Larch Timberline and its Development in North China

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Alpine vegetation and timberline development were investigated on 4 high mountains in North China: Mt. Taibai (34°N, 108°E; 3767 m), Mt. Guandi (38°N, 111.5°E; 2831 m), Mt. Wutai (39°N, 113.6°E; 3058 m), and Mt. Xiaowutai (40°N, 115°E; 2882 m). The relationships between distribution of tree species and climatic factors on the uppermost parts of these mountains were established. As a result of the continental climate, their timberlines are composed of larch species, such as Larix chinensis *on Mt. Taibai and* Larix principis-rupprechtii *on the other mountains. Two climatic indices, a warmth index (WI) and a humidity index (HI), were calculated for a differentiation of tree species near the timberline. A WI of 15 °C mo has been commonly regarded as the limit for the timberline in East Asia. In addition, we suggest that the* Larix *timberline is formed when the HI is lower than 210. The understorey species of the forest patches inside the timberline and the* L chinensis *forest are similar on Mt. Taibai. These species are also distributed mostly in subalpine scrubs and meadows rather than in the* Abies fargesii *forest. This implies greater resistance to cold and drought in* L chinensis *than in* A fargesii. *Timberline movements were roughly reconstructed through analysis of sediments from the alpine zone of Mt. Taibai. A drier climate during 1830–1450 ^{14}C years BP resulted in a lower* Abies *timberline and was favorable for distribution of* Larix, *reflected by pollen diagrams and palaeolimnological evidence, such as grain size and total organic carbon. Percentages of* Abies/Picea *pollen recurred from 1450 to 680 ^{14}C years BP, implying an upward movement of* Abies/Picea. Abies/Picea *then moved downward, and the timberline was possibly replaced by* Larix. *In recent centuries,* Picea/Abies *has tended to move upward again.*

Keywords: Alpine timberline; Larix; *vegetation–climate relationship; palaeovegetational reconstruction; temperate broadleaved forest zone; China.*

Introduction

Different authors use various definitions for the upper limit of forests on high mountains (Körner 1999). In the present article we use "forestline" as the upper limit of closed forest, "treeline" as the upper limit of trees with a height of more than 2 m, and "timberline" as the ecotone between forestline and treeline, a definition
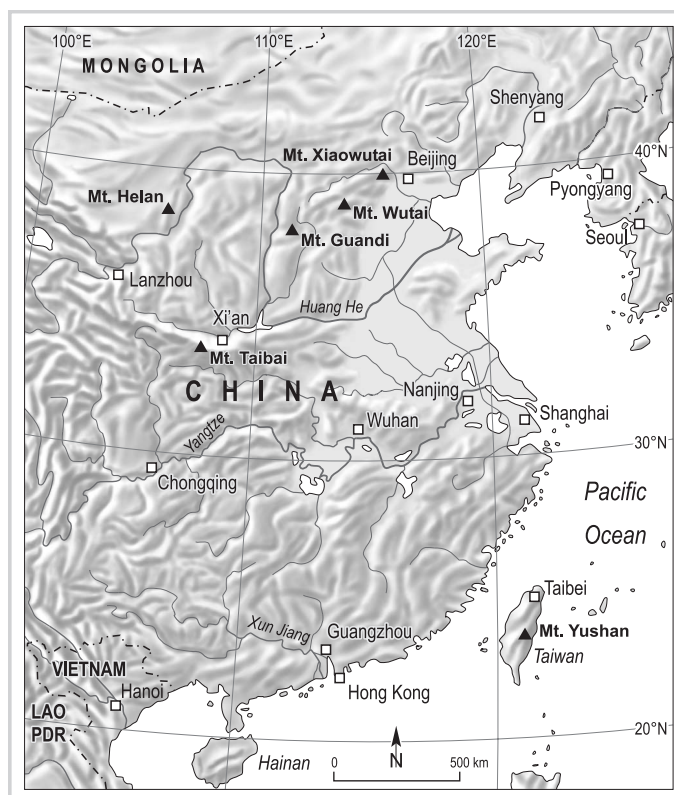

FIGURE 1 Locations of some selected high mountains on map of mountain ranges in China. (Map by Andreas Brodbeck)

that has been widely accepted in recent years (Bliss 1985; Slatyer and Noble 1992; Holtmeier 1994; Pott et al 1995). The "alpine zone" refers to altitudes above the treeline, whereas the "subalpine zone" is roughly equal to the timberline (Cui 1983; Bliss 1985; Didier and Brun 1998), although some authors refrain from using these terms (Körner 1999).

The upper limits of forests are characterized by different plant species, including evergreen conifers (such as *Picea, Abies,* and *Pinus*), deciduous conifers (such as *Larix*), and deciduous broadleaved trees (such as *Betula, Fagus, Ulmus, Acer, Sorbus,* and *Alnus*) in the temperate zone (Walter 1979; Körner 1999). The tree species that constitute the timberline differ according to the climatic zone in which the mountain is located. Studies of the climatic factors that determine alpine tree species differentiation have been carried out for several decades and are helpful in modeling and predicting the migration of tree species under estimated future climatic changes (Fischlin and Gyalistras 1997). Based on regional and even global data, warmth conditions, such as temperature sum, temperature in summer or winter, and seasonal thermal amplitude, were usually linked to the species composition of the timberline (Ives and Bar-

ry 1974; Tranquillini 1979; Ohsawa 1990; Jobbagy and Jackson 2000).

Only a few mountains are high enough to show timberline and alpine vegetation in China's warm temperate forest zone (Cui 1983). Located at the transition between the subtropical zone and the temperate zone, Mt. Taibai (34°N, 108°E; 3767 m), the highest peak of the Qinling Mountain Range, is also the second highest mountain in the eastern part of China, next to Mt. Yushan on the Island of Taiwan. At the center of the temperate forest zone, Mt. Guandi (38°N, 111.5°E; 2831 m), Mt. Wutai (39°N, 113.6°E; 3058 m), and Mt. Xiaowutai (40°N, 115°E; 2882 m) are high enough or nearly high enough to reach the climate-controlled timberline (Figure 1).

Ohsawa (1990) pointed out that the forest limits consist mostly of evergreen needle-leaved trees, with some deciduous broadleaved trees on mountains in humid East Asia. Temperature indices were used to interpret the latitudinal patterns of forest limits in his work. In the warm temperate forest zone in northern China, the high mountains are located in the semiarid region (Department of Geography of Northwest Normal University and Map Press 1984). In contrast with humid East Asia, their alpine timberlines are composed of larch species. It is still unclear how environmental factors affect the larch timberline in North China and how the larch timberline has developed under changed climate conditions.

To explain the occurrence of the larch timberline, current vegetation–climate relationships should be established. In China several indices have been introduced to link vegetation patterns to climatic conditions (Ni 1998). Kira's warmth index (WI) is useful for interpreting the vegetation–climate relationship in North China (Ni 1997). This index was also used to study altitudinal distribution of vegetation at the edge of the Tibet Plateau (Li 1983; Li et al 1985; Zheng 1995). On the basis of Kira's WI, Li (1983) further suggested a humidity index (HI, also abbreviated as MI in some references) to reflect the effect of combined warmth and humidity on vegetation differentiation at the edge of the Tibet Plateau. In temperate China no research work has focused on vegetation–climate relationships in the alpine and subalpine zones so far. Accordingly, 2 main questions will be addressed here. Are humidity conditions critical to the differentiation of spruce or fir timberline and larch timberline? Is an HI also feasible for temperate China?

The current timberline is also a result of past climatic changes (Körner 1999). Although several palaeoecological studies have been done on Mt. Wutai and Mt. Taibai (Tong et al 1996; Rost 1999), they have not explained how the larch timberline developed. The present article uses palynological and palaeolimnologi-

cal evidence to explain the late Holocene development of a larch timberline in temperate China.

Methods

Vegetation survey

Sample plots of plant communities were made for alpine and subalpine vegetation every 10 m along an altitudinal gradient on the 4 mountains studied. Five samples were taken at each altitude under different topographical conditions. Plot size for scrub communities was 2×2 m, whereas that for meadow communities was 1×1 m (Mueller-Dombois and Ellenberg 1974).

On Mt. Taibai, species of shrubs and herbs under scattered trees and forest patches inside the timberline were surveyed. Tree height, growth conditions (eg, the number of cones), soil depth, and topographic conditions were also recorded. A total of 68 scattered trees and forest patches were sampled.

Calculation of warmth and humidity indices

Kira (1948) defined the WI by using a sum of mean monthly temperatures with a threshold of 5°C:

$$WI = S(t_i - 5°C),$$

where t_i represents the mean monthly temperature when it exceeds 5°C. A WI of months with temperatures of 15°C indicates the upper limit of forests in East Asia (Xu 1981). Similar to the WI, the HI suggested by Li (1983) was used to describe humidity conditions:

$$HI = S(p_i/2 - t_i),$$

where p_i is the mean monthly precipitation when the mean monthly temperature exceeds 5°C. The meaning of t_i is the same as that in the calculation of WI.

Changes in WI and HI along the altitudinal gradient were calculated in this study. Temperature is assumed to decrease linearly with increase in altitude. The lapse rate on Mt. Guandi, Mt. Wutai, and Mt. Xiaowutai ranged between 0.44°C/100 m in December and 0.73°C/100 m in May, and the mean lapse rate on the northern slope of Mt. Taibai was 0.44°C/100 m (Li and Fu 1984; Cheng et al 1993). The mean monthly temperature at a different altitude was then estimated from the data of meteorological stations at the foot of the mountains, subtracting the corresponding lapse for different months.

The altitude with maximum precipitation varies on different mountains (Fu 1983). It has been demonstrated that precipitation reaches its maximum at an altitude of 2928.7 m on Mt. Wutai (Cheng et al 1993), which approximates the peak. Therefore, changes in precipitation with altitude on Mt. Wutai, Mt. Xiaowutai, and Mt. Guandi were calculated using a definite lapse rate obtained from 2 stations on Mt. Wutai, one at its foot and the other at Zhongtai at an altitude of 2895.8 m.

The altitude with maximum precipitation is 1900 m in the summer months and 2500 m in the winter

months on the northern slope of Mt. Taibai (Li and Fu 1984). Precipitation at different altitudes was estimated according to the following formula:

$$P_z = P_h + b[(2H - z)z - (2H - h)h],$$

where H is the altitude with the maximum precipitation, P_z is the precipitation at altitude z, b is a constant related to seasons and geographical locations of a mountain and was obtained after an observation on Mt. Taibai (Li 1983), and h is the altitude of the meteorological station at the foot of the mountain (Taibai Station, 1643 m). HI was then calculated with mean monthly precipitation and mean monthly temperature at different altitudes.

Palaeoecological analysis

A sediment pit 210 cm deep was dug at Dongfoyechi, a desiccated glacial lake on Mt. Taibai. It is located at 3410 m, which is higher than the present forestline.

The pit was resampled at 4-cm intervals. Pollen from two subsamples, where the limnological phases obviously changed, were used for radiocarbon dating at Leibnitz Laboratory in Kiel, Germany. The depth of 198.5 cm had an age of 2220 ± 90 ^{14}C years BP, and that of 60.5 cm had an age of 1530 ± 120 ^{14}C years BP. Pollen analysis with acetolysis treatment was done for palaeoecological reconstruction (Moore et al 1992). From a depth of 80 cm to the surface, all the subsamples with a minimum of 500 pollen grains were counted. The sedimentation rate was very high from 80 cm to the bottom; therefore, every fifth subsample was counted to save time. Grain size and total organic carbon (TOC) analyses were done for palaeoclimatic reconstruction.

Results

Vegetation zonation and characteristics of alpine vegetation

The vertical distribution of vegetation is presented for the northern slopes of Mt. Taibai (Figure 2A) and Mt. Xiaowutai (Figure 2B), where detailed surveys were conducted. The vertical zones on the northern slope of Mt. Taibai can be described as follows (Fang 1963; Lei 1999). The basal zone (480–780 m) is represented by artificial vegetation. Deciduous oak forest dominates from 780 to 2300 m, including *Quercus variabilis* forest at the bottom, *Q. aliena* var. *acuteserrata* in the middle, and *Q. liaotungensis* at the top. *Betula albo-sinensis* forest dominates from 2300 to 2730 m. The evergreen coniferous forest zone, consisting mostly of *Abies fargesii, A. chinensis,* and *A. sutschuensis,* is distributed from 2730 to 3200 m. *Larix chinensis* forest, occurring from 3200 to 3400 m, constitutes the upper limit of the forest. On the subalpine and alpine zones, scrubs and meadows dominate, whereas scattered trees and small forest

FIGURE 2 Vertical distribution of vegetation on (A) Mt. Taibai and (B) Mt. Xiaowutai.
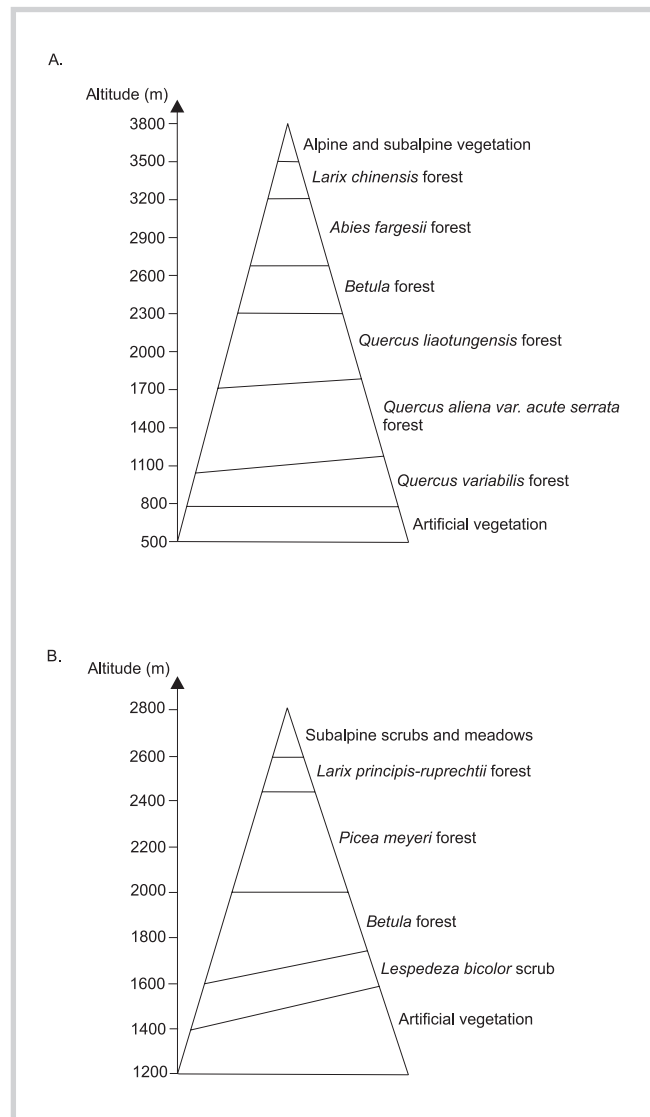
patches of *L. chinensis* characterize the timberline.

The basal zone is characterized by *Ostryopsis davidiana* scrub and *Lespedeza bicolor* scrub, whereas the original vegetation has been thoroughly damaged on Mt. Xiaowutai. From about 1550 m upward, *Betula platyphylla* forest and *B. costata* forest dominate. Above the *Betula* zone is the zone dominated by a mixed forest of *Picea meyeri* and *B. costata*, distributed from 1850 to 2450 m. *P. meyeri* and *B. costata* are mixed with *Larix principis-rupprechtii* from 2450 to 2600 m. From 2600 m upward, *P. meyeri* is no longer present. The upper limit of forest is mostly composed of *L. principis-rupprechtii,* with a small amount of *B. albo-sinensis*. The vertical distribution of vegetation on the northern slope of Mt. Wutai is quite similar to that of Mt. Xiaowutai. No typical alpine vege-

TABLE 1 Altitudes (m) of timberline and treeline on high mountains in North China, based on data from the northern slopes.

	Mt. Taibai	Mt. Wutai	Mt. Xiaowutai	Mt. Guandi
Timberline	3370	2810	2620	2730
Treeline	3600	3015	2800	2790

tation occurs on Mt. Guandi because the timberline is close to its summit.

The altitudes of the timberline and the treeline of these mountains are listed in Table 1. It must be emphasized that the common characteristic of these 4 mountains is that a *Larix* zone usually occurs above the *Picea* or *Abies* zone. The forestline and the timberline are usually composed of *Larix* species, especially on their northern slopes.

Table 2 shows species composition for different vegetation types in the alpine and subalpine zones of these 4 mountains. A *Kobresia*-dominated meadow is an indicator of the alpine zone in China and is typical for Mt. Taibai and Mt. Wutai (Wu 1980). The subalpine meadow is composed of abundant herb species, as listed in Table 2. The alpine and subalpine scrub communities are dominated by such species as *Caragana jubata* and *Potentilla fruticosa* on Mt. Wutai and Mt. Guandi and by *Rhododendron przewalskii, Rh. capitatum, Spiraea alpina,*

and *Salix cupularis* on Mt. Taibai. As for Mt. Xiaowutai, the species composition is quite simple.

Scattered trees or small patches of forest occur and form the timberline. Some of the trees bear cones on their twigs, demonstrating their self-regeneration. The understorey species of the timberline forest patch and the *L. chinensis* forest are similar on Mt. Taibai. These species are all distributed in subalpine scrubs and meadows rather than in the *A. fargesii* forest. Greater resistance to cold and drought is implied for *L. chinensis* than for *A. fargesii*. It was further deduced that the *Larix* forest succeeded from subalpine scrubs and meadows, with no evidence of further development to *Abies* detected.

Climatic indices

Vertical changes in both temperature and precipitation are similar on Mt. Wutai, Mt. Xiaowutai, and Mt. Guandi. Figure 3 shows the changes in the calculated WI (A) and HI (B) with altitude on Mt. Xiaowutai. The altitude with a WI of 15°C month is about 2750 m. The HI first increases with increasing altitude and then decreases at about 2600 m. From Table 3 it is evident that the HI decreases, although the annual precipitation still

TABLE 2 Comparison of dominants in alpine and subalpine vegetation on high mountains in North China.

Vegetation types	Mt. Taibai	Mt. Wutai	Mt. Xiaowutai	Mt. Guandi
Alpine meadow	*Kobresia graminifolia*	*K. bellardii*	*K. bellardii*	*K. bellardii*
		K. pygmaea		
			K. humilis	
Subalpine meadow	*Saussurea iodostegia*	*Koeleria litvinovii*	*S. iodostegia*	*Agrostis gigantea*
	Festuca ovina	*S. iodostegia*	*Libanotis condensata*	*S. iodostegia*
	Allium pratii	*Anemone obtusiloba*	*Astragalus moellendorfii*	*Poa sphondyloides*
	Polygonum sphaerostachyum	*Trollius chinensis*	*Polygonum viviparum*	*Carex lanceolata*
	Pedicularis rhinanthoides var. *labellata*	*Primula farinosa*		*Ligusticum jeholense*
		Potentilla nivea		
		Papaver nudicaule		
Alpine and subalpine scrub	*Rhododendron przewalskii*	*Caragana jubata*	*Salix phylicifolia*	*C. jubata*
	Rh. capitatum	*Potentilla fruticosa*		*P. fruticosa*
	Spiraea alpina	*Salix characta*		*S. alpina*
	Salix cupularis	*Lonicera caerulea*		
		Lonicera hispida		
Forest patches and scattered trees	*Larix chinensis*	*L. principis-rupprechtii*	*L. principis-rupprechtii*	*L. principis-rupprechtii*

FIGURE 3 Changes of climatic indices with altitude on Mt. Xiaowutai: (A) WI and (B) HI.
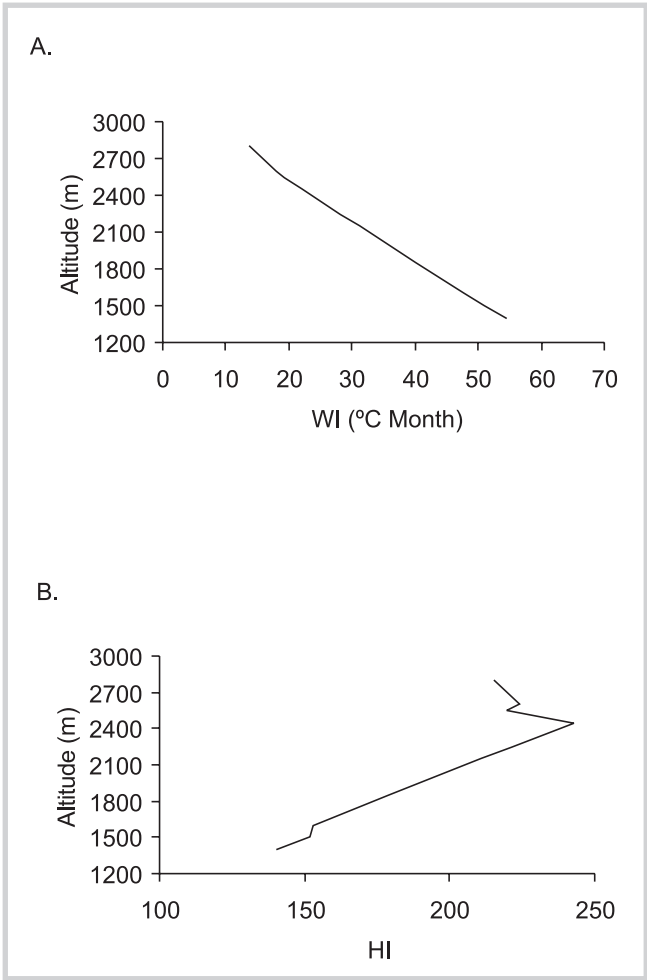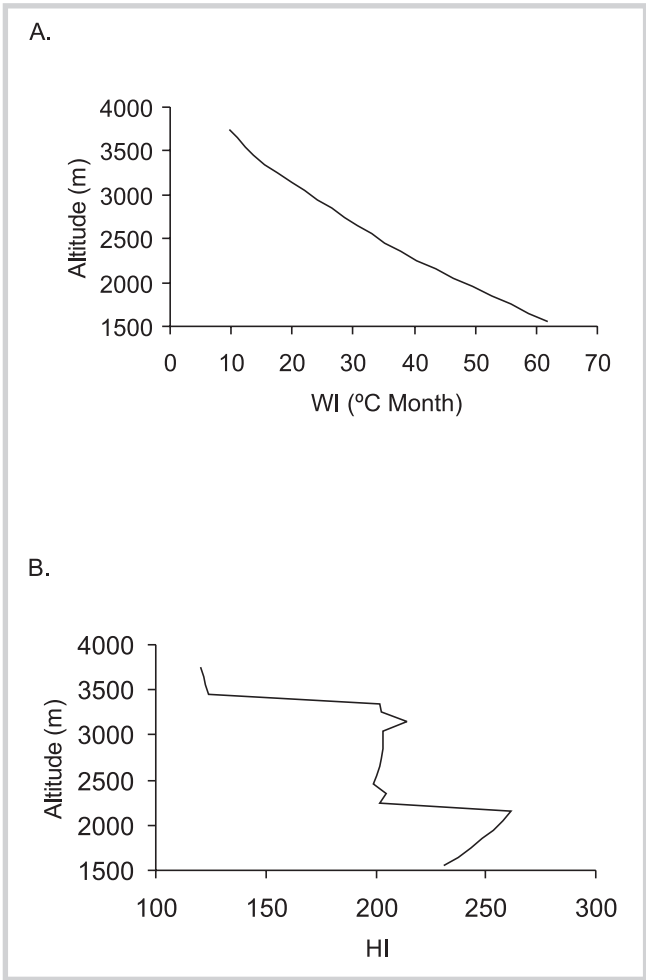

FIGURE 4 Changes of climatic indices with altitude on Mt. Taibai: (A) WI and (B) HI.

increases when the altitude exceeds 2600 m, implying a low efficiency of water use by the plants due to low temperatures.

  Changes in WI and HI with altitude on the northern slope of Mt. Taibai are presented in Figure 4. WI (A) is below 15°C month, and HI (B) decreases rapidly to a level of less than 200 at about 3400 m. Annual precipitation generally decreases from 2350 m upward on Mt. Taibai (Table 4). However, the HI oscillates between 200 and 210 from 2350 to 3350 m and then decreases abruptly, because of the shortening of the temperature-related growing season.

Palaeoclimatic and palaeovegetational reconstruction
The results of pollen analysis as well as palaeolimnological analysis (grain size and TOC) are presented in Figure 5. The most common pollen taxa are *Cyperaceae, Pinus, Tsuga, Betula, Picea,* and *Abies.* Except that *Tsuga* is not present in modern vegetation, the other taxa reflect the vegetation characteristics of Mt. Taibai.

TABLE 3 Calculated climatic conditions for different altitudes on Mt. Xiaowutai. (HI, humidity index; WI, warmth index.)

Altitude (m)	Mean temp. in Jan. (°C)	Mean temp. in Jul. (°C)	Mean annual temp. (°C)	Mean annual precip. (mm)	WI (°C mo)	HI
1400	−15.2	19.2	3.5	528	54.5	140.1
1600	−16.4	18.0	2.3	572	47.6	152.7
2250	−20.3	14.1	−1.6	717	28.1	221.4
2600	−22.4	11.9	−3.7	796	18.1	224.0
2800	−23.6	10.8	−4.9	840	13.7	215.0

FIGURE 5 Diagrams of grain size, TOC, and pollen from Dongfoyechi Lake, Mt. Taibai. Sand represents sediments with a grain size >0.063 mm.

Discussion
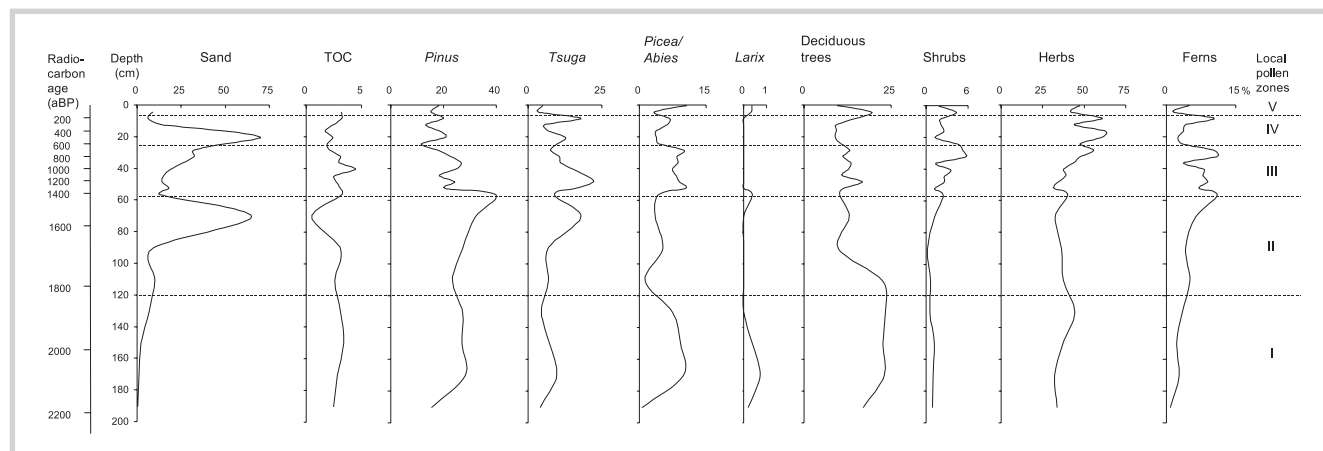
Assuming the transportation rate of the same pollen type to be constant, the percentages of pollen are related to the relative distance from the pollen source to the location of the lake. Thus, species movement can be inferred from the changes in the pollen values.

During 2150–1830 ^{14}C years BP, *Abies* and *Picea* pollen had a peak, which implies that the *Abies/Picea* timberline had reached a high altitudinal level. The timberline then obviously decreased and remained at a low level during 1830–1450 ^{14}C years BP. Percentages of *Abies/Picea* pollen recurred from 1450 to 680 ^{14}C years BP. Another valley of *Abies/Picea* pollen was retained from 680 to 200 ^{14}C years BP. In recent centuries, *Picea/Abies* has tended to move upward.

Palaeolimnological evidence, including percentages of sands with grain sizes >0.063 mm and TOC values, was used to reconstruct palaeoclimatic conditions. When the climate became drier, the sedimentation rate decreased because of minimal transportation by water. The weathering residue contained coarser materials as a result of a relatively lower weathering rate. A high percentage of sand thus occurred, and TOC had a converse tendency. A good negative correlation between the percentages of sand and *Abies* + *Picea* pollen is observed in the diagrams, demonstrating that movement of the *Abies* timberline was caused by climate change. A dry climate dominated during 1830–1450 ^{14}C years BP, as indicated by the high percentage of sand and the low TOC.

Larix pollen remains low in the whole diagram, because of its low preservation ability. Therefore, it is difficult to determine the exact altitudinal ranges and composition of the timberline for lack of macrofossil evidence. However, it is speculated that the *Abies/Picea* zone might have been higher than its present level from 2250–1830 ^{14}C years BP, after which it spread out to a lower altitude from 1830–1450 ^{14}C years BP, for which a cold and dry climate was inferred from historical documents (Zhu, 1973).

Relationship between climate and species composition on the timberline in China

Warmth conditions are usually among the important considerations in studies of alpine vegetation–climate relationships (Körner 1998). Jobbagy and Jackson (2000) suggested that temperatures during the warm part of the year are the main factor controlling forestline elevation in extratropical regions, whereas temperatures during the cold part of the year affect the dominant life form of trees. It was further concluded that along a gradient of increasing seasonal thermal amplitude (STA, ie, mean of the warmest month minus mean of the coldest) and decreasing winter temperatures, forestlines were first dominated by evergreen broadleaf trees, followed by deciduous broadleaf species, evergreen conifers, and finally deciduous conifers. Our results suggest that the distribution of the *Picea* zone under the *Larix* zone is controlled by humidity, and the *Larix* timberline in China's temperate broadleaved forest region is caused by both warmth and humidity conditions.

The timberline in the study area is different from the *Picea/Abies* timberline in East Asia's humid area as described by Ohsawa (1990). Although *Picea/Abies* forest and *Larix* forest can both tolerate cold and form a timberline, the higher humidity requirement of *Picea/Abies* has limited its distribution on high mountains in a continental climate. However, the timberline in China's semi-arid areas is composed of *Larix* species adapted to a dry climate. Li (1983) demonstrated that the timberline is made up of *Picea/Abies* when HI exceeds 210 in China's subtropical zone. He also used this threshold to distinguish a semiarid climate from a humid one. Our study draws similar conclusions and further demonstrates that an HI of 210 can be used as a threshold for a *Larix* timberline. However, the timberline in China's desert zone is constituted by *Picea* species, such as *P. schrenkiana* on

the Tianshan Mountain Range and *P. crassifolia* on Mt. Helan (Wu 1980; Tian 1996). Fu (1983) suggested that the altitude with maximum precipitation increases when the climate becomes drier; therefore, the *Picea* timberline in China's desert zone may be ascribed to higher-humidity conditions on the timberline because of the higher altitude and maximum precipitation. We still require a detailed study of this phenomenon. Moreover, the *Larix* timberline is not unique in the temperate zone of China. The timberline on the central Alps is composed of *Larix* species, which is quite different from that on the southern and northern Alps. Humidity conditions also contribute to this (Walter 1979).

   Different indices are used to show vegetation–climate relationships in different parts of the world. WI and HI are not commonly used, except in East Asia. For a comparison, other temperature parameters are also listed in Tables 3 and 4. The mean temperatures in the warmest month are 10–11°C on both Mt. Xiaowutai and Mt. Taibai, close to temperatures in the northern temperate zone, such as those in the central Alps (Körner 1999). Other indices such as mean temperature in the coldest month, mean annual temperature, and annual precipitation at the timberline show great discrepancies between Mt. Xiaowutai and Mt. Taibai.

   The HI takes into consideration both temperature and precipitation during the growing season for tree species and is thus another useful tool for explaining vegetation distribution in mountainous areas. Using this index is better than using only annual precipitation. However, there are still several shortcomings. First, it is usually difficult to calculate HI, owing to the

lack of microclimate studies on high mountains, especially to determine the altitude with maximum precipitation. Second, the time ranges of climatic data also affect HI estimation, owing to climatic fluctuations. Third, the complicated topographic conditions in mountainous areas play an important role in the distribution of precipitation and temperature, but it is usually difficult to give an exact estimation. Even with these shortcomings, the HI is useful for describing the vegetation pattern of an alpine zone on a regional scale, in addition to the WI, and it is also useful in understanding the differences between humid and semiarid areas.

Development of the *Larix* timberline

Past rather than current climates may have determined treelines (Körner 1999). Generally, the response of vegetation to climatic changes is more pronounced near vegetation ecotones at medium and higher altitudes than in the lowlands (Wick 2000). Pollen and macrofossil evidence are good indicators of changes in the position and species composition of timberlines. Some authors have studied timberline development on the Alps and concluded that spruce expansion from 7500 to 6300 ^{14}C years BP was due to a more humid climate. Spruce then spread out, whereas *Larix* spread into the timberline, owing to a more continental climate (Bauerochse and Katenhusen 1997; Wick and Tinner 1997). We suggest a process of *Abies* spreading out on Mt. Taibai, but *Larix* dynamics are difficult to observe in pollen diagrams.

   Rost (1999) found that a significant lowering of the timberline, which might have been initiated by climate

TABLE 4 Calculated climatic conditions for different altitudes on Mt Taibai. (HI, humidity index; WI, warmth index.)

Altitude (m)	Mean temp. in Jan. (°C)	Mean temp. in Jul. (°C)	Mean annual temp. (°C)	Mean annual precip. (mm)	WI (°C mo)	HI
1550	−4.8	19.0	7.6	755.3	61.9	231.0
1750	−5.6	18.1	6.7	775.5	55.7	243.1
1950	−6.5	17.3	5.8	789.6	49.6	253.3
2150	−7.4	16.4	5.0	797.5	43.4	261.8
2350	−8.3	15.5	4.1	799.2	37.7	204.6
2550	−9.2	14.6	3.2	794.8	33.0	200.5
2750	−10.0	13.7	2.3	784.3	28.6	202.7
2950	−10.9	12.9	1.4	767.6	24.2	203.6
3150	−11.8	12.0	0.6	797.5	19.8	214.2
3350	−12.7	11.1	−0.3	715.7	15.4	201.6
3550	−13.6	10.2	−1.2	680.5	12.4	122.8
3750	−14.4	9.3	−2.1	639.1	9.7	120.3

change, occurred 2000–3000 years ago on Mt. Wutai. Wood and charcoal fragments of both *Larix* and *Picea* have been observed, indicating that the previous timberline had consisted of both *Picea* and *Larix*. The distribution of *Picea* was reduced, and *Larix* was retained in the timberline, possibly because of climatic drying. A reduction of *Picea/Abies* on Mt. Taibai also can be observed during the same period from pollen diagrams. Fire might also be favorable for *Larix* during such climatic transitions, as inferred from the charcoal on Mt. Wutai (Rost 1999). However, fire initiation and frequency also are controlled by climatic conditions. Climate is critical for development of timberline composition.

It can be implied from this study that *Larix* forest would not show any succession to *Picea* or to *Abies* forest under current climatic conditions. The *Larix* timberline cannot be regarded simply as a pioneer stage of *Abies* or *Picea* forest, as suggested by Liu (1985). It might develop to *Abies* or *Picea* forest in the future but only when the climate becomes more oceanic.

Conclusions

We conclude that both temperature and precipitation control the composition of the timberline in China's temperate broadleaved forest zone. *Larix* species characterize the timberline, and *Picea* and *Abies* species form a belt under the *Larix* belt. The occurrence of *Larix* may be caused by drought during the growing season. The distribution of *Picea* and *Larix* is well differentiated by HI, which shows the humidity conditions during the growing season. Palaeoecological evidence shows a decline of *Abies* on Mt. Taibai caused by climatic drying from 1830–1450 ^{14}C years BP, which further demonstrates that the current occurrence of *Larix* timberline is controlled by climate. The *Larix* forest is not a pioneer stage of succession. Replacement of *Abies/Picea* forest by *Larix* forest will occur only under a more oceanic climate.

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