

# Mountain forest islands and Holocene environmental changes in Central Asia: A case study from the southern Gobi Altay, Mongolia

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## Abstract

A multi-proxy case study conducted on Central Asia's most isolated mountain forest sheds light on the apparent decline of forest in the Subboreal time period and the incisive environmental changes from dark taiga to steppe in the Gobi Altay of Southern Mongolia over the last 5000 yr.

New vegetation records from the 'Gobi Gurvan Saykhan' (43°30' N/103°10' E) reveal long distance disjunctions of birch–willow forests as well as a number of herbaceous forest plants. Thus the question arises as to whether long-distance dispersal or fragmentation, following climatic changes and human interference, are more plausible explanations for such a pattern. Analysis of current plant distribution patterns lead to conclusions which are corroborated by zoological surveys of the Gobi Altay: During the Holocene, dark taiga forests apparently existed approximately 600 km to the southeast of their present range, and pollen analysis and charcoal remains provide evidence of a forest decline during the Subboreal time period. The presence of humans during these environmental changes is highly probable as pollen indicating human presence was found. Thus, it is assumed that humans at least contributed to the subboreal forest decline and the spreading of sagebrush and pastures. Moreover we cannot rule out with certainty that disjunctions of forest flora between the Gobi Altay and the forests of north-eastern Tibet are indicative of migration through the present North China desert, as forests may have partly replaced deserts during the moister periods of the Holocene. This multidisciplinary approach implies a mid-Holocene and subboreal scenario, which is new for Central Asia and more in accordance with the environmental history of the Holocene in the western desert belt of the Old World.

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## 1. Introduction

Islands of mountain forest surrounded by vegetation typical of non-forest climates have attracted considerable

attention from biogeographers worldwide. Here we present a study on one of the most isolated mountain forests of Central Asia in the south-eastern Gobi Altay of Mongolia and discuss its implications for regional biogeography and environmental change throughout the Holocene.

In the tropical Andes, the East African Mountains, and the Cordillera of New Guinea, forest islands surrounded

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by tropical-alpine grassland occur at altitudes of 4000 m, several hundred metres above the upper limit of continuous forest. Sites are often characterised by having higher soil temperatures and providing warm niches for tree growth (Troll, 1959; Walter and Medina, 1969). A contrasting view is that high altitude forests were simply fragmented as a result of human impact (Ellenberg, 1979; Miehe and Miehe, 1994; Wesche, 2002), which in the Andes may date back to between 3000 and 5000 yr BP (Kessler, 2002).

In the past, isolated forest stands in the arid part of western High Asia have been thought to be relicts of former forests and have been used for mapping the potential natural vegetation of, e.g., Afghanistan (Freitag, 1971). In the deserts of southern Tibet forest fragments have been observed at up to 650 km beyond the present-day western limit of forests (Miehe et al., 2003). Since these isolated trees fruit and regenerate in localities with no apparent environmental advantage, the only possible explanation for their continued presence is their protection as sacred groves. Isolated trees occur as remnants of a forest belt in southern Tibet that was destroyed over the last few centuries. Further examples are found at the eastern declivity of the Tibetan Highlands where pastures of alpine Cyperaceae are dominant, but isolated groves of juniper or spruce occur as well. Vegetation patterns here are similar to those of forest islands surrounded by alpine vegetation in the alpine grasslands of the tropics. The reasons for the apparent forest fragmentation in eastern Tibet are still not clear. Forests may have been cleared in the mid-Holocene (Thelau, 1992), or perhaps re-colonisation of sites after the last glacial maximum was constrained by an almost closed turf cover of alpine Cyperaceae (Miehe et al., 1998).

In Central Asia the striking pattern of forested north-facing slopes and steppe in southern exposures had been widely accepted as natural (Walter, 1974; Dulamsuren et al., 2005), but the occurrence of individual elm trees or even larch or pine among the meadow steppes has raised doubts as to the validity of such a presumption. Several authors regard meadow steppe as replacement communities of forests (Hilbig, 1995; Sommer, 1998). Moreover, trees of *Ulmus pumila* are found over a wide precipitation range, and even grow in zonal desert steppes of southern Mongolia (Lindeman, 1981). Isolated trees, and sometimes even extended open forests, occur in semi-desert vegetation with *Stipa glareosa* and *Anabasis brevifolia* at sites with a mean annual precipitation of less than 130 mm (Wesche et al., 2005). These stands might represent remnants of former forests which have maintained access to groundwater

owing to their long-lived habit, a mechanism described for *Populus euphratica* in the neighbouring Taklamakan (Bruehlheide, 2003).

The most extreme case in Central Asia is however provided by the *Betula–Salix* forests of the study area in the Zuun Saykhan, eastern Gobi Altay (Fig. 1). These forests are more isolated from the boreal forests to the north, the mountain forests of Middle Asia to the west, and the forests of the Tibetan Highlands in the south than any other mountain forest in Central Asia. In contrast to findings of substantial environmental change over time in the Sahara (Pachur, 2001), the eastern periphery of the Old World's desert belt is believed by some authors to have maintained its arid character throughout the Holocene (Frenzel, 1992; Petit-Maire and Bouysse, 2002). Other authors (e.g. Gunin et al., 1999; Herzschuh et al., 2003; Ma et al., 2004) recognized considerable wet phases during the Holocene. However, few of these authors have so far considered the possibility of human impact.

We studied the forests in the Zuun Saykhan in some detail in order to shed light on the environmental changes in Central Asia following the mid-Holocene climatic optimum, and raise the question of whether environmental changes, such as forest fragmentation during a dry Subboreal after the Atlantic climate optimum, were simply caused by climate change, or whether early human impact also played a significant role. Our hypothesis therefore is that humans at least accelerated forest fragmentation in Central Asian mountains. We employed a multi-proxy approach as a supplement to our palynological data. Not surprisingly for a semi-desert environment, pollen preservation was limited in the lower profile horizons so we were obliged to include evidence from soil profile and charcoal analysis, vegetation science and biogeography.

## 2. Study area

### 2.1. Location

The sampling sites are located in the Zuun Saykhan, the most easterly of three isolated mountain massifs of the southern Gobi Altay in Mongolia. These mountains are known as “Gobi Gurvan Saykhan” – the “Three Beauties of the Gobi” – paying tribute to the impression of green islands rising 800 m from the surrounding Central Asian desert pediments, sand dunes and salt pans. The massifs are part of the Gobi Gurvan Saykhan National Park and the forests under consideration belong to the core area of the park (Fig. 2). The highest summits, as well as the forests themselves, are sacred for

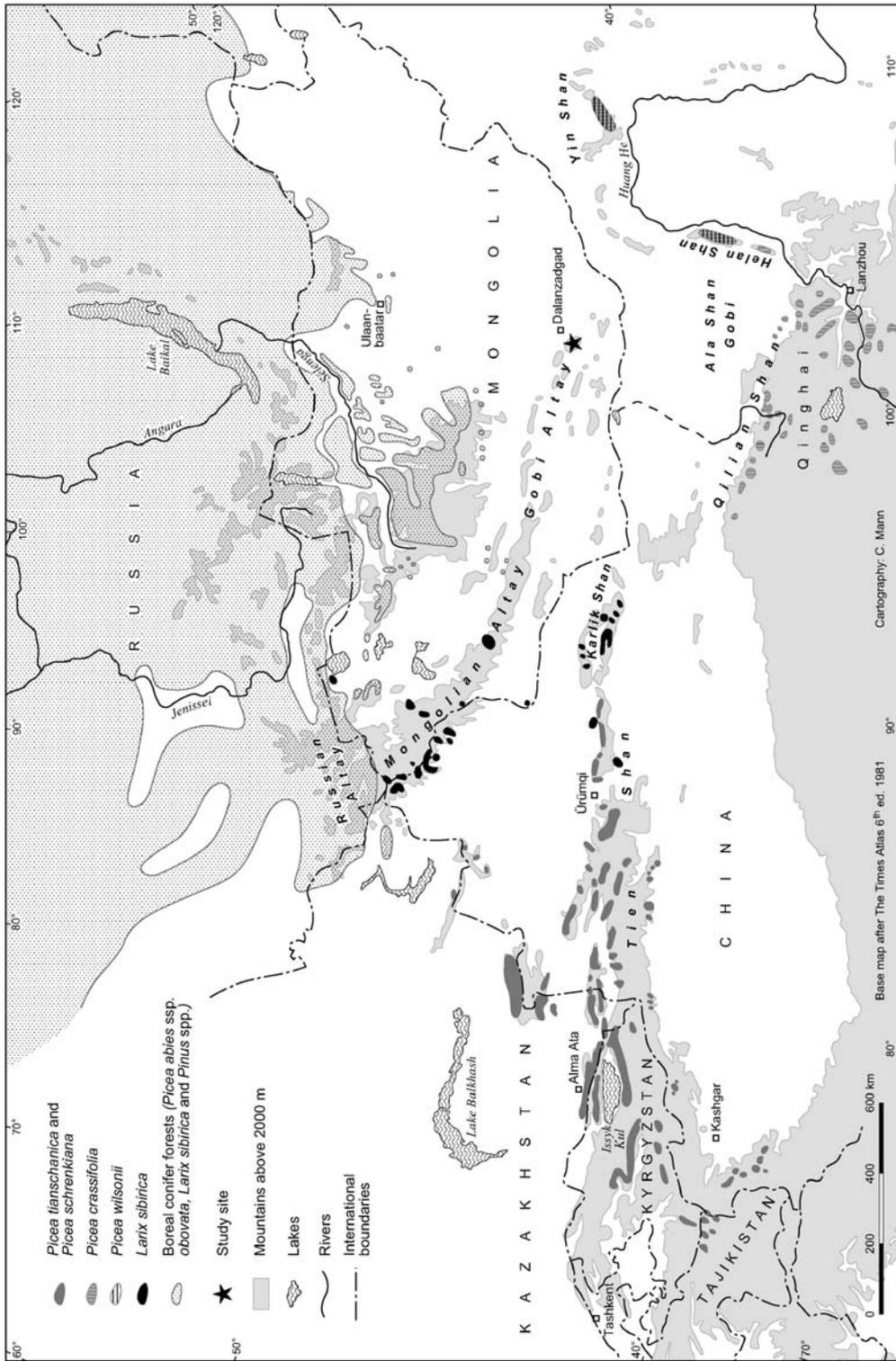


Fig. 1. Present conifer forest islands of Central Asian mountains (Draft: G. Mieke and E. Jäger).

the Buddhist nomads living in the area. Nonetheless, their horses, yaks and cows browse in and around the forests with destructive effects on tree regeneration.

The scale of the isolation of the Gobi Gurvan Saykhan forests is evident from the distance to the next forest stands (Figs. 1 and 3). The nearest birch forests are 300 km to the northwest in the Ih Bogd, while the nearest conifer forests are found approximately 320 km to the north (Changai), 520 km to the southeast (Helan Shan and Yinshan), 600 km to the south (Qilian Shan), and 750 km to the west (Karlik Shan). In terms of plant dispersal in Central Asia, the cool and humid mountain massifs act as stepping stones, while the intramontane depressions act as barriers (Fig. 3). The north-eastern barrier to the Arc Bogd is a basin with a width of ca. 60 km reaching down to an elevation of 1500 m, and the western depression towards the Žinst Uul stretches over ca. 70 km with minimum altitudes of 1000 m. In the south, the hyper-arid depressions of the north Chinese deserts are even lower than 1000 m and extend over 300 km.

## 2.2. Climate

The climate of the study site reflects the extremely continental situation of Mongolia with the nearest ocean being some 1200 km to the east. Dalanzadgad, the closest climate station to the study site, lies 25 km east-northeast at an elevation of 1465 m. The average annual precipitation in Dalanzadgad is 131 mm (1937–1999, after data from the Meteorological Service of Mongolia), 70% of which falls in June, July and August. Summer rainfall decreases from the easternmost mountain massif to the west, indicating the influence of the east Asian summer monsoon brought in by (north-) easterly winds during the growing season. During spring strong westerly winds prevail. Dalanzadgad displays the highest variability of summer precipitation in the whole of Mongolia (between 8 and 162 mm in August) with very unreliable timing. Snowfall is rare but more common in the mountains. Temperatures are unknown for the forests; higher cloudiness on the mountain massif in summer and cold-air pooling in the intermontane basins in winter render simple temperature lapse rates inapplicable. Although valleys provide shelter from strong winds, nomads avoid camping there during winter due to snow drifts — an important indicator of the winter conditions in the birch forests.

Transects of rain gauge measurements between the pediment at 2000 m and the mountain summit at 2850 m are available for the Dund Saykhan, which is situated some 30 km west of the *Betula–Salix* forests. In the

drought year of 2001 mountain summits received some 125 mm of precipitation, compared to 50 mm in the lowlands (Retzer, 2004). In the moister years of 2003/2004 the summit region received 201 mm (Wesche unpubl.), which is close to values obtained from climatic models (Hijmans et al., 2005). Mean annual precipitation at the permanent weather station nearest to the Dund Saykhan (Bayandalay, 20 km south, 1570 m asl.) is 110 mm. This altitudinal precipitation gradient corresponds to the zonal gradient between desert steppes in southern Mongolia and grass steppes in central Mongolia. Even Ulaanbaatar, situated in the southern part of the forest steppe ecotone, receives only a mean annual precipitation of 250 mm (Hilbig, 1995). We have no measurements from the *Betula–Salix* forest in the Zuun Saykhan, but we expect moisture there to be somewhat higher, because the mountain is more exposed to summer rains brought in by weather systems from the east. Annual precipitation is estimated to range between 200 and 300 mm.

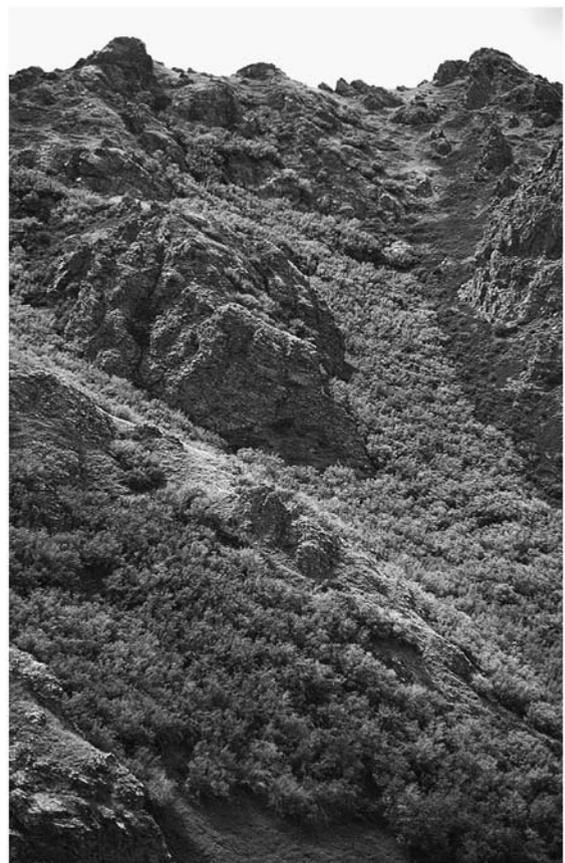
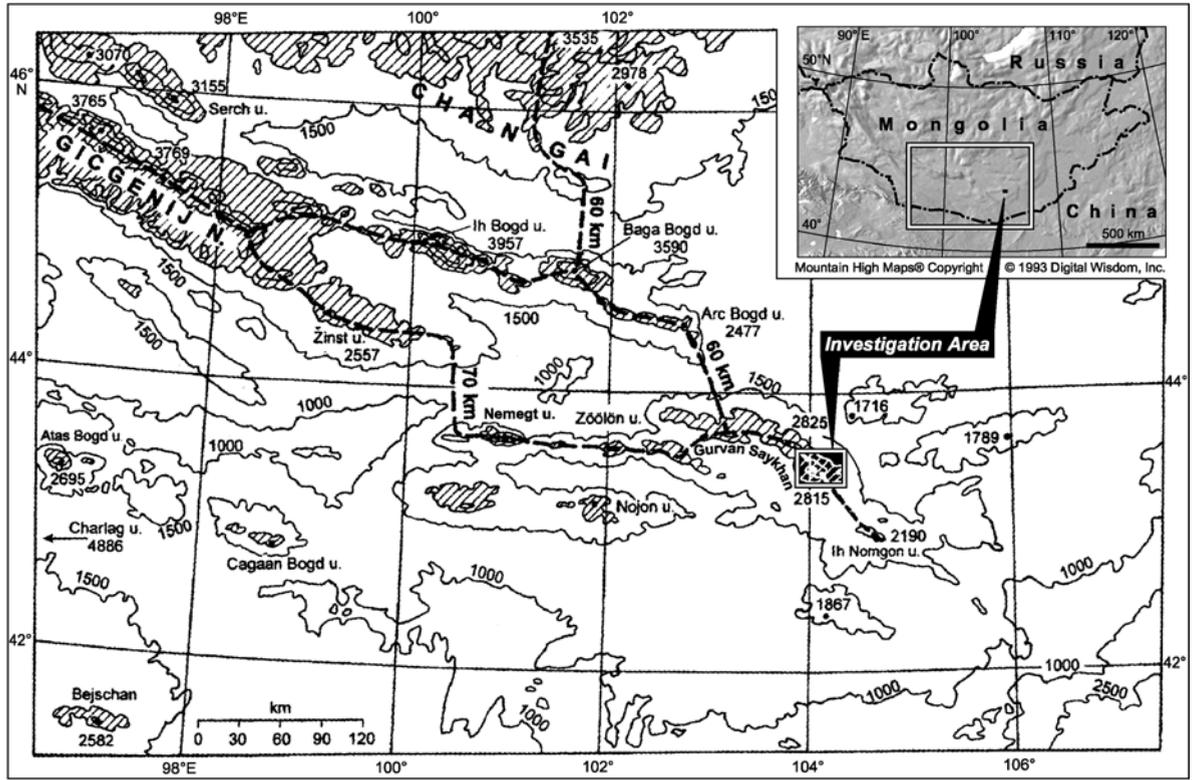


Fig. 2. Birch–willow forests in the Zuun Saykhan, south-eastern Gobi Altay, Mongolia (43°30' N/103°10' E) between 2400 and 2600 m on northerly exposures (photo: G. Miehe, August 1996).

a)



b)

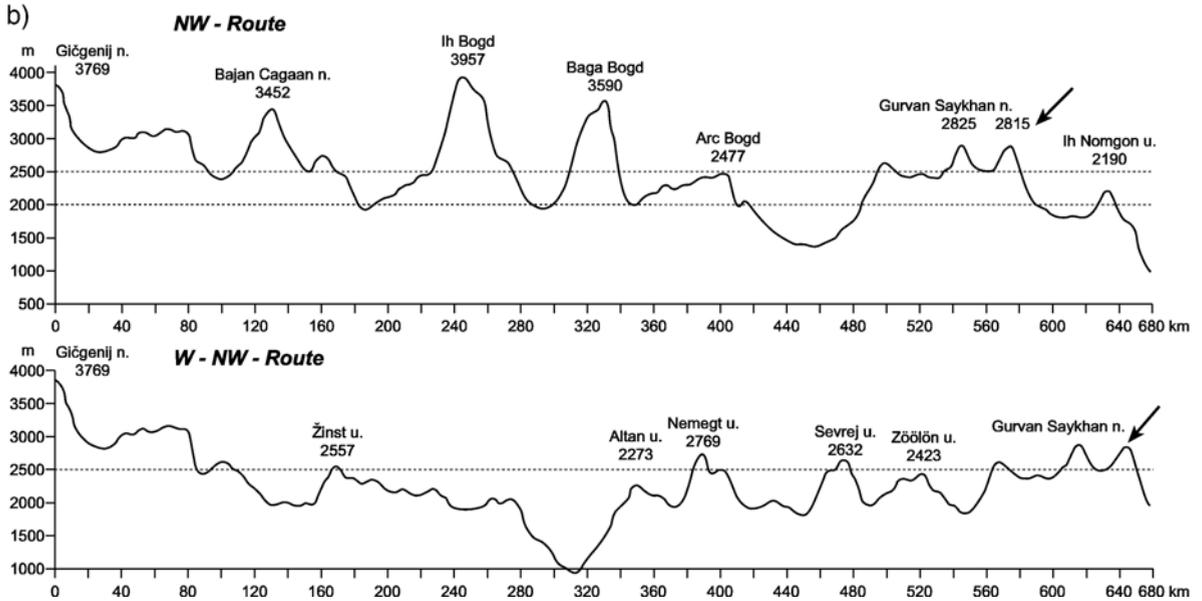


Fig. 3. a) Mountain islands of the south-eastern Gobi Altay and possible migration paths of forest plants. b) Profile from Gurvan Saykhan to the nearest high mountains of the Mongolian Altay. The black arrow marks the approximate location of the *Salix-Betula* forest sites. (draft: E. Jäger, after Anonymous, 1990, changed).

### 3. Vegetation

The intermontane basins separating the mountain massifs under consideration are overwhelmingly dominated by desert steppe of *Stipa glareosa* and *Anabasis brevifolia*, changing to *Stipa gobica*–*Allium polyrrhizum* desert steppe on the pediments (Wesche et al., 2005). Between 2300 and 2700 m, mountain steppe with *Stipa krylovii*, *Artemisia frigida* and *Agropyron cristatum* covers the uppermost pediments and lower slopes. Southern exposures and scree slopes of the mountain massifs have extended patches of *Juniperus sabina* scrub with disturbed sites such as the earthen mounds of small mammal burrows being colonized by the suffruticose *Artemisia santolinifolia* (Wesche et al., 2005).

The forests, composed of both birch and willow, are bordered by a narrow belt of meadow steppe hardly wider than five metres consisting of *Helictotrichon schellianum* and *Festuca valesiaca*. The occasional presence of *Betula* saplings points to the successional character of the meadow steppe as replacement communities of forest vegetation (Sommer and Treter, 1999; Wesche et al., 2005). As the Zuun Saykhan barely reaches 2800 m, the alpine belt is almost entirely absent with only a few mats of *Kobresia myosuroides* present in north-facing cirques.

#### 3.1. Soils

The soil types encountered in the study areas are Phaeozems rich in organic material inside the forests, and Kastanozems soils in the surrounding steppe areas. Forest soils have permafrost layers at depths of 80 cm and below. In a number of locations, continuous layers of charcoal are found at various depths within the soil.

### 4. Methods

#### 4.1. Vegetation and flora

A total of 10 relevés of two birch–willow forests were sampled in 1988, 1991, 1996 and 2001 following a modified Braun–Blanquet approach, with plots measuring 10 × 10 m, and the cover of all species estimated directly in percent (Mueller-Dombois and Ellenberg, 1974; Kent and Coker, 1992). The forests are strictly confined to upper slopes of northerly exposures at 43°30' N and 103°10' E between 2400 and 2600 m. All species not identified with certainty in the field were checked in the herbarium of the Institute of Geobotany, at the University of Halle–Wittenberg. Nomenclature follows Grubov (2001).

A list was compiled including all species of higher plants given by Grubov (1982, 1963 ff.) and Gubanov (1996) for the Gobi Altay, focusing particularly on the Gurvan Saykhan and excluding species of desert steppes and other semi-desert communities. As many of these plants as possible were mapped using the currently available literature (mainly Russian and Chinese floras), with data supplemented by some personal observations (Jamsran et al., 2005; Jäger, 2005). The range limits were interpreted climatically in order to deduce information on the necessary climatic conditions that would have enabled the plants to cross the lowlands around the Gurvan Saykhan. Distribution limits were interpreted based on isotherms and isohyets deduced from mean monthly and annual climate data published in the relevant large-scale Atlas volumes (Anonymous, 1972; Anonymous, 1981; Anonymous, 1990). We refrained from numerical analysis as neither distribution nor climatic data are available in a suitable resolution to formally calculate and interpolate climatic envelopes. The possibility of long-distance dispersal was judged on the basis of a range of literature sources on the species in question or closely related taxa, as well as on the morphology of diaspores.

#### 4.2. Soil and charcoal analyses

Several soil profiles were dug in representative locations in and around the birch–willow forests and were analysed diagnostically in the field. Charcoal fragments found in coherent layers within some of the profiles were identified to plant genus (Schoch, 1986) and dated using the AMS method (Fig. 4, Table 1).

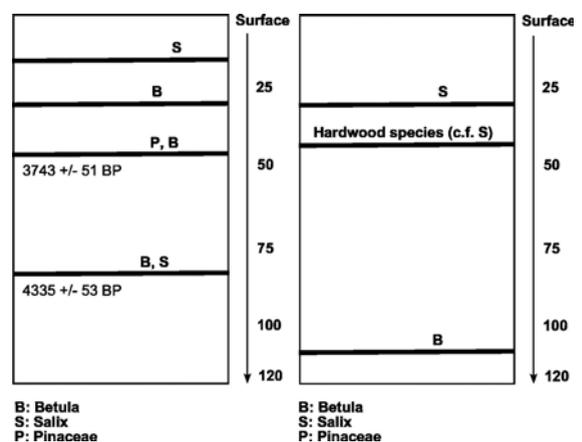


Fig. 4. Two soil profiles with charcoal layers. Species and 14C ages are given where known. (draft: J. Cermak).

Table 1  
Radiocarbon dates of the pollen diagram “Yolin Am” and charcoals from soils

No.	Depth [cm]	Laboratory No.	<sup>14</sup> C age [yr BP]	δ <sup>13</sup> C [o/oo]	Time range cal yr BC/AD	Mean age cal yr BP	Dated material
1	67.5–75.5	Erl.-5648	243±55	–24.3	1547–1793 AD	280±123	Diaspores
2	191.5–200	Erl.-5649	2371±57	–26.7	648–410 BC	2479±119	Diaspores
3	245	Erl.-7535	4719±85	–26.5	3607–3401 BC	5454±103	Pollen fraction
4	260	Erl.-7536	4074±61	–26.6	2814–2539 BC	4627±137	Pollen fraction
5	50	Erl.-5517	3743±51	–23.0	2068–2240 BC	4104±86	Charcoal, <i>Picea/Larix</i>
6	85	Erl.-5518	4335±53	–26.6	2917–3038 BC	4928±60	Charcoal, <i>Betula + Salix</i>

### 4.3. Palynology

As stated above, the quality of the available samples of pollen diagram “Yolin Am” (Fig. 5) limited the possibilities of direct interpretation, obliging us to use additional observations and literature data to reconstruct a plausible history of the vegetation under the influence of climate change and human activity.

The profile Yolin Am was taken at an elevation of 2390 m at 43°26' N/104°06' E, ca. 5 km south of the site of the two birch–willow forests in an adjacent watershed. The present vegetation at the profile site is a treeless mountain steppe dominated by *Agropyron cristatum*, *Caragana leucophloea* and *Artemisia santolinifolia* on the slopes, and a Cyperaceae sward at the valley bottom. Here, terrestrial sediments were exposed by water erosion in a flat U-shaped valley. Only the upper 145 cm of the soil were predominantly organic; living roots reached down to about 65 cm. The matrix was mainly minerogenic between 145–165 cm and 205–235 cm. Several sharp layers of decomposed organic matter occurred between 165–205 cm. Below 235 cm the matrix was again sandy–silty with some skeletal content.

Owing to the unfavourable sediment composition, pollen analyses were restricted to selected horizons. Some prepared samples were not analysed due to the sparseness or near absence of pollen content. The samples were prepared by standard methods using KOH, HF and acetolysis. Afterwards the samples were sieved in an ultrasonic bath (mesh 6 µm, 50 KHz) to improve the insufficient concentration of pollen and spores and stored in glycerine (Erdtman, 1960; Moore et al., 1999).

About 90 types of pollen and spores were identified based on type slides and literature (Beug and Mieke, 1999; Schlütz, 1999; Beug, 2004). The calculation of percentages is based on the pollen sum of arboreal pollen (AP) and non-arboreal pollen (NAP). Cyperaceae are excluded due to their local character. The pollen sum averages about 350 (320–425) but only about 150 in the 3

base samples. A selection of palynological taxa is presented in the pollen diagram (Fig. 5) arranged according to their modern ecology and chronological emergence. The two unsampled minerogenic segments are shaded gray. To avoid optical overrepresentation, the start and end of curves are plotted between samples. The number of carbonised plant particles was estimated in four classes. Based on the changes in the pollen records, we divided the pollen diagram Yolin Am visually into 4 local pollen zones (YAZ 1–4).

Following Schlütz and Lehmkuhl (2007), so-called “pollen clumps” of immature grains sticking together were also considered as an additional palaeoecological tool. The number of grains in clumps was counted (up to 20 pollen grains) or estimated in very dense clumps; sums were graphed for the individual types. Especially in High Asia (Tibet, Karakorum, Himalaya, Altai) such clumps can be found regularly but have not so far been accorded much attention by palynologists. The occurrence of unripe pollen in a profile can have several climatic or (anthropo-)zoogenic reasons (shortened growing seasons, strong rain — or snowfall, mechanical stress by grazing, etc.). Due to their lower potential for aerial transport, they should indicate mostly short-distance transport and are helpful to assess the appearance of nearby wind-pollinated plants. We believe that closer analysis of pollen clumps will facilitate future progress in palaeoecology.

Four AMS-radiocarbon dates (Table 1) from hand-picked (Schlütz) diaspores as well as pollen fractions (Morgenroth et al., 2000) were prepared and analysed in the Erlangen laboratory. The calibration of all dates (pollen profile, charcoal from soils and dates from literature) was done with the online program CalPal ([www.calpal-online.de/CalPal2005\\_SFCP](http://www.calpal-online.de/CalPal2005_SFCP)). Datings for the two lowest samples contradicted each other. We assume the older age to be wrong, possibly due to redeposited older charcoal particles. We used the remaining three dates for our depth-age model (Fig. 6). This yields an age of about 4350 cal yr BP (4400 cal yr before 2000) for the transition from YAZ 1 to YAZ 2.

5. Results and discussion

5.1. Site conditions

The two birch–willow forests of the Zuun Saykhan cover 0.5 and 30 ha respectively and are confined to upper slopes of northern exposures. The estimated annual

rainfall of 200 to 300 mm is supplemented by water surplus from the surrounding rock walls. However, soil surveys in the forest and in the neighbouring steppe, as well as dendroecological analyses, support the assumption that the timing of moisture availability, storage of moisture, and water-uptake by the plants play a decisive role in the survival of the two forest stands (Fig. 7;

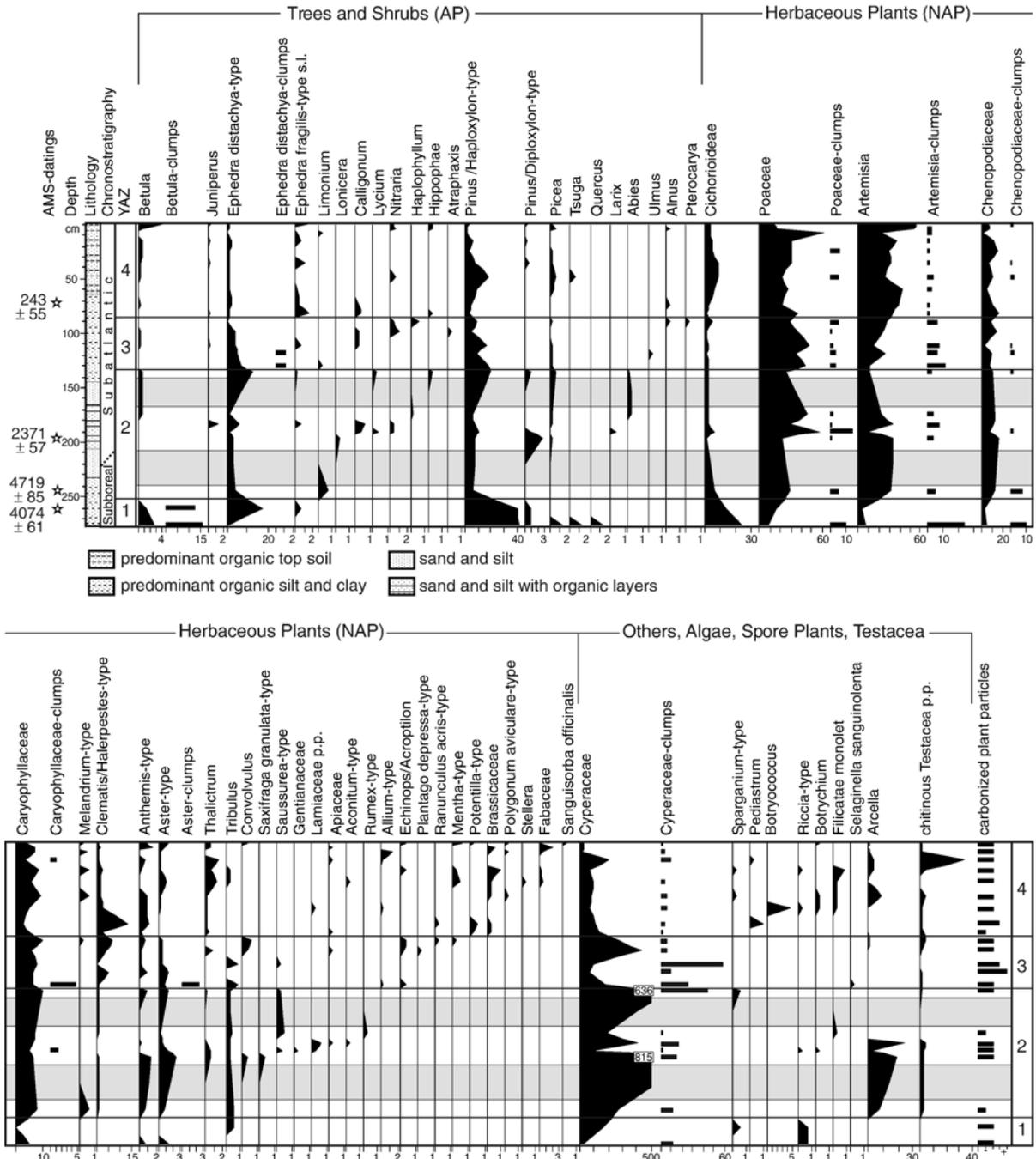


Fig. 5. Simplified pollen diagram ‘Yolin Am’, 2390 m, Gobi Altay (pollen sum=AP+NAP). Dates in uncal. BP (illustration F. Schlütz).

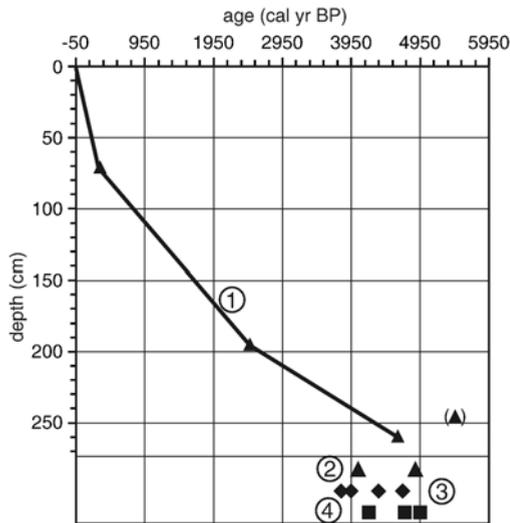


Fig. 6. Age depth model of the pollen profile Yolín Am (1), charcoal findings from soils (2) and macro remains of *Abies* (3) and *Picea* (4) (3 and 4 after data from Dinesman et al., 1989). The Yolín Am section was dug in 2000 AD = -50 cal yr BP (illustration F. Schlütz).

Cermak et al., 2005). When the snow melts in early spring low temperatures do not allow plant growth. When temperatures rise in May and June precipitation levels are still low thus creating water stress for plants and prohibiting extensive growth. In fact, most rain falls in summer when evaporation levels are at their maximum.

Positive feedback mechanisms are apparent throughout the intact forests. Owing to the microclimate in the forests, snow cover remains in place for a longer time, allowing for moisture availability in spring when it is needed most. Even though winter precipitation is relatively low, its availability in spring, when the water stress is highest, appears to be of crucial importance. The significant correlation between precipitation levels and annual growth rates supports this interpretation (Cermak et al., 2005).

Another aspect related to the forests' microclimate is the presence of a permafrost layer starting at a relatively shallow depth of 80 cm below the surface. In northern Mongolia the presence of permafrost has been described as a function of forest cover. Canopy and organic soil layers protect the soil from solar radiation in summer and, while air temperatures show no marked differences between steppe and forest areas, soil temperatures do (Treter, 1996). When the forest is cleared, the permafrost layer soon disappears; snow thaws early and the conditions for forest growth deteriorate. The permafrost layer in the study sites is accordingly expected to have important ecological functions in terms of water retention (Haase, 1983; Brzezniak and Pacyna, 1989).

In northern Mongolia, permafrost is usually found at depths between a few decimetres and 150 cm in summer, and rises to include the upper soil layers in winter. The forest topsoil freezes later than that of 'open' vegetation, leaving more time for the absorption of water from early snowfall events (Bernatzky, 1978). In the process of freezing, the lower part of the soil is dehydrated and the moisture is concentrated in the topsoil. When temperatures start to rise in spring the active layer thaws and releases its moisture to the vegetation (Succow and Kloss, 1978; Haase, 1983). Correspondingly, the lowest water deficit in the forest steppe zone occurs in May, at the beginning of the growing season (Glazik, 1999).

A second positive feedback switch operates via the infiltration of precipitation. When rainwater becomes available during the summer months, it quickly infiltrates into the forest soil and, with the forest canopy in place, direct evaporation from the soil surface is kept to a minimum. Therefore, the forest soil retains water more efficiently than the adjacent steppe soil.

Thirdly, the trees' multi-stemmed growth habit can be interpreted as an adaptation to water stress. On average trees are around 5 m in height with the highest individuals reaching 7.5 m. They grow single-stemmed as well as multi-stemmed throughout the forests (about 1/3 of the willows and 1/10 of the birches grow single-stemmed) with most stems being sickle-shaped. As dendrochronological investigations have shown (Cermak et al., 2005) the multi-stemmed habit leads to successive stem turnovers over the years with old stems gradually dying and new ones in turn emerging from the same base connecting to a common root system. This ensures the presence of a fully established root system for newly emerging stems and thus a very efficient water

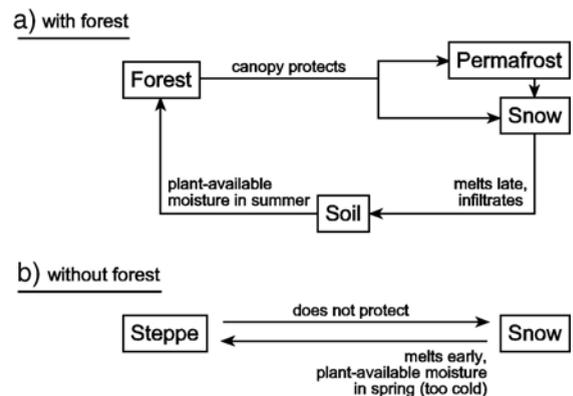


Fig. 7. Hypothesised hydrological mechanisms under protective forest cover (a) and in the surrounding meadow steppe after forest retreat (b) (draft: J. Cermak and L. Opgenoorth).

uptake at all stages of the tree's development (Crombie, 1997 demonstrated a similar phenomenon for stump coppice in *Eucalyptus marginata*). Furthermore, gaps in the forest canopy can be closed quickly by 'waiting' minor stems, thereby keeping the microclimate largely constant at all times (Cermak et al., 2005). These inferences clearly demonstrate the self-supporting mechanisms operating in the forest ecosystem; once destroyed the re-establishment of a forest under today's environmental conditions would be at least difficult, if not unlikely.

### 5.2. Current vegetation and biogeography

The birch–willow forests are composed of *Betula microphylla*, *B. platyphylla*, *Salix taraiensis*, and *S. bebbiana* and grow in thickets on north to north-east facing slopes at altitudes between 2400 and 2600 m. The undergrowth of the dwarf forests is dominated by caespitose phanerophytes (*Cotoneaster mongolica*, *C. melanocarpa*, *Lonicera altaica*, *Ribes rubrum*, *Grossularia acicularis*, *Spiraea media*) 1–2 m in height with 5 to 20% cover. In open stands a second shrub layer is poorly developed with *Rosa acicularis* and *Juniperus sabina* growing to heights of 20 to 30 cm. Both species are common along forest edges together with the sole liana, *Atragene sibirica*. The herbaceous undergrowth is poor and rarely covers more than 5%.

*Moehringia laterifolia*, *Viola dissecta*, *Adoxa moschatellina* and *Paeonia anomala* are examples of species whose distribution patterns link the forests of the study area to the boreal conifer forests to the north and even to forest islands in northeast Tibet to the south. The records of some species in the birch–willow forests, as shown in Table 2, represent the most isolated populations of forest flora in Central Asia known so far. The obvious questions are: How did the plants reach these south-easternmost mountain islands of the Gobi Altay? Where did they come from and along which route did they migrate? How long have they been isolated?

For some of the species, long-distance dispersal cannot be excluded. Wind measurements near the summit of one of the massifs of the Gobi Gurvan Saykhan revealed wind speeds of 120 km/h (Retzer, 2004). Thus, the presence of *Betula*, *Salix*, most of the Compositae, *Pyrola*, *Atragene*, Gentianaceae and *Valeriana* could easily be explained by long-distance dispersal. Others like *Paeonia anomala*, *Ribes nigrum*, *R. rubrum* and *Lonicera* could have been distributed by birds; these plants are also anthropochorous. But there are also some species which do not have the option of long-distance dispersal by wind or animals, e.g.,

*Moehringia laterifolia*, *Viola dissecta*, and *Adoxa moschatellina* (Figs. 8 and 9). Such species can only migrate or exchange pollen/seeds in a step-wise manner and thus require reasonably continuous habitats for dispersal.

The most probable connection routes are located along the mountains northwest of the study sites. The chains of the Gobi Altay may have provided stepping stones, but the hot and dry depression separating the mountains would still have to be crossed (Fig. 3). As *Viola* and *Adoxa* are conifer forest plants we may simplify the issue by asking how much rainfall is needed to allow conifer forests to invade the depressions. Considering that the drought limit of the nearest conifer species (*Picea obovata* and *Larix sibirica* in the north and *Picea crassifolia* in the south) is approximately 250 mm/yr (Anonymous, 1990, Miehe et al., 2001), about 250 mm of summer precipitation would allow forests to cross the intermontane basins and to form a closed mountain belt conifer forest. The given relief situation, the known drought line of the nearest conifer forests, and the finding of macro-remains and pollen all point towards an increase of 100–200 mm compared to the current conditions in order to facilitate a bridging over the present driest gaps.

Although the northbound link to the boreal flora is the most obvious explanation, there are also links to conifer forests in north-eastern Tibet (Liu, 1996–1999). *Viola dissecta* and *Adoxa moschatellina* are recorded from spruce forests in Qinghai. Thus, the question arises whether the boreal forests could have been linked directly with conifer forests of Tibet. Where human impact is moderate, the Gobi even today hosts woodlands (Lindeman, 1981). These are formed by *Ulmus pumila*, which can form extensive woodlands wherever at least occasional surface water flow allows for establishment of seedlings. Elms have been cleared from many potentially suitable sites by human impact (Hilbig, 1987, 2000), and if we assume that precipitation levels had also been higher in northern China, elm forest can be expected to have been more extensive than it is today. Indeed, there is palynological evidence of *Ulmus pumila* in the Ala Shan Gobi 250 km to the southwest of the Gobi Gurvan Saykhan — nearly halfway to the forests of the northern declivity of the Qilian Shan (Herzschuh et al., 2003), which hint at the presence of more than just a few gallery forests of limited extent.

The environmental shifts deduced here contrast with the "Atlas of Palaeoclimates of the Northern Hemisphere" (Frenzel, 1992), and with the "Cartes des environnements du monde pendant les deux derniers extreme climatiques" (Petit-Maire and Bouysse, 2002),

Table 2

Vegetation records of the birch–willow forests from north-facing upper slopes of the Zuun Saykhan (after data of Jäger 1988, 1991, Mieke and Mieke, 1996, Cermak and Opgenoorth, 2001). Species with distribution links to the boreal forest are given in bold. Cover degree is given in percent

Record number	1	2	3	4	5	6	7	8	9	10		
<i>Atragene sibirica</i>	18	5	+	+	+	+	11	11	r	+	100	
<i>Rosa acicularis</i>	5	5	10	4	7	.	5	5	5	6	90	
<i>Betula microphylla</i>	.	5	46	22	40	.	39	13	4	2	80	
<i>Silene repens</i>	5	18	2	4	4	2	.	+	.	+	80	
<i>Spiraea media</i>	.	18	+	1	1	5	5	19	10	.	80	
<i>Ribes rubrum</i>	5	+	2	1	2	3	.	.	+	.	70	
<i>Salix bebbiana</i>	38	18	30	40	31	50	.	.	.	.	60	
<i>Thalictrum foetidum</i>	5	5	.	.	.	r	1	+	.	+	60	
<b>Campanula turczaninovi</b>	.	18	+	+	+	.	.	.	.	+	2	60
<i>Juniperus sabina</i>	+	+	+	1	2	.	13	35	.	.	70	
<i>Carex pediformis</i>	38	18	.	.	1	.	45	.	.	20	50	
<i>Cystopteris fragilis</i>	.	r	+	+	+	+	.	.	.	.	50	
<b>Pyrola incarnata</b>	5	.	.	.	.	.	r	1	2	.	40	
<i>Cotoneaster mongolicus</i>	5	.	2	.	+	.	.	.	2	7	50	
<i>Aster alpinus</i>	+	.	.	.	.	.	.	+	r	2	40	
<i>Adoxa moschatellina</i>	5	18	.	+	.	.	.	.	r	.	40	
<i>Salix taraiensis</i>	.	.	.	.	4	.	35	4	.	.	30	
<i>Bistorta vivipara</i>	.	18	.	.	.	.	r	.	.	2	30	
<i>Lagotis integrifolia</i>	+	18	.	1	.	.	.	.	.	.	30	
<i>Saxifraga sibirica</i>	.	.	+	+	+	+	.	.	.	.	30	
<i>Lonicera altaica</i>	.	.	1	2	1	.	.	.	.	.	30	
<i>Carex obtusata</i>	.	.	+	+	.	+	.	.	.	.	30	
<i>Androsace septentrionalis</i>	.	+	.	.	.	r	.	.	.	r	30	
<b>Moehringia lateriflora</b>	.	.	+	.	+	.	+	.	.	.	30	
<i>Artemisia santolinifolia</i>	5	.	.	.	.	.	.	3	.	.	20	
<i>Rhodiola rosea</i>	.	.	.	.	.	.	.	.	+	r	20	
<i>Artemisia phaeolepis</i>	.	.	.	.	.	.	r	.	.	+	20	
<i>Carex amgunensis</i>	.	.	+	+	.	.	.	.	.	.	20	
<i>Lophanthus chinensis</i>	+	+	.	.	.	.	.	.	.	.	20	
<i>Potentilla nivea</i>	.	.	.	.	.	.	.	.	r	1	20	
<i>Lonicera microphylla</i>	18	.	.	+	.	.	.	.	.	.	20	
<i>Rheum undulatum</i>	+	5	.	.	.	.	.	.	.	.	20	
<i>Poa attenuata</i>	5	+	.	.	+	+	.	.	.	.	40	
<i>Galium boreale</i>	.	+	.	.	.	.	.	.	.	+	20	
<i>Peucedanum hystrix</i>	.	.	.	.	.	.	+	.	.	r	20	
<i>Poa pratensis</i>	.	+	.	.	.	.	.	.	.	+	20	
<i>Allium amphibolum</i>	.	.	.	.	.	.	.	+	.	+	20	
<i>Viola rupestris</i>	.	.	+	+	.	.	.	.	.	.	20	
<i>subsp. rupestris</i>	.	.	.	.	.	.	.	.	.	.	20	
<i>Rubia cordifolia</i>	.	.	.	+	+	.	.	.	.	.	20	
<i>Koeleria cristata</i>	.	5	.	.	.	.	.	.	.	+	20	
<i>Astragalus frigidus</i>	r	.	.	.	.	.	.	.	.	r	20	
<i>Berberis sibirica</i>	+	.	.	.	.	.	.	.	.	r	20	
<i>Betula platyphylla</i>	18	.	.	.	.	.	.	.	.	8	20	

Table 2 (continued)

Record number	1	2	3	4	5	6	7	8	9	10	
<i>Paeonia anomala</i>	5	.	.	.	.	.	.	.	.	.	10
<i>Viola dissecta</i>	.	+	.	.	.	.	.	.	.	.	10
<i>Viola mauritii</i>	.	r	.	.	.	.	.	.	.	.	10

*Betula reznitzenkoana* 1:5; *Heracleum dissectum* 1:++; *Odontites vulgaris* 1:++; *Ribes aciculare* 1:++; *Veronica incana* 1:r; *Aquilegia viridiflora* 2:++; *Bromus inermis* 2:++; *Dracocephalum fruticosum* 2:++; *Draba nemorosa* 2:++; *Gentiana pseudoaquatica* 2:5; *Heracleum sibiricum* 2:++; *Lappula cf. intermedia* 2:5; *Nepeta sibirica* 2:r; *Polygonum angustifolium* 2:++; *Potentilla gelida* 2:++; *Arabidopsis* sp. 4:++; *Cerastium arvense* 5:++; *Cotoneaster melanocarpus* 5:1; *Galium verum* 6:++; *Potentilla desertorum* 6:6; *Myosotis sylvatica* 7:r; *Viola biflora* 7:++; *Elymus komarovii* 8:r; *Festuca cf. kryloviana* 8:20; *Galium vaillantii* 8:r; *Papaver croceum* 8:r; *Papaver nudicaule* f. *nudicaule* 8:++; cf. *Deschampsia caespitosa* 9:r; *Trisetum spicatum* 9:r; *Allium cf. prostratum* 10:++; *Amblynotus rupestris* 10:++; *Androsace dasyphylla* 10:++; *Artemisia pycnorhiza* 10:++; *Bromus pumpeianus* 10:++; *Bupleurum bicaule* 10:++; *Draba* sp. 10:r; *Elymus gmelinii* 10:++; *Festuca lenensis* 10:++; *Festuca rubra* 10:++; *Festuca cf. valesiaca* ssp. *hypophila* 10:++; *Gentianella acuta* 10:++; *Helictotrichon schellianum* 10:8; *Heteropappus altaicus* 10:r; *Kobresia myosuroides* 10:40; *Lloydia serotina* 10:++; *Orostachys spinosa* 10:++; *Oxytropis tragacanthoides* 10:r; *Poa palustris* 10:3; *Poa angustifolia* 10:r; *Potentilla conferta* 10:++; *Spiraea flexuosa* 10:1;

which both show the same vegetation types as today, even for the humid periods of the Holocene.

The question as to when the forests became fragmented can be most easily answered by checking macro-remains of conifer charcoal and conducting pollen-analyses, as discussed below. Biogeographical data permit an estimation of the time period when the fragmentation should have occurred. Almost all of the 50 (–70) species of specialised forest plants of the Gobi Gurvan Saykhan are morphologically and taxonomically identical with the populations from their main, northern distribution area. An isolation older than the last glaciation should have resulted in a taxonomic differentiation at subspecies or species levels in at least some of these species. An example for such a differentiation is the Alvar region of Öland in Sweden, where the date of isolation is known. Sites were totally covered by ice up to 11,000 BP; after re-immigration several species became rapidly isolated by the spreading forests in the course of the Holocene. Of a total of 150–200 plants typical of open Alvar sites, nine have become differentiated at subspecies level over the last few thousand years (Sternér, 1938), and similar patterns are known from other sites where the date of isolation is known. Thus, the phytogeographical evidence suggests that the fragmentation of forest vegetation in the Gobi Altay is likely to be of Holocene rather than early Quaternary age.

Zoogeographical data also hint at the former presence of widespread boreal forests in the Gobi Altay. The

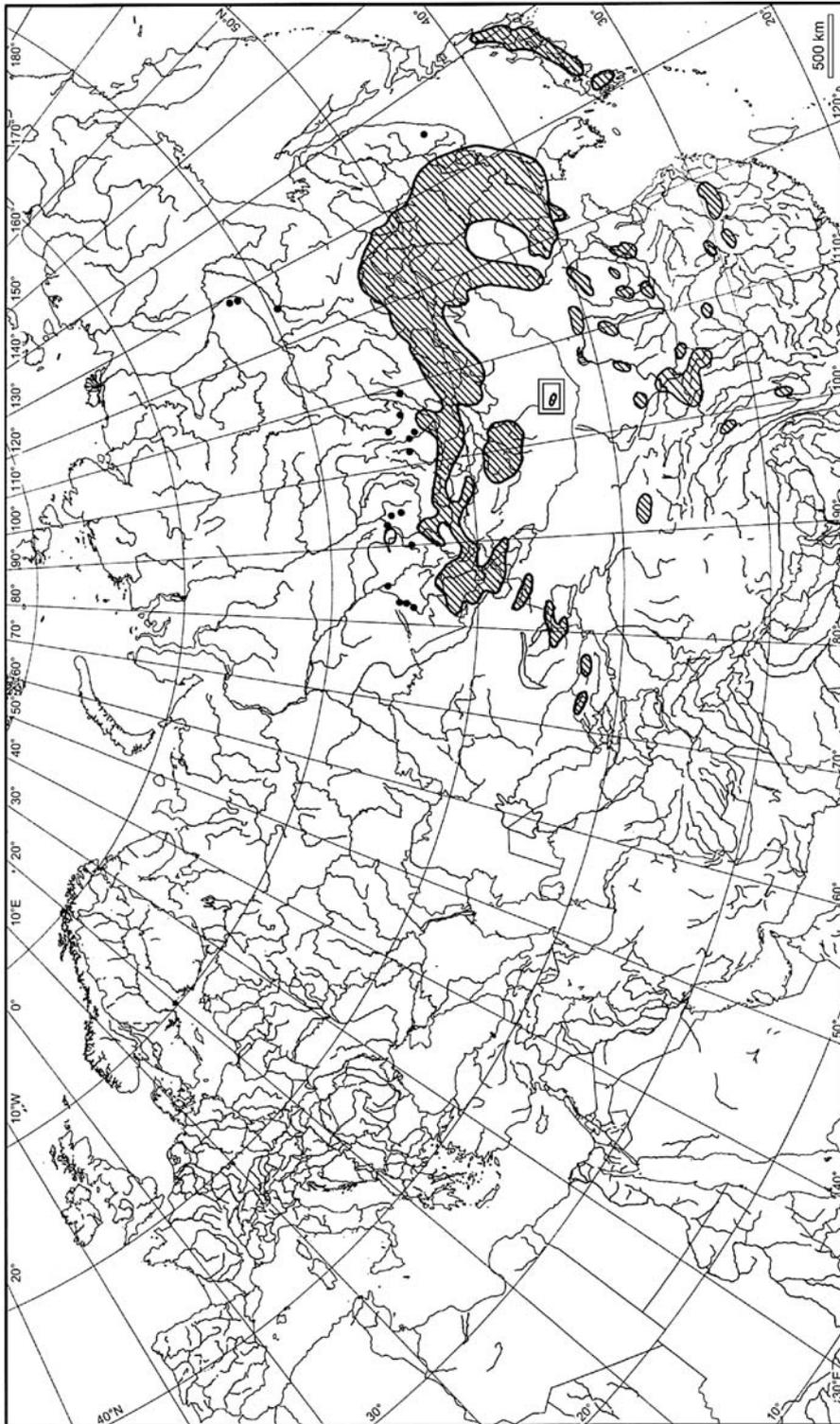


Fig. 8. General distribution of *Viola dissecta* Ledeb. The record in the Zaun Saykhan is framed (draft: E. Jäger).

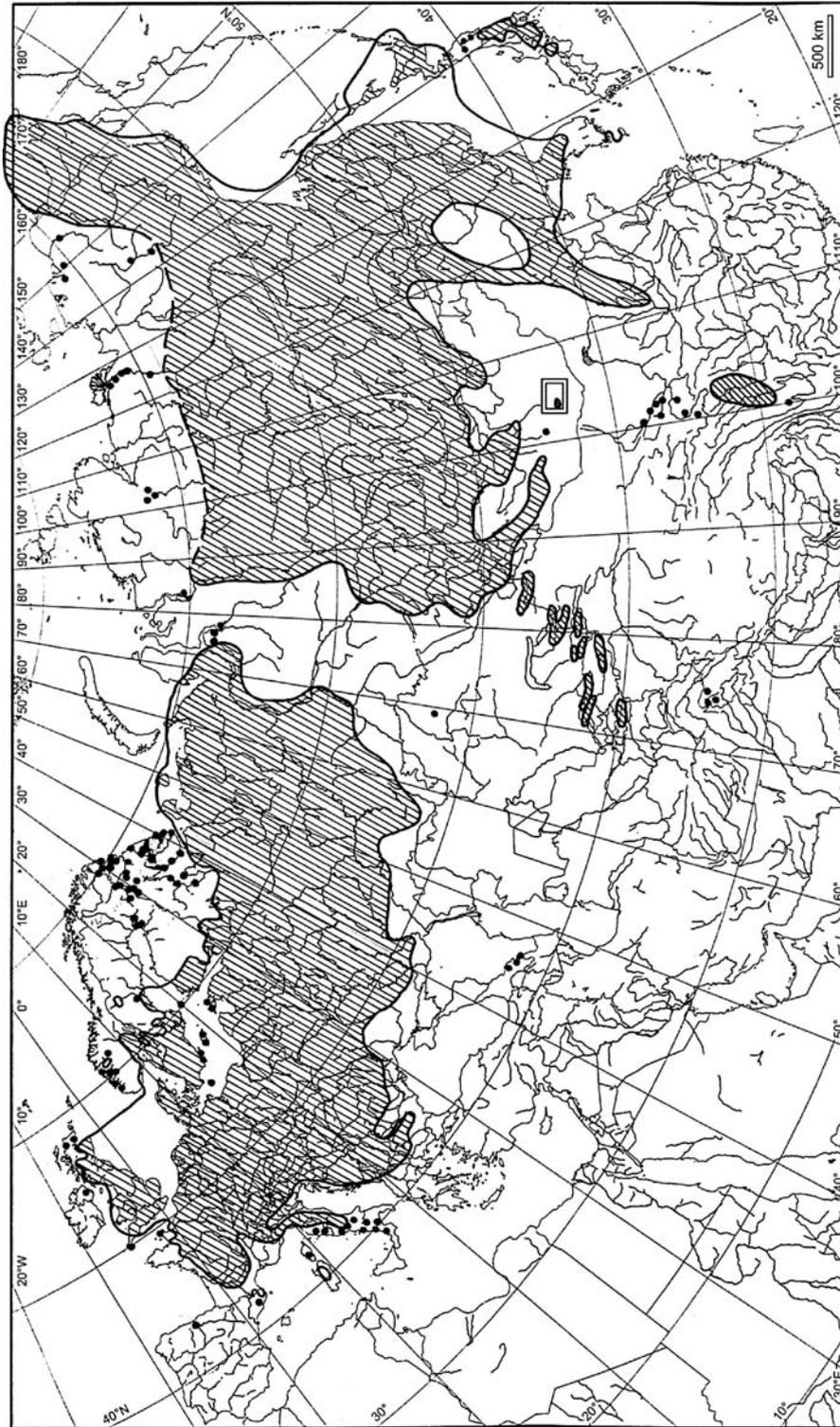


Fig. 9. Distribution of *Adoxa moschatellina* L. in Eurasia. The record in the Zuun Saykhan is framed (draft: E. Jäger).

grey-sided vole (*Clethrionomys rufocanus*, Sund. 1846–1847) was found in isolated birch forests of the Ih Bogd in the eastern Gobi Altay (Fig. 3), although its centre of distribution is in the boreal forests of northern Mongolia (Lkhagvasuren and Samiya, 2004). Again a relatively recent isolation is inferred based on a comparison of highly plastic morphological characteristics. The shape of the upper third molar (M3), the fur colour and skull dimensions show no distinct differences between populations of the Ih Bogd and those of northern Mongolia. Similar links are shown by microarthropods (oribatid mites) in the Gobi Gurvan Saykhan (Bolortuya and Bayartogtokh, 2005). No less than 24.4% of the species found in the mountain steppes of the three mountain massifs of the Gobi Gurvan Saykhan belong to the boreal conifer forest fauna of northern Mongolia. However, in this case the available knowledge is not sufficiently detailed to infer anything about the timing of the isolation event.

## 6. Paleocological evidence from pollen and macro-fossils

The most significant change in the pollen diagram Yolín Am appears at the turn from YAZ 1 to YAZ 2 around 4350 cal yr BP with a drastic decrease in pollen of the *Pinus*/Haploxylon-type and *Betula*. The former presence of *Betula* forests nearby is proven by high values of *Betula* pollen clumps, transported from the catchment area by water. Based on our experience from other parts of the Altay (Schlütz, 2000, 2002; Schlütz and Lehmkuhl, 2007) we regard pollen of the *Pinus*/Haploxylon-type as originating from long-distance transport. Such pollen was washed out by rain together with that of other taxa (*Tsuga*, *Quercus*) coming from the south during times of strong summer monsoon rainfall. The pollen diagram points to a decrease of the summer monsoon at around 4350 cal yr BP, when steppe and deserts rich in Poaceae, *Artemisia* and Chenopodiaceae began to develop under the dry climate of the YAZ 2. In contrast to the regional climate the local conditions at the profile site were quite moist, leading to a dramatic increase in sedges (Cyperaceae) and their corresponding micro-fauna (*Arcella* Testacea p.p.). The well developed vegetation apparently attracted grazing animals, as indicated by the appearance of the ectozoochorous grazing weed *Tribulus*. Later on, above a hiatus of non-pollen bearing sediment, pollen types clearly attributed to deserts (*Calligonum*, *Lycium*, *Nitraria*) reflect the turn to a drier climate.

The shift to a drier climate and/or the presence of nomads may have been the reason for fires that are

presumed to have occurred near the site of today's birch forests (some 5 km distant). Continuous layers of charcoal were found in several soil layers (Fig. 4). Since these samples occurred in coherent bands and in a number of profiles, they are interpreted to indicate forest fires. Charcoals found at a depth of 85 cm were identified as *Betula* and *Salix* and dated to  $4928 \pm 60$  cal yr BP. Fire impacts appear to have continued, as documented by charcoal remains of *Larix/Picea* (W. Schoch, pers. comm.) found at depths of 50 cm in the mentioned soil profile and dated to  $4104 \pm 86$  cal yr BP. It was unfortunately not possible to differentiate between the two genera based on the charcoal. Because *Larix sibirica* forms the southernmost forests in Mongolia today, and any *Picea* forests should have been indicated by a clear pollen signal, we suppose that the remains are from *Larix sibirica*. The discovery of charcoal in those layers excludes the possibility that fires had occurred only in a spot-wise fashion. If *Larix* had not been found growing around the site, it is likely that people would have used the surrounding scrub vegetation which provides good fuel wood instead of carrying *Larix* wood over hundreds of kilometres for that purpose. Due to the very short distance transport of *Larix* pollen, the history of possible *Larix* forests is not reflected in the pollen diagram, which came from another watershed. Stomata were not found and not expected due to the limited catchment area of the profile site. The carbonised plant particles in the pollen profile (Fig. 5) also indicate that fire probably was a driving factor over more or less the entire time span covered by the diagram.

At the beginning of pollen zone YAZ 3 the sharp decline of Cyperaceae as well as the occurrence of pollen clumps of the *Ephedra distachya*-type, the Caryophyllaceae, the *Aster*-type and of Cyperaceae (first three samples) indicate a phase of strong disturbance of the vegetation. This is most readily explained by strong grazing impact at the site. This phase (age-depth model: 1190 to 1370 AD) appears to correspond with the time period 1100–1380 AD known from the Russian Altai, concomitant with the decrease in vegetation due to a cold-dry climate combined with pronounced human influence during the expansion of the Mongolian Empire (Schlütz and Lehmkuhl, 2007). After this period of intensified grazing, the Cyperaceae recovered.

The beginning of the youngest pollen zone (YAZ 4) at about 1600 AD is marked by an increase in *Artemisia* and the *Ephedra fragilis*-type pointing to a drier climate but also possibly to the re-establishment of stronger anthropo-zoogenic influence (*Artemisia*, *Potentilla*-type, Brassicaceae) due to animal husbandry. Wetter

conditions indicated at a depth of about 50 cm (somewhat younger than 1670 AD) by the increase of *Pinus* pollen and the decrease of the *Artemisia* curve may reflect the Little Ice Age. Afterwards the grazing pressure became even stronger as indicated by the occurrence of *Thalictrum*, *Mentha*-type, Brassicaceae, *Stellera* and Fabaceae.

Our results from pollen and charcoal reveal a striking aspect of the history of forests in the Gobi Altay mountains during the Subboreal time period. A decrease of precipitation around 4350 cal yr BP (pollen) brought the end of even the drought-resistant *Larix* forest in the southernmost Gobi Altay (charcoal). The reason for this moisture decrease can be seen in a distinct warming during the middle Subboreal as demonstrated for the continental part of Eurasia by Chotinskij (1982) and especially for the Russian Altay by Schlütz and Lehmkuhl (2007), leading to arid conditions in the Gobi Altay.

The progressive desiccation of the Altay range is demonstrated by the disappearance, in the subsequent time period, of *Abies* and *Picea* in regions 600 km WNW of Dalanzadgad in the southern Mongolian Altay at the latest around 3800 cal yr BP (*Abies*) and 4200 cal yr BP (*Picea*), respectively (Fig. 6), as indicated by macro-remains (Dinesman et al., 1989 in Gunin et al., 1999). Whereas in the relatively wet Russian Altai, the Subboreal forest decline was driven by a more recent temperature decline around 3700 cal yr BP (Schlütz, 2002; Schlütz and Lehmkuhl, 2007).

The pollen diagram from Yolin Am and the charcoal records from the neighbouring forest soils furthermore point to a considerable human contribution to these forest declines. *Tribulus terrestris*, for instance, is a zoochorous ruderal weed associated with animal husbandry widespread in the Old World desert belt. The occurrence of *Tribulus* already at the time of forest decline before 4350 cal yr BP and the findings of tree charcoal suggest the presence of nomads and their livestock. Fires could have been lit to favour the growth of grasses and to drive out predators. Taken together, our evidence implies that nomadic husbandry in southern Mongolia dates back to about 5000 yr. This of course remains speculative, because *Tribulus* may have also been brought in by wildlife migrating between the mountains and their forelands.

## 7. Conclusions

Results of biogeographical, ecological and palaeoecological analyses support the view that today's most isolated mountain forests in Central Asia persist due to self-supporting meso-climatic effects. These meso-

climatic effects are related to the presence of permafrost-layers sheltered by the closed canopy of dwarf birch–willow forest. *Larix* charcoal and pollen analyses indicate that those birch–willow forests were once connected to a much more extensive taiga forest that was reduced by climatic shifts and human influence during the warm and dry middle Subboreal at around 4350 cal yr BP in the Gobi Altay and 3800 cal yr BP in the southern Mongolian Altay. This is also supported by biogeographical inferences drawn from the presence of several species typical of coniferous forests that must have migrated into the area under a moister climate. The precipitation increase is believed to have been about 100–200 mm compared to modern levels, i.e., an amount sufficient to alter the vegetation of large parts of the now (semi-) desertic Gobi. Vegetation types that would have been more common under such a scenario would have included elm woodlands, which may have played a role in facilitating the dispersal of some species up to the Qilian Shan in northern China. The presence of human-indicating pollen and charcoal suggests that the Subboreal forest fragmentation was probably enhanced by nomads to an extent which is difficult to assess with the currently available data.

We found a related pattern, i.e., a decrease of forests paralleled by drying of the climate and followed by the establishment of rich grazing grounds and evidence of increasing grazing pressure, in several other currently arid regions. Similar events occurred in the eastern Hindukush (Pakistan) at around 5200 cal yr BP (Schlütz, 1999), the Tibetan Himalaya of Nepal at 6100 cal yr BP (Mieke et al., 2002) and in Lhasa (southern Tibet) at around 5300 cal yr BP (Mieke et al., 2006). In all cases humans had either actively accelerated climatic forest decline or at least suppressed the re-establishment of forests by fires and/or the keeping of livestock. Once those forests were destroyed, regeneration was probably impeded not only by humans and their livestock and fires, but also by the loss of the self-supporting mechanisms of vegetation persistence (Fig. 7). Thus, Central Asia might have been subject to similar environmental changes to those of the Saharan woodlands and lakes in the western desert belt of the Old World.

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