Natural and anthropogenic forest fires recorded in the Holocene pollen record from a Jinchuan peat bog, northeastern China

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Abstract

Pollen and charcoal particles from a Jinchuan peat (northeastern China) were examined to investigate the fire origin and interaction between climate, vegetation, fire and human activity during the Holocene. Pollen results show that: (i) a broadleaved deciduous forest was dominant during the early Holocene; (ii) from ~5500 cal. yr B.P. there was a gradual increase in coniferous trees (mainly *Pinus*), and a decrease in broadleaved deciduous trees (e.g. *Quercus*, *Juglans*, and *Ulmus-Zelkova*); (iii) after ~4200 cal. yr B.P., the deciduous forest was replaced by a mixed forest of coniferous and deciduous trees; (iv) coniferous trees including *Pinus*, *Abies* and *Picea* further increased after ~2000 cal. yr B.P., reflecting a cooler and drier climate after ~5500-4200 cal. yr B.P. Two layers of abundant microfossil charcoal particles (250-10μm) and the coexistence of macrofossil particles (>2 mm) suggest two local fires: fire event 1 (5120±66 cal. yr B.P.) and fire event 2 (1288±8 cal. yr B.P., AD 662±8). Charcoal layer 1, with a large amount of Monolete psilate spores, is superimposed on the long-term trend of vegetation changes, indicating a natural origin for fire event 1 that was probably facilitated by drying environmental conditions since the mid-Holocene. Cerealia-type pollen and a low percentage of Monolete psilate spores were observed in charcoal layer 2, indicating that fire event 2 was caused by clearing. We suggest that fire event 2 may be related to the spread of the Han farming culture accompanied by the terrestrial expansion of the Tang Dynasty to the studied area in AD 668.

Keywords: Pollen record; Fire; Vegetation; Human activity; Holocene; Northeastern China

1. Introduction

Fire is recognized as an important agent in ecological systems (e.g. Cochrane et al., 1999; Haberle et al., 2001; Whitlock et al., 2003). It also affects the global carbon cycle and climate through emissions of CO_2 and other greenhouse gases (Page et al., 2002; Kurtz et al., 2003). For example, the 1997 Indonesian fire caused by long-term droughts led to the destruction of the rainforest and establishment of pioneer species within the southeastern Asia and the New Guinea region (Haberle et al., 2001), and the greatest annual increase in atmospheric CO_2 of the past 50 years (Page et al., 2002). In addition to natural fire triggers such as droughts, human activities can also play an important role in the occurrence of fire. It is important to differentiate the origin of fire for an improved understanding of the interaction between vegetation, climate and human activity in the geological past (Edwards et al., 2007).

Fire used to play an essential role in the advancement of human civilization. It was used as a source of heat and light, and was also used for cooking and to fend off wild animals. In agriculture, fire was used to clear lands in preparation for planting (de Vries and Marchant, 2002). China ranks amongst the world's great centres of ancient civilization, with a recorded history of at least 5000 years. Archaeological findings have demonstrated that agriculture was first established in the Yellow and Yangtze valleys (Yasuda, 2002; Kong et al., 2003) (Fig. 1A), and then gradually spread out to the surrounding areas. However, the pattern and pace of this agricultural spread remains unclear. Solutions to this problem largely depend on more high-quality historical documents and precisely-dated geological records.

Northern China is climatically influenced by the East Asian monsoon (Fig. 1A), where more than 0.4 billion people live (Ye et al., 2002). Agricultural activities, i.e. cultivation and herding, are closely linked to monsoonal precipitation. During years of extreme monsoon activity, severe disasters (dust storms, droughts and floods) resulting from the monsoon can impact hundreds of thousands of people. By contrast, excessive agricultural activities have led to desertification, soil erosion/degradation, and pollution (Ye et al., 2002). These impacts on the ecosystem are considerable and often even irreversible. Therefore, it is essential to achieve sustainable development through management of modern agriculture, which demands a better understanding of the complex interactions between human activities and the natural ecosystem. However, in the East Asian monsoon region, little is known about the relationship between human activity and the natural ecosystem (Dodson et al., 2006). Here we present records of pollen and charcoal, and high-resolution pollen assemblages in two radiocarbon-dated charcoal layers, from a peat bog in Jinchuan, northeastern China. Our aim is to separate the origin of fire events through high-resolution pollen analyses, and to explore the effect of climate and human activity on vegetation changes and fires.

2. Field and methods

2.1. Geographical background

The Jinchuan peat bog (42°22'N, 126°26'E, 662 m a.s.l.) is located to the west of Jinchuan village in Huinan County, Jilin province, northeastern China. The bog is nearly circular, with a diameter of ~1 km. It is believed that the Jinchuan bog grew in a hollow left by a maar (Liu, 1999) or from a barrier lake formed by volcanic activity (Hong et al., 2000). It sits on the western edge of the Longgang mountainous area, which is known for its Late Pleistocene and Holocene volcanic activity and especially its maar lakes (Fig. 1B), with a relief between ~400 and ~1200 m a.s.l. Approximately 150 km to the east of the studied site, the Changbai Mountains lie on the border of China and Korea (2691 m a.s.l., the highest peak on the Chinese side).

The climate of the region is sub-humid temperate, with a mean annual temperature of 3°C. The mean temperature in January is -18°C, whereas in July it is 20°C (Sun and Yuan, 1990). The East Asian monsoon system brings warm and wet humid weather in summer and cold, dry weather in winter. Mean annual precipitation is ~700 mm. The mean January precipitation is less than 25 mm, the value for July is ~200 mm.

The region falls within a temperate mixed deciduous and coniferous forest zone (Editorial Board for Flora of China, 1995; Hou, 2001) (zone II on Fig. 1A). As the Longgang Mountains and Changbai Mountains lie to the east, the natural vegetation shows zonal distribution along the altitudinal gradient (Table 1). Bog vegetation today mainly includes *Carex, Sphagnum* and *Betula* (Sun and Yuan, 1990).

2.2. Sampling

A thick outcrop of peat sediments remained in the field after extensive peat exploitation. An undisturbed stratigraphic sequence is preserved at the side of the excavation. In this study (fieldwork in 1999), two parts were stacked to form the profile. The lower part (depth 330-500 cm) was taken by a hand corer. The upper part (depth 0-330 cm) was taken from the outcrop. There is a change in lithology, from lake/river sediments (Zone B, depth 500-412 cm) to peat deposits (Zone A, depth 412-0 cm) (Fig. 2). Zone B consists of two grey silty marl beds intercalated by two beds of sands and angular pebbles. Zone A consists of peat. Six modern samples were also collected in the study area (Fig. 1B). Surface samples collected in June 1997 at altitudes ranging from 600 to 800 m in the mixed conifer and broadleaved deciduous forest were taken either from lake-sediment interfaces by a simple grab-like technique or from moss polsters. They complement the existing data sets of surface samples of northern China (Sun and Wu, 1988; Sun and Yuan, 1990; Li et al., 2000; Sun et al., 2003; Li et al., 2005a, b; Xu et al., 2005, 2007).

2.3. Methods

Fifty-three samples were analysed for pollen assemblages. To aid pollen concentration calculations, *Lycopodium* spore tablets were added to the samples. Then all samples were treated with sodium pyrophosphate, hydrochloric acid (HCl), hydrofluoric acid, HCl again and acetolysis, and the residues washed by sieving through 250 μm and 10 μm meshes. The pollen residues were suspended in glycerol. More than three hundred land pollen grains were identified at X400 magnification, with X1000 magnification employed for difficult identifications. Charcoal selection was restricted to fragments that were opaque and black, with angular-irregular and elongated forms or cellular structures (Fig. 3). Those fragments between 250 and 10 μm were counted. High-resolution pollen analysis was then carried out on two layers with abundant charcoal fragments at an interval of 0.5-1 cm. Sieving through a 2-mm mesh was also carried out on these two charcoal layers. Many large charcoal particles (>2 mm) were found and picked out for ^{14}C dating (Table 2).

Percentages of each pollen taxon, including charcoal, aquatic pollen, spores and algae, were calculated relative to the sum of land pollen. Using the Psimpoll 4.25 plotting programme (Bennett, 2005), the pollen percentage record was divided into assemblage zones based on constrained cluster analysis (the pollen percentage values above 0.5 % were transformed into the square root) (Grimm, 1987). The fossil pollen data were then assigned to plant functional types (PFT) using the PFT classification scheme of Yu et al. (2000). PFT scores are defined as the sum of the square root of the pollen percentage values above 0.5 %

(Prentice et al., 1996). Then the changes in vegetation were reconstructed based on the affinity scores for steppe vegetation, deciduous and coniferous trees.

3. Results

3.1. Age model

The age model is based on four AMS ^{14}C dates of bulk organic carbon and two charcoal dates (Table 2; Fig. 2). The age model was established using the method of Depth-Age Conversion (Maher, 1992). These six age control points were fitted to a second-degree polynomial. A 2nd-order function of dates was established (R^2=0.99). With that function, the original depth of each sample was converted to age. Dates quoted in the text are expressed as calendar years. Ages for samples below the depth of 330 cm were constructed by extrapolation, as all six ^{14}C ages were from the portion above that depth.

3.2. Pollen assemblages of modern samples

Sample numbers 1-5 were collected from surface sediments of lakes, and sample No. 6 from the moss polsters of the top of the Jinchuan peat bog (Fig. 1B). For modern samples, arboreal pollen ranges from 56 to 85 %, averaging ~76 % (Fig. 4). The arboreal pollen is mainly composed of *Pinus* and *Betula* and to a lesser degree, *Quercus*, *Juglans*, *Fraxinus*, *Populus*, *Salix*, *Ulmus*, *Abies* and *Picea*. Herbaceous pollen averages ~24 %, mainly *Artemisia*, Cyperaceae, Poaceae, Tubuliflorae, Liguliflorae, *Sanguisorba officinalis* and *Thalictrum*. Cerealia-type pollen, produced by cultivated species (Cerealia), was observed in two of the modern samples. Aquatic pollen and spores are present in very low percentages.

The vegetation type reflected by modern pollen spectra is consistent with the regional vegetation: a mixed coniferous and deciduous forest.

3.3. Pollen assemblages of fossil samples

The pollen profile can be divided into five zones (Figs. 5-1A and 5-2A). Throughout the pollen profile, arboreal pollen dominates the total pollen sum. Herbaceous pollen comprises 20-50 %. Aquatic pollen, spores and algae are present in very small amounts, except in Pollen Zone 2, where large amounts of Monolete psilate spores emerge. Two layers of abundant charcoal debris were found, one in Pollen Zone 2 and the other in Pollen Zone 4.

Pollen Zone 1 (Depth 465-302 cm; ~10,800-5500 cal. yr BP)

The basal age of this zone is the least robust of the chronological model. Arboreal pollen (AP) comprises up to 60-80 % of the total pollen sum, with *Quercus*, *Juglans*, *Fraxinus* and *Ulmus-Zelkova* as the main types. Other arboreal pollen taxa, such as *Acer*, *Alnus*, *Betula*, *Carpinus*, *Corylus*, *Salix*, and *Tilia* are present in smaller percentages. Herbaceous pollen is mainly composed of Cyperaceae, *Artemisia* and Poaceae. Pollen concentrations are consistently low except at ~6600 cal. yr B.P. Vegetation reconstructions (Fig. 6A) show that deciduous trees dominated the region at this time.

Pollen Zone 2 (Depth 302-250 cm; 5500-4200 cal. yr B.P.)

AP decreases to 50-60 %, the minimum percentage over the whole pollen profile, due to a drop in the values of *Juglans*, *Quercus* and *Ulmus-Zelkova*, and an increase in Cyperaceae. Conifers such as *Pinus* and *Abies* increase. The PFT score of coniferous trees rises, mainly due to an increase in *Pinus*. This zone is also characterized by a large amount of Monolete psilate spores and a thick charcoal layer from depth 295 to 267 cm.

Pollen Zone 3 (Depth 250-135 cm; 4200-1980 cal. yr B.P.)

Coniferous trees increase, attributable to a rise in *Pinus, Abies* and *Picea* percentages. Deciduous trees show little variation (Fig. 6A). *Artemisia* increases and Cyperaceae begins to decrease.

Pollen Zone 4 (Depth 135-45 cm; 1980-930 cal. yr B.P.)

More than 50% of arboreal pollen is from *Pinus*, and *Abies* is present up to ~5 %. From 1990 to 1300 cal. yr B.P., coniferous scores increase to the maximum of the whole pollen profile (Fig. 6A, B). Deciduous trees decline due to decreases in *Betula*, *Quercus*, *Juglans* and *Ulmus-Zelkova*. Cyperaceae values drop to the minimum for the whole pollen record. After 1200 cal. yr B.P., *Pinus* gradually decreases and *Betula* increases. Another charcoal layer is observed at the depth of 85-77 cm and at a higher abundance than in the first charcoal layer. Monolete spores are only present in very small amounts, in contrast to the first charcoal layer.

Pollen Zone 5 (Depth 45-0 cm; 930 cal. yr B.P.-present)

AP decreases due to a fall in *Pinus* percentages, and increases in *Artemisia*, Cyperaceae and *Sanguisorba officinalis*. Other arboreal pollen such as *Abies*, *Betula*, *Quercus* and *Juglans* show little variation. Pollen assemblages in this zone are similar to those of the modern samples (Fig. 4).

3.4. High-resolution pollen records in two charcoal layers

Two charcoal layers are present in the Jinchuan peat bog (Fig. 6E). Charcoal layer 1 is dated at 5120±66 cal. yr B.P., and charcoal layer 2 dated at 1288±8 cal. yr B.P.

Charcoal layer 1 (depth 295-267 cm; 5320-4600 cal. yr B.P.): The relative percentage of each pollen taxon shows little variation (Figs. 5-1C, 5-2C, Fig. 6C). A drop of pollen concentrations is observed from 5000 to 4600 cal. yr B.P. (Fig. 5-1C). It seems that the fire occurred at a time when deciduous trees began to decrease and coniferous trees increased (Fig. 6A). Fern spores, reflected by Monolete psilate spores, increased substantially (Fig. 5-2C).

Charcoal layer 2 (depth 85-77 cm; 1320-1240 cal. yr B.P.) is characterised by a sudden peak of charcoal contents (Fig. 6E), around the maximum of *Pinus* values. Despite a drop of pollen concentrations from 1290 to 1250 cal. yr B.P., the relative percentage of each pollen taxon shows little variation (Figs. 5-1B, 5-2B, Fig. 6B). Another important feature is the increased numbers of the Cerealia-type pollen (Fig. 6D).

4. Discussion

4.1. Vegetation changes: climate- or human-induced?

The pollen record in the Jinchuan peat bog results from a combination of changes in local and regional factors. During the early Holocene, the local site vegetation was dominated by Cyperaceae. Other vegetation includes aquatic plants, e.g. *Menyanthes*, *Myriophyllum*, *Potamogeton*, *Typha-Sparganium*, and herbaceous plants, e.g. *Artemisia* and Poaceae. It is inferred that the site was a shallow lake surrounded by a sedge-fern fen. The regional vegetation on the surrounding hills began with a *Quercus* and *Juglans* dominated forest accompanied by *Fraxinus*, *Ulmus-Zelkova*, *Tilia* and *Carpinus*. PFT reconstruction shows that a broadleaved deciduous forest was dominant at this time (Fig. 6A, P-1).

From ~5500 to ~1300 cal. yr B.P. (from P-2 to P-4, Fig. 5-1A), pollen of coniferous trees (mainly *Pinus*) progressively increased to a maximum for the record, while that of broadleaved deciduous trees (e.g. *Quercus*, *Juglans* and *Ulmus-Zelkova*) decreased to a minimum. The mixed coniferous and deciduous forest replaced the deciduous forest after ~4200 cal. yr B.P. (P-3, Fig. 6A). Coniferous trees increased after ~2000 cal. yr B.P., as shown by increasing amounts of *Pinus*, *Abies* and *Picea* (P-4, Fig. 5-1A).

The early to mid-Holocene vegetation pattern from this work is consistent with those of previous studies (Liu, 1989; Yuan and Sun, 1990; Sun et al., 1991; Makohonienko et al., 2001) (Fig. 1B), suggesting that the vegetation changes were of a regional nature. Meteorological data from northern China (Domrös and Peng, 1988) indicate that precipitation and temperature are key factors responsible for the spatial differentiation of modern vegetation (Editorial Board for Flora of China, 1995; Hou, 2001) (Fig. 1A). At present, the temperate mixed coniferous and deciduous forest is the regional vegetation in the studied area, and the broadleaved deciduous forest is located in a warm temperate zone, south of the mixed forest. Therefore, the pollen characteristics suggest a cooler and drier climate after ~5500-4200 cal. yr B.P.

This mid-Holocene drying is well documented in various sediments across China, which is related to the weakening of the East Asian summer monsoon (e.g. Hong et al., 2001; Wang et al., 2005; Li and Sun, 2006; Shao et al., 2006; Tarasov et al., 2006; Jiang and Liu, 2007). The Hulun Buir Desert (47º49'-49º35'N, 117º16'-119º32'E) is also located in northeastern China. Sand dunes are distributed mainly in the northern and southern parts of the desert. Previous studies indicate that the onset of dune stabilization and soil development occurred at ~11000 cal. yr B.P. This early episode of dune stabilization lasted until ~4400 cal.

yr B.P., implying the climate became arid after 4400 cal. yr B.P. (Li and Sun, 2006). High-resolution oxygen-isotope records of precisely-dated stalagmites from Shanbao Cave and Dongge Cave in the East Asian monsoon region also reveal an abrupt decrease in monsoonal precipitation at 6000-4400 cal. yr BP (Dykoski et al., 2005; Wang et al., 2005; Shao et al., 2006). These records reinforce our suggestion that vegetation changes during the mid-Holocene in the studied site were natural and climate-induced.

Our study also shows a decrease in *Pinus* and an increase in *Betula* since ~1200 cal. yr B.P. (Fig. 5-1A, P-4), while other arboreal pollen taxa have little variations. This selective vegetation change suggests that human activity was possibly instrumental in pine removal. Reasons for pine decrease in the Changbai Mountainous area include its preferred use as construction timber, and extensive collection of pine nuts by breaking down all the branches, etc. *Betula* is considered as the pioneer species in the studied area, because it colonizes the land rapidly after slash and burn activity (Zhang, 1983; Editorial Board for flora of China, 1995).

4.2. Fire events: natural or human-induced?

Two fire events, as inferred from the two charcoal peaks, occurred at 5120±66 cal. yr B.P. (fire event 1) and 1288±8 cal. yr B.P. (fire event 2). Charcoal concentrations are higher than the background by 3 times for charcoal layer 1, and 110 times for charcoal layer 2 (Fig. 6E). A higher proportion of the larger particles (>2 mm) was also found in these two charcoal layers and selected for ^{14}C dating (Table 2). According to Lynch et al. (2004), large particles (>1 mm) are characteristic of nearby fires, and charcoal accumulation declines rapidly with distance from the burn edge. Therefore, the occurrence of many large charcoal particles and an increase in charcoal accumulation in our case suggest that the two fire events are of local origin (Whitlock and Larsen, 2001; Lynch et al. 2004).

High-resolution pollen analyses within the two charcoal layers show different pollen patterns. Emergence of large amounts of Monolete psilate spores is the main feature of charcoal layer 1 (Fig. 5-2C), while in charcoal layer 2, the Cerealia-type pollen, produced by cultivated crops, is present (Fig. 6D). These differences suggest that the two fire events were probably related to different causes.

4.2.1. Fire event 1: the spread of fernland and climate changes

Fire event 1 occurred at a time when deciduous trees began to decrease, and coniferous trees began to increase (Fig. 6A). Within charcoal layer 1, deciduous trees, coniferous trees and steppe vegetation show little variation (Fig. 6C). From the top of this charcoal layer upward, pollen of the coniferous trees (mainly *Pinus*) continues to increase, while that of the deciduous trees (e.g. *Quercus*, *Juglans* and *Ulmus-Zelkova)* decreases. Therefore the implication is that the vegetation after fire event 1 follows the same ecological trend as that of pre-fire (Figs. 5-1A, 6A). Thus it appears that fire event 1 did not disturb the long-term ecological pattern of the local ecosystem.

Charcoal layer 1 has a thickness of 28 cm (depth 295-267 cm). Interpolation using six ^{14}C dates yields a time interval between 5300 and 4600 yr B.P. (Fig. 6E). A large amount of Monolete psilate spores occurred in charcoal layer 1 (Fig. 5-2A, C), reflecting a period of fernland spread. It is similar to the pollen and charcoal records from Lake Teletskoye, the northern Altai Mountain region, which show synchronous increases in spore and charcoal particles between ca. AD 1100 and 1200 (Andreev et al., 2007). The spread of fernland may be related to the burning of peatlands and their environs. The death of large-scale canopy trees led to clearings that favoured the growth of ferns. After the burning phase, the land was progressively re-occupied by trees, and ferns decreased because they could not adapt to a dense forest cover. These features suggest that fire event 1 could have a natural origin.

A more specific explanation for this wildfire may be related to mid-Holocene climate changes. Page et al. (2002) suggested that it was the unusually long dry season that caused the 1997 Indonesian fires to spread out of control. Again, the fires between ca. AD 1100 and 1200 recorded in Lake Teletskoye were related to arid climate conditions (Andreev et al., 2007). Pollen assemblages of this study and other records indicate a progressive change from a wet and warm climate in the early Holocene to a drier and colder climate in the mid-Holocene (Liu, 1989; Yuan and Sun, 1990; Sun et al., 1991; Makohonienko et al., 2001; Wang et al., 2005; Li and Sun, 2006; Shao et al., 2006; Jiang and Liu, 2007). Therefore a shift toward a drier climate during the mid-Holocene could trigger the burning of peatlands and their surroundings.

4.2.2. Fire event 2: hypothesis of territorial expansion of Tang Dynasty and accompanying spread of farming culture

The charcoal concentrations within charcoal layer 2 are much higher than those of charcoal layer 1 (Fig. 6E), implying that fire event 2 (~1300 cal. yr B.P.) was possibly of greater intensity than the previous wildfire (~5200 cal. yr B.P.). The significant presence of Cerealia-type pollen in charcoal layer 2 indicates land clearance for agriculture at ~1300 cal. yr B.P. (Fig. 6D). The local cultivation could prevent the spread of fernland, because in contrast to charcoal layer 1, Monolete psilate spores in charcoal layer 2 are only present in a very low percentage (less than 2 %) (Fig. 5-2B). The decrease in pine is interpreted to be the result of human slash-and-burn activity for building materials and firewood.

The timing of the presence of Cerealia–type pollen in charcoal layer 2 agrees well with the territorial expansion of the Tang Dynasty (Ouyang and Song, 1060; Tan, 1991) (Fig. 7).

Historical documents have shown that prior to the Tang Dynasty, there were mainly nomadic tribes in the studied area (Ouyang and Song, 1060; Li, 2003). These nomadic people had no fixed dwellings, and moved from place to place in search of food, water, and grazing land. Although the nomadic people possibly used fire to encourage the growth of grass for their animals, their impact on the local ecosystem was generally less than that of settled farming communities.

The Han nationality/ethnic group is the largest in China. It is characterized by fixed settlement and the cultivation of crops such as rice, sorghum and millet. Archaeological investigation has shown that farming in the valley of the Yellow River began at least by 7000 cal. years ago (Zhu, 2001; Kong et al., 2003). The Tang dynasty emerged in AD 618. Its capital, Changan (current name: Xian, Fig. 7) was located in the valley of the Yellow River. The Tang dynasty (AD 618 to 907) has been described as a high point in Chinese civilization, a golden age of literature and art. It was also one of the most prosperous empires in the medieval world. In AD 668, the Tang land expanded to northeastern Asia, reaching the studied area (Fig. 7A). During the period AD 682-755, the Tang Dynasty extended further north (Fig. 7B). The northeastern part was named as Andong Duhufu and was of provincial level administration (Tan, 1991). The good agreement between the ^{14}C age of fire event 2 (AD 662±8) and the land expansion of the Tang Dynasty in AD 668 suggests that fire event 2 may be closely related to the spread of the Han farming culture, as the expansion was one of the important ways in which ancient imperial culture spread (Bentley, 1996). However, this interpretation must remain tentative until more evidence is available.

5. Conclusions

Records of pollen and charcoal in the Jinchuan peat bog, northeastern China, reflect vegetation changes, fire events, and the impact of climatic changes and human activity on the natural ecosystem. The pollen record shows that: (i) a broadleaved deciduous forest was dominant during the early Holocene; (ii) a gradual increase in coniferous trees and a decrease in deciduous trees started around 5500 cal. yr B.P., (iii) after ~4200 cal. yr B.P., the mixed coniferous and deciduous forest replaced the deciduous forest, and (iv) coniferous components, including *Pinus*, *Abies* and *Picea*, further increased after ~2000 cal. yr B.P., reflecting a cooler and drier climate after ~5500-4200 cal. yr B.P.

Two local fire events were identified in the Jinchuan peat bog. The high-resolution pollen records of the two charcoal layers show different causes for the two fire events. Fire event 1 was probably natural in origin, facilitated by drying since the mid-Holocene. We suggest that the presence of Cerealia-type pollen and the low Monolete psilate spores percentage in charcoal layer 2 was related to clearing for cultivation, which may be closely related to the spread of the Han farming culture accompanied by the terrestrial expansion of the Tang Dynasty to the studied area in AD 668.

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Figure captions

Figure 1. (A) Modern vegetation zones in China (after Editorial Board for flora of China (1995) and Hou (2001)). I, Cold-temperate conifer forest; II, Temperate mixed conifer-broadleaved forest; III, Warm-temperate broadleaved deciduous forest; IV, Subtropical evergreen broadleaved forest; V, Tropical rainforest and seasonal rainforest; VI, Steppe; VII, Desert; VIII, Tibet-Qinghai cold and highland vegetation. The dashed and solid arrows indicate winter monsoon and the dominant direction of the summer monsoon precipitation belt, respectively. (B) Location of studied site and surface pollen sites.

Figure 2. Stratigraphy and the time-depth curve of the Jinchuan peat bog.

Figure 3. Transmitted light photomicrographs of charcoal fragments. (A) Charcoal layer 1 (depth 295-267 cm); (B) Charcoal layer 2 (depth 85-77 cm).

Figure 4. Surface pollen assemblages in the Jinchuan peat bog area (Analyses: S. Leroy).

Figure 5. (A) Pollen diagrams for the Jinchuan peat bog (Analyses: W. Jiang); (B) High-resolution pollen record for charcoal layer 2 (Analyses: S. Leroy); (C) High-resolution pollen record for charcoal layer 1 (Analyses: S. Leroy). Solid circles indicate values lower than 0.5 %. An open curve to the right of a solid one represents 10×exaggerations.

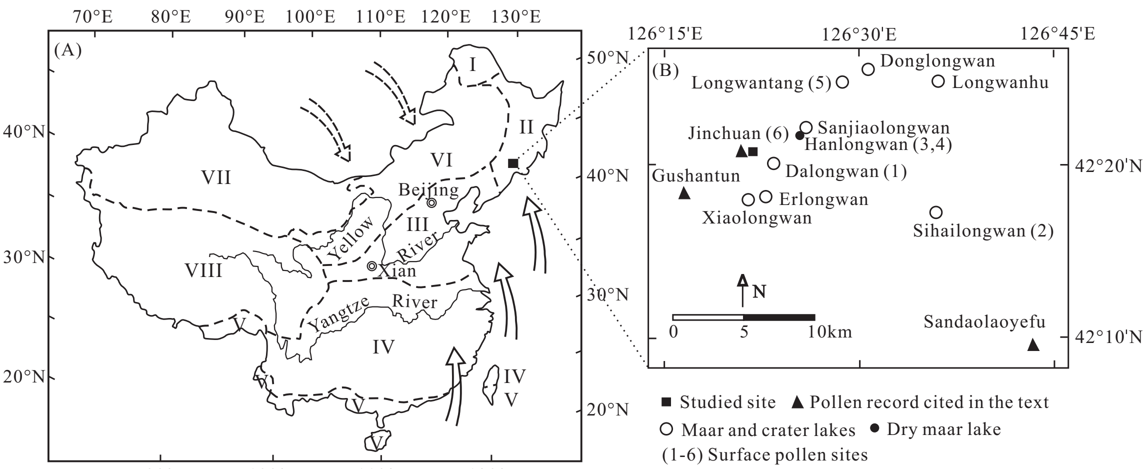
Figure 6. (A) Affinity scores of dominant PFTs, showing changes in different vegetation types for the whole sequence; (B) Affinity scores of dominant PFTs for charcoal layer 2; (C) Affinity scores of dominant PFTs for charcoal layer 1; (D) Numbers of Cerealia-type pollen

grains identified from the whole sequence (the criterion of Cerealia-type pollen is from Faegri et al. (2000)); (E) Charcoal concentrations for the whole sequence.

Figure 7. Chinese territory (shaded area) during the early and middle Tang Dynasty (AD 618-907) (modified from Tan, 1991). (A) Early Tang Dynasty (from AD 668 to 682); (B) Middle Tang Dynasty (from AD 682 to 755).

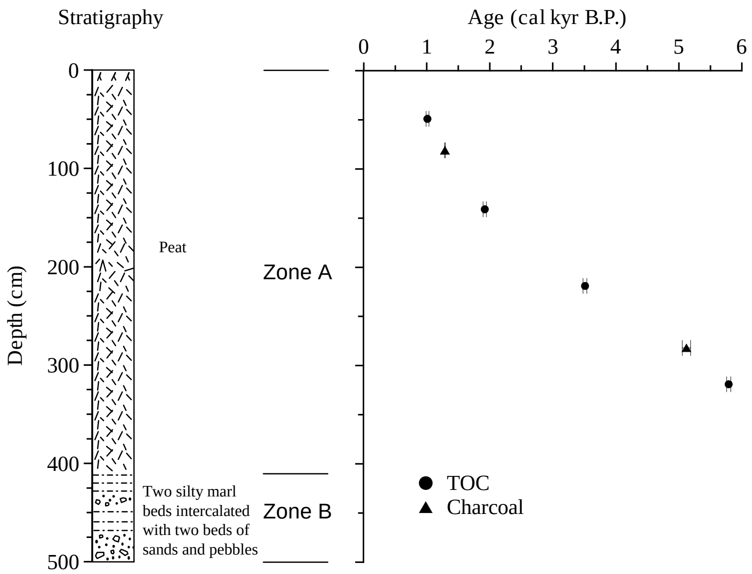
Table 1. Vegetation distribution along the altitudinal gradient in the studied region (after Editorial Board for flora of China, 1995).

Table 2. AMS ^{14}C dates of the Jinchuan peat bog.



(A)
70°E
80°E
90°E
100°E
110°E
120°E
130°E
50°N
40°N
30°N
20°N
40°N
30°N
20°N
90°E
100°E
110°E
120°E
I
II
VI
VII
VIII
III
IV
IV
V
V
V
Beijing
Yellow
River
Xian
Yangtze
River
(B)
126°15'E
126°30'E
126°45'E
42°20'N
42°10'N
Donglongwan
Longwantang (5)
Longwanhu
Sanjiaolongwan
Jinchuan (6)
Hanlongwan (3,4)
Dalongwan (1)
Gushantun
Erlongwan
Xiaolongwan
Sihailongwan (2)
N
0
5
10km
Sandaolaoyefu
Studied site
Pollen record cited in the text
Maar and crater lakes
Dry maar lake
(1-6) Surface pollen sites

Figure 1



Stratigraphy
Age (cal kyr B.P.)
0
1
2
3
4
5
6
0
100
200
300
400
500
Depth (cm)
Peat
Two silty marl
beds intercalated
with two beds of
sands and pebbles
Zone A
Zone B
TOC
Charcoal

Figure 2

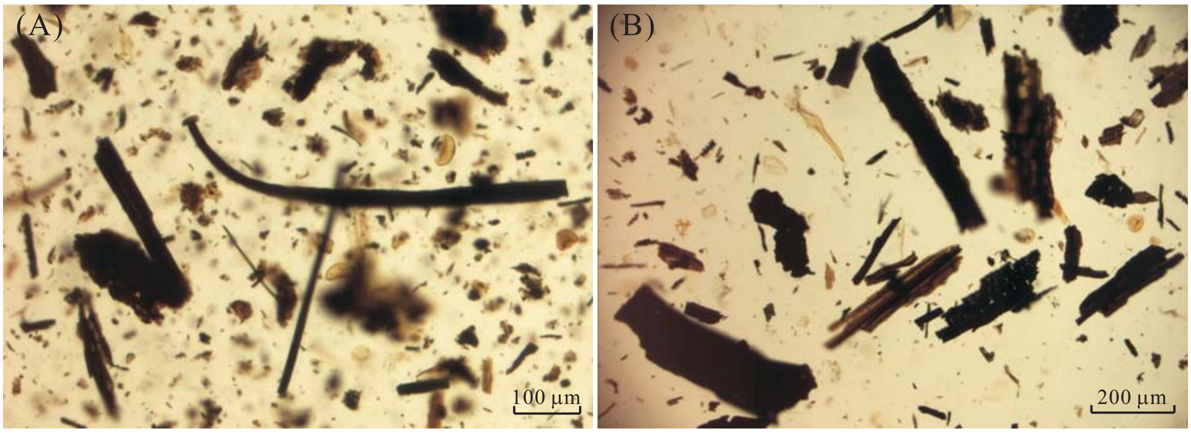


Figure 3

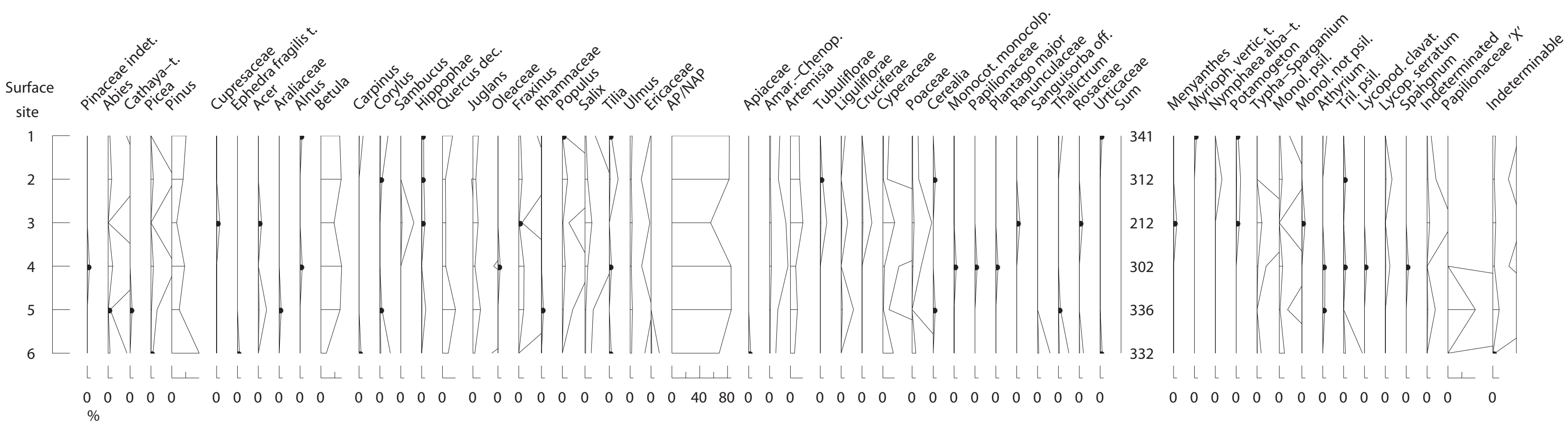

Surface site
Pinaceae indet.
Abies
Cathaya–t.
Picea
Pinus
Cupresaceae
Ephedra fragilis t.
Acer
Araliaceae
Alnus
Betula
Carpinus
Corylus
Sambucus
Hippophae
Quercus dec.
Juglans
Oleaceae
Fraxinus
Rhamnaceae
Populus
Salix
Tilia
Ulmus
Ericaceae
AP/NAP
Apiaceae
Amar.–Chenop.
Artemisia
Tubuliflorae
Liguliflorae
Cruciferae
Cyperaceae
Poaceae
Cerealia
Monocot. monocolp.
Papilionaceae
Plantago major
Ranunculaceae
Sanguisorba off.
Thalictrum
Rosaceae
Urticaceae
Sum
Menyanthes
Myrioph. vertic. t.
Nymphaea alba–t.
Potamogeton
Typha–Sparganium
Monol. psil.
Monol. not psil.
Athyrium
Tril. psil.
Lycopod. clavat.
Lycop. serratum
Spahgnum
Indeterminated
Papilionaceae 'X'
Indeterminable
1
2
3
4
5
6
341
312
212
302
336
332
0
%
40
80

Figure 4

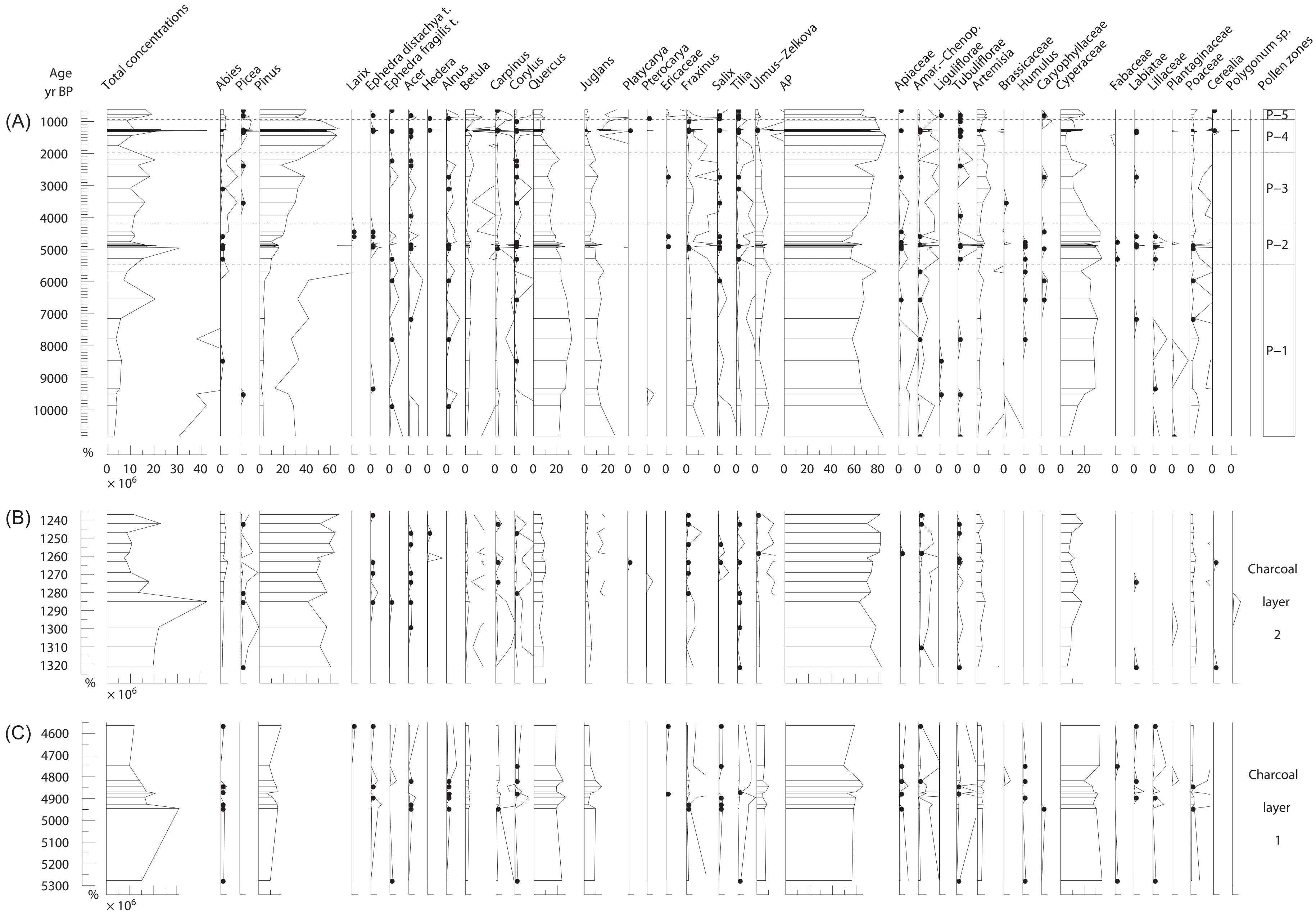
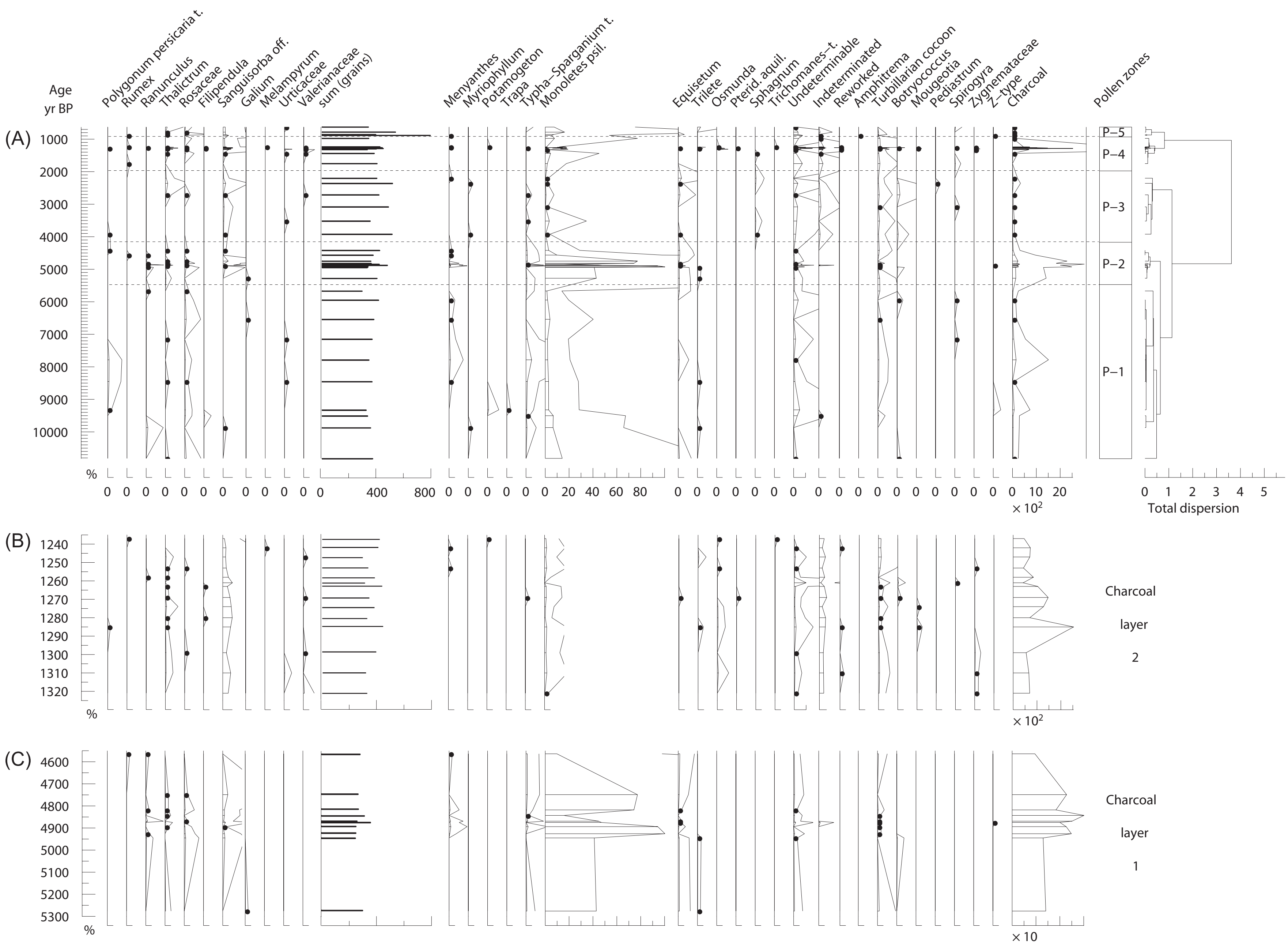

Age
yr BP
Total concentrations
Abies
Picea
Pinus
Larix
Ephedra distachya t.
Ephedra fragilis t.
Acer
Hedera
Alnus
Betula
Carpinus
Corylus
Quercus
Juglans
Platycarya
Pterocarya
Ericaceae
Fraxinus
Salix
Tilia
Ulmus–Zelkova
AP
Apiaceae
Amar.–Chenop.
Liguliflorae
Tubuliflorae
Artemisia
Brassicaceae
Humulus
Caryophyllaceae
Cyperaceae
Fabaceae
Labiatae
Liliaceae
Plantaginaceae
Poaceae
Cerealia
Polygonum sp.
Pollen zones
(A)
P–5
P–4
P–3
P–2
P–1
%
× 10⁶
(B)
Charcoal
layer
2
(C)
Charcoal
layer
1

Figure 5-1



Age
yr BP
Polygonum persicaria t.
Rumex
Ranunculus
Thalictrum
Rosaceae
Filipendula
Sanguisorba off.
Galium
Melampyrum
Urticaceae
Valerianaceae
sum (grains)
Menyanthes
Myriophyllum
Potamogeton
Trapa
Typha–Sparganium t.
Monoletes psil.
Equisetum
Trilete
Osmunda
Pterid. aquil.
Sphagnum
Trichomanes–t.
Undeterminable
Indeterminated
Reworked
Amphitrema
Turbillarian cocoon
Botryococcus
Mougeotia
Pediastrum
Spirogyra
Zygnemataceae
Z–type
Charcoal
Pollen zones
(A)
P–5
P–4
P–3
P–2
P–1
Total dispersion
× 10²
(B)
Charcoal layer 2
(C)
Charcoal layer 1
× 10
%

Figure 5-2

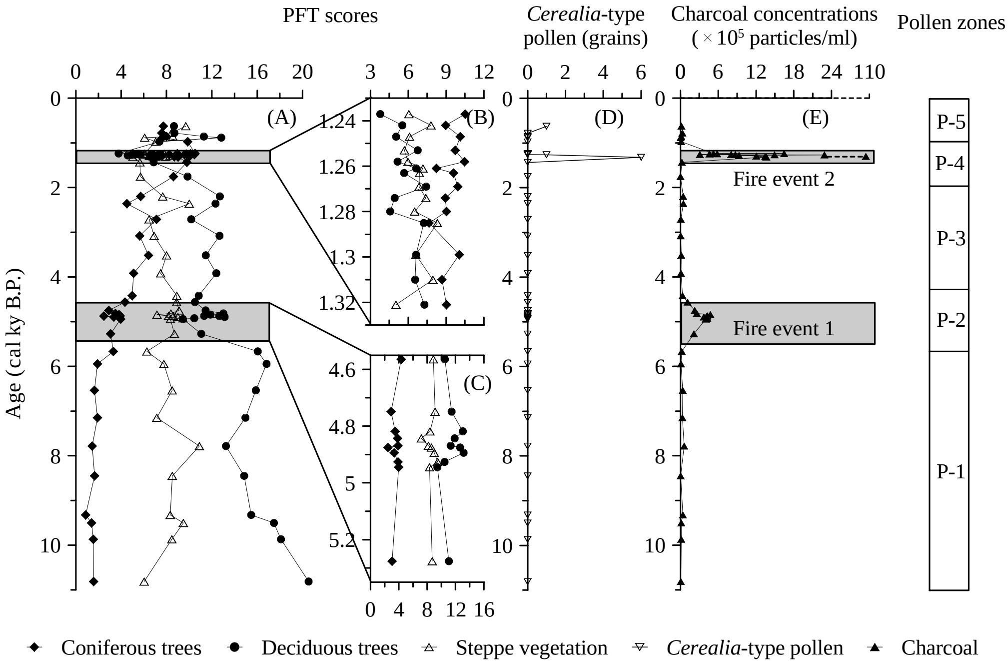

PFT scores
Cerealia-type pollen (grains)
Charcoal concentrations (× 10^5 particles/ml)
Pollen zones
Age (cal ky B.P.)
(A)
(B)
(C)
(D)
(E)
Fire event 1
Fire event 2
P-1
P-2
P-3
P-4
P-5
Coniferous trees
Deciduous trees
Steppe vegetation
Cerealia-type pollen
Charcoal

Figure 6

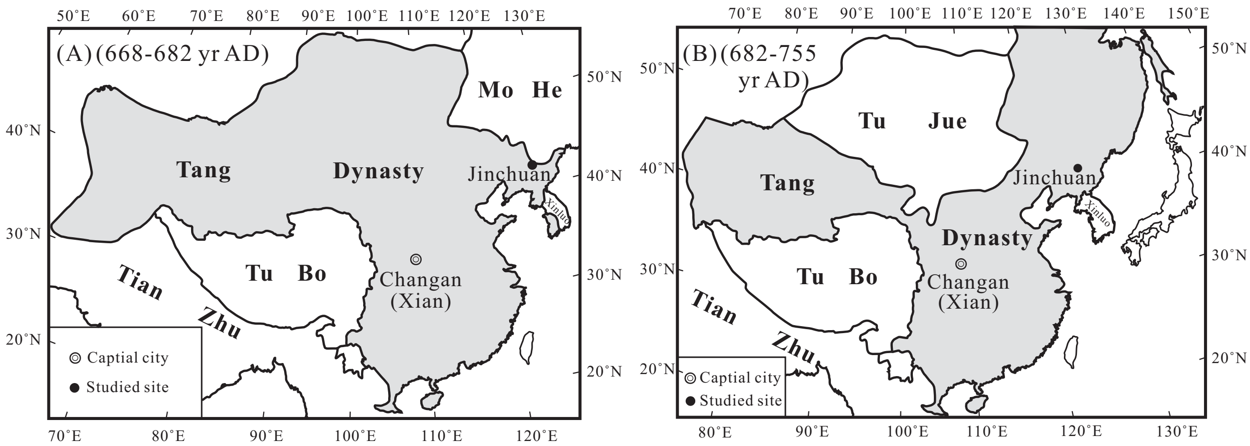

(A) (668-682 yr AD)
Mo He
Tang
Dynasty
Jinchuan
Xinluo
Tu Bo
Changan
(Xian)
Tian
Zhu
Captial city
Studied site
(B) (682-755 yr AD)
Tu Jue
Tang
Jinchuan
Xinluo
Dynasty
Tu Bo
Changan
(Xian)
Tian
Zhu
Captial city
Studied site

Figure 7

Table 1. Vegetation distribution along the altitudinal gradient in the studied region (after Editorial Board for flora of China, 1995).

Altitude (m a.s.l.)	Vegetation zone	Main taxa
>2100	Alpine tundra	*Dryas octopetala, Salix rotundifolia,* Rhododendron spp.
1800-2100	Sub-alpine dwarf shrub	*Betula ermanii*
1100-1800	Coniferous forest	*Pinus koraiensis, Picea jazoensis, Picea koraiensis, Abies nephrolepis*
<1100	Mixed deciduous and coniferous forest	*Pinus koraiensis, Abies holophylla, Carpinus cordota, Ulmus propinqua, Acer mono, Quercus mongolica, Fraxinus mandshurica, Juglans mandshurica, Tilia amurensis, Betula costata, Betula platyphylla*

Table 2. AMS ^{14}C dates of the Jinchuan peat bog.

Depth (cm)	Lab number [a]	Material	^{14}C age (yr B.P.)	2σ–calibrated range (cal yr B.P.) [b]	Dynasty
48-50	AA-60306	Bulk sediment	1139±40	988-1032	AD 918-962, Five Dynasties and Ten Kingdoms (AD 907-960)
78-84	Poz-8875	Charcoal	1350±30	1280-1295	AD 655-670, Tang (AD 618-907)
140-142	Poz-8876	Bulk sediment	1975±35	1893-1946	AD 4-57, Han (206 BC- AD 220)
218-220	AA-60307	Bulk sediment	3312±44	3481-3541	1592-1532 BC, Shang (1765-1122 BC)
278-285	Poz-8877	Charcoal	4510±40	5055-5186	3237-3106 BC
318-320	Poz-8879	Bulk sediment	5090±40	5758-5821	3872-3809 BC

[a] Lab numbers refer to NSF-Arizona AMS Facility (AA) and Poznan Radiocarbon Laboratory (Poz).
[b] Calib5.0: Calib radiocarbon calibration (http://calib.qub.ac.uk/calib/).