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Climate of the Past Discussions

The quantitative reconstruction of the paleoclimate between 5200 and 4300 cal yr BP in the Tianshui Basin, NW China

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Abstract

The quantitative reconstruction of the paleoclimate is the ultimate goal of studying past global change. Here, the Coexistence Approach (CA) was applied to reconstruct climatic factors quantitatively based on the fossil charcoal records between 5200 and 4300 cal yr BP in the Tianshui Basin, NW China. The climate of the Tianshui Basin belonged to the northern subtropical zone from 5200–4300 cal yr BP. The climatic tolerance ranges were selected, and the lower limit value was regarded as the logical climate factor to reflect the values of climatic factors. The CA analysis showed that the mean annual temperature (MAT) was approximately 13.2°C, and the mean annual precipitation (MAP) was approximately 778 mm between 5200 and 4900 cal yr BP. The MAT was approximately 13.2°C, and the MAP was approximately 688 mm between 4800 and 4300 cal yr BP. The MAT increased approximately 2.2°C, and the MAP increased approximately 280 mm from 5200–4900 cal yr BP. The MAT also increased approximately 2.2°C from 4800–4300 cal yr BP, while the MAP increased around 196 mm. No climate event occurred from 5200–4300 cal yr BP; however, a drought tendency appeared after 4800 cal yr BP.

1 Introduction

In the next 100 yr, the average global temperature is expected to increase 1.8–4°C, leading to disastrous consequences (Mann et al., 1998; IPCC, 2007; Solomon et al., 2009). Global warming has made a profound impact on governments and the public, but the extent of warming and its ecological effects remain uncertain. Therefore, understanding the processes and rules that drive climate variation and finding similar patterns of warming in the geological record have become the key requirements for future prediction.

The Holocene Megathermal was a much warmer phase in the East Asian monsoon areas (Shi, 1992; An et al., 2000; Sun et al., 1999; Wang et al., 2005). Warming started

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8000 yr ago, and the Holocene Megathermal Maximum occurred between 7200 and 6000 yr BP. After 3000 yr BP, the climate showed a cold-dry tendency (An et al., 2000; Shi et al., 1993). To date, most of the work concerning the Holocene Megathermal is focused on the qualitative description of the event, and quantitative reconstruction studies are limited.

Based on the records of pollen, soil, lake, ice-core, archaeological record, sea level, and so on, Shi et al. (1993) suggested that the warming extent during the Holocene Megathermal Maximum varied throughout China. Comparing the modern climate data, the temperature increased approximately 1°C in southern China, 2°C in the Yangtze River valley, and 3°C in northern China, northeastern China, and northwestern China. The largest extent of increasing temperature could reach about 4–5°C in the southern Tibetan plateau.

Using the phytolith-climate transfer function, Lu et al. (1996) concluded that the mean annual temperature was 14–16°C, and the mean annual precipitation was 700–800 mm at Baoji in the southern Loess Plateau. Recently, climate transfer functions have been carried out based on the records of carbon and oxygen isotopes and magnetic susceptibility; however, the quantitative results are uncertain because of the limitation between the proxies and the climate mechanism (Ning, 2010).

Plant growth and vegetation types are controlled by the climatic environment. The botanical records are direct proxies that can be used to reconstruct the climate factors quantitatively. Forest vegetation is sensitive to the water-heat conditions, especially in the arid and semi-arid areas of northern China. Temperature and precipitation control the formation and succession of the natural forest, the extent of the forest zone, and the height of the of vertical vegetation belt (Li and Wang, 1988). Therefore, the high-resolution records of plant species are recognized as the foundation for recovering the vegetation type, distribution pattern, and climate reconstruction.

Fossil charcoal comes from the incomplete burning of wood, and the anatomical characters of the original wood are retained (McGinnes et al., 1974). This raises the possibility of much greater precision in the level of taxonomic identification, overcoming

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the limitation of some plant microfossils (Shackleton and Prins, 1992; Cui et al., 2002). Additionally, the fossil charcoal belongs to the sedentary product, and the spreading range of the charcoal is limited (Shackleton and Prins, 1992). Therefore, fossil charcoal has significant potential for reconstructing the regional vegetation history and climatic factors (Shackleton and Prins, 1992; Cui et al., 2002; Li et al., 2011).

The Tianshui Basin is one of the Neolithic centers of northern China where the Neolithic Cultures of Yangshao, Majiayao and Qijia developed (Institute of Archaeology of CASS, 1999; Xie, 1985). The Dadiwan and Xishanping sites in the Tianshui Basin are famous for the most complete cultural sequence that preserved numerous Neolithic archaeological remains. Here, the coexistence approach was applied to reconstruct the climatic factors quantitatively based on the fossil charcoal records between 5200 and 4300 cal yr BP in the Tianshui Basin, NW China.

2 Study area

The Tianshui Basin is located in the northern Qinling Mountains in NW China and belongs to the semi-humid region, which is sensitive to climate change. The mean annual temperature is 11.6°C, and the mean annual precipitation is 491.6 mm. The natural vegetation includes warm-temperate mixed conifer-broadleaved forests, woodland and grasslands (Wu and Wang, 1983). However, it has been greatly altered for agriculture. The common natural woody plants are members of the Fagaceae, Betulaceae, Pinaceae, Salicaceae, Ulmaceae, Aceraceae, Rosaceae and Tiliaceae. The main herbaceous plants are Gramineae, Compositae, Leguminosae and Ranunculaceae.

The Xishanping site (34°33′50′′ N, 105°32′41′′ E, 1330 m a.s.l.) is located on a terrace on the southern bank of the Xihe River, and it is approximately 50 m above the river bed (Fig. 1). The site covers an area of 204 800 m^2, and the stoneware and pottery are mainly from the Majiayao and Qijia cultures of the middle-late Neolithic (Institute of Archaeology of CASS, 1999; An et al., 2005). Archaeobotanical evidence from Xishanping site indicates the broadening of early agriculture during the middle-late Neolithic (Li et al., 2007a, b).

The Dadiwan site (35°0′29″ N, 105°54′41″ E, 1500 m a.s.l.) is located on the I and II terraces of the southern bank of the Qingshuihe River to the north of the Tianshui Basin (Fig. 1). Extensive excavation projects have been conducted at the Dadiwan site (Gansu Provincial Institute of Archaeology, 2006), which is supposed to be the location of the most developed and continuous cultures: the Pre-Yangshao culture (8000–7000 yr BP), the Yangshao culture (7000–5000 yr BP), the Majiayao culture (5000–4100 yr BP), and the early phase of the Qijia culture (4100–3800 yr BP).

3 Methods

A 650 cm section of continuous and undisturbed cultural sediment on the northern of Xishanping site was selected, and the records of the pollen, phytoliths, and seeds have been published (Li et al., 2007a, b). Eight accelerator mass spectrometry (AMS) radiocarbon dates, including 6 charcoal samples and 2 charred seeds, were calculated at the University of Tokyo. The calendar ages were estimated using the Radiocarbon Calibration Program (Reimer et al., 2004). The chronological framework was established by Li et al. (2007a), and it is quoted in this study (Fig. 2, Table 1).

The sediment above 40 cm had been disturbed by modern agriculture. The fossil charcoals below 460 cm depth are rare and small, which makes them difficult to identify reliably. Therefore, seven samples were collected from the cultural sediment between 40 and 450 cm depth with abundant fossil charcoal, corresponding to the period between 4800 and 4300 cal yr BP.

The Dadiwan section is located on the second terrace of the south Qingshuihe River. The total thickness is 820 cm, and the Neolithic culture layer occurs between 400 and 820 cm. Five charcoal AMS radiocarbon dates were calculated at the Australian Nuclear Science and Technology Organisation (ANSTO), and the calendar ages were estimated (Reimer et al., 2004). The sediment between 400 and 820 cm depth was deposited between 5200 and 4900 cal yr BP, and it belongs to the Late Yangshao and the early Majiayao cultures (Fig. 2, Table 1).

The fossil charcoal was recovered using the floatation method (Tsuyuzaki, 1994). Sufficient charcoal fragments were selected for identification and counting. Typically, the number of taxa present in a sample increases sharply while the first few charcoal specimens are examined and then settles down as more fragments are identified (Keepax, 1988; Smart and Hoffman, 1988). Keepax (1988) suggested that a minimum of 100 charcoal fragments per sample should be examined in temperate regions to provide a good representation of the types of wood present.

At least 100 pieces were examined and identified from the Xishanping and Dadiwan sites following the standard procedures. First, pressure fractured charcoal were prepared with a razor blade to produce fresh, clean surfaces to show the transverse, radial and tangential sections (Leney and Casteel, 1975). Then, these charcoal samples were examined under a stereomicroscope and categorized, and one or two samples from each type were photographed under a scanning electron microscope (SEM). The identification of the taxa was carried out according to the reference of wood collection and atlases of wood anatomy.

The Coexistence Approach (CA) is often used in the quantitative reconstruction of the paleoclimate during the Tertiary. The CA finds the nearest living relative species of the fossils and superimposes the climatic tolerance range of each nearest living relative species, the overlap of which can reflect the paleoclimate (Mosbrugger and Utescher, 1997). The reliability of the CA has been validated by previous studies (Li et al., 2003; Yang et al., 2007).

The tolerance range varies in different plant taxa and can be obtained through the following steps: (1) confirming the distribution range of the plant species; (2) using the meteorological data from meteorological stations in the distribution range; and (3) defining the maximum and minimum value of the meteorological data as the plant tolerance range of the climate. Here, three main climatic factors are calculated including mean annual temperature (MAT), mean annual precipitation (MAP) and mean

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annual relative humidity (RH). The modern climatic factors come from the Surface Meteorological Data of China (1971–2000) (http://cdc.cma.gov.cn/).

4 Results

A total of 2307 charcoal fragments were identified, and 34 different taxa were identified in the 17 samples from the Dadiwan section (Fig. 3; Table 2). *Betula*, *Corylus*, *Ulmus*, *Quercus mongolica* and *Acer* were present in all 17 samples, whereas *Picea brachytyla*, *Abies*, *Ostrya*, *Quercus aliena*, *Xylosma racemosum*, *Toxicodendron* and *Liquidambar formosana* were present in 16 samples. *Alnus*, *Sorbus pohuashanensis*, *Juglans*, *Gymnocladus chinensis*, *Eucommia ulmoides*, *Ehretia* and *Fargesia* appeared in more than 10 samples.

A total of 808 pieces of charcoal were identified, and 20 different taxa were identified from the samples in the Xishanping section (Fig. 4; Table 2). The most abundant taxa were *Picea*, *Castanea*, *Betula*, *Ulmus*, *Quercus*, *Carpinus*, *Toxicodendron*, *Acer*, *Liquidambar formosana* and Bambusoideae, which were present in all samples. *Padus*, *Castanopsis*, *Pseudotsuga sinensis*, *Cerasus* and *Eucommia ulmoides* appeared in four samples, and *Corylus*, *Picrasma* and *Diospyros* were only present in two samples.

The charcoal assemblage at the Dadiwan and Xishanping sites include warm temperate taxa such as *Picea, Betula, Acer, Ulmus, Carpinus* and *Quercus*; subtropical evergreen broad-leaved taxa such as *Castanopsis* and Bambusoideae; and subtropical deciduous taxa such as *Liquidambar formosana* and *Toxicodendron*. Thus, the assemblages of fossil charcoal at the Dadiwan and the Xishanping sites reflect the vegetation type of the evergreen broadleaved and the mixed conifer-broadleaved forest from 5200–4300 cal yr BP, which indicates a warmer and wetter climate for the subtropical zone in the Tianshui Basin.

The climatic factors of the Tianshui Basin from 5200–4900 cal yr BP were obtained by applying the CA to 34 fossil charcoal taxa from the Dadiwan site. The CA results show that the MAT was 13.2–14.7 °C, the MAP was 778–816 mm, and the RH was

69–70 % (Fig. 5). The climatic factors of the Tianshui Basin from 4800–4300 cal yr BP were obtained from the CA analysis based on 20 fossil charcoal taxa from the Xishanping site. The CA results show that the MAT was 13.2–16.5°C, the MAP was 688–1147.8 mm, and the RH was 67–70 % (Fig. 6).

5 Discussion

The quantitative reconstruction of the paleoclimate record is the ultimate goal of studying past global climate change. The transfer function from the geological and biological record has been used as a popular method to successfully reconstruct the paleoclimate quantitatively (Webb et al., 1972; Bartlein, 1986; Farquar, 1989; Maher, 1995; Wu et al., 1994; Porter, 2001; Lu et al., 2006). However, the transfer functions still include randomness in the implementation of process. Even the best regression model based on the F-test still lacks sufficient scientific evidence (Zhang, 1988). Therefore, the reliability and effectiveness of the proxy and the method are crucial for quantitative reconstruction of the climate.

Plant distribution is mainly controlled by climate (Good, 1974). The existence of the plant indicates that the plant's growth can adapt to the climate conditions (Gribbin, 1978). Vegetation can be formed only if the climate is suitable for each plant species of the community (Wang, 1992). The Coexistence Approach (CA) is an important method for quantitatively reconstructing the paleoclimate. One of the most important preconditions is that the climatic tolerance of the fossil plants is similar to the nearest living relative species. Generally, the closer relation between the plant species and fossil, the more taxa identified will lead to the higher resolution and accuracy of the climatic data (Mosbrugger and Utescher, 1997). The Holocene plants are the result of long-term natural evolution, and their ecological amplitude and climatic tolerance are similar to modern plant types; thus, the CA is well suited for obtaining the paleoclimatic factors.

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The modern subtropical taxa are distributed in the southern area of the Qinling Mountains and the Yangtze River valley. Therefore, the development of subtropical vegetation from 5200–4300 cal yr BP in the Tianshui Basin indicates warmer and wetter climate conditions than today. Compared with the modern plant community of typical subtropical vegetation, a few temperate taxa of *Sorbus pohuashanensis* and *Armeniaca sibirica,* which almost disappear in the subtropical area, occur in a relatively high proportion at the Xishanping and the Dadiwan sites. Thus, the vegetation in the Tianshui Basin from 5200–4300 cal yr BP should belong to the northern subtropical zone. According to the Surface Meteorological Data of China (1971–2000), the climate between 5200 and 4300 cal yr BP in the Tianshui Basin is similar to the modern climate of the Lueyang basin in the southern Qinling Mountains (Fig.1; Table 3).

Lueyang (33°19′ N, 106°09′ E) is an intermountain basin in the southern Qinling Mountains that belongs to the northern border of the subtropical monsoon climate. Comparing the longitude and latitude between the Lueyang and the Tianshui Basin (34°34′ N, 105°33′ E), the difference of latitude is approximately 1.2°. Thus, we conclude that the subtropical vegetation zone expanded northward by approximately 1.2° and reached the northern Qinling Mountains between 5200 and 4300 cal yr BP.

The Dadiwan site from 5200–4900 cal yr BP had the following climatic factors: the mean annual temperature (MAT) was between 13.2 and 14.7°C, the mean annual precipitation (MAP) was between 778 and 816 mm, and the mean annual relative humidity (RH) was 69–70 %. The Xishanping site from 4800–4300 cal yr BP had the following climatic factors: the MAT was between 13.2 and 16.5°C, the MAP was between 688 and 1147.8 mm, and the RH was 67–70 %. Because the climate of the Tianshui Basin belongs to the northern subtropical zone from 5200–4300 cal yr BP, the lower limit value can be regarded as the logical climate factors to reflect the climate when the climatic tolerance ranges are selected.

Comparing the climatic factors from the CA to the modern meteorological data in the Tianshui Basin, the MAT increased approximately 2.2°C, and the MAP increased approximately 280 mm from 5200–4900 cal yr BP. The MAT retained the increase of approximately 2.2°C from 4800–4300 cal yr BP, while the MAP increased approximately 196 mm. The RH decreased approximately 2 %. Therefore, the MAT of the Tianshui Basin was roughly constant, suggesting that no drastic climate event occurred from 5200–4300 cal yr BP. However, the MAP decreased approximately 90 mm, and the RH decreased 2 % after 4800 cal yr BP, which are consistent with the weakening of the East Asian monsoon that led to the precipitation decrease after 5000 yr BP (Wang et al., 2005; Fleitmann, 2007).

6 Conclusions

The paleoclimatic factors in the Tianshui Basin were obtained by applying the CA using fossil charcoal data. From 5200–4900 cal yr BP, the MAT was 13.2 °C, and the MAP was 778 mm. From 4800–4300 cal yr BP, the MAT was 13.2 °C, and the MAP was 688 mm; these conditions are similar to the modern climate at Lueyang in the southern Qinling Mountains. From 5200–4900 cal yr BP, the MAT increased approximately 2.2°C, and the MAP increased approximately 280 mm. From 4800–4300 cal yr BP, the MAT also increased approximately 2.2°C, while the MAP increased approximately 196 mm. No climate event occurred during 5200–4300 cal yr BP; however, a drought tendency appeared after 4800 cal yr BP.

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Table 1. Accelerator mass spectrometry (AMS) dates from the Xishanping and Dadiwan sites.

Sample Location	Depth (cm)	Lab. No	Sample Type	AMS Age (yr BP)	Calibrated Age (cal yr BP, 2σ)
XXP-1	60 cm	TKal3882	Charcoal	3900 ± 35	4236 ~ 4419
XXP-2	130 cm	TKal3883	Charcoal	2785 ± 30	2839 ~ 2949
XXP-3	345 cm	TKal3884	Charcoal	4430 ± 35	4870 ~ 5069
XXP-4	490 cm	TKal3885	Charcoal	4855 ± 35	5579 ~ 5655
XXP-5	560 cm	TKal3886	Charcoal	4360 ± 35	4845 ~ 4983
XXP-6	570 cm	TKal3887	Charcoal	4400 ± 35	4859 ~ 5051
XXP-7	585 cm	TKal3888	Charred seed	4430 ± 100	4833 ~ 5312
XXP-8	620 cm	TKal3889	Charred seed	4490 ± 35	5035 ~ 5295
DDW-3	420 cm	OZK647	Charcoal	4470 ± 60	4960 ~ 5306
DDW-4	500 cm	OZK648	Charcoal	4485 ± 50	5028 ~ 5303
DDW-5	640 cm	OZK649	Charcoal	4370 ± 50	4842 ~ 5055
DDW-6	760 cm	OZK650	Charcoal	4445 ± 50	4950 ~ 5288
DDW-7	810 cm	OZK651	Charcoal	4555±50	5048~5324

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Table 2. The taxa of fossil charcoal and their ubiquity from the Xishanping and Dadiwan sites.

Taxa	Xishanping		Dadiwan	
	Fragment count	Ubiquity	Fragment count	Ubiquity
Picea sp.	86	7	–	–
Picea brachytyla	–	–	33	16
Abies sp.	–	–	46	16
Pseudotsuga sinensis	15	4	–	–
Castanea sp.	28	7	22	9
Castanopsis sp.	14	5	–	–
Quercus sp.	61	7	–	–
Quercus mongolica	–	–	138	17
Quercus aliena	–	–	190	16
Toxicodendron sp.	48	7	102	16
Carpinus sp.	61	7	–	–
Betula sp.	69	7	166	17
Corylus sp.	5	2	65	17
Alnus sp.	–	–	78	14
Ostrya sp.	–	–	118	16
Ulums sp.	105	7	200	17
Cerasus sp.	14	4	–	–
Padus sp.	20	6	–	–
Liquidambar formosana	63	7	103	16
Acer sp.	65	7	246	17
Picrasma sp.	3	2	7	5
Diospyros sp.	15	2	–	–
Eucommia ulmoides	7	4	74	12
Phyllostachys sp.	56	6	97	15
Phyllostachys glauca	61	6	–	–
Indocalamus sp.	12	5	6	5
Fargesia sp.	–	–	34	11
Sorbus pohuashanensis	–	–	52	15
Juglans sp.	–	–	53	12
Tilia sp.	–	–	42	8
Alangium sp.	–	–	15	7
Prunus armeniaca	–	–	3	3
Firmiana sp.	–	–	4	4
Prunus sp.	–	–	2	1
Gymnocladus chinensis	–	–	84	14
Xylosma racemosum	–	–	87	16
Lonicera sp.	–	–	10	4
Cercidiphyllum japonicum	–	–	55	15
Ehretia sp.	–	–	48	10
Cyclobalanopsis sp.	–	–	90	15
Fagus sp.	–	–	5	2
Vaccinium sp.	–	–	20	6
Osmanthus fragrans	–	–	12	6

Table 3. The comparison of the climatic factors among Dadiwan, Xishanping, Tianshui and Lueyang.

Locality	Period (cal yr BP)	MAT/°C	MAP/mm	RH/%
Dadiwan	5200 ~ 4900	13.2	778	69
Xishanping	4800 ~ 4300	13.2	688	67
Tianshui	present	11	491.6	67
Lueyang	present	13.3	791.9	71

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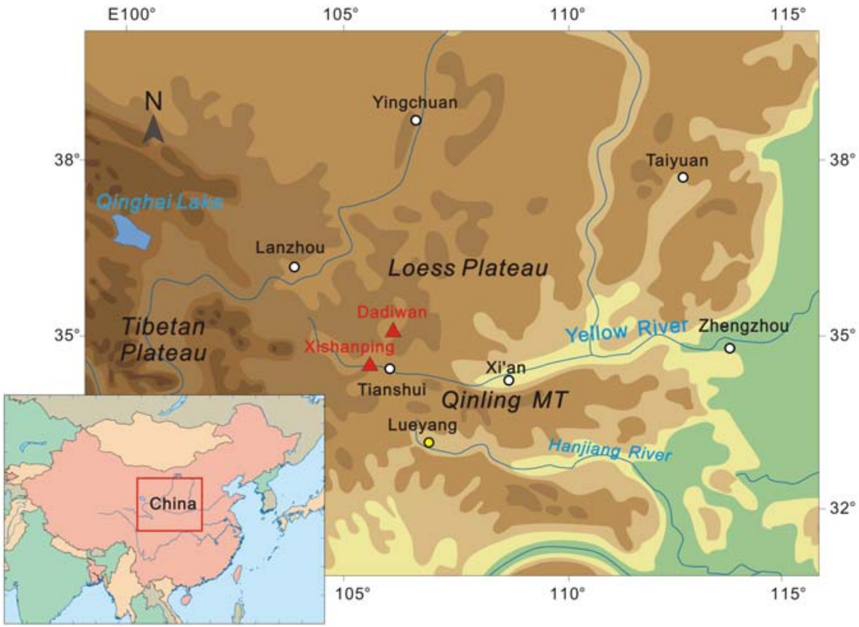

Fig. 1. Location of the study area.

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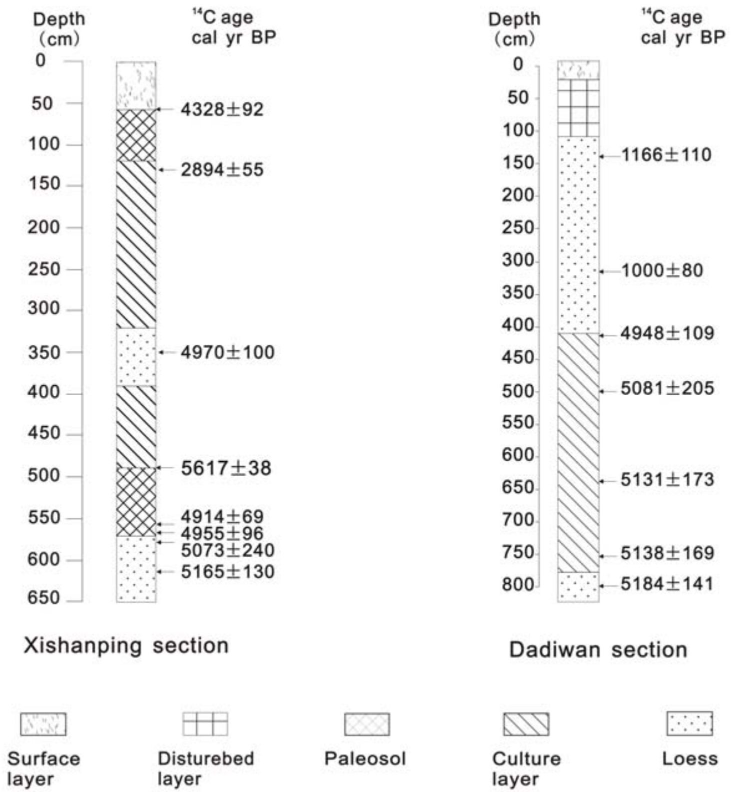

Fig. 2. Stratigraphic sections from the Xishanping and Dadiwan sites and their radiocarbon results.

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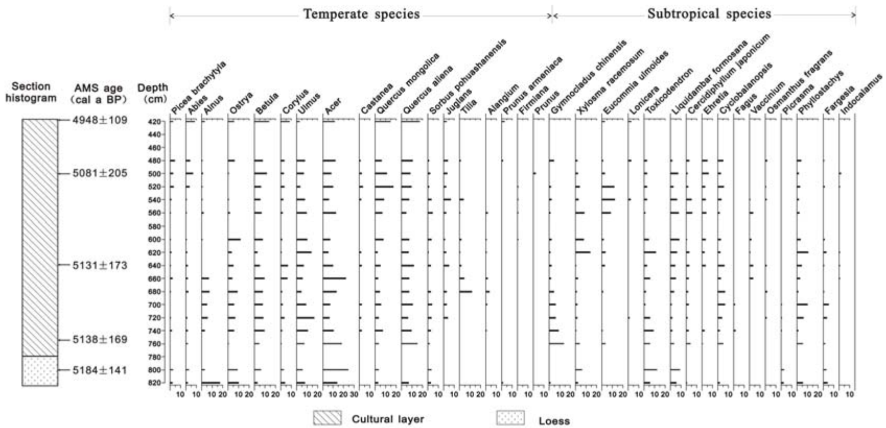

Fig. 3. The abundance ratio of fossil charcoal from the Dadiwan section.

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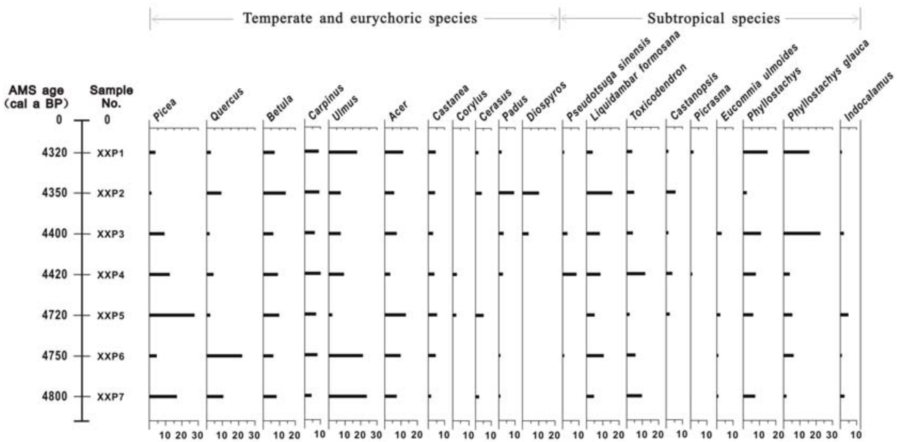

Fig. 4. The abundance ratio of fossil charcoal from the Xishanping section.

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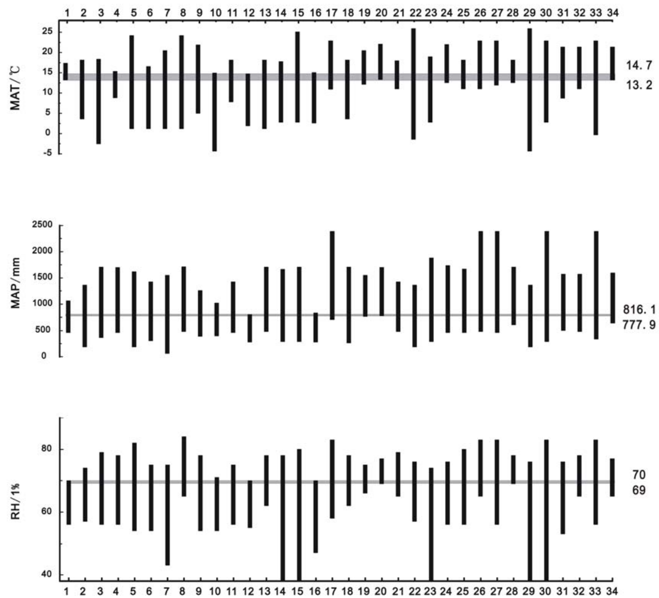

Fig. 5. Coexistence intervals for the Dadiwan section.
1. *Picea brachytyla*; 2. *Abies* sp.; 3. *Alnus* sp.; 4. *Ostrya* sp.; 5. *Betula* sp.; 6. *Corylus* sp.; 7. *Ulmus* sp.; 8. *Acer* sp.; 9. *Castanea* sp.; 10. *Quercus mongolica*; 11. *Quercus aliena*; 12. *Sorbus pohuashanensis*; 13. *Juglans* sp.; 14. *Tilia* sp.; 15. *Alangium* sp.; 16. *Armeniaca sibirica*; 17. *Firmiana* sp.; 18. *Prunus* sp.; 19. *Gymnocladus chinensis*; 20. *Xylosma racemosum*; 21. *Eucommia ulmoides*; 22. *Lonicera* sp.; 23. *Toxicodendron* sp.; 24. *Liquidambar formosana*; 25. *Cercidiphyllum japonicum*; 26. *Ehretia* sp.; 27. *Cyclobalanopsis* sp.; 28. *Fagus* sp.; 29. *Vaccinium* sp.; 30. *Osmanthus fragrans*; 31. *Picrasma* sp.; 32. *Phyllostachys* sp.; 33. *Fargesia* sp.; 34. *Indocalamus* sp.

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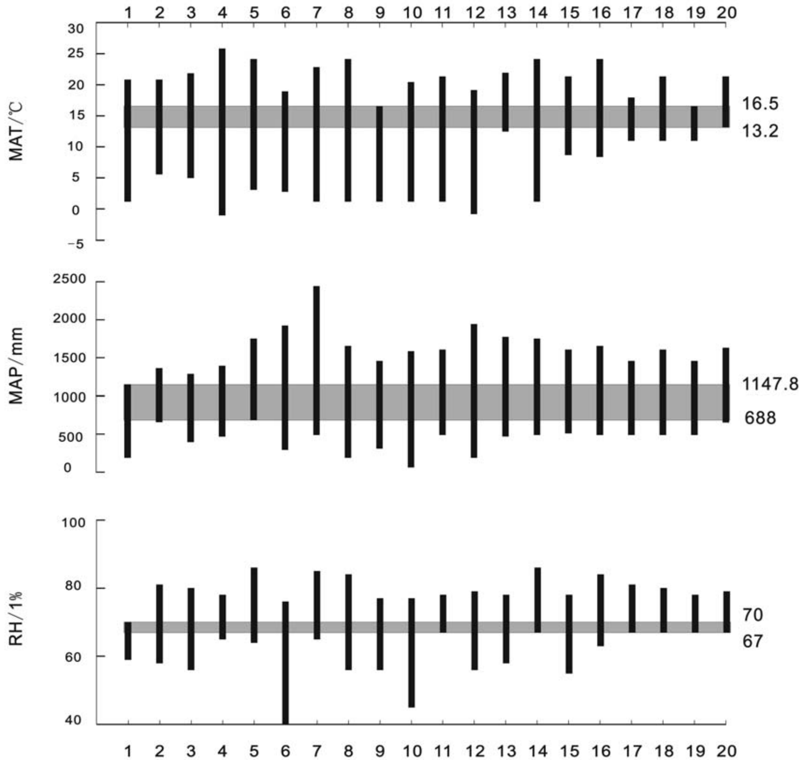

Fig. 6. Coexistence intervals for the Xishanping section.
1. *Picea sp.*; 2. *Pseudotsuga sinensis*; 3. *Castanea sp.*; 4. *Quercus sp.*; 5. *Castanopsis sp.*; 6. *Toxicodendron sp.*; 7. *Carpinus sp.*; 8. *Betula sp.*; 9. *Corylus sp.*; 10. *Ulums sp.*; 11. *Prunus sp.*; 12. *Padus sp.*; 13. *Liquidambar formosana*; 14. *Acer sp.*; 15. *Picrasma sp.*; 16. *Diospyros sp.*; 17. *Eucommia ulmoides*; 18. *Phyllostachys sp.*; 19. *Phyllostachys glauca*; 20. *Indocalamus sp.*

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