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ORIGINAL PAPER

An inventory of forest relicts in the pastures of Southern Tibet (Xizang A.R., China)

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Abstract An inventory of isolated tree stands surrounded by desert pastures in Southern Tibet (A.R. Xizang, China) revealed more than 50 sites with vigorous trees of *Juniperus convallium* Rehder & E.H. Wilson and *Juniperus tibetica* Kom and additional more than 10 records where juniper trees had been destroyed between 1959–1976. The tree stands are not restricted to any specific habitat, and occur within an area stretching 650 km westwards from the current forest border of Southern Tibet. The trees are religious landmarks of the Tibetan Buddhists. The highest trees were found at an elevation of 4,860 m. Vegetation records, rainfall correlations and temperature data collected by local climate stations and successful reforestation trials since 1999 indicate that forest relicts fragmented through human interference could regenerate if current cattle grazing and deforestation practices are halted. The drought line of *Juniperus* forests in Southern Tibet is approximately 200–250 mm/a. A first pollen diagram from Lhasa shows forest decline associated with the presence of humans since at least 4,600 yr BP. The currently degraded commons developed in the last 600 yr. To date, no findings of remains of ancient forests in the Central Tibetan Highlands of the Changtang have been reported.

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Introduction

The issue of isolated *Juniperus* tree stands in arid Southern Tibet gives occasion to re-consider perceptions of the dimension of global change during the Holocene in the desert belt of the Old World. This is particularly challenging due to the fact that the reconstruction of Holocene environments is nowhere more difficult than in arid environments. While sediment, landform, pollen and molecular analyses may provide valuable information about shifts of vegetation belts and reforestation migration routes during the Holocene, it is nearly impossible to detect the human impact on environmental changes from hunters and gatherers, nomadic pastoralists or sedentary agriculturalists because archaeological findings are rare and palynological detection of human indicator pollen in the area under consideration is still in its infancy. Owing to the weak regeneration ability of natural resources of pastures and forests in arid climates, human interference is more devastating than in moist climates and can easily lead to desertification. The result is that the natural vegetation is largely replaced by plant species commonly associated with arid environments and believed to reflect an arid ecosystem. While the primacy of desiccation since 5000 BP is widely accepted for the Sahara, where it changed *Acacia* woodlands and lakes to hyper-arid deserts (e.g., Pachur and Altmann 2006), the perception of environmental changes and especially human impact in Central Asian deserts is controversial.

This is particularly the case when considering forest distribution during the mid-Holocene climatic optimum and the Subboreal forest decline. In contrast to fragmentary evidence for dark taiga replaced by steppe following fire in the Gobi Altay after 4,000 yr BP (Dinesmann 1989, cited in Gunin et al. 1999) and the far reaching conclusions possible from forest plant disjunctions (Jäger 2005), palaeoclimatic maps of Frenzel et al. (1992) and Petit-Maire and Bouysse (2002) for Central Asia show steppe for the mid-Holocene climatic optimum. This observation is however not consistent with higher humidity during the Atlanticum which is confirmed with regional deviations by multi proxies of northern China (An et al. 2006). It is rarely even discussed whether the recent treelessness of Central Asia may have been, at least partially, influenced by humans. While evidence exists for fires ignited by Palaeolithic steppe hunters in the forest steppe ecotone of southern Siberia (Blyakharchuk et al. 2004), evidence connecting humans to forest fires in the Subboreal forest refugium of southern Mongolia has been reported (Miehe et al. Ms.in Review). For the Tibetan Plateau, the evidence is less divergent. During the mid-Holocene climatic optimum, ''temperate deciduous forest'' is mapped in arid Southern Tibet westwards to the Indus Yarlung Zhangbo watershed (Petit-Maire and Bouysse 2002; Tang and Shen 1996). *Pinus* and *Quercus* forest (Yu 2004) is even claimed in the Central Tibetan Highlands with alpine steppe and discontinuous permafrost in altitudes of 4,500 m (Atlas of Tibet 1990). The possibility of long distance dispersal of pollen is however not considered. Van Campo et al. (1996) could even demonstrate modern pollen rain of *Pinus*, *Tsuga* and *Quercus* in the alpine deserts of western Tibet at 5,000 m elevation and with 50 mm/a precipitation.

A highly confusing contradiction concerns the ''alpine'' pastures of north-eastern Tibet with forest relicts (Zhang et al. 2005) in a forest climate with 500–600 mm/a precipitation and summer temperatures well above 10°C (Miehe et al. 2001). *Picea* and *Juniperus* forest had been detected there for the mid-Holocene optimum but their decline has been explained by the adverse Subboreal climatic conditions (Herzschuh et al. 2006; Da et al. 1989). Even the review of Ren (2000) underestimates the capacity of even small numbers of humans to clear forests for rangeland using fire as a tool. He concedes human interference on the Tibetan Plateau only in the last millennium and explains this late impact by the remoteness of the area—which is certainly true from the standpoint of a sedentary agricultural society with high population density in the Chinese mainlands. He accepts human interference in the forest belt of the eastern declivity of the Tibetan Plateau since 2,000 yr BP whereas Thelaus (1992) and Frenzel (1994) see human impact on forest since 5,000 yr BP.

The presence of humans in Southern Tibet is documented by hand and footprints of hot springs for the Last Glacial Maximum (Zhang and Li 2002), through upper Palaeolithic sites, and a number of Neolithic sites (Chayet 1994; Fu et al. 2000; Aldenderfer and Zhang 2004). Currently only a single pollen diagram from arid Southern Tibet shows human impact. The ''Lhasa 1'' site (3648 m, 29°10′ N/91°04′ E) shows the decline of *Juniperus* forests since 4,600 yr BP with the presence of pollen indicative of human use and cereal pollen in parallel with *Juniperus* charcoal remains of the same period, and intensified erosion (Schlütz 1999; Kaiser et al. 2006; Miehe et al. 2006). The authors suggest that there were *Juniperus* forests in Southern Tibet, which had been cleared by humans. This supports Zhang (1988: 40) who lists *Juniperus tibetica* stands in the Yarlung Zhangbo gorge east of Xigaze, Namling, Damxung, Reting and Nagarze (appendix: 14, 15, 31, 33, 48). Zhang assumes already that human impact destroyed the forests. In contrast Lauer et al. (1996) interpret the current desert-like vegetation as natural. Similarly, Song et al. (2004) state that the vegetation of Tibet is undisturbed. *Juniperus* is not considered in their models of tree species distribution. Thus, it is evident on the one hand that the current treelessness of arid environments of Southern Tibet is considered by some authors to be natural. On the other hand, other authors suggest that the current degraded pastures of Southern Tibet are human-caused. The results of a forest inventory in Southern Tibet since 1984 (Fig. 1) may contribute to the elucidation of the human dimension of global change. The hypothesis of the present paper is that isolated tree stands in the arid environments of Southern Tibet are relicts of a once closed forest belt, which had been fragmented. The absence of forests in non-water-surplus habitats today is considered to be human-caused. Although the region's population density is relatively low, people were able to replace forests with pastures and create the present cultural landscape of semi-desert rangelands.

Study area

Location

The area under consideration belongs to the Yarlung Zhangbo catchment of Southern Tibet (Xizang Autonomous Region, China) in the rain shadow of the Himalayas. The locations where forest relicts were recorded stretch from the current western border of the mountain forests of the south-eastern Himalayas (approx. 93°E) 650 km to the west (approx. 86°E) roughly between 28°30′ N and 30°30′ N. The valley bottoms rise from 3,200 in the east to 4,200 m in the west. Slopes mostly are smooth and easily accessible with a few intermittent gorges with precipices providing safe sites for trees.

Climate

Southern Tibet has a pronounced highland climate of the subtropics. The radiation values regularly exceed the solar constant especially during fair weather conditions with cumulus clouds in summer (Kuhle and Jacobsen 1988). Evaporation is especially high in the main valleys with the reflection of the cloud bands of the valley air circulation system and the daily valley winds. Penman-Monteith potential evaporation estimates of Lhasa amount to 1,328 mm/a and in Xigaze to 1,259 mm/a (Thomas and Chen 2002). The Transeau ratio of Lhasa is 0.379 and of Xigaze 0.217 (Böhner and Lehmkuhl 2005). This would support Henning's (1994) conclusion that the threshold of forests equates a Transeau ratio of 0.2. The fact that trees are found in extremely wind-exposed arid run-off-sites in the vicinity of Xigaze (appendix: 14) supports the validity of the Transeau ratio. The

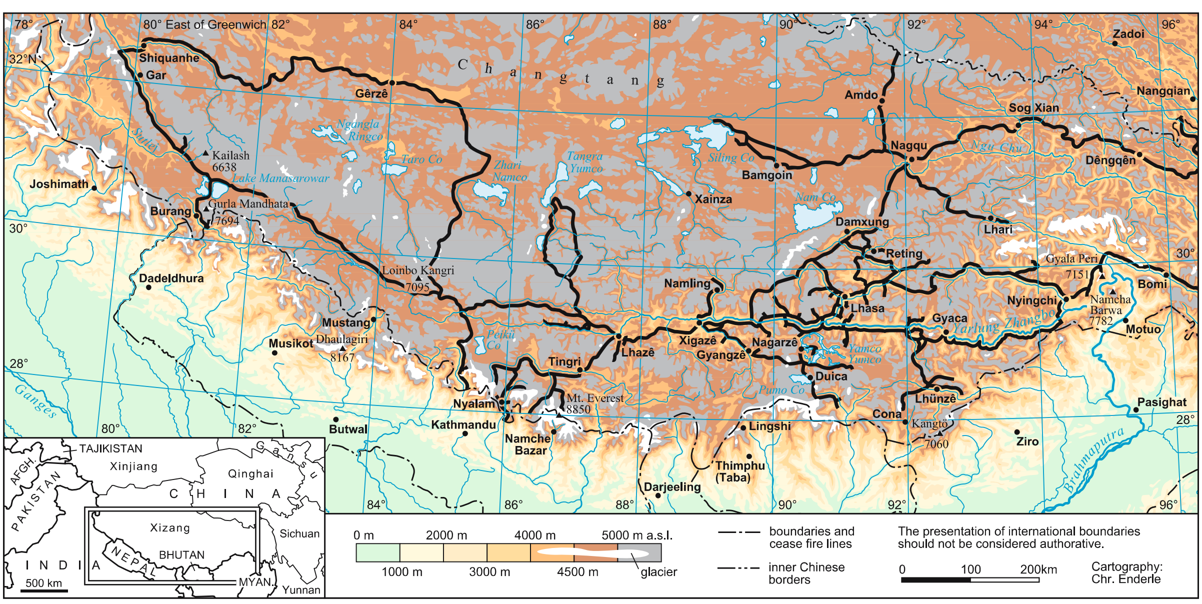


Fig. 1 Survey routes of the inventory, 1984, 1993–1995, 1997–1999, 2001–2006. Base map altered from Miehe et al. (2001)

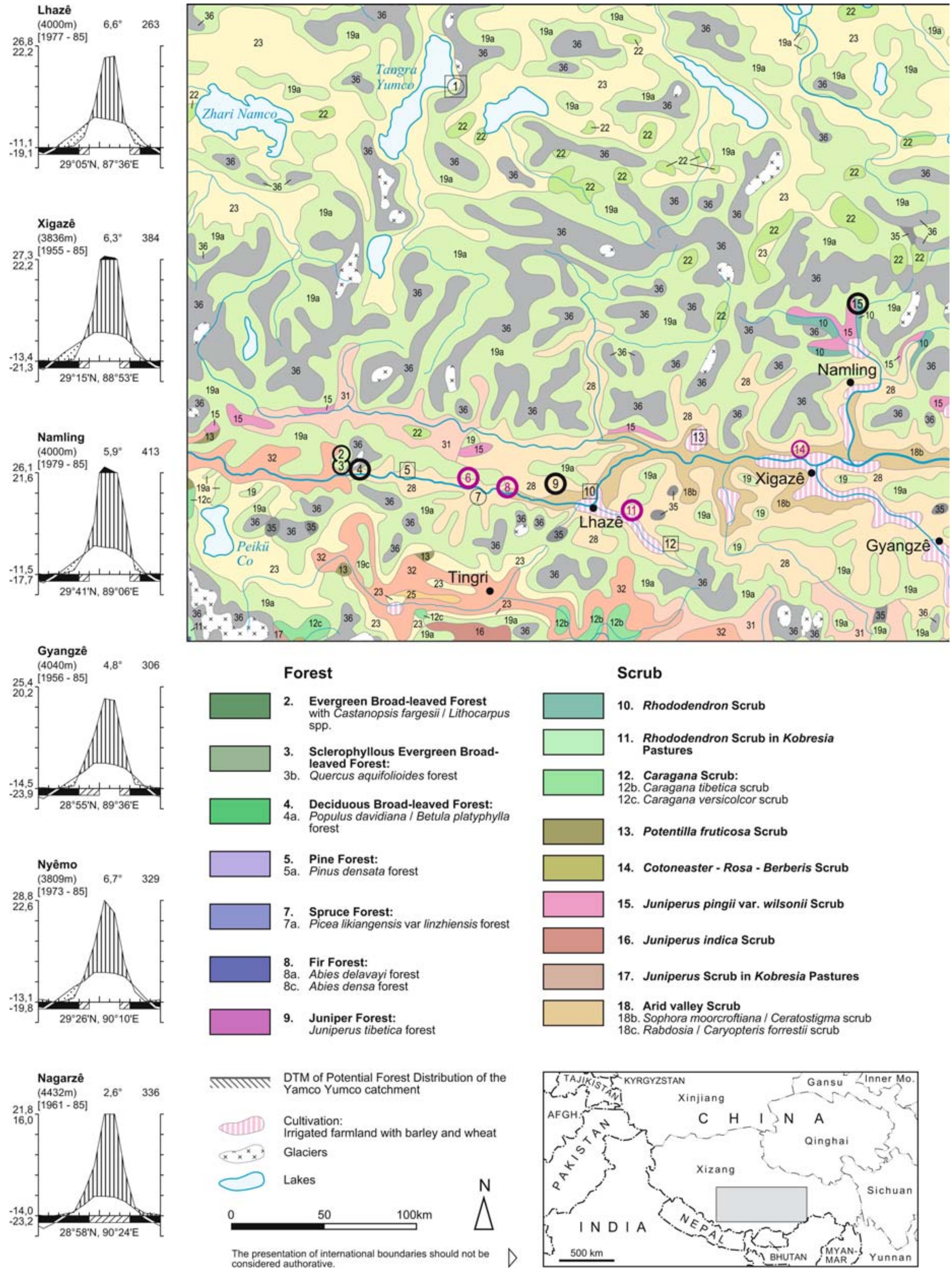
conclusion however that a given evaporation value inhibits tree growth is defeated with the factual presence of vigorous trees.

The rainy season starts in mid-June and lasts until mid-September; torrential rainfall is common, sometimes with hail in the late afternoon or during night time after thunderstorms. Advective rainfall lasting for a few days is usual during the end of the rainy season in September bringing the first snow in alpine areas above 4,800 m. Snowfall in winter is rare and the snow melts within hours at least on the sunny slopes. Especially for *Juniperus*, which clearly prefer southern exposures, snow is certainly not a decisive ecological factor. Rainfall data provided by the Meteorological Service of China give the minimum possible values, because all climate stations are situated in the centre of cloudless arid valley bottoms with strong daily up-valley winds. However, even the data of the most arid sites indicate enough rainfall to allow for forest: along the Yarlung Zhangbo the rainfall decreases from approx. 400 mm/a to 260 mm/a westwards (see Fig. 2). Locations in the vicinity of higher mountain massifs attain higher rainfall and this is applicable as well to the upper side valleys. Rain-gauge measurements on southern slopes above Lhasa since 1997 reveal values reaching nearly twice the rainfall of the valley bottom in altitudes of the upper treeline ecotone in 4,650 m, 1,000 m higher than Lhasa (Miehe et al. 2004). Despite the high altitudes temperatures are suitable for forests: between May and September mean monthly temperatures are above 10°C. The growing season with mean monthly temperatures above 5°C covers 8 months. On the southern exposures where *Juniperus* usually grow, temperatures are certainly even higher than the data delivered from the climatic stations. Soil temperatures in altitudes of the upper treeline ecotone in 10 cm soil depth of southerly exposures show daily ranges of 15 K during fair weather. Maximum subsoil temperature reached 15–20°C during winter. Only occasionally did subsoil temperatures drop below 0°C. Thus permanently frozen ground during winter in fair weather as a precondition for frost drought is not probable. Ice and frost heave of open soil, which may destroy seedlings, occurs rarely because the soil is mostly too dry to allow the formation of needle ice. Thus the climate of Southern Tibet between 86°E and 93°E can be classified as a forest climate. This contrasts to the treeless, arid appearance of the pastures of Southern Tibet.

Fig. 2 The vegetation of Xizang (changed from Zhang 1988), ▶ with climatic diagrams (based on data of the Meteorological Service of China) and *Juniperus* tree sites (see appendix)

Vegetation and human impact

The vegetation of Southern Tibet reflects the effects of desertification through fuel wood extraction of all woody plants mostly with the roots (including the most spiny dwarf shrubs), the effects of soil compaction and trampling of livestock leading to gully erosion of the loamy, deeply weathered bedrock and the long lasting result of selective grazing leaving only plants of little grazing value with rhizomes, bulbs, spines or repellent characters of the leaves. The irregularly rhombic pattern of cattle tracks on the slopes displays the most important character of the vegetation structure. The vegetation structure is diffuse but patchy and the presence of plants useful for fuel or grazing exhibit clear gradients from the irrigation oasis. All shrubs, herbs and graminoids suitable for fuel or grazing are missing around the settlements and only in greater distance to the villages does the vegetation cover increase and the shrubs may attain their natural habit. The most common phanerophytes in Southern Tibet (*Sophora moorcroftiana* (Benth.) Benth. ex Baker, *Artemisia santolinifolia* Turcz. ex Bess., *Buddleja crispa* Benth., *Cotoneaster* spp.) display a dwarf habit of rarely more than half a metre, but grow as shrubs of 2 m or even as multi-stemmed trees of 5 m height in safe sites. Grasses grow mostly in the protection of spiny shrubs; only *Pennisetum flaccidum* Griseb. is common below 4,000 m and is not preferably grazed. *Carex duriuscula* is as common and widely grazing-resistant. Amongst the herbs Lamiaceae, Boraginaceae and aromatic Asteraceae or those with woolly leaves (*Artemisia* spp., *Anaphalis* spp., *Leontopodium* spp., *Pulicaria insignis* Drumm. ex Dunn, *Dolomiaea* spp.) prevail. *Stellera chamaejasme* L., *Arisaema flavum* (Forssk.) Schott or *Iris* spp. are common grazing weeds of more humid pastures. Where slopes are not permanently affected by hoofs and claws


Lhazê
(4000m) 6,6° 263
[1977 - 85]
26,8
22,2
-11,1
-19,1
29°05'N, 87°36'E
Xigazê
(3836m) 6,3° 384
[1955 - 85]
27,3
22,2
-13,4
-21,3
29°15'N, 88°53'E
Namling
(4000m) 5,9° 413
[1979 - 85]
26,1
21,6
-11,5
-17,7
29°41'N, 89°06'E
Gyangzê
(4040m) 4,8° 306
[1956 - 85]
25,4
20,2
-14,5
-23,9
28°55'N, 89°36'E
Nyêmo
(3809m) 6,7° 329
[1973 - 85]
28,8
22,6
-13,1
-19,8
29°26'N, 90°10'E
Nagarzê
(4432m) 2,6° 336
[1961 - 85]
21,8
16,0
-14,0
-23,2
28°58'N, 90°24'E
Tangra Yumco
Zhari Namco
Peikü Co
Namling
Xigazê
Lhazê
Gyangzê
Tingri
Forest
2. Evergreen Broad-leaved Forest with Castanopsis fargesii / Lithocarpus spp.
3. Sclerophyllous Evergreen Broad-leaved Forest:
3b. Quercus aquifolioides forest
4. Deciduous Broad-leaved Forest:
4a. Populus davidiana / Betula platyphylla forest
5. Pine Forest:
5a. Pinus densata forest
7. Spruce Forest:
7a. Picea likiangensis var linzhiensis forest
8. Fir Forest:
8a. Abies delavayi forest
8c. Abies densa forest
9. Juniper Forest:
Juniperus tibetica forest
Scrub
10. Rhododendron Scrub
11. Rhododendron Scrub in Kobresia Pastures
12. Caragana Scrub:
12b. Caragana tibetica scrub
12c. Caragana versicolcor scrub
13. Potentilla fruticosa Scrub
14. Cotoneaster - Rosa - Berberis Scrub
15. Juniperus pingii var. wilsonii Scrub
16. Juniperus indica Scrub
17. Juniperus Scrub in Kobresia Pastures
18. Arid valley Scrub
18b. Sophora moorcroftiana / Ceratostigma scrub
18c. Rabdosia / Caryopteris forrestii scrub
DTM of Potential Forest Distribution of the Yamco Yumco catchment
Cultivation:
Irrigated farmland with barley and wheat
Glaciers
Lakes
0 50 100km
N
The presentation of international boundaries should not be considered authorative.
TAJIKISTAN
KYRGYZSTAN
Xinjiang
Gansu
Inner Mo.
AFGH.
PAKISTAN
C H I N A
Qinghai
Xizang
Sichuan
INDIA
NEPAL
BHUTAN
MYAN-MAR
Yunnan
500 km

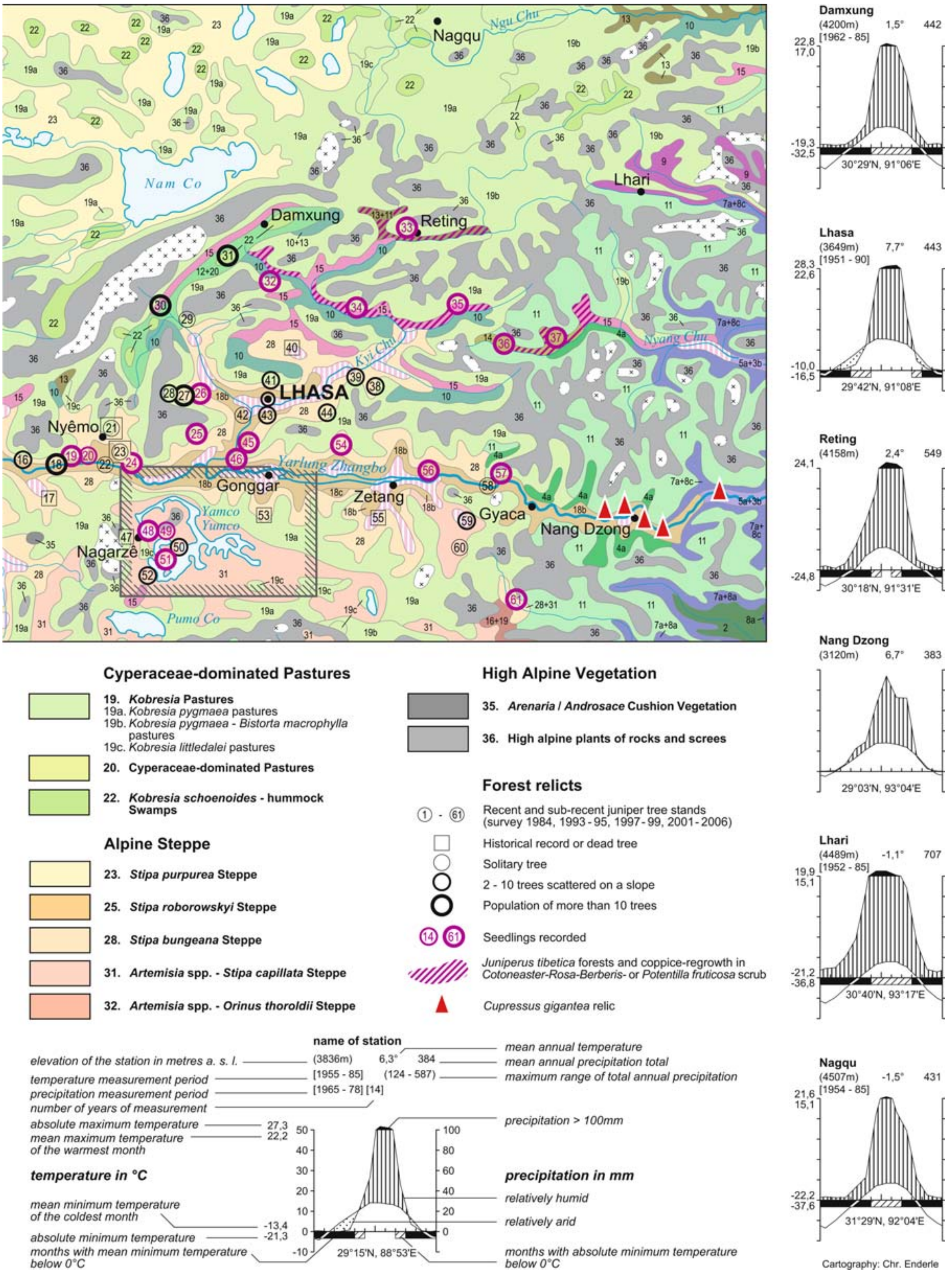


Fig. 2 continued

surfaces are sealed by Hepaticae *(Riccia)* or Pottiaceae and Cyanophyceae or the rosettes and carpets of *Selaginella* spp.

The ''Vegetation of Xizang'' (Zhang 1988) describes a larger number of vegetation units named after dominant species (see Fig. 2). The vegetation units roughly described here are mostly found on southerly exposures. Despite the existence of a few records of *Juniperus* on north-facing cliffs surrounded by dwarf thickets of rhododendrons, *Juniperus* of Tibet are primarily bound to sunny slopes.

Most of the relictual tree stands of our inventory are located in open dwarf shrublands of *Sophora moorcroftiana*. These heathlands dominate the river terraces and the colluvial soils of the lower slopes. They are regularly cut for tinder and resprout from the base. These shrublands are in the daily range of goats and sheep using the nearest pastures around the settlements. Annual grazing weeds (Chenopodiaceae, Polygonaceae, Boraginaceae) are common and the total plant cover rarely exceeds 50%. As soon as grazing is excluded, recovery takes place, starting with grasses; within a few years the plant cover reaches 100% (Miehe et al. 2004).

The second largest pasture type is widespread in intramontane basins of Southern Tibet mostly in altitudes above 4,000 m. Various *Artemisia* spp. are dominant, first of all *Artemisia santolinifolia*; in more strongly degraded sites annual *Artemisia* spp. prevail. The most common grasses are *Stipa* spp. Even in altitudes well below the upper treeline cushion plants of alpine origin like *Androsace tapete* Maxim. and *Arenaria kansuensis* Maxim. occur. Open dwarf shrublands of *Potentilla fruticosa* L., *Berberis* spp., *Rosa* spp. and *Cotoneaster* spp. are mostly found on slopes beyond the radius of easy fuel wood gathering or around monasteries where fuel wood eradication is sometimes forbidden. They are mostly confined to steep, rocky slopes, likely owing to the more difficult access. *Potentilla fruticosa* however colonizes open soil patches as does *Juniperus*. The flora of these shrubberies is nearest to that of *Juniperus* forest relicts and they probably represent an early degradation type. This is as well the case where only shrubby *Juniperus pingii* W.C. Cheng ex Ferré v. *wilsonii* (Rehder) Silba are left and the *Juniperus* trees had been cut and removed. These are the only current remains of larger *Juniperus* resources in Southern Tibet. They are rapidly vanishing. Where they are accessible along roads they have been eradicated, carried away with vans to Lhasa and sold at night.

The *Kobresia* pastures of the study area are the southwestern extension of the largest pasture type of the southeastern half of the Tibetan Plateau. They are still believed to be an alpine vegetation formation (Zhang 1988; Yu et al. 2001; Song et al. 2004). Their successional status is unclear because open soil patches surrounded by the felty turf of *Kobresia pygmaea* (C.B. Clarke) C.B. Clarke are colonized by *Juniperus* groves up to 4650 m. However, *Juniperus* never establishes directly in the *Kobresia pygmaea* pastures but only where the sods have been removed through chafing of yaks, soil-dwelling pika or marmots, rockfall, slope movements or gelifluction (Miehe et al. 1998).

Summing up, there is a wide range of pasture types in Southern Tibet over 1,600 m in altitude where *Juniperus* trees can be found.

Unlike *Juniperus communis* L. in European heathlands, the *Juniperus* of Tibet do not profit from uncontrolled grazing even they are not intentionally browsed. The worst grazing impact affects the seedlings by trampling and grazing of yaks, which do not graze selectively as do sheep or goats. As the southern exposures in altitudes below 4,800 m are the best winter pastures and the nearest to settlements, the grazing impact is strongest during winter.

Material and methods

Plant names are given according to ''Flora Xizangica'' (Wu 1983–1987); the taxonomy of Cupressaceae follows Farjon (2005).

Vegetation surveys undertaken in Southern Tibet since 1984 (Fig. 1) provided information about isolated *Juniperus* stands or potential *Juniperus* forest islands in currently treeless environments. The genus *Juniperus* includes mostly trees and a few caespitose phanerophytes such as *Juniperus communis* or *Juniperus sabina* L. The *Juniperus* of High Asia however show a very flexible growth habit and can grow as a shrub under adverse conditions or after disturbances (e.g., fire or logging). Thus along an altitudinal gradient there is a decline in height from several metres to a half a metre and a transition from a single-stemmed tree to a multi-stemmed tree merging into a globular bush of 2 m or less until the size of a dwarf shrub (0.5 m) is attained. These transitions are not unique but typical treelines (e.g., Miehe and Miehe 2000a) and therefore it is adequate to refer to ecotones rather than to distinct borderlines. In Tibet woodlands of globular bushes are widespread where tree stands had been destroyed by logging during the Cultural Revolution and now exhibit a coppice regrowth, which will lead to a forest of multi-stemmed trees. As timberline descriptions are often difficult to compare due to lack of precise information about size and growth form, the list in the appendix gives the height of the *Juniperus*, regrowth form and the diametre at breast height. In the strict sense a tree is a phanerophyte with a stem and a crown regardless the size, but it is admitted that trees shorter than one metre are very rare. As the life form is not defined by a quantity (e.g., ''smaller than 2 m: bush; larger than 2 m: tree'') it is not meaningful to communicate imprecise measures. To avoid misunderstandings the appendix gives life form and the height. The diversity of classification concepts of vegetation formations makes it necessary to premise that a forest consists of trees, although the anglophone world knows ''woodlands'' as a second tree formation. Most tree stands of Southern Tibet would refer to ''woodlands''. To avoid misunderstandings we only use the term ''forests'' because the present status of relictual trees makes it difficult to decide which crown cover degrees a recovered tree community would achieve.

Juniperus are sacred trees according to the beliefs of the local Buddhist population; the trees are worshipped religiously and are part of the national identity of Tibetans. Accordingly there is a common knowledge about tree stands and their fate in the past. Interviews were held with the help of English-speaking Tibetans. The interviews were semi-formal in the sense that they were opened with the specific questions about what the local informant knows about *Juniperus* in the area. In many cases the place of the (rebuilt) Buddhist temple (''gompa'') was the best spot to gain information about recent to sub-recent tree stands because most gompas had a sacred forest. The Tibetan language differentiates between *Juniperus* trees and coppice regrowth forming mostly a globular bush of one to two metres on one hand and dwarf-shrub *Juniperus* on the other hand. This is useful for identification of species: As there are only two *Juniperus* tree species west of 93°E (*Juniperus tibetica* and *Juniperus convallium*) information about sites must refer to one of these species, whereas information about dwarf shrubs refer to *Juniperus pingii* var. *wilsonii*.

In addition, written sources were evaluated. This includes travel journals of foreigners reporting about their travels in Tibet (e.g., the Japanese Buddhist monk Katoxitu in the 1920s; Peter Aufschnaiter in the late 1940s). Both sources were cross-checked by local informants. Information of the pundit Sarat Chandra Das (1902) could not be confirmed and was omitted. Information in Tibetan religious or historical literature was another valuable incidental source. Most of the texts had not been edited but relevant information was cited here as personal communication of tibetologists (e.g., Per Sörensen, University of Leipzig). So far, early evidence of *Juniperus* forests as derived from historical documents had been crossed-checked with the help of pollen analysis only in Lhasa (Schlütz in Miehe et al. 2006). In a few of the sites cited in Fig. 2 tree ring analysis had been carried out giving some information about the age of the oldest trees and climatic shifts (Bräuning 1999). Most of the recent sites had been checked in the course of vegetation records. Recorded parameters included GPS location, altitude (Thommen altimeter and/or maps), growth and structure (if forests), seed production, distribution of monoecy or dioecy, presence of seedlings or younger trees, drought damage, parasites (*Arceuthobium oxycedri* (DC.) M.Bieb.), grazing impact, and human interference (incense, fuel wood or timber extraction). In selected sites used as gene pools for nursery purposes, seeds where checked for vitality (Miehe et al. 2003). In 14 sites seedling data could not be obtained due to inaccessibility of the locality (e.g., rock walls, single trees in yards, remote slopes); where records rely on local informants only data about rejuvenation were not available (two sites).

The potential natural distribution of *Juniperus* (Fig. 6) was mapped using GRASS (Geographical Resources Analysis Support System) version 5.0.

Results and discussion

Inventories in the pastures of Southern Tibet since 1984 revealed more than 60 isolated sites of *Juniperus* trees in an environment, which has in the common consensus of the scientific community no potential for tree growth except on sites with water surplus such as floodplains with natural *Hippophae*- or *Salix* thickets. The inventory includes 13 locations where *Juniperus* trees or forests were known in the past from historical documents or oral tradition, but destroyed during warfare or during the Cultural Revolution. Out of the 51 locations of present-day tree stands 24 sites are forests covering an area of more than one square kilometre. Four sites cover an area between one and five ha. Around 14 sites have between two and ten trees; seven sites consist of only a single tree. The western-most trees of *Juniperus tibetica* to date were found 650 km west of the current forest border near Nang Dzong. The fact that *Juniperus* trees are adored as sacred trees in the believes of Buddhist Tibetans means that the local population knows every stand in the region as a religious landmark. Interviews revealed that these trees mapped in Fig. 2 (appendix: 2) are known to be the western-most in Southern Tibet. The altitude of these trees is 4850 m. They represent the highest tree stands of the northern hemisphere (Miehe et al., in review MRD). *Juniperus* in similar altitudes are rare and mostly only globular shrubs of half a metre can be found. In the Yamco Yumco basin all transect studies revealed a greater number of small individuals towards higher altitudes in parallel with linear decrease of growth height (see Fig. 5). It is uncertain if this reflects the impact of adverse growing conditions or an upslope shift of the forest line due to global warming. Tree ring analysis (Bräuning 1999) and evaluation of climatic data (Böhner 1996) however show a recent rise of temperatures in the area,although between 1961 and 2000 the potential evatranspiration has decreased (Chen et al. 2006). Yet it has to be considered that the treeline ecotone is less affected by grazing and trampling than the foot of the slopes, which are closer to settlements.

The northern-most tree records towards the alpine steppe of the Central Tibetan Highlands (‘‘Changtang’’) are situated on south-facing slopes of valleys bordering the Changtang (Fig. 2: 1, 15, 30–33) and on the eastern bank of the Tangra Yumco. So far there have been no records of trees or macrofossil remains such as determined charcoal in the Changtang.

All of the *Juniperus* species of High Asia are restricted to open sandy or rocky soils. They do not grow in humic, densely rooted soils of grasslands or Cyperaceae mats; sites with standing water are also avoided. They are found on all kinds of weathered bedrock, in limestone cliffs as well as between granite boulders or in slate screes. All records (except no. 42 and 58) cited in the appendix are not restricted to sites with a water surplus, nor do they exhibit a special preference for any favourable microclimatic conditions. Field evidence suggests that most tree stands occupy normal sites. Nursery experiments in Lhasa revealed that *Juniperus* develop very deep roots (1 year after germination seedlings of 3–5 cm height had tap-roots of 30–40 cm) and it can be assumed that old trees survive drought through their deep reaching roots. Thus the presence of native trees even in most exposed sites (Fig. 4) does not necessarily imply that young trees can establish today. Records of seedlings therefore are a pre-requisite for the conclusion that the juniper populations are vigorous and that the area where isolated trees had been recorded is potentially forested.

Out of the 51 present tree stands no seedling records have been obtained in 23 sites. From these 14 sites were not accessible (trees on remote slopes, in steep rock walls or yards); from two sites the local informants did not provide data about seedlings; in six sites no seedling data were recorded.

For the remaining 28 sites records on rejuvenation exist. In 23 out of these 28 sites seedlings could be traced. The majority of populations showing rejuvenation (20 out of 23—see Table 1) belong to size class 3 thus being made up of at least 10 trees. This is not surprising as it has been observed frequently that the germination rate of individual trees vary significantly thus the probability of a mother tree increases with population size apart from apparent effects of genetic drift in small populations.

It is striking that from the 25 populations with more then 10 trees for which regeneration records exist only the two northernmost populations (15, 31) bordering the Central Tibetan Highland of the Changtang do not show any signs of rejuvenation. Here it can be assumed that the conditions of establishment of young trees are unfavourable in the moment due to climatic reasons and due to strong grazing pressure.

The other three cases where a total absence of current rejuvenation is confirmed are solitary trees extremely exposed to trampling and grazing. In the

Table 1 Rejuvenation in present juniper stands of Southern Tibet

No[a]	Location	Elevation	Species	Size class[b]	Rejuvenation
Populations with rejuvenation					*23*
8	29°09′ N/87°09′ E,	4,250–4,650 m	*J. tibetica*	3	Seedlings
11	29°06′ N/87°57′ E	4,300–4,750 m	*J. tibetica*	3	Seedlings
14	28°21′ N/88°42′ E	3,980 m	*J. convallium*	2	Seedlings
19	29°20′ N/89°57′ E	3,980–4,850	*J. convallium, J. tibetica*	3	Seedlings
20	29°22′ N/90°09′ E	4,080 m	*J. convallium*	2	Seedlings
24	29°20′ N/90°21′ E	4,350–4,500 m	*J. tibetica*	3	Seedlings
25	29°28′ N/90°43′ E	4,100–4,300 m	*J. tibetica*	3	Seedlings
26	29°45′ N/90°41′ E	4,340–4,450 m	*J. tibetica*	3	Seedlings
32	30°15′ N/91°17′ E	4,100 m	*J. tibetica*	3	Seedlings
33	30°18′ N/91°31′ E	4,200–4,860 m	*J. tibetica*	3	Seedlings
34	30°05′ N/91°33′ E	4,000–4,800 m	*J. tibetica*	3	Seedlings
35	30°00′ N/92°02′ E	4,300–4,600 m	*J. tibetica*	3	Seedlings
36	29°54′ N/92°27′ E	4,470 m	*J. tibetica*	3	Seedlings
37	29°57′ N/92°51′ E	4,600 m	*J. tibetica*	3	Seedlings
45	29°27′ N/91°01′ E	4,300–4,480 m	*J. tibetica*	3	Seedlings
46	29°22′ N/90°53′ E	3,600–4,200 m	*J. convallium*	3	Seedlings
48	28°59′ N/90°26′ E	4,400–4,650 m	*J. tibetica*	3	Seedlings
49	28°59′ N/90°28′ E	4,450–4,550 m	*J. tibetica*	2	Seedlings
51	28°47′ N/90°30′ E	4,450–4,850 m	*J. tibetica*	3	Seedlings
54	29°22′ N/91°32′ E	4,070–4,600 m	*J. tibetica*	3	Seedlings
56	29°16′ N/91°57′ E	3,650–4,600 m	*J. convallium, J. tibetica*	3	Seedlings
57	29°18′ N/92°08′ E	3,800–4,770 m	*J. tibetica*	3	Seedlings
61	28°36′ N/92°32′ E	4,070 m	*J. tibetica*	3	Seedlings
Populations without rejuvenation					*5*
15	30°03′ N/89°06′ E	4,410–4,470 m	*J. tibetica*	3	No seedlings
31	30°23′ N/90°54′ E	4,250–4,300 m	*J. tibetica*	3	No seedlings
42	29°38′ N/91°00′ E	3,640 m	*J. tibetica*	1	No seedlings
58	29°14′ N/92°00′ E	3,560 m	*J. convallium*	1	No seedlings
60	29°02′ N/92°12′ E	4,150 m	*J. tibetica*	1	No seedlings
Populations with no rejuvenation data[c]					*23*
1	31°06′ N/86°48′ E	4,590 m	*J.* spec.	1	No data
2	29°14′ N/86°15′ E	4,850 m	*J. tibetica*	2	No data
3	29°12′ N/86°16′ E	4,850 m	*J. tibetica*	2	No data
4	29°93′ N/86°18′ E	4,200–4,600	*J. tibetica*	3	No data
7	29°09′ N/86°55′ E	4,350	*J. tibetica*	1	No data
9	29°19′ N/87°23′ E	4,440–4,600 m	*J. tibetica*	3	No data
16	29°18′ N/89°44′ E	4,200 m	*J.* spec.	2	No data
18	29°19′ N/89°56′ E	3,820–4,000 m	*J. convallium*	3	No data
21	29°24′ N/90°10′ E	3,850 m	*J. convallium*	1	No data
22	29°20′ N/94°14′ E	3,720 m	*J. convallium*	1	No data
23	29°22′ N/90°20′ E	4,080 m	*J. tibetica*	1	No data
27	29°44′ N/90°42′ E	4,050–4,400 m	*J. tibetica*	3	No data
28	29°44′ N/90°44′ E	4,500–4,700 m	*J. tibetica*	2	No data
29	30°03′ N/90°35′ E	4,300 m	*J. tibetica*	1	No data

Table 1 continued

No[a]	Location	Elevation	Species	Size class[b]	Rejuvenation
30	29°50′ N/90°21′ E	4,300 m	*J.* spec.	3	No data
38	29°42′ N/91°40′ E	4,200 m	*J. tibetica*	2	No data
39	29°53′ N/92°20′ E	4,050 m	*J.* spec.	2	No data
41	29°43′ N/91°07′ E	4,600 m	*J. tibetica, J. convallium*	2	No data
43	29°35′ N/91°07′ E	3,680 m	*J. convallium*	2	No data
44	29°33′ N/91°24′ E	4,200 m	*J. tibetica*	2	No data
50	28°58′ N/90°35′ E	4,500–4,600 m	*J. tibetica*	2	No data
52	28°52′ N/90°22′ E	4,400–4,600 m	*J. tibetica*	2	No data
59	29°04′ N/92°10′ E	3,0900 m	*J. tibetica*	2	No data
Population total					*51*

[a] No. refers to the number of the population description in the Appendix. They are grouped geographically—No.1 being the westernmost population and No.61 the easternmost

[b] Size Classes used: class 1 refers to a solitary tree, class 2 refers to 2–10 trees scattered on a slope, class 3 refers to a population of more then 10 trees

[c] Population with no rejuvenation data: the sites were not accessible or data could not be obtained

case of site 42 we may additionally assume that the female tree is too old to produce fertile seeds.

The 23 populations with rejuvenation are distributed almost over the entire remaining range regardless of the longitude and thus despite the westwards decreasing rainfall.

However young trees (approx. 5–20 years) are extremely rare and most stands seemed overaged. Some populations show great changes in fructification others are constantly extremely rich. The discrepancy of luxuriantly fruiting trees and the scarceness of seedlings is striking. This phenomenon has been observed in other juniper species worldwide but is not yet well understood (e.g., *Juniperus communis* in Germany, Michalczyk in prep.; *Juniperus sabina* in the Gobi Altay of Southern Mongolia, Wesche et al. 2005). Both, the fertility of the embryos as investigated through tetrazolium tests (less then 3% of the embryos investigated in the Reting Forest were fertile, Opgenoorth unpublished data) as well as germination rates are generally low, especially in the largest and overaged forests (seeds from Reting have germination rates of 1%, Meng unpublished data). Even after exclosure of livestock in Reting Forest only very few mother trees had seedlings and only few seedlings survive the first winter. As dead seedlings could not be found, it is assumed that hares, pika, mice and scratching birds extinguish the seedlings. In all other tree stands seedlings only were detected in safe sites (e.g., between boulders or at cliffs, in the shelter of thorny shrubs). As *Juniperus* is bound to southern exposures and those sunny slopes are the winter pastures, grazing pressure is extreme leaving only safe sites for rejuvenation. Thus the effect of low germination rate of overaged trees and the scarceness of safe sites lead to an extremely poor regeneration. As the junipers of Tibet reach an age of 800 and more years (Bräuning 1999) very few establishing events are needed for the survival of the forests.

In addition, tree ring analysis even of the drier sites (appendix: 48) shows no specific borderline symptoms (Bräuning 1999). The final proof that isolated tree stands show a forest potential is provided by a successful reforestation trial with *Juniperus convallium, Juniperus tibetica* and *Cupressus gigantea* W.C. Cheng & L.K. Fu on exclosure plots of southern slopes above Lhasa where *Juniperus* and *Cupressus* have grown since 1999 without irrigation (Miehe et al. 2003).

Most *Juniperus* relicts cited in our inventory are located on southern exposures. There are however exceptions which permit one to draw various scenarios of the potential altitudinal forest belts in Southern Tibet, as given in Fig. 3. Furthermore, by comparing all *Juniperus* sites in Southern Tibet along a humidity

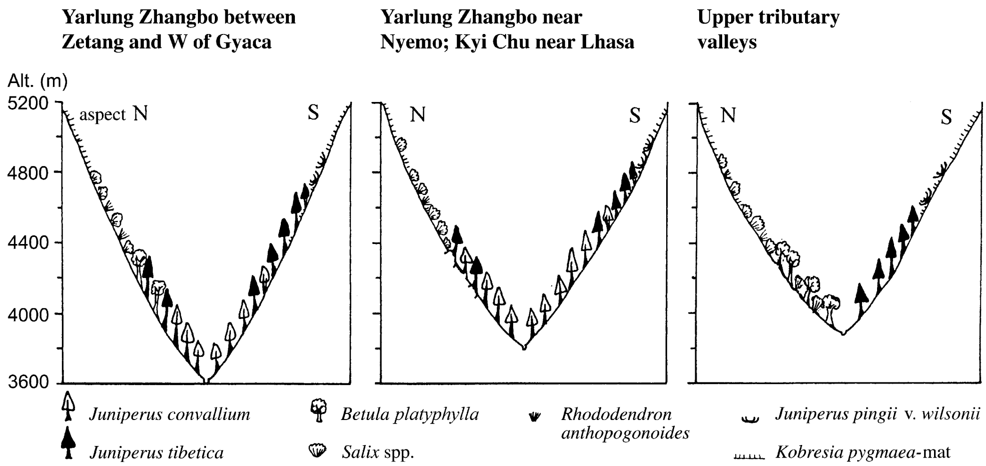


Fig. 3 Natural altitudinal forest belt types of Southern Tibet derived from isolated tree stands and vegetation records. The sketch only shows the dominant species. Draft S Miehe et al. (2002)

gradient starting in the southwestern-most arid locations (appendix: 6, 7, 50, 51) towards the humid *Picea*- and *Abies*-forests of southeastern Tibet we are able to apply principal ecological laws of plant ecology: In the arid locations *Juniperus* grow on all exposures including open slopes of strictly northern exposure. Along with increasing humidity the number of phanerophytic species increases and *Juniperus* are only found on sunny exposures, leaving shady slopes to *Betula* forests with *Rhododendron* thickets in the understorey or at the treeline ecotone. In such areas, *Juniperus* are only found on exposed cliffs (appendix: 37). Farther to the southeast, where spruce and fir forests cover all slopes, *Juniperus* are rare and restricted to south-facing cliffs. The gradual change of biotope is consistent with the ''ecological law of relative habitat constancy and changing biotope'' (Walter and Walter 1953; Miehe 1986).

The two *Juniperus* tree species of Southern Tibet show a distinct distribution. *Juniperus convallium*, which was so far not known from Southern Tibet (Wu 1983) is found in the Yarlung Zhangbo valley between 93°E and 88°42′ E and in the lower Kyi Chu valley south of Lhasa. Only two of the surveyed sites cover several hectares and deserve to be called forest (appendix: 46, 57). *Juniperus convallium* is found on all exposures in these wide valleys (see Fig. 3). *Juniperus* stands on northern exposures may attain interlocking crowns, while on all other sites tree cover percentages range between 10% and 60%. On shady slopes the highest *Juniperus convallium* trees were found at 4,000 m in the east (appendix: 57), increasing in elevation westwards with the concomitant decrease of humidity to 4,280 m (appendix: 19). On sunny slopes *Juniperus convallium* ascends slightly higher and is found up to 4,200 m in the east (appendix: 57) and 4,580 m in the West (appendix: 19). The highest record so far is in the northern outskirts of Lhasa at 4,600 m on a steep, south-facing granite cliff (appendix: 41). The range of *Juniperus convallium* thus covers 400 km in an altitudinal belt between valley bottom (3,600–4,000 m) and 4,600 m.

Juniperus tibetica has a slightly greater distribution. This tree generally forms the upper tree line and is present in the more humid side valleys where it is obviously too cold for *Juniperus convallium* (see Fig. 3). The species is found primarily on sunny slopes, except where it occurs on steep, north-facing cliffs emerging from *Rhododendron*-*Salix* thickets.

The drought limit of *Juniperus* trees is difficult to assess. Lhaze (Fig. 2) has 263 mm summer rainfall and the last trees close to the climate station were destroyed during Cultural Revolution (appendix: 10). The nearest living *Juniperus* trees are *Juniperus tibetica* (appendix: 6–9, 11). The closely related *Juniperus indica* in arid environments of North Central Nepal, 320 km to the west of Lhaze, are found near climate stations with 200–250 mm rainfall (Miehe et al. 2002). These values compare well with reports of *Juniperus* woodlands in southeastern Spain (Freitag 1972) or the La Sal Mountains of Oregon

(Henning 1975). It is thus an open question whether the reforestation trials carried out in Lhasa (443 mm/a) would be successful further west. However there are seedlings and young trees found in the localities west of Lhaze showing clearly the vitality of the forests. From field evidence it seems implausible that the western *Juniperus* populations would regenerate into closed forests if firewood or incense extraction could be excluded. The tree stands, which survived so far in the west, suggest open forests with a crown cover between 10% and 30%. The most arid stands are heavily infested by mistletoe-like parasites (*Arceuthobium oxycedri*). Whether this is due to adverse climatic conditions or additional factors is not known.

The altitudinal range of *Juniperus* trees comprises vegetation units of the ''Vegetation of Xizang'' which had been translated according to the UNESCO classification (Mueller-Dombois and Ellenberg 1974) as ''scrub'', ''Cyperaceae-dominated pastures'' and ''alpine steppe''. The presence of trees in vegetation units classified as ''alpine'' is somewhat contradictary because ''alpine'' is by definition beyond the upper treeline and treeless due to growing conditions hostile for trees. The issue of forest islands in Tibet resembles the ''*Polylepis* problem'' in tropical alpine Paramo grassland of the Andes (Miehe and Miehe 1994; Kessler 2002). Considering the possible succession between the forest islands and the surrounding pasture types there is a clear divide between the stands in open dwarf shrublands (Fig. 2: vegetation units 12b, 12c, 13, 14, 18, 28, 32), on the one hand, and *Juniperus* groves on open soil patches surrounded by a closed cover of felty turf build of *Kobresia pygmaea*, on the other (Fig. 2: vegetation units 2–53, except 28, 30–32, see Figs. 4, 5). *Juniperus* stands in dwarf shrublands are common along the Yarlung Zhangbo and in the lower Kyi Chu. Figs. 4 and 5 show the quasi-erratic trees in desert-like commons. Taken together, the exclosure experiments near Lhasa, the field evidence of seedlings

Fig. 5 Upper treeline ecotone at 4,850 m with multi-stemmed trees of *Juniperus tibetica* on the southern Yamco Yumco peninsula (28°54′ N/90°34′ E, Fig. 2: 51), southern exposure. August 1998. Photo G Miehe

and *Juniperus* trees in the bird-dependent dispersal range of mother trees, and vegetation records in relict sites all reveal the potential of *Juniperus* forests with *Prunus mira* Koehne and *Buddleja crispa* as understorey trees and a larger number of shrubs and grasses. Pollen analysis close to the sites where reforestation trials were established provide evidence of *Juniperus* forests around Lhasa which were cleared around 4,600 yr BP and replaced by the current *Artemisia*-dominated pastures for the last 600 yr (Miehe et al. 2006). Thus the *Sophora moorcroftiana* heathlands of the Yarlung Zhangbo (Fig. 2: 18b), the *Stipa bungeana* steppe and the *Artemisia-Stipa capillata* steppe (Fig. 2: 28, 32) once were forests (or woodlands) and could be forest again because there are isolated tree stands on normal sites, including seedlings and young trees. These scenarios are given on the Digital Terrain Model of the Yamco Yumco basin (Fig. 6). The mapped area has a forest potential of 2,628 km^2 which is 22.4% of the total area of 11,730 km^2.

In the east (appendix: 32–37), especially in the headwaters of valleys of the eastern declivity of the

Fig. 4 Isolated *Juniperus tibetica* tree of 3 m height, south of the Yarlung Zhangbo (29°09′ N/86°55′ E, Fig. 2: 7), 4,350 m on a southeast-facing ridge. This is a windward water deficit site near the drought line of *Juniperus*. March 1998. Photo G Miehe

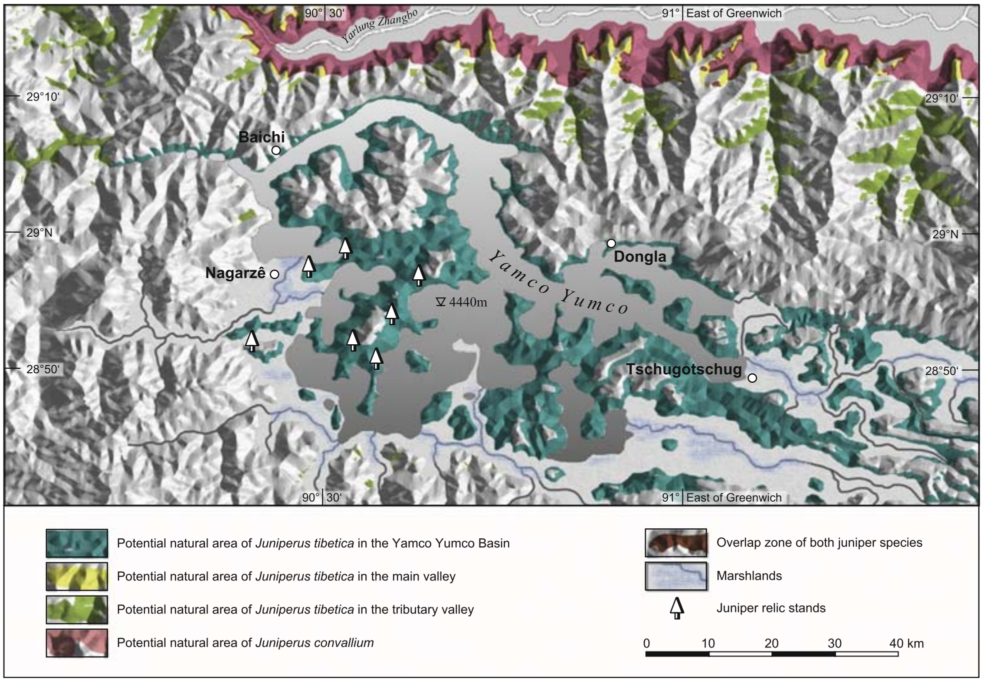


Fig. 6 Digital Terrain Modell of the Yamco Yumco Basin with potential natural *Juniperus* forests. The total surface is 11,730 km^2, the forest potential area is 2,628 km^2 (22.4%). Based on the *Juniperus* inventory, vegetation records, indicator values of plants, precipitation records and weather observations three types of potential *Juniperus* forests are designated: (1) the intramontane basin of the Yamco Yumco is assumed to have *Juniperus tibetica* forests in all exposures between 4,400 and 4,850 m; (2) in the Yarlung Zhangbo valley *Juniperus convallium* forests are mapped in all exposures up to 4,000 m; (3) this zone is followed by *Juniperus tibetica* to the upper treeline (4,600 m). Side valleys have only *Juniperus tibetica* forests. Draft M Will 2002. Software: GRASS (GIS, Microsoft Excel 1997)

Tibetan Plateau (Lhari, Fig. 7), the successional status is complex. The humidity is more than two times higher than in the western margin of an assumed *Juniperus* forest belt (Fig. 2: Lhari 707 mm/a), and *Juniperus* groves are distributed only spottily where the *Kobresia pygmaea* turf has been destroyed. The turf is part of the world's largest alpine ecosystem, covering ca. 450,000 km^2 in the south-eastern humid quarter of the Tibetan highlands (Miehe and Miehe 2000b). Exclosure experiments in Reting (appendix: 33, Miehe et al. 2004) have posed even more questions: Reting Forest, the largest and most sacred *Juniperus* forest of Tibet, has trees of 2 m dbh and 16 m in height, diffusely growing in a carpet-like felty turf of *Kobresia pygmaea*, the female trees surrounded by open soil. The forest is mentioned in the earliest documents of the monastery founded here in 1057 AD (P. Sörensen, pers. comm.); rejuvenation is poor most probably due to the low germination rate because trees are overmature. The *Kobresia pygmaea* mats are grazed yearround by yak but the grazing pressure is highest during winter. Two exclosure plots in those *Kobresia pygmaea* pastures revealed a total change from a Cyperaceae-dominated pasture resembling a golf course to a 50 cm tall *Stipa*

Fig. 7 South-facing *Juniperus tibetica* trees in the upper treeline ecotone (4,500 m) colonizing open soil patches in the felty turf of *Kobresia pygmaea* pastures of southeastern Tibet. East of Lhari, 30°38′ N/93°18′ E. July 2004. Photo G Miehe

grassland in only 4 yr time. Thus the relationship between the *Juniperus* trees and the Cyperaceae mats or grasslands is unknown. As *Kobresia pygmaea* has an altitudinal range reaching nearly 6,000 m a.s.l. (Miehe 1989) it is certainly less temperature demanding than *Juniperus* trees. It is therefore easy to assume that *Kobresia pygmaea* spread to cover the highlands with the present green golf course-like turf earlier than we could expect the re-migration of trees. In addition, *Kobresia pygmaea* establishes more readily and is wind dispersed, unlike *Juniperus*, which probably disperse more slowly because it is dispersed by birds (*Turdus merula*, *Babax Waddelli* Dresser; M. Karlstetter, pers. comm.). It is thus possible that *Kobresia pygmaea* turfs impeded the reforestation. The recent forest outposts of Reting and Lhari (see Fig. 6) have an upper treeline ecotone between 4,600 and 4,860 m. This raises the question why the *Kobresia*-covered highland pastures around Nagqu, with altitudes of 4,400–4700 m, are treeless. Rainfall (Nagqu 431 mm/a) would permit the development of forests and there are enough open sites where the *Kobresia pygmaea* turf has been destroyed. The explanation could be that winter temperatures are too cold for *Juniperus tibetica*: the Changtang, where Nagqu is situated, is exposed to catastrophic intrusions of cold air masses of the Siberian High during winter in contrast to the forest of Reting and Lhari which spread well above the cold air ponding effects of the tongue basins of those valleys (where the climate stations are situated). Moreover they are sheltered from cold air masses by mountain ranges toward the North.

Conclusion

Isolated *Juniperus* trees or forest islands in the pastoral desert environments of Southern Tibet are religious landmarks for Tibetan Buddhists. They are worshipped and protected. During the Cultural Revolution, many sacred trees were removed. Up until now, the natural resource potential of these forests has gone unrecognized in the scientific community. Vegetation surveys since 1984 have revealed more than 50 sites with vigorous *Juniperus* trees, which are not limited by water surplus, or any other obvious habitat factor. Additionally 13 sites are known from historical documents or are cited according to oral tradition that trees were destroyed during warfare or during the Cultural Revolution. The forest relicts are mostly dominated by a single tree species. Two *Juniperus* tree species have been found. *Juniperus convallium* is so far not known to occur in Southern Tibet but is present in an area of 400 km west of the current forest limits. The second tree species, *Juniperus tibetica*, stretches from the outer declivities of the Tibetan Plateau up to an area 650 km west of the present forest border. It is concluded that treeless areas between the current relicts were forested in the past and could become forested again if human interference were excluded. To prove this assumption experimental reforestation trials on southern slopes above Lhasa have been carried out since 1999 with non-irrigated plantations of nursery-raised seedlings of *Juniperus convallium, Juniperus tibetica* and *Cupressus gigantea*. Sampling after three years indicated survival rates of nearly 100%. The highest trees of *Juniperus tibetica* were found at an elevation of 4,860 m. Except the trees growing in rockwalls all relict stands are heavily grazed and seedlings or young trees survive only where grazing and trampling is light. A correlation with tree stands and rainfall data of the nearest climate stations reveal that the drought line of *Juniperus* forests in Southern Tibet is approximately 200–250 mm/a. Vegetation records allow the reconstruction of three potential forest types (see Fig. 3). Under more arid conditions, even northern exposures have *Juniperus* forests but in general *Juniperus* are found on southern exposures. In the eastern part of the distribution area and in the cloudy cooler side valleys, *Betula* forests form the upper treeline ecotone of the shady slope, or at least have the potential to do so. As *Betula* is heavily browsed, the reconstruction of the natural range of *Betula* forests is even more difficult than *Juniperus* because there are very few remaining relicts. The first pollen diagram from the area (Schlütz in Miehe et al. 2006) dates human use, at least for the area of Lhasa, to as early as 4,600 yr BP: Pollen of ruderal weeds and cereals indicative of human use are synchronous with the decline of *Juniperus* pollen. Human impact increased during the last 600 years, supporting the evolution of the present degraded pastures.

It remains unknown when forests began to spread following the Last Glacial Maximum, and from where. Altitudes, relief and current climatic conditions make it most probable that the lower Yarlung Zhangbo valley downstream of 93°E is the nearest forest refugium.

In more humid Eastern Tibet, *Juniperus* are strictly bound to open soil patches surrounded by a dense, felty Cyperaceae mat of *Kobresia pygmaea*. It is unknown whether *Juniperus* colonize the open soil patches after the removal of the felty turf or whether the *Kobresia pygmaea* pastures colonized space that had been cleared from forests. It cannot be excluded that this turf cover impeded the re-migration of forests to the plateau in the early Holocene.

Most of the forests are protected for religious reasons, and since 2002 have acquired the official status of protected area (under the responsibility of the Forestry Bureau of the Xizang Autonomous Region). Despite this, they are prone to extinction due to lack of regeneration stemming from low viability of the embryos, low germination rates, genetic drift following fragmentation and due to grazing and trampling impacts. Timber extraction or fire wood use and in some sites even incense collecting is now banned and widely obeyed. All isolated *Juniperus* sites of Southern Tibet are threatened; this is especially true of the few populations of *Juniperus convallium* and the western-most outposts of *Juniperus tibetica*. The IUCN information about the status as given in Farjon (2005) is misleading.

As the lack of fire wood is a severe limitation of rural economy in Southern Tibet, it is necessary to introduce forest rehabilitation measures with indigenous forest species that do not depend on the decreasing supply of irrigation water (Miehe et al. 2003). The current inventory could be used as a data base for GIS modelling of potential reforestation areas which are currently not believed to have natural forests.

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Appendix

1. Tangra Yumco-basin, 30°30′–31°30′ N/86°20′–86°50′ E, 4.500–4.800 m: According to local oral tradition (Nam Thag, Sheshik gompa, pers. comm., Sept. 9th 2003) the *Juniperus* forests of the lake basin were destroyed by fire during warfare ca 650 AD. Actually no remains, except of two *Juniperus* trees on the eastern bank of the lake at Kisum (31°06′ N/86°48′ E, 4,590 m), ca. 2.5 m, single-stemmed, 0.4 m Dbh (Dorgeh, pers. comm., April 6th 2006). No *Juniperus pingii* v. *wilsonii*. No seedling data.
2. Langma Chu near Tagtse, 29°14′ N/86°15′ E, 4,850 m, S-exp.: *Juniperus tibetica*, ♂ and ♀,30 cm Dbh, 3.5 m. Sacred. Known as westernmost *Juniperus*-tree along the Yarlung Zhangbo. More multi-stemmed individuals 0.8–2 m on the same slope. No seedling data.
3. Cliffs of the Yarlung Zhangbo gorge East of Tagtse, 29°12′ N/86°16′ E, 4,850 m, S-exp.: 6 *Juniperus tibetica* ♂ and ♀, 0.6–2 m, multi-stemmed, partly lopped. No seedling data.
4. Semik. Cliffs of the Yarlung Zhangbo gorge between Tagtse and Chung Riwoqe, 29°93′ N/86°18′ E, 4,200–4,600 m, S-exp.: *Juniperus tibetica* trees in steep rocks. Exploited for incense from villagers of Tagtse and Chung Riwoqe. No seedling data.
5. Chung Riwoqe, 29°11′ N/86°36′ E, 4,180 m: *Juniperus*-forests according to the pilgrimage record of Katoxitu of 1920 (K.H. Everding, pers. comm., 1997). Actually no remains.
6. Lheding, 29°13′ N/86°52′ E, 4300–4950 m, W-S-E-exp.: above the gompa and on neighboring slopes: *Juniperus tibetica* ♂ and ♀, open forest, multi-stemmed, to 3.5 m; at the upper limit gradually dwarf (0.5 m) with *Juniperus pingii* v. *wilsonii*. Seedlings.
7. South bank of the Yarlung Zhangbo East of Dobe, 29°09′ N/86°55′ E, 4,350 m, SE-exp. on ridge: solitary *Juniperus tibetica* tree, ca. 3 m (see Fig. 4). No seedling data.
8. Yarlung Zhangbo gorge between 87°07′ and 87°12′ E, 4,100–4,650 m, on both banks of the river, but mostly on sunny exposures of the northern bank. Best preserved tree stands around the ruins of Chugdö gompa (29°09′ N/87°09′ E, 4,250–4,650 m): *Juniperus tibetica*, ♂ and ♀,

multi-stemmed, 6 m. Mostly resprouting globular bushes 2–3 m. Seedlings.

9. Limestone scree slope above La'ang Co, 29°19′ N/87°23′ E, 4,440–4,600 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, several multi-stemmed lopped bushes up to 2.5 m in *Lonicera-Rosa* thickets. Several stunted dwarf *Juniperus* trees on inaccessible rock-walls. No seedling data.
10. Kjelde near Lhaze: Northern bank of the Yarlung Zhangbo, 29°08′ N/87°35′ E, 4,034 m, S-exp.: Single *Juniperus* tree, close to the destroyed Tachung gompa, blasted and eradicated 1959, according to local informant (Sept. 18th 2003).
11. Sim Gompa, 29°06′ N/87°57′ E Gr., 4,300–4,750 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, 5 m, max. 0.4 m Dbh. Open forest and resprouting bushes. Seedlings. Largely depleted for road construction purposes around 1970 (according to local informants, Sept. 18th, 2003).
12. Sakya monastery, 28°54′ N/88°01′ E, 4,350 m, S-exp.: Several *Juniperus* trees destroyed during the Cultural Revolution (according to local informants, August 30th, 2005).
13. Intramontane basin of Zhetongmen, 29°23′ N/88°10′ E, 4,020 m, S-exp.: At Entsang several *Juniperus* trees were destroyed with the gompa during Cultural Revolution (local informant, August 30th, 2005).
14. Northern bank of the Yarlung Zhangbo,east of Xigaze, above Tuge, 28°21′ N/88°42′E, 3,980 m, S-exposed on granite crest 80 m above the floodplain: Westernmost record of *Juniperus convallium*, 3 monocious trees 4–6 m, single and multi-stemmed, max. 0.5 m Dbh. Seedlings, no drought damages. Remains of a sacred forest of more than 100 trees, largely destroyed during Cultural Revolution (according to local informant, August 31st˙, 2005).
15. Rindu, North of Namling, 30°03′ N/89°06′ E, 4,410–4,470 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, 2.5–4 m, open forest and resprouting bushes, young trees. No seedlings. Known as the northernmost *Juniperus* trees in this valley.
16. Northern bank of the Yarlung Zhangbo gorge near Tschewa, 29°18′ N/89°44′ E, ca. 4,200 m, NW-exp.: Several solitary *Juniperus* trees (4–8 m), at least partly religiously preserved. No seedling data.
17. Rimphu-valley, 29°12′ N/89°52′ E, 3,970 m: *Juniperus tibetica*, 8 m, 0.5 m Dbh. Dead tree in yard, 1995 crown damaged by storm. Local traditions tell about a *Juniperus* forest in the upper Rimphu valley, which was burnt (local informant, August 12th 1999).
18. Southern bank of the Yarlung Zhangbo gorge, 29°19′ N/89°56′ E, 3,820–4,000 m. Northern exposures: *Juniperus convallium*, ♂ and ♀, multi-stemmed trees 2–3 m, resprouting bushes and obviously young *Juniperus* (<0.5 m). Inaccessible rocky slopes have scattered stands of *Juniperus convallium* trees. No seedling data.
19. Southern (29°20′ N/89°57′ E) and northern (29°20′ N/89°59′ E) bank of the Yarlung Zhangbo gorge W of Nyemo: *Juniperus convallium* shrubs in leeward southern exposures until 4,580 m. Trees 6 m, 0.5 m Dbh, 3,980 m, S-exp. next to ruins of gompa. On the southern bank *Juniperus convallium* and *Juniperus tibetica* until 4,280 m; *Juniperus convallium* trees and shrubs only in easterly and westerly exposures, northerly facing stands only on very exposed rocky ridges. *Juniperus tibetica* only in northern exposures. *Juniperus tibetica* trees between 2 and 4 m, mostly multi-stemmed on sunny exposures between 4,500 and 4,850 m. Highest *Juniperus tibetica* tree of 4 m in 4,850 m. Seedlings on both banks.
20. Yarlung Zhangbo gorge West of Nyemo, 29°22′ N/90°09′ E, 4,080 m, SW-facing: 6 isolated *Juniperus convallium*, ♂ and ♀, 1.5–4 m, max. 0.3 m Dbh, known to locals as ''seven brothers''. Seedlings.
21. Nyemo, 29°24′ N/90°10′ E, 3,850 m, in the yard of a farmhouse: *Juniperus convallium*, 0.3 m Dbh, 6 m, brought as a small tree from the Yarlung Zhangbo gorge and planted in the yard. No seedling data. *Juniperus* groves with deer are reported from the upper Nyemo valley as late as in 1947 (fide Aufschnaiter in Brauen 1983).
22. Yarlung Zhangbo gorge East of Nyemo, 29°20′N/94°14′ E, 3,720 m; boulder of ca. 30 m^3 at the southern bank of the river: *Juniperus convallium* ca 1 m, growing on top of the boulder. No seedling data.

23. Tunda valley, 29°22′ N/90°20′ E, 4,080 m: *Juniperus tibetica*, 12 m, 0.3 m Dbh in a yard. Brought as a small tree from Loura. 29°24′ N/90°23′E, 4,350 m, S-exp.: Single *Juniperus* tree close to the gompa, destroyed by blasting during the Cultural Revolution. Tunda is famous for its incense products since 700 years. The main ingredient is *Juniperus* which was taken until 1984 totally from this valley. For the traditionally grounding technique in water mills logs need to have a diametre of at least 20 cm. No seedling data.
24. Loura: Northern tributary valley of the Yarlung Zhangbo gorge east of Tunda, 29°20′ N/90°21′ E, 4,350–4,500 m, SE-exp.: *Juniperus tibetica*, ♂ and ♀, single-stemmed trees up to 5 m and coppice regrowth or resprouting trees 2.5–4 m, juvenile specimens of 50 cm. Seedlings.
25. Above Chuba, 29°28′ N/90°43′ E, 4100–4300 m, all exposures: *Juniperus tibetica*, ♂ and ♀; single, mostly multi-stemmed trees and bushes, 1.5–3 m, in open woodlands. Seedlings.
26. Nienang monastery, 29°45′ N/90°41′ E, 4,340–4,450 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, 12 m, max. 0.4 Dbh, trees and resprouting bushes around the monastery. Seedlings.
27. Western tributary of the Tolung Chu, 29°44′ N/90°42–43′ E, 4,050–4,400 m, southern and eastern exposures: *Juniperus tibetica*, ♂ and ♀, 0.5–1 m, trees and resprouting bushes. No seedling data.
28. E of Tsurphu monastery N of 29°44′ N/90°44′ E, ca. 4,500–4,700 m relic trees on S-facing slopes: *Juniperus tibetica*. No seedling data.
29. Upper Tolung Chu near Yangpachen, 30°03′ N/90°35′ E, 4,300 m, S-exp.: *Juniperus tibetica*, tree, 3 m. No seedling data.
30. East of Yangpachen, 29°50′ N/90°21′ E, 4,300 m, SW-exp.: *Juniperus* grove was cut for military purposes in the 1960s and regenerates with coppice regrowth. No seedling data.
31. Nindung Xiang, 30°23′ N/90°54′ E, 4,250–4,300 m, southern exposures: *Juniperus tibetica*, ♂ and ♀, trees up to 3 m, max. 0.3 m Dbh. Open tree stands in scree of roche moutoneé, sacred forest depleted during Cultural Revolution. No seedlings.
32. Western branch of the upper Kyi Chu (Rong Chu) between 30°15′ N/91°17′ E and 30°20′ N/91°04′ E from the foot of the slope (4,100 m) to the crest in southerly exposures: Open *Juniperus tibetica* forests and coppice regrowth after timber extraction, with interlocking crowns in undisturbed sites under religious protection (Tsowa gompa, 30°16′ N/91°10′ E, above 4,150 m). Seedlings.
33. Upper Kyi Chu catchment between 30°15′–30°24′ N and 91°23–91°43′ E, 4,200–4,860 m, preferably in southern exposures, extending to rocky easterly and westerly facing slopes, even on exposed rock cliffs of northern exposures: *Juniperus tibetica*, ♂ and ♀, trees, up to 16 m, max. 2.5 m Dbh (in the sacred forest of Reting monastery, 30°18′ N/91°31′ E) and resprouting bushes in non-protected areas. Seedlings. Ludlow (1951) reports of deer, bears and leopards in great numbers in this forest.
34. Middle Kyi Chu catchment between 30°11′ N/91°21′ E and 30°00′ N/91°53′ E, 4,000–4,800 m, southern exposures: *Juniperus tibetica*; several sacred groves above villages and lopped bushes in the commons around the preserved groves. Largest groves above Barza gompa (30°05′ N/91°33′ E) and Shoten gompa (30°08′ N/91°33′ E). Seedlings.
35. Drigung in the eastern upper Kyi Chu catchment between 30°00′ N/92°02′ E and 30°06′ N/92°20′ E, 4,300–4,600 m; southern exposures: *Juniperus tibetica*, ♂ and ♀, up to 7 m, 0.3 m Dbh, scattered tree stands and lopped bushes. The sacred forest around Drigung monastery was destroyed during the Cultural Revolution. Resprouting multi-stemmed trees up to 2 m. Seedlings.
36. Upper Nyang Chu, 29°54′ N/92°27′ E, 4,470 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, up to 0.3 m Dbh, up to 3 m, open tree stands. Westernmost forest in the upper Nyang Chu catchment. Seedlings.
37. Northern bank of the Nyang Chu upstream of 29°57′ N/92°51′ E: *Juniperus tibetica*, ♂ and ♀, up to 7 m, up to 0.4 m Dbh. Numerous open forests on sunny slopes of winter pastures. On northern exposures confined to cliffs. Upper treeline ca. 4,600 m. Seedlings.
38. Gyama Chu, 29°42′ N/91°40′ E, 4,200 m: *Juniperus tibetica*, ♂ and ♀, 5 and 6 m, 0.3 m

Dbh, trees on hilltop and on SW-facing slope near gompa. No seedling data.

39. East bank of the Kyi Chu, Dako, 10 km NE of Meldro Gungkar, 29°53′ N/92°20′ E, 4.050 m: 2 *Juniperus*-trees. According to a local informant a greater number of trees were removed during Cultural Revolution. No seedling data.
40. Intramontane basin of Phempo: Sacred *Juniperus* trees and groves were destroyed together with the gompas during Cultural Revolution at Nalendra gompa (29°52′ N/91°07′ E, 3,900 m), and Ragme Jamkang (29°54′ N/91°02′ E, 4,000 m), according to local informant, Sept. 4th, 2005.
41. Lhasa, above Porong Ka and Chupsang monastery, 29°43′ N/91°07′ E, ca. 4,600 m S-exp.: 3 *Juniperus tibetica* and *J. convallium* (1–3 m tree + shrub) in steep cliff. The foundation legend of Tashi Tsöling monastery (4,050 m, above Chupsang) says that the monastery was situated amongst *Juniperus* trees. The last individuals are said to be cut during Cultural Revolution (head of Tashi Tsöling monastery, pers. comm. 1997). Aufschnaiter (in Brauen 1983) mentions a large *Juniperus* tree trunc W of Sera monastery in the late 40's, obviously close to the locality of 41. No seedling data.
42. Tschalö, south of Lhasa, 29°38′ N/91°00′ E, 3,640 m: *Juniperus tibetica*, ♀, 15 m, 2 m Dbh, partly decayed, fenced and religiously worshipped. The tree most probably reaches the ground water in the gravel terrace of the Kyi Chu. No seedlings.
43. Eastern bank of the Kyi Chu, south of Lhasa, 29°35′ N/91°07′ E, 3,680 m, W-exp.: 2 *Juniperus convallium* trees in steep cliff. No seedling data. Nyima Thang (29°30′ N/91°07′ E, 3,900–4,200 m: Several *Juniperus tibetica* trees (12 m, up to 0.5 m Dbh), religiously protected. No seedling.
44. Upper Datse valley 29°33′ N/91°24′ E, 4,200 m S-exp.: *Juniperus tibetica* trees, 4 m, 0.2 m Dbh, trees near houses and in steep rock walls. No seedling data.
45. Chungse monastery, 29°27′ N/91°01′ E, 4,300–4,480 m, southern exposure: *Juniperus tibetica* ♂ and ♀, numerous caespitose resprouters from tree-stumps cut during Cultural Revolution around the monastery. Seedlings.
46. Chirong, 29°22′ N/90°53′ E, 3,600–4,200 m (crest), all exposures: *Juniperus convallium*, above 4,100 m in northern exposures *Juniperus tibetica*, ♂ and ♀, 5 m, up to 0.3 m Dbh. Open forest, best preserved above the village as sacred, partly cleared during Cultural Revolution. Seedlings. *Juniperus tibetica*, ♂ and ♀, single and multistemmed trees up to 0.3 m Dbh and 4 m on N-exposed slope above 3,900 m south of the village. Seedlings.
47. Nagarze, 28°58′ N/90°24′ E, 4,450 m, SE-exp.: Dead multi-stemmed *Juniperus* tree, 9 m, near to the gompa.
48. Tsamchü, 3 km east of Nagarze, 28°59′ N/90°26′ E, 4,400–4,650 m; ESE- to WNW-exposed: *Juniperus tibetica*, ♂ and ♀, open forest, single and multi-stemmed, max. 0.5 m Dbh, 3–6 m, at the upper limit gradually dwarf (highest caespitose *Juniperus tibetica* shrubs 0.3 m, 4,750 m). Largest sacred forest south of the Yarlung Zhangbo, partly cleared during Cultural Revolution. Seedlings.
49. Samding monastery, 6 km east of Nagarze, 28°59′ N/90°28′ E, 4,450–4,550 m: Several *Juniperus tibetica* trees below the monastery, 2–5 m, 0.2–0.4 m Dbh. Seedlings.
50. Atsha, central peninsula of the Yamco Yumco, 28°58′ N/90°35′ E, 4,500–4,600 m, on open ridge: Several lopped *Juniperus tibetica*-trees. No seedling data.
51. Southern peninsula of the Yamco Yumco, 28°47–50′ N/90°30–48′ E, 4,450–4,850 m, all exposures (even north!): *Juniperus tibetica* ♂ and ♀, single and multistemmed trees (up to 0.4 m Dbh, up to 4 m), open woodlands, upslope gradually caespitose with *Juniperus pingii*—shrubs (see Fig. 5). Seedlings in all exposures.
52. Hills north of Taglung, 28°52′ N/90°22′ E, 4,400–4,600 m, S- and SW-exp.: *Juniperus tibetica*, 0.5–3 m, trees and scattered resprouting bushes. No seedling data. In Taglung: *Juniperus tibetica*, multi-stemmed tree, 5 m, in yard.
53. Upper Drip Chu, 29°01′ N/91°05′ E, 4400 m, E-exp.: The last four *Juniperus* trees were destroyed during a landslide in 1999, according to local informants (Sept. 19th, 2002). It is commonly believed in the valley that in the unknown past there were *Juniperus* forests below Drip (north of 29°00′ N/91°05′ E).

54. Chimpu monastery above Samye, 29°22′ N/91°32′ E, 4,070–4,600 m, S-exp.: *Juniperus tibetica*, ♂ and ♀, trees max. 6 m, 0.4 m Dbh, resprouting bushes around the monastery. Seedlings.
55. Hills south of Zetang: During warfare of the 6th century AD. soldiers hid in (*Juniperus*) forests near Pyingiba. Forests were burnt down near Thangboche before the foundation of the monastery (11th century AD.) (P. Sörensen, pers. comm.).
56. Northern bank of the Yarlung Zhangbo above Pamtschü, 29°16′ N/91°57′ E, 3,650–4,600 m: *Juniperus convallium* ♂ and ♀, up to 4,100 m, where *Juniperus tibetica* continues up to the treeline at c. 4,600 m, ♂ and ♀. Trees of 0,4 m Dbh and up to 9 m only around the Densatil monastery (4,450 m). Seedlings.
57. Northern bank of the Yarlung Zhangbo above Halung, 29°18′ N/92°08′ E, 3,800–4,770 m, all exposures: *Juniperus convallium*, ♂ and ♀, lopped trees (up to 3 m, up to 0.3 m Dbh) in open woodlands, all exposures between 3,800 and 4,000 m; on southerly slopes up to 4,200 m. *Juniperus tibetica* between 4,050 and 4,770 m with single and multistemmed trees (up to 5 m, up to 0.3 m Dbh) on all exposures seemingly too dry for *Betula* and dense *Salix-Sibiraea* scrub. Seedlings.
58. Yarlung Zhangbo bridge at Sangri, 29°14′ N/92°00′ E, 3,560 m: *Juniperus convallium*, ♀, tree, 0.3 m Dbh, 6 m, in reach of the ground water. Believed of having been planted as sacred tree near the bridge. No seedlings.
59. Intramontane basin of Qusum, 29°04′ N/92°10′ E, 3.900 m: several isolated *Juniperus tibetica* trees mostly in yards. No seedling data.
60. South of Qusum, 29°02′ N/92°12′ E, 4,150 m: *Juniperus tibetica*-tree, 8 m, 0,3 m Dbh, on cliff of river terrace. No seedling.
61. Northern tributary of the Subansiri, 28°36′ N/92°32′ E, 4,070 m, all exposures: *Juniperus tibetica*, ♂ and ♀, single-stemmed trees, 3–6 m, 0.2–0.5 m Dbh. Seedlings.

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