Highest Treeline in the Northern Hemisphere Found in Southern Tibet

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Three new records of the highest treelines in the northern hemisphere are presented here, based on the definition of a "tree." The tree species with the highest treeline in the northern hemisphere is Juniperus tibetica *Kom. The highest forest stand is located at 4900 m in southeast Tibet. The highest tree stands of* Juniperus indica *Bertol. in the Himalaya were found in northern Bhutan at 4750 m. Information from such observations is decisive for the development of hypotheses on the limits of tree growth. We compare the present findings with findings on highest treelines in other mountain areas worldwide and draw some conclusions.*

Keywords: *Highest treeline;* Juniperus *spp.; Himalaya; Tibet.*

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Introduction

Determining the upper treeline is certainly one of the most interesting research challenges in comparative high mountain research. Careful compilations (Hermes 1955; von Wissmann 1961; Schickhoff 2005) have documented that the highest treelines in the northern hemisphere are found on the eastern declivity of the Tibetan Highlands. However, regional and global synopses of upper treeline altitudes can only be useful sources when information on growth form and habitat structure as well as data on human impact are provided. Therefore, all available compilations admittedly compare data of differing reliability. Inconsistencies result from different definitions of what constitutes a tree, or from failure to take account of human interference (Troll 1948; Figure 1).

Material and methods

According to Raunkiaer (Mueller-Dombois and Ellenberg 1974), trees are scapose woody phanerophytes, no matter how tall they are. The UNESCO classification by Mueller-Dombois and Ellenberg (1974) gives 5 m as a minimal height; Körner (1999) and Körner and Paulsen (2004) suggest 3 m. Although a height of 3 m would allow the inclusion of more mountain forests than the threshold of 5 m, it is questionable whether it is meaningful to amalgamate a classification based on qualitative criteria with a quantitative scale. The inadequacy of such an approach becomes evident if we ask whether it would be appropriate to delimit *humans* by a height of 1.8 m. Extended treeline surveys in Africa and High

FIGURE 1 The timberlines in the asymmetrical vegetation belts of the world; based on Troll (1948) as modified by Miehe and Miehe (2000) and changed for the present paper. Sources: Bendix and Rafiqpoor 2001; Bykov 1978; Chen 1987; Ellenberg 1996; Finsterwalder and Jordan 1987; Gorchakovsky and Shiyatov 1978; Hermes 1955; Herzog 1931; Hildebrand-Vogel and Vogel 1995; Hoch and Körner 2005; Holtmeier 1995; Jordan 1983; Kessler 1995; Klötzli 1975; Laegaard 1992; Lauer and Klaus 1975; Miehe 1991; Miehe 1994; Miehe and Miehe 1994; Pérez 1994; Ruthsatz 1977; P. Sklenár, personal communication 14.12.1998; Troll 1939; Walter 1974; Walter and Breckle 1994; Walter and Medina 1969; Wardle 1974; Werdecker 1955.

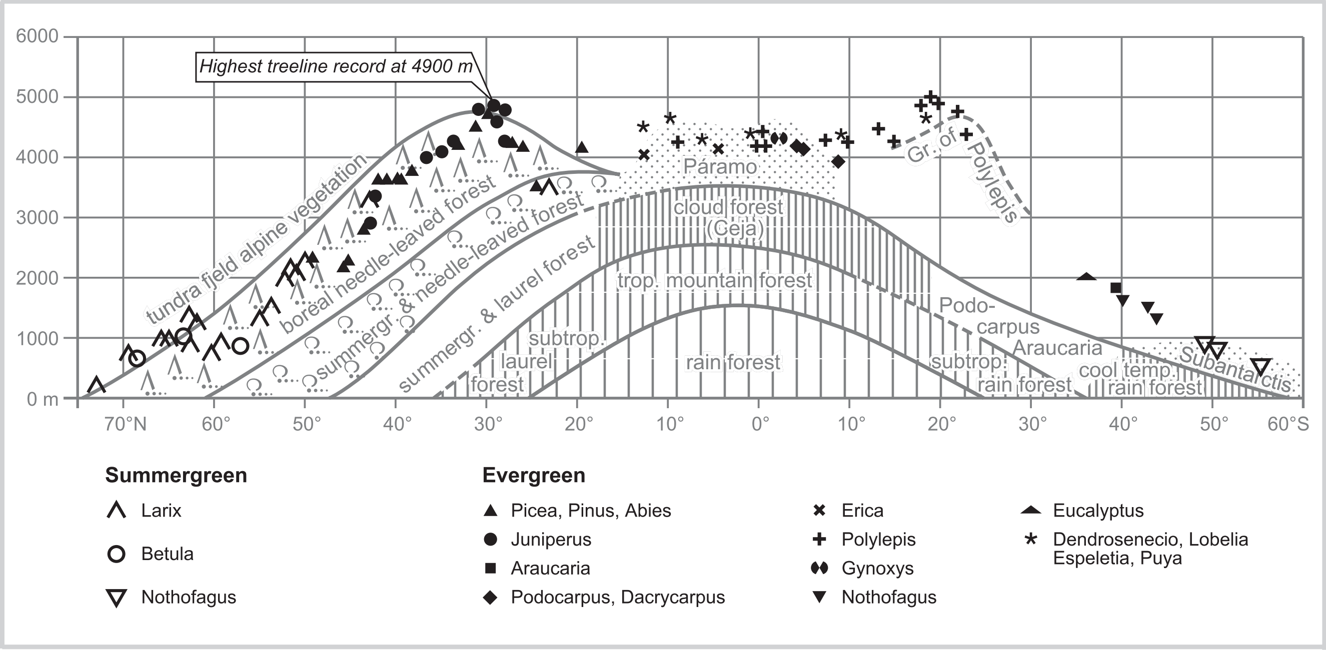

FIGURE 2 Highest forest stand of *Juniperus tibetica* in southeastern Tibet, located at 4900 m (29°42' N / 96°45' E Gr). (Photo by Georg Miehe, 17 September 2004)

Asia (Miehe and Miehe 2000) confirm widely accepted evidence that the upper limit of the forest belt is not a line but an ecotone (Körner 1999). The 'highest treeline' therefore designates an imaginary line connecting scapose phanerophytes. In most humid mountain ranges, single or multi-stemmed woody perennials become increasingly less abundant, forming a pattern that shifts from a closed crown-interlocking forest to isolated individuals. Simultaneously, their heights gradually decrease until they barely emerge from a closed layer of shrubs (Miehe and Miehe 2000).

All the highest treelines in High Asia consist of *Juniperus* species, and all records above 4850 m refer to *Juniperus tibetica* Kom. (Farjon 2005). The latter species is only known in southern and southeastern Tibet (Xizang Autonomous Region, China) and is mainly restricted to southern exposures and rocky open substrates. Nearly all sites are within reach of humans and their cattle, and even remote stands have been interfered with due to demand for timber (Miehe et al 2003). Specifically, junipers of the same taxon become small, stunted, and multi-stemmed with increasing altitude, to the point where distinction between tree and shrub becomes difficult.

However, the sites described here contain trees matching the minimum height required according to Körner's definition of a tree (1999). Our barometric altitude measurements rely on map-adjusted readings of Thommen altitude meters.

Results and discussion

Site 1 is situated in the upper Kyi Chu catchment north of Lhasa in Pando County, above the Reting Monastery, at 4850 m (30°18' N / 91°31' E Gr). The single-stemmed *Juniperus tibetica* tree, 2 m in height, has a crown diameter of 1.5 m and a diameter at breast height (DBH) of 5 cm. The tree grows in isolation on a SE-facing slope at the upper western limit of Reting Forest—the sacred forest most worshiped by Buddhist Tibetans—in an open shrub layer consisting of *Juniperus pingii* var. *wilsonii*, *Potentilla fruticosa*, *Lonicera* spp., and *Caragana* spp.

During a survey of isolated juniper groves in southern Tibet (Miehe et al 2007), more records at corresponding altitudes were collected, including the westernmost *Juniperus tibetica* tree, which was found 650 km west of the actual forest border at 4850 m. This suggests that vast areas of now treeless southern Tibet were once forested (Miehe et al 2003, 2006).

Site 2 (Figure 2) is located at 29°42' N 96°45' E at 4900 m above a side valley of the roughly south–north oriented Salween–Yarlung Zhangbo Watershed in southeastern Tibet (Xizang Autonomous Region, Baxoi County). The W-exposed slope has a gradient of 28° and is covered with coarse boulders. The female and male *Juniperus tibetica* trees attain a height of slightly more than 3 m in the center of the grove, and have interlocking crowns. The largest individuals have a DBH of 0.25 m. The grove is the highest single-stemmed juniper site containing distinct trunks. Further up the slope at an elevation of 4930 m, the junipers are gnarled and multi-stemmed, and carry more than 30% deadwood. Below the grove, a *Juniperus tibetica* forest covers the slope with trees 4 to 6 m in height. Larger trees have apparently been felled.

The relief situation, the known atmospheric circulation, and weather observations during the fieldwork

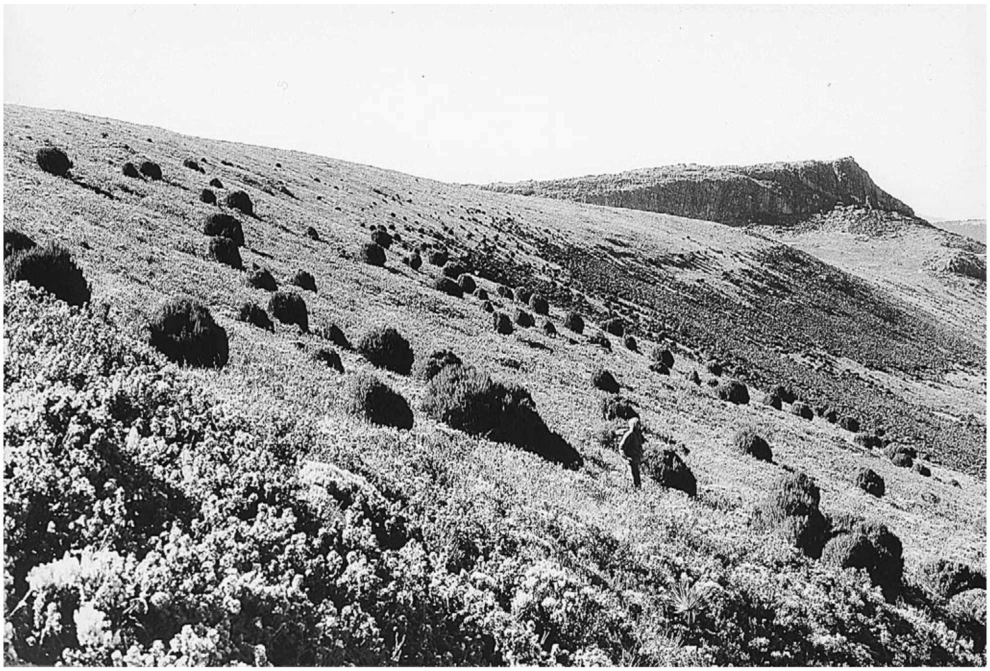

FIGURE 3 Probably undisturbed treeline ecotone in southern Ethiopia: *Erica* thicket disintegrates into isolated spherical individuals. The soil is completely shaded with a thicket of 30 to 50 low scrambling *Alchemilla haumannii*. Bale Mountains, Wasama, 6°55' N / 39°46' E, 4080 m. (Photo by Georg Miehe, 11 January 1990)

(21 August, 16–19 September 2004) suggest that this valley is a wind channel for strong and dry southerly winds. Since the radiative forcing at the site is certainly very different from that recorded at the nearest climate stations, it is doubtful whether any conclusions about the climatic conditions at the local treeline can be drawn, as the climatic causes of treelines are still under-investigated (Körner and Paulsen 2004).

Further south in the rain shadow of the Inner Himalaya of northern Bhutan (28°06' N 90°17' E), the highest juniper trees were found at 4750 m (3 m, single-stemmed *Juniperus indica* Bertol.; Miehe 2004) on a steep SE-exposed 35° slope. On the neighboring slopes at 4650 m, trees 6 m high can be found.

All sites mentioned are normal habitats in the sense that no particular site conditions provide an advantage for tree growth. Our findings surpass the detailed records of Frenzel et al (2003) by 130 to 180 m. It does not seem feasible to establish climatological measurement units at these sites, as they may possibly be deconstructed in due course. However, soil temperature measurements should be made to contribute to the global network of soil temperature measurements directed by Christian Körner (Körner and Paulsen 2004).

Conclusion

Since Earth is a forested planet, the treeline assumes a special significance. It is particularly conspicuous in high mountains, owing to the steepness of the gradient between treed and untreed formations. Surprisingly, the debate surrounding treelines of the world has been overshadowed in the past by 2 misunderstandings that have hindered the development of hypotheses as to their origin: one is rooted in terminological confusion, the other in a lack of precise field observations. Körner and Paulsen (2004) addressed the first question, while Holtmeier (2005) contributed a wealth of detailed habitat types from various mountain ranges of the Holarctic.

Since forests are made up of trees, the outermost sentinels acquire the role of chief witness. This can serve as the justification for providing the present observations. Information from such observations is decisive for the development of hypotheses on the limits of tree growth. It is true of the highest treelines in both hemispheres that the highest trees grow in isolation and become smaller with increasing elevation, decreasing in size from 3 m to 1 m within a 100-m elevation zone. This has been described for Cerro Sajama (Ellenberg 1996; Purcell et al 2004; Hoch and Körner 2005) and is also applicable to the Tibetan treeline. Both *Polylepis tarapacana* and *Juniperus tibetica* are rooted in open substrates that are not shaded by a surrounding herb or shrub layer or neighboring trees. This is also true of the highest-elevation occurrences of arborescent *Erica* on the East African mountain massifs (Bale Mountains, southeastern Ethiopia, 7°10' N / 40° E). Whether the absence of shade over the roots is limiting for tree growth or not is questionable, given the tree group in Figure 2 and the record of a tree near Reting surrounded by a closed stand of knee-high shrubs. Similar structures are known on the moister slopes of the Bale Mountains (Figure 3) and the rainshadow areas of the inner Himalayas of Bhutan (Figure 4). At both sites the

FIGURE 4 Black Mountains, Central Bhutan, 27°23' N / 0°42' E, 4250 m: probably undisturbed treeline ecotone of the southeastern Himalaya: in the treeline ecotone with a closed evergreen broadleaved rhododendron thicket, closed *Abies densa* forests disintegrate into isolated trees. (Photo by Georg Miehe, 16 October 1998)

highest vegetation layer disintegrates over a vertical distance of only 50 to 100 m into isolated *Erica* shrubs or *Abies densa* trees, emerging from a closed carpet of 30–50-cm tall *Alchemilla haumannii* in Africa, or a closed thicket of 1- to 2-m tall evergreen rhododendrons in the Himalayas.

The *Ericas* of southern Ethiopia and the firs of the eastern Himalayas have in common that they acquire a shorter growth habit before reaching their altitudinal limits. The firs seem unable to reduce their height indefinitely, while other treeline phanerophytes like *Erica* and *Juniperus* gradually reduce their height until they are dwarf shrubs.

In conclusion, it is apparent that the examples from different treeline ecotones have in common that trees decrease in height with increasing altitude; the majority of the treelines cited exhibit increasingly caespitose growth forms and withdraw to the layer of air nearest to the ground. Moreover, all examples have in common that closed stands dissolve into loose assemblages of well-spaced individuals. In humid treeline ecotones, the area of the roots remains shaded, while in semiarid to subarid treeline ecotones the rooting area is fully exposed to the sun. It could possibly be concluded from this that the warming of the rooting zone is not a driving ecological factor. Beyond this possibility, it is an open question as to which limiting factors might be responsible for the hyperoceanic treelines of *Nothofagus*. Studies of root physiology (Hertel and Wesche 2007) and regeneration (Cierjacks et al 2007) could bring some clarity to this. Perhaps phanerophytes such as *Lobelia rhynchopetalum* or *Dendrosenecio* (Wesche 2004) deserve to be included in the treeline discussion as well.

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