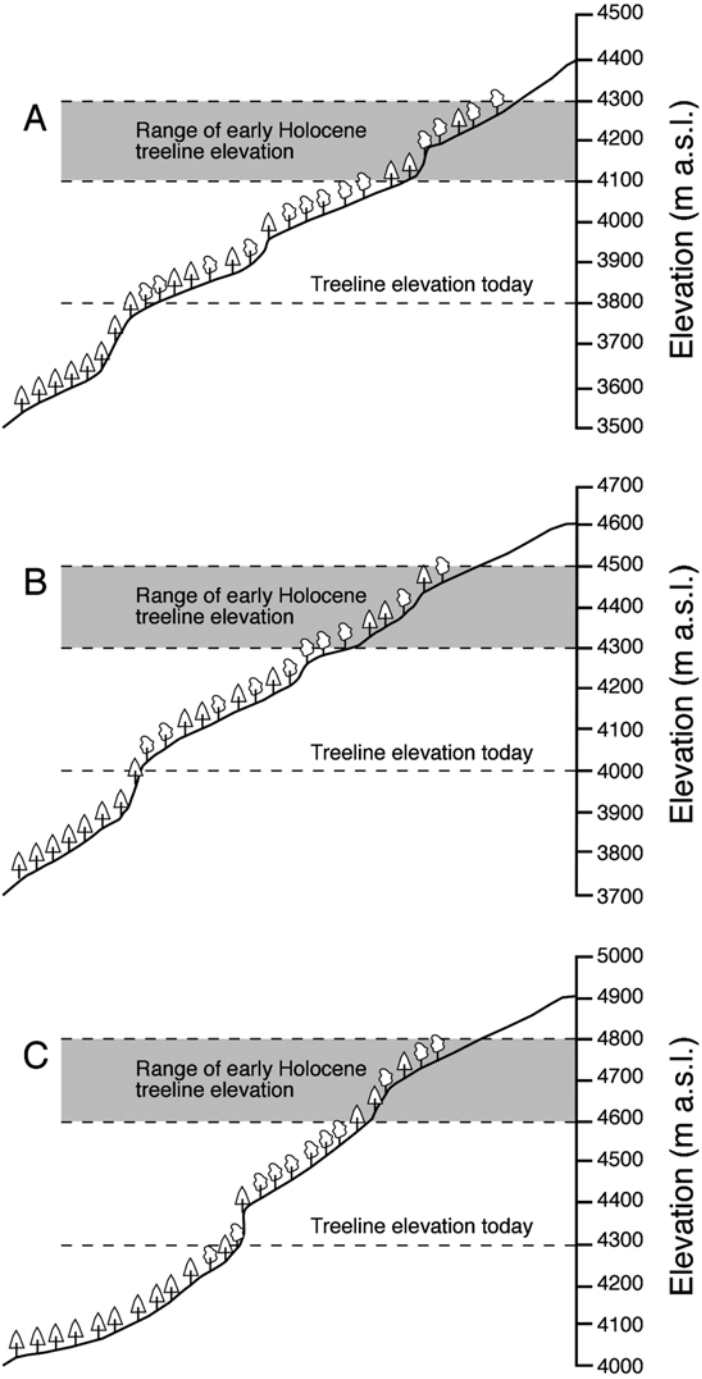

Fig. 15.2 Himalayan treeline elevation today and in the early Holocene, based on temperatures 1.5–2.5 K higher than today and using a lapse rate of 0.5 K per 100 m (cf. Böhner 2006; Reasoner and Tinner 2009; Kramer et al. 2010a; treeline elevations after Schickhoff 2005). (**a**) W Himalaya; (**b**) central Himalaya; (**c**) E Himalaya (Source: Udo Schickhoff)

today during early to mid-Holocene. Decreasing monsoonal precipitation and increasing aridity after c. 5.0 kyr BP are documented for the wider region (Overpeck et al. 1996; Morrill et al. 2003) including the Ganga Plain (Sharma et al. 2004) and were also inferred from pollen analyses in Yasin Valley (Schlütz 1999). Drier conditions resulted in the dwindling of more hygrophilous species (*Pinus* in Yasin; *Betula*, *Salix*, *Picea* at Nanga Parbat) (Schlütz 1999). The general climate deterioration after 5.0 kyr BP, in particular decreasing temperatures, suggests a decline of subalpine forests and a treeline depression close to current elevations. Substantial human activities at treelines in the far NW can be anticipated at least for the past five millennia but most probably go back to the mid-Holocene. Miehe et al. (2009a) attribute the decline of high-altitude conifer forests in the E Hindukush around 5.7 kyr BP to the influence of mobile livestock keepers. Increased grazing intensity since 2.7 kyr BP and significant land-use intensification in the past centuries are evident from the reinforced occurrence of grazing weeds and other cultural indicators in pollen profiles from Yasin and Nanga Parbat (Jacobsen and Schickhoff 1995; Schlütz 1999). Available data are not sufficient to assess whether the medieval warm period (MWP), which is reflected in tree ring growth in the Karakorum (Esper et al. 2007), and/or the following ‘Little Ice Age’ (LIA) caused significant treeline dynamics. However, the cold-wet LIA period (fifteenth to eighteenth centuries) in the wider region with widespread glacial advances (Yang et al. 2009) might have caused dieback and recruitment gaps at treeline elevations and suggests a slight downward shift of treelines.

15.2.2 West and Central Himalaya in India

Available information on Holocene climate history and vegetation dynamics in the West and Central Himalaya in India is much more comprehensive due to a larger set of pollen analyses and other proxy data. In agreement with climate reconstructions for the far NW, the postglacial climate amelioration that had proceeded with several setbacks culminated after the Pleistocene-Holocene transition. Rawat et al. (2015) ascertained increased monsoon intensity with a warm and wet climate for Lahaul between 11.6 and 8.8 kyr BP. Likewise, maximum monsoonal activity and a change to warmer and most humid conditions were inferred for Ladakh between c. 11.0 and 9.2 kyr BP (Bhattacharyya 1988; Demske et al. 2009; Leipe et al. 2014). A palynological analysis of a sediment profile from the Garhwal Himalaya adjoining to the SE corroborated the early Holocene climatic amelioration (Bhattacharyya et al. 2011), which continued until mid-Holocene throughout the West and Central Himalaya in India (Bhattacharyya 1989; Sharma 1992; Sharma and Gupta 1997; Phadtare 2000; Ranhotra et al. 2001; Anoop et al. 2013; Rawat et al. 2015). An enhancement of the winter westerly flow, assessed for Ladakh between 9.2 and 4.8 kyr BP (Demske et al. 2009), contributed to maximum humidity levels. However, the early Holocene climatic amelioration was interrupted by several cooler and/or drier spells, e.g. between 8.8 and 8.1 kyr BP in Lahaul (Rawat et al. 2015) and between 7.2 and 6.6 kyr BP in Garhwal (Phadtare 2000). Nevertheless, in response to favourable climatic conditions, species composition and distribution of forest types changed remarkably during the early Holocene. In Ladakh, a significant expansion of open juniper forests (Bhattacharyya 1989) indicates the increase in temperature and humidity. On the more monsoon-influenced Himalayan south slope (Jammu and Kashmir, Himachal Pradesh, Uttarakhand), thermophilous trees of the genera *Quercus*, *Pinus*, *Alnus*, *Juglans*, etc. became established reflecting a general increase of later successional broadleaved trees and forests at the expense of conifers (Singh and Agrawal 1976; Dodia et al. 1985; Bhattacharyya et al. 2011; Rawat et al. 2015). At higher altitudes, the replacement of alpine meadows by subalpine birch (*Betula utilis*) forests, as inferred for Himachal Pradesh and Garhwal (Bhattacharyya 1988; Bhattacharyya et al. 2011), indicates a widespread treeline advance by several 100 m during the early Holocene (cf. Fig. 15.2). The upward shift of treelines was most likely interrupted during cooler and drier phases as suggested by a treeline descent below Gangotri Glacier between 8.3 and 7.3 kyr BP (Bhattacharyya et al. 2011). Here, climate reverted to warm-moist conditions between 7.3 and 6.0 kyr BP, causing the re-expansion of birch forests and the decline in steppe elements which had become prominent during the period of decreasing humidity (Bhattacharyya et al. 2011).

The mid-Holocene thermal optimum with a stronger-than-present summer monsoon was followed by slightly cooler and distinctly drier conditions, albeit not synchronously throughout the West and Central Himalaya in India. Bhattacharyya et al. (2011) assessed a trend towards drier climatic conditions for the Gangotri Valley (Garhwal) already after 6.0 kyr BP. At lower elevations and further south in Garhwal, Kotlia and Joshi (2013) inferred a cold and dry phase between 5.1 and 3.5 kyr BP. A significant shift towards aridity was described for Ladakh and Lahaul after 4.8 kyr BP (Demske et al. 2009; Leipe et al. 2014; Rawat et al. 2015). The majority of palynological case studies from Jammu and Kashmir to Kumaon reconstructed the weakest monsoon phase with decreasing rainfall and cooler climatic conditions for the time period between 5.0 and 3.0 kyr BP (Dodia et al. 1985; Sharma and Chauhan 1988; Sharma and Gupta 1997; Phadtare 2000; Trivedi and Chauhan 2008). These findings are in line with a significant decline of the Asian monsoon between 5.0 and 4.3 kyr BP identified by Morrill et al. (2003), which triggered severe drought events on the Tibetan Plateau (Herzschuh 2006) and most likely even the collapse of the Indus Valley Civilization (Staubwasser et al. 2003; Gupta et al. 2006). The change to cooler and drier climatic conditions provoked a decline in oak and other broadleaved tree species, while conifers regained dominance (Dodia et al. 1985; Sharma and Gupta 1997), and the treeline presumably shifted downwards (cf. Kramer et al. 2010a). From 4.0 kyr BP onwards, it is increasingly difficult to disentangle climatic and human impacts on treeline dynamics. The first appearance of Cerealia and cultural pollen indicates the introduction of farming and the proliferation of cultivation between 4.0 and 3.0 kyr BP in the West and Central Himalaya in India (Vishnu-Mittre 1984; Dodia et al. 1985; Sharma and Gupta 1997; Trivedi and Chauhan 2008). The development of mixed mountain agriculture with pastoralism on alpine meadows marks the beginning of human-induced treeline decline in the late

Holocene which was most likely several orders of magnitude higher than climate-driven subalpine forest retreat and treeline depression, in particular on south-facing slopes (cf. Schickhoff 2005; Schickhoff et al. 2015).

The more recent millennia saw the consecutiveness of climatic oscillations between cold-dry and warm-humid phases. In most of the subregions relatively dry and cold conditions prevailed between c. 2.5 kyr BP and 500 AD (Kar et al. 2002; Chauhan and Sharma 2000; Chauhan et al. 2000; Chakraborty et al. 2006; Phadtare and Pant 2006; Demske et al. 2009), followed by the MWP and the transition to the LIA. The latter phases become apparent in all palynological analyses, albeit not exactly synchronous in terms of age dating. Morrill et al. (2003) date the transition between MWP and LIA to 1300 AD in the Asian monsoon realm. These more recent climatic oscillations are associated with moderate treeline shifts. Chauhan et al. (2000) and Chauhan (2006) inferred from their pollen profiles a treeline advance in response to the MWP and a subsequent treeline descent during LIA in upper Spiti and in Kullu District, Himachal Pradesh (see also Yadav et al. 2011). Likewise, palynological data for the post-LIA phase suggest a treeline advance to higher elevations in the Gangotri Valley (Kar et al. 2002). An upward shift of the treeline in the range of 750 m since 1730 AD as postulated by Phadtare and Pant (2006) for the Pinder Valley (Kumaon) seems, however, to be unrealistic in the light of reference data from other mountain regions. Körner (2012) even considers the LIA too small an event to trigger a significant treeline shift. Massive deforestation and dramatically increased anthropogenic activities during the past centuries which can be reconstructed from palynological analyses (Sharma and Chauhan 1988; Sharma 1992; Sharma and Gupta 1995; Gupta and Nautiyal 1998; Trivedi and Chauhan 2008) as well as from historical documents (Schickhoff 1995, 2005, 2012) complicate the attribution of treeline dynamics to climatic forcing.

15.2.3 Nepal Himalaya

As in the regions adjoining to the west, the climatic amelioration after the Pleistocene-Holocene transition is associated with an upward shift in treeline position. Yonebayashi and Minaki (1997) inferred a treeline advance and an expansion of *Pinus* and *Quercus* trees under warmer climatic conditions in the Arun Valley, E Nepal, after c. 11.0 kyr BP. The change to warmer and more humid conditions in W Nepal in the further course of the early Holocene is indicated by an increase of *Quercus* and temperate genera at the expense of conifers and birch (Yasuda and Tabata 1988). Stronger summer monsoons with increased rainfall were also assessed for the Kali Gandaki Valley, Central Nepal (Saijo and Tanaka 2002), where inner-Himalayan *Pinus wallichiana* forests had established in the early to mid-Holocene (Miehe et al. 2009a). The end of the Holocene climatic optimum around 5.5 kyr BP as determined by Schlütz and Zech (2004) for Gorkha roughly parallels the climate history of the West Himalaya. Drier climatic conditions were assessed in the Muktinath Valley (Kali Gandaki) after 5.4 kyr BP (Miehe et al. 2002) and in W

Nepal after 4.5 kyr BP (Yasuda and Tabata 1988). The general climatic decline in the Subboreal is characterized by a downward shifting of altitudinal vegetation zones and a treeline depression (Schlütz and Zech 2004). As in other Himalayan regions, late Holocene treeline decline was most likely not triggered by climatic forcing alone. Miehe et al. (2002) dated the onset of pastoral land use and barley cultivation in Muktinath to 5.4 kyr BP and 4.5 kyr BP, respectively. Miehe et al. (2009a) argue that the sudden decline of *Pinus* forests in Muktinath around 5.4 kyr BP was related to the use of fire and other activities of early nomads and settlers. First significant human impact and deforestation in Gorkha as well as increasing human impact in Muktinath was detected for the time period between 3.0 and 2.0 kyr BP (Schlütz and Zech 2004; Miehe et al. 2002). Likewise, effects of climatic forcing and human impact on treeline dynamics during recent centuries are hardly to disentangle. The LIA shrinking of *Abies* and *Tsuga* in Gorkha is accompanied by increased grazing pressure and fire frequency (Schlütz and Zech 2004); a similar interference of effects can be presumed for the Langtang Valley after its colonization in the fifteenth century (cf. Beug and Miehe 1999).

15.2.4 East Himalaya

The transition to warmer and more humid conditions in the early Holocene parallels the climate development in other Himalayan regions and has been documented in several studies (e.g. Sun et al. 1986; Walker 1986; Jarvis 1993; Shen et al. 2006; Kramer et al. 2010a, b; Song et al. 2012; Xiao et al. 2014). Investigations of the corresponding vegetation dynamics point to distinct expansions of high-altitude forest cover and a significant treeline advance. In the Hengduan Mountains (Yunnan, Sichuan), alpine vegetation was replaced by early successional *Betula* forests, *Picea-Abies* forests and *Rhododendron* shrublands after 11.7 kyr BP (Kramer et al. 2010a; Xiao et al. 2014). In the further course of climate warming, a temperature increase of 3–4 K from pre-Holocene conditions triggered an enhanced upward shift of treelines to a position around 400–600 m higher than today after 10.7 kyr BP (Kramer et al. 2010a) (cf. Fig. 15.2). Higher temperatures and the intensification of the summer monsoon resulted in a substantial expansion of forest cover also in other parts of Yunnan and in Arunachal Pradesh after 10.2 kyr BP (Sun et al. 1986; Walker 1986; Ghosh et al. 2014). Recent palaeoecological studies with higher temporal resolution (Kramer et al. 2010a) detected a climate deterioration in the Hengduan Mountains between 8.1 and 7.2 kyr BP which is related to the 8.2 kyr BP event observed in most records from the northern hemisphere (Alley et al. 1997; Dixit et al. 2014). The return to colder and drier conditions involved a downward shift of treelines indicated by a sharp decrease of *Betula* and other tree pollen (Kramer et al. 2010a; Yang J et al. 2010). After this cold spell, treelines shifted upwards again under warm and wet climatic conditions. The Holocene climatic optimum between c. 6.9 and 4.4 kyr BP (Kramer et al. 2010a; Xiao et al. 2014) is characterized by advancing treelines, e.g. in E Tibet to an elevation 500 m higher than today (Yu et al. 2000). Dense moist evergreen forest cover was prevalent at lower elevations (Ghosh et al. 2015), while broadleaved trees, *Tsuga*, *Picea* and *Abies*, were dominant in the upper montane and subalpine belt (Kramer et al. 2010a; Song et al. 2012; Xiao et al. 2014).

After 4.4 kyr BP, colder and drier climatic conditions prevailed in the Hengduan Mountains. Mean July temperatures decreased to about 2–3 K below the mid-Holocene level, and treelines shifted downwards, probably attaining a magnitude of 400–600 m (Kramer et al. 2010a). A rising trend of dryness was assessed for Arunachal Pradesh after 3.8 kyr BP (Ghosh et al. 2014), a weakening of the summer monsoon for Assam after 4.2 kyr BP (Bera and Basumatary 2013). Thus, palaeoclimatic data indicate a later onset of temperature and humidity decline after the mid-Holocene climate optimum compared to the West Himalaya. Relatively cold and dry conditions prevailed in NE India until 2.2 kyr BP (Mehrotra et al. 2014). As in other Himalayan regions, climate-driven forest retreat and treeline depression during late Holocene were reinforced by human influence. Earliest records of human activity and grazing indicators in pollen profiles in Yunnan and Sichuan were traced back to c. 3.4 kyr BP (Kramer et al. 2010a; Yang J et al. 2010), but anthropogenic interferences might have played a major role much earlier as it has been ascertained for other parts of the Tibetan Plateau (Frenzel 1994; Miehe et al. 2008, 2009b). Thus, treeline oscillations during the past three millennia seem to be rather related to human impact than to climatic forcing. In spite of increased anthropogenic disturbance in the past centuries (Jarvis 1993; Chauhan and Sharma 1996), palynological data suggest a treeline advance during the MWP, a decline in arboreal pollen and treeline descent during LIA, an increase of *Quercus*, *Betula*, *Alnus* and Rosaceae pollen at higher altitudes and a renewed treeline shift towards higher elevation after LIA (Sharma and Chauhan 2001; Bhattacharyya et al. 2007). However, given the alternating regional temperature history during the past centuries (Yang B et al. 2010), it is still unclear whether significant climate-driven treeline shifts before, during and after the LIA actually occurred.

15.3 Treeline Sensitivity and Response

15.3.1 Treeline Types and Treeline Forms

It is evident from past treeline fluctuations that treeline elevation has always been tracking changing temperatures in the course of the Holocene, albeit with varied time lags which are hard to quantify given the available data. Since the future thermal level at treeline elevations will most likely be distinctly higher compared to present conditions and to conditions during the mid-Holocene climate optimum (IPCC 2013), an upslope movement of subalpine forests and a treeline advance to higher elevations can be anticipated, given that no other factors adversely affect tree growth and regeneration (Holtmeier 2009).

Fig. 15.3 Climatic treeline at c. 4050 m with *Abies densa* and several *Rhododendron* spp., Kangchendzonga National Park, Sikkim (Schickhoff, 2015-03-26) (Source: Udo Schickhoff)

The susceptibility of treelines to respond to changing climatic conditions varies considerably among different treeline types and treeline forms (Schickhoff et al. 2015). Climatic treelines (Fig. 15.3) show comparatively high susceptibility and are more likely to reflect climate tracking since increases in temperature sums and growing season length will affect growth patterns, regeneration and treeline position, at least in the long term (Holtmeier and Broll 2007; Körner 2012). However, the direct influence of climate warming is variegated in complex ways by local-scale abiotic and biotic site factors and their manifold interactions acting as thermal modifiers. For instance, the varying microtopography in treeline ecotones exerts a modified influence on soil temperatures, soil moisture or the distribution of trees (Holtmeier and Broll 2005, 2012; Case and Duncan 2014). Notwithstanding the basically high susceptibility of climatic treelines, their sensitivity is controlled by these thermal modifiers with a notable scope of fluctuation in the medium term (several years to a few decades), while the long-term response in terms of treeline shifts might be more homogeneous.

By contrast, orographic and edaphic treelines are largely resistant to the effects of climate warming. The establishment of trees in orographic treeline ecotones remains primarily under the control of orographic factors such as debris slides, rockfalls, snow avalanches, etc., regardless of higher temperatures. Likewise, edaphic treelines are hardly affected in the medium term, unless pedogenetic processes accelerate and favour the establishment of tree seedlings and tree invasion. Anthropogenic treelines are comparable to climatic treelines in terms of sensitivity

Fig. 15.4 Anthropogenic treeline in Manang, Nepal, showing an abrupt transition to alpine grazing lands (Schickhoff, 2013-09-24) (Source: Udo Schickhoff)

to climate warming. In many mountain regions, cessation of pastoral use and other human impact in recent decades has generated prolific regeneration, increased tree establishment within the treeline ecotone and invasion into treeless areas above the anthropogenic forest limit. These directional changes are readily attributed to effects of global warming; they result, however, in most cases from decreasing land use (Gehrig-Fasel et al. 2007; Vittoz et al. 2008; Holtmeier 2009; Schickhoff 2011).

In the Himalayan mountain system, we consider the vast majority of treelines to be anthropogenic (Fig. 15.4) and a relatively low percentage to be orographically/edaphically and climatically determined (Schickhoff et al. 2015). Animal husbandry, timber logging, fuelwood collection and the like are integral parts of village economies for millennia (see above), and have transformed treeline ecotones, in particular on south-facing slopes, to such an extent that treeline depressions of up to 500–1000 m occur (Miehe 1997; Miehe and Miehe 2000; Schickhoff 2005; Miehe et al. 2015). On north-facing slopes, which have a much lower utilization potential, the extension of alpine grazing grounds and the overuse of subalpine forests (Schmidt-Vogt 1990; Schickhoff 2002) have resulted in substantial treeline depressions as well. For instance, a difference between current and potential treeline of up to 300 m was assessed in Kaghan Valley, West Himalaya (Schickhoff 1995). Thus, present-day landscape patterns at treeline elevations are cultural landscape patterns. Treelines on south slopes are almost exclusively anthropogenic. Only very few near-natural treeline ecotones, more or less undisturbed by human impact, persist in remote, sparsely populated valleys which are not connected to the road network and/or where plants and animals are protected for religious reasons (Miehe et al. 2015; Schickhoff et al. 2015). A substantial medium-term treeline response to climate warming is to be expected from the tiny fraction of climatic treelines only and from those anthropogenic treelines which are no longer exposed to important human disturbance. However, the vast majority of anthropogenic treelines will be subjected to continued intensive land use in the foreseeable future. Thus, the proportional distribution of treeline types in the Himalaya suggests a rather low responsiveness to climate warming, at least in terms of treeline shifts (Schickhoff et al. 2015).

To explain the variability of treeline response to climate warming, treeline spatial patterns have to be taken into consideration. A general link between treeline form and dynamics (Lloyd 2005; Harsch et al. 2009) was recently substantiated by Harsch and Bader (2011), who distinguished in their global study four treeline forms with wide geographic distribution (diffuse, abrupt, island, krummholz). They found diffuse treelines, formed and maintained primarily by growth limitation, to exhibit a strong response signal, while abrupt, island and krummholz treelines, controlled by seedling mortality and dieback, are comparatively unresponsive. Since treeline forms in the Himalaya are predominantly controlled by anthropogenic disturbances, they cannot easily be classified into discrete classes. Diffuse treelines are largely limited to less disturbed or near-natural sites in southern aspects which have become very rare. The occurrence of abrupt and island treelines under natural conditions can be virtually excluded. When abrupt treelines occur (Fig. 15.4), e.g. *Betula* treelines in Manang Valley, Nepal, they are caused by land use (cf. Shrestha et al. 2007). The far majority of less disturbed or near-natural Himalayan treelines, mainly confined to north-facing slopes, has to be categorized as krummholz treelines (cf. Fig. 15.1; Schickhoff et al. 2015). Since krummholz treelines usually show a rather low responsiveness to climate warming, substantial treeline shifts at these near-natural Himalayan treelines are to be expected in the long term only. However, a substantial short- to medium-term response can be anticipated in terms of increased vertical stem growth and enhanced recruitment of seedlings (Schickhoff et al. 2015).

15.3.2 Seed-Based Regeneration

The establishment of seedlings and a successful performance during early life stages is the prior condition for any treeline advance to higher elevations (Holtmeier 2009; Smith et al. 2009; Zurbriggen et al. 2013). In the Himalaya, tree recruitment in treeline ecotones is not well understood. Nevertheless, some conclusions on effective regeneration with regard to treeline response to climate warming can be drawn. The number of respective seedling studies is limited, and available studies are reviewed in Schickhoff et al. (2015). High levels of recruitment in recent decades become apparent from these studies, as long as the respective treeline ecotones are not too heavily disturbed by grazing and other human impact. Little information on treeline seed-produced regeneration is available from the northwestern,

western and central Himalayan mountain regions in Pakistan and India. Generally low regeneration rates were assessed in subalpine forest stands in the Karakoram, in line with retarded growth processes and slow stand development cycles under semiarid-subhumid climatic conditions (Schickhoff 2000b). By contrast, intense recruitment patterns were reported from the humid Himalayan south slope. Treeline elevations in Himachal Pradesh and Uttarakhand showed high levels of recruitment, with increasing establishment of pine (*Pinus wallichiana*) and birch (*Betula utilis*) seedlings even above the treeline zone (Dubey et al. 2003; Gairola et al. 2008, 2014; Rai et al. 2013). An increasing number of studies on seed-based regeneration are available from Nepal. Sufficiently regenerating treeline forests with high densities of seedlings and saplings and seedlings occurring above the treeline are consistently reported from Manang Valley, Annapurna Conservation Area (Shrestha et al. 2007; Ghimire and Lekhak 2007; Ghimire et al. 2010; Kharal et al. 2015). Similar results were achieved at different treeline sites in Langtang National Park (Gaire et al. 2011; Shrestha et al. 2015a), in Manaslu Conservation Area (Gaire et al. 2014) and in Mt. Everest Nature Reserve (S Tibet) (Lv and Zhang 2012). High levels of recruitment of *Abies spectabilis* in recent decades with seedlings and saplings at much higher elevations than uppermost cone-bearing tree individuals were a consistent result of these studies. By contrast, a relatively low number of *Abies* seedlings and saplings above treeline was assessed in Makalu Barun National Park (Chhetri and Cairns 2015). Seedling abundance is often positively correlated with soil moisture (Ghimire and Lekhak 2007; Zhang et al. 2010) and temperature parameters (Lv and Zhang 2012; Gaire et al. 2014). Concordant results were obtained in the East Himalaya, including intense recruitment of *Abies densa* in subalpine forests of Bhutan (Gratzer et al. 2002; Gratzer and Rai 2004), considerably increased Smith fir (*Abies georgei* var. *smithii*) recruitment in recent decades in the Sygera Mountains (SE Tibet) (Ren et al. 2007; Liang et al. 2011; Wang et al. 2012) and high rates of Smith fir regeneration with the percentage of seedlings/saplings increasing upslope across the treeline ecotone in the Hengduan Mountains (NW Yunnan) (Wong et al. 2010).

The emerging pattern of a generally intense regeneration at Himalayan treeline sites which are less or not disturbed by pastoral use is corroborated by new results from ongoing research projects of the present authors in two study areas in Nepal (Rolwaling Valley, Gaurishankar Conservation Area; Langtang Valley, Langtang National Park) (cf. Schickhoff et al. 2015; Schwab et al. 2016). At a newly established treeline study site in Rolwaling Valley, east-central Nepal, we assessed largely prolific regeneration (Table 15.1) with seedling establishment of *Betula utilis*, *Abies spectabilis*, *Rhododendron campanulatum* and *Sorbus microphylla* and thriving of saplings to some extent far above the upper limit of adult trees (Fig. 15.5). Some individuals of more than 2 m height even grow vigorously above the *Rhododendron campanulatum* krummholz belt, i.e. 100–150 m above the treeline which is located at 3900 m (NW-exp.)/4000 m (NE-exp.). In spite of this recruitment, we found the dense krummholz belt to be an effective barrier for upslope migration of other tree species, expressed by a negative correlation between abundance and density of *R. campanulatum* and recruitment of other tree species (Schwab et al. 2016).

Table 15.1 Number of seedlings/saplings (<7 cm breast height diameter; N ha^{-1}) of *Betula utilis*, *Abies spectabilis*, *Rhododendron campanulatum* and *Sorbus microphylla* in the treeline ecotone in Rolwaling Valley according to slope exposure and altitudinal zone

Altitudinal zone		Altitude (m)	*Betula utilis*	*Abies spectabilis*	*Rhododendron campanulatum*	*Sorbus microphylla*	Total
NE slope	A	3780–3880	754	453	1209	1450	3866
	B	3920–3980	179	872	5388	975	7414
	C	4020–4080	104	53	6103	2257	8517
	D	4120–4220	0	0	819	191	1010
	Total	–	1013	1378	13,519	4873	20,807
NW slope	A	3760–3780	3517	1996	612	2058	8183
	B	3820–3880	1288	819	8338	825	11,270
	C	3920–3980	69	81	4125	269	4544
	D	4020–4240	12	25	1712	238	1987
	Total	–	4886	2921	14,787	3390	25,984

Updated from Schickhoff et al. (2015)

Fig. 15.5 *Abies spectabilis* sapling at 4200 m in *Rhododendron anthopogon* dwarf scrub heath, Rolwaling, Nepal, c. 200 m above treeline (Schickhoff, 2013-08-20) (Source: Udo Schickhoff)

Permanently dense foliation of evergreen *Rhododendron* and potential allelopathic effects that have been shown for other species of this genus (Chou et al. 2010) obviously prevent the establishment of seedlings of competing tree species to a large extent. Maximum seedling/sapling density of more than 11,000 N/ha occurs in uppermost subalpine forests immediately below the transition to the krummholz belt (elevational zone B; NW slope). *R. campanulatum* has its most intense

Table 15.2 Cumulative numbers of seedlings/saplings (N ha^{-1}) of *Betula utilis*, *Abies spectabilis*, *Rhododendron campanulatum* and *Sorbus microphylla* in the treeline ecotone in Langtang Valley according to altitude and size classes

Size class (cm)										
Altitude (m)	0–19	20–49	50–99	100–149	150–199	200–299	300–399	400–499	500–7 cm dbh	Total
3850	5441	1134	522	631	603	131	69	69	78	8678
3900	6269	1834	909	628	719	172	59	41	34	10,665
3950	6778	1225	566	500	434	122	75	169	206	10,075
4000	4741	772	513	459	425	63	34	84	159	7250
4050	3694	403	231	213	253	97	75	78	75	5119
4100	3631	497	253	269	259	113	69	34	25	5150
4150	397	184	69	47	75	31	22	16	19	860
4200	19	28	16	13	9	3	0	0	0	88
Total	30,970	6077	3079	2760	2777	732	403	491	596	47,885

dbh diameter at breast height

recruitment at treeline elevations (zones B and C; cf. Table 15.1; Schwab et al. 2016). We assessed significantly positive correlations of seedling/sapling abundance with soil moisture for *Abies*, *Betula* and *Rhododendron* and with soil temperature for *Abies*, *Betula* and *Sorbus*, in each case over almost all size classes. Thus, higher soil moisture and higher soil temperatures indicate higher recruitment density of the majority of treeline tree species. *R. campanulatum* saplings (up to a height of 2 m) were found to be negatively correlated with soil temperature; germinants and large shrubs of this species, however, showed a positive correlation (Schickhoff et al. 2015).

In accordance with the observations in Rolwaling, we found the production of viable seeds and the supply of treeline ecotones with fertile seeds in Langtang Valley to be sufficient to generate relatively high rates of seedling establishment, even beyond the actual upper limit of contiguous forests between 4000 and 4100 m. We assessed maximum seedling/sapling density at 3900 and 3950 m with 10,665 N/ha and 10,075 N/ha, respectively, before the recruit abundance sharply decreases above 4100 m, slightly above the transition from cloud forests to dwarf scrub heaths (Table 15.2). In contrast to countless seedlings/saplings of *Sorbus microphylla* and *R. campanulatum*, recruitment of *Abies spectabilis* is relatively sparse and obviously related to grazing impact and the removal of adult trees as seed sources (Fig. 15.6). Regeneration of *Betula utilis* is also less intense; birch seedlings, however, are far more homogeneously distributed across size classes compared to the other species, with numerous saplings of greater size classes established at the treeline and above the upper limit of contiguous forests (cf. Schickhoff et al. 2015; see also Sujakhu et al. 2014). We conclude from these high levels of recruitment within and beyond treeline ecotones in both near-natural study sites (Rolwaling, Langtang) that seed-based regeneration will not restrict future treeline advance to higher elevations.

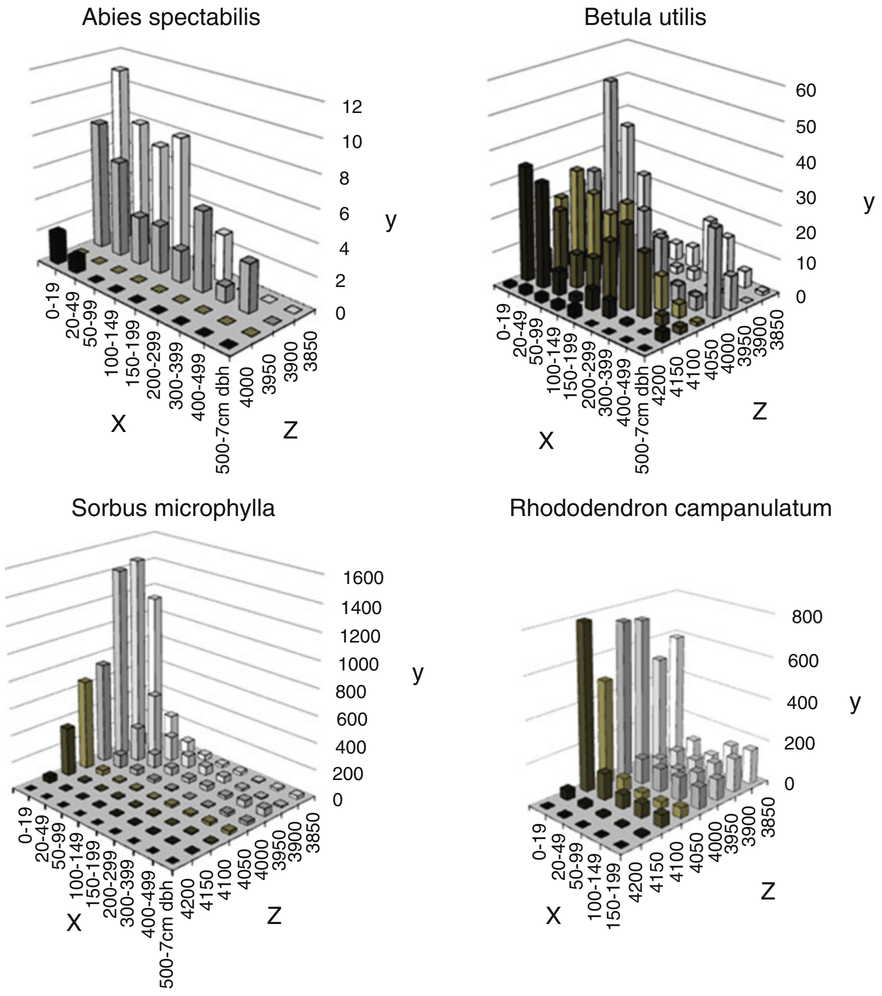

Fig. 15.6 Seedling/sapling density in the treeline ecotone in Langtang Valley according to altitude and size classes (*x* axis = size class; *y* axis = quantity; *z* axis = altitude) (Modified from Schickhoff et al. 2015) (Source: Udo Schickhoff)

15.3.3 Tree Growth-Climate Relationships

As evident from climatically shaped growth forms at treeline elevations, tree growth is sensitive to decreasing temperatures and related harsh climatic and climatically induced ecological conditions. Thus, tree physiognomy usually reflects changing environmental conditions related to climatic alteration. Accelerated, climate warming-induced height growth of previously low-growing tree individuals has been reported from different treeline ecotones for recent decades (e.g.

Lescop-Sinclair and Payette 1995; Kullman 2000; Kullman and Öberg 2009). As for the Himalaya, the recent expansion of treeline ecotones, subalpine forests and alpine scrub detected, for instance, by Rai et al. (2013) in Himachal Pradesh and Uttarakhand during 1980–2010, has most likely been accompanied by enhanced height growth of individual trees as well. Regeneration analyses at the Langtang and Rolwaling study sites provide evidence of successful regeneration even under the harsh climatic conditions above the krummholz belt, with saplings partially projecting above the snow cover (Fig. 15.7; Schwab et al. 2016). Height growth of these recruits might have accelerated recently. Further analyses and data evaluations will provide more detailed information on physiognomic changes in response to climate warming from Rolwaling and other Himalayan treelines.

In contrast to height growth, radial growth is less affected by decreasing temperatures when approaching the upper treeline but shows more pronounced response to climate warming (Körner 2012). In humid mountain regions, climate warming usually results in enhancements of tree radial growth, but under arid or semiarid conditions or in regions with seasonal drought periods, climate warming is often associated with a decline in tree radial growth (Schickhoff et al. 2015 and further references therein). In the Himalaya, dendroclimatological results available to date are inconsistent with studies showing evidence of climate warming-related increase in tree-ring widths and others that detected decreasing tree radial growth (see below). In general, radial growth response to changing climatic conditions is spatially differentiated and species-specific (Schickhoff et al. 2015; Schwab et al. 2015). Himalayan treeline conifers seem to be more responsive to temperature than precipitation change, with W and central Himalayan conifers being more responsive to winter and pre-monsoon temperatures and E Himalayan conifers being more responsive to summer temperatures in most case studies. Tree-ring growth in E Himalaya is obviously less sensitive to climate variation compared to W Himalayan sites and trees (Bhattacharyya and Shah 2009).

Tree growth-climate relationships in the NW and W Himalaya are not consistent. Growth of high-elevation junipers has been shown to be more responsive to temperature variation in the Karakorum (Esper et al. 2002, 2007), while in Lahaul it is more influenced by precipitation (Yadav et al. 2006; Bräuning et al. 2016). Some studies, based on tree-ring width chronologies of *Pinus wallichiana*, *Cedrus deodara* and *Picea smithiana* from high-altitude forests and treeline sites, point to distinctly positive responses of tree growth to recent climate warming, reflected by accelerated growth in the past decades and significantly positive correlations with mean annual and winter (DJF) temperatures (Singh and Yadav 2000; Borgaonkar et al. 2009, 2011). However, another pattern of tree growth-climate relationships is currently emerging from an increasing number of studies: ring-width chronologies from treeline sites and other high-elevation sites in Himachal Pradesh and Uttarakhand reveal a strong sensitivity of tree growth to pre-monsoon temperature and humidity conditions. Bhattacharyya and Yadav (1990), Yadav and Singh (2002) and Yadav et al. (2004) detected significantly negative correlations with long-term pre-monsoon temperature series using *Abies spectabilis*, *Taxus wallichiana* and *Cedrus deodara* tree-ring sequences. A negative correlation of pre-monsoon

Fig. 15.7 Tall saplings of *Betula utilis* (c. 2 m) growing 100–150 m above the current treeline in Langtang Valley, Nepal (Schickhoff, 2010-07-21) (Source: Udo Schickhoff)

temperature with total ring width and a positive correlation of pre-monsoon precipitation with ring width are apparently widespread dendroecological patterns in the West and Central Himalaya in India (cf. Borgaonkar et al. 1999; Pant et al. 2000; Bhattacharyya et al. 2006; Ram and Borgaonkar 2013, 2014). Increased evapotranspiration and soil moisture deficits induced by higher temperatures during the relatively dry spring months obviously impede tree growth in particular on sites which are prone to drought stress.

Recent dendroecological studies in Nepal corroborate these results. Significantly negative correlations with long-term pre-monsoon temperature series were detected in *Abies spectabilis* tree-ring data from near-treeline sampling locations in Humla District (Sano et al. 2005) and in Langtang National Park (Gaire et al. 2011; Shrestha et al. 2015b). The pre-monsoon period has been shown to be also critical for broad-leaved treeline trees. Dawadi et al. (2013) assessed for the growth of birch trees at treeline sampling sites in Langtang Valley a positive correlation with March-May precipitation and an inverse relationship with pre-monsoon temperatures. Liang et al. (2014) confirmed for study sites in Sagarmatha National Park, Langtang National Park and Manaslu Conservation Area that reduced pre-monsoon moisture availability is a primary growth-limiting factor for *Betula utilis* at treeline and that years with high percentage of missing rings or narrow rings coincide with dry and warm pre-monsoon seasons (see also Gaire et al. 2014). These findings are in accordance with results from current research of the present authors based on a ring-width chronology of *Betula utilis* from treeline sites in Langtang Valley dating back to AD 1657, showing a negative correlation of tree-ring width with pre-monsoon temperature and a positive correlation with pre-monsoon precipitation (unpubl. data). A significant negative correlation with May temperature has also been detected for *Juniperus tibetica* on the semiarid southern Tibetan Plateau (He et al. 2013; Liu et al. 2013). Other studies from Nepal highlight a strong positive relationship of *Abies spectabilis* ring width with higher winter temperatures prior to growing season (Bräuning 2004; Gaire et al. 2014).

In the E Himalaya, the ring width of several treeline conifers was also found to be sensitive to winter season temperature, while their maximum latewood density was positively correlated with summer temperature (Bräuning and Mantwill 2004; Bräuning 2006; Bräuning and Grießinger 2006; Fan et al. 2009). Positive relationships with winter temperatures for *Abies densa* and with May temperature for *Larix griffithiana* were assessed near treelines in Sikkim and Arunachal Pradesh, while tree growth was inversely related to summer temperatures (Chaudhary and Bhattacharyya 2000; Bhattacharyya and Chaudhary 2003). Ring-width chronologies of *Abies georgei* var. *smithii* growing at treeline in the Sygera Mountains (SE Tibet) revealed accelerated growth in the past decades and significantly positive correlations with monthly mean and minimum temperatures of most months, particularly in summer (Liang et al. 2009, 2010). Zhu et al. (2011) reported a similar response to summer temperatures for *Picea likiangensis* var. *balfouriana* at treelines in the Bomi-Linzhi region (SE Tibet).

Summing up, studies on tree growth-climate relationships in the Himalaya show non-uniform, species-specific and spatially differentiated results. However, most case studies concordantly indicate a positive relationship of ring width with higher winter temperatures. Warmer conditions during winter season facilitate the storage of higher levels of hydro-carbonates and are beneficial to root system activity and carbon absorption and transportation (He et al. 2013). At W and central Himalayan treelines, growth patterns are particularly responsive to pre-monsoon temperature and humidity conditions. Here, treeline trees may be increasingly subjected to drought stress during the dry pre-monsoon season for which high temperature trends were determined for the entire Himalayan Arc (Gerlitz et al. 2014; Schickhoff et al. 2015). Thus, tree growth in the more humid E Himalaya will most likely be positively influenced by climate warming during the coming decades. Pre-monsoon temperature and humidity conditions will control tree growth in the W and central Himalaya to a considerable extent, in spite of facilitation by higher winter temperatures.

15.4 Treeline Shifts

Under natural conditions, treeline advance to higher elevation in response to a warming climate is normally a medium- to long-term process in the order of several decades to hundred or more years. It is assumed that treeline positions are always lagging behind climatic fluctuations and that global treelines we observe today are each in a specific state of climate tracking. Since the responsiveness of treelines to changing climatic conditions is varied, it is understandable that current observations on treeline shifts in response to recent climate change are globally heterogeneous. The varying degree of human impact on treelines adds to this heterogeneity in response. Response patterns include advancing as well as stagnating or rather unresponsive treelines. The comparability of global observations is limited since they are not based on a uniform treeline concept. The mere presence of seedlings is not synonymous with an actual treeline advance. Only the sustainable transition into subsequent sapling size classes and the establishment of trees beyond the current tree limit is indicative of a treeline shift (cf. Graumlich et al. 2005).

Hitherto documented Himalayan treeline shifts mirror the global pattern, in terms of both response heterogeneity and comparability of observations. Only very few studies addressed this topic to date; they can be grouped into studies based on dendroecological and forest ecological field data and those based on remote sensing and repeat photography (cf. Schickhoff et al. 2015). Most of the studies reported higher population density of trees and considerably increased number of seedlings in the treeline ecotone, but more or less stationary treeline positions or insignificant treeline shifts over recent decades. This applies in particular to field data-based studies (Gaire et al. 2011; Liang et al. 2011; Shrestha et al. 2015a; Chhetri and Cairns 2015; Schickhoff et al. 2015). When migration rates are calculated on the basis of uppermost seedling position, higher rates of upslope movement are found (Gaire et al. 2014). However, seedling establishment is not equivalent to effective regeneration and not to treeline advance. Seedlings have a generally low survival rate during the first years after germination and have to survive critical later life stages after projecting above the winter snow cover. Only when uppermost individuals survive, become established as trees and mature, an ecotone expansion should be termed treeline shift.

Remote sensing studies largely confirm the results of field studies. Landsat-based change detection of treeline ecotones in Himachal Pradesh and Uttarakhand indicated a general increase in green biomass and an expansion of fir and birch forests in recent decades, but no treeline shifts (Bharti et al. 2012; Rai et al. 2013). Bold statements of recent exceptional treeline advances in other remote sensing studies (Panigrahy et al. 2010; Singh et al. 2012) have turned out to be implausible (cf. Bharti et al. 2011; Negi 2012; Rawat 2012). A repeat photography study actually documented a treeline shift of almost 70 m in elevation at a slope in the Hengduan Mountains (NW Yunnan) since AD 1923 (Baker and Moseley 2007). Such great altitudinal shifts can be expected from anthropogenic treelines where treeline advance is rather a result of the cessation of pastoral use and other human disturbances than a clear climate change signal.

Modelling approaches are increasingly used to gain a better understanding of treeline dynamics in response to climate and land-use change and of underlying process-pattern relationships and to explore potential range shifts of treeline tree species (e.g. Dullinger et al. 2004; Wallentin et al. 2008; Paulsen and Körner 2014). In the Himalaya, modelling studies to project future geographic distribution of tree species have hardly been conducted so far. Recently, initial modelling studies with

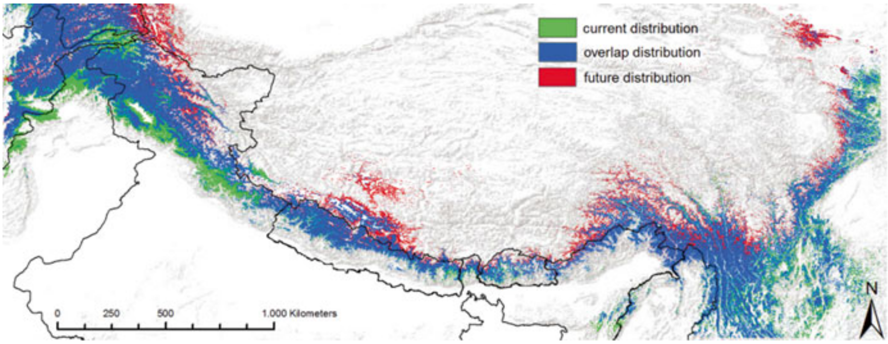

Fig. 15.8 Potential range shift of *Betula utilis* under novel climate conditions in AD 2070 (Modified from Schickhoff et al. 2015) (Source: Udo Schickhoff)

regard to environmental niches of the genus *Rhododendron* in Sikkim and of *Betula utilis* in Uttarakhand were published (Kumar 2012; Singh et al. 2013). In a preliminary study, we used ecological niche modelling to forecast the range shift of *Betula utilis* under novel climate conditions in AD 2070 (Schickhoff et al. 2015). The potential habitat of *Betula utilis* was predicted to shift to higher elevations and to expand into new habitats north of the Himalayan range (Fig. 15.8). Significant upslope expansions are modelled for Trans-Himalayan ranges in S Tibet. Range contractions are forecasted for the Indian W Himalaya, the S Hindukush and the Wakhan Corridor. Further modelling studies are badly needed in order to predict more accurately patterns and rates of treeline dynamics driven by climate change.

15.5 Conclusions

In view of the heterogeneity of treeline environments in the vast Himalayan mountain system, it is difficult to infer generally acceptable statements on treeline sensitivity and response to changing climatic conditions. However, several conclusions can be drawn from the present review that might be of relevance for treeline dynamics in other mountain regions beyond the Himalayan system. The Holocene Himalayan treeline history substantiates the conception that treeline elevation has been tracking temperatures over the postglacial millennia. The basic pattern of treeline fluctuations during the Holocene resembles those of other extratropical mountain regions but is accentuated by spatial and temporal differences at regional to local scales. Himalayan treelines reached uppermost limits during the Holocene thermal optimum, before a general and widespread downward shift of treelines was induced by deteriorating climatic conditions after c. 5.0 kyr BP. The palaeo-data suggest that treelines are currently in a dynamic process of climate tracking in response to recent climate warming and that a future advance of treelines is plausible at continued warming.

At near-natural Himalayan treelines, a significant move in elevation seems to be possible only in the long term. Near-natural or less disturbed treelines on north-facing slopes are usually developed as krummholz treelines which show a low responsiveness. Strong competition within the krummholz belt and dense dwarf scrub heaths further upslope adversely affects upward migration of tree species and retards treeline shifts. Nevertheless, high levels of recruitment with huge amounts of seedlings/saplings present within the treeline ecotone and to some extent beyond suggest that favourable preconditions for a future treeline advance exist. Species-specific competitive abilities during the recruitment phase or rather the effectiveness of recruitment suppression in the krummholz and dwarf scrub belts will control this advance. By contrast, anthropogenic treelines, predominant in the Himalaya, will show substantial short- and medium-term effects once pastoral use and other human disturbances will have ceased. Dendroecological studies point to a high sensitivity of mature Himalayan treeline trees to temperature. Tree radial growth is positively influenced by higher winter temperatures, and negatively influenced by higher pre-monsoon temperatures and increased drought stress in the pre-monsoon season, in particular in the W and central Himalaya. These findings suggest that moisture supply might be an effective control of future treeline dynamics. In general, the bioclimatic preconditions for a future treeline advance will be existent as indicated by predicted shifts to higher elevations of treeline tree species based on ecological niche modelling. Treeline shifts into treeless ecosystems will have large-scale consequences in terms of biodiversity, ecosystem function and ecosystem services, including reductions in alpine diversity and alterations of ecosystem productivity and carbon storage. A widespread upward encroachment of subalpine forests would also affect land-use potentials and tourism economies.

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