# Pollen records of Holocene vegetation and climate changes in the Longzhong Basin of the Chinese Loess Plateau*

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**Abstract** Pollen records with an average time resolution of 20—200 years from Holocene loess sections at Dingxi, Qin'an, and other localities of Gansu Province reveal a detailed history of vegetation and climate changes in the western Loess Plateau. For most time of the Holocene, the landscape was dominated by grasslands or forest steppes. However, during the middle Holocene (7.5—5.8 ka BP), relatively dense forests developed, and the endemic vegetation flourished, suggesting a much warmer and more humid climate condition than the present. Superimposed upon this general pattern are several dry intervals marked by the episodic expansion of grasslands or forest steppe. Xeric vegetation expanded after 3.8 ka BP, indicating a trend towards dry conditions.

**Keywords:** pollen records, glasslands, coniferous forests, Holocene, Loess Plateau

The dryland ecosystem is very sensitive to climate changes. To unravel the vegetation history of the Chinese Loess Plateau during the Late Pleistocene and Holocene, a number of pollen work have been done over the last decades[1—9]. In these earlier studies, the major difficulty is the extraction of enough quantities of spores and pollen grains from loess. In addition, the low sampling resolution and the poor age control of the pollen records are unable to provide a thorough understanding of the about past vegetation and climate changes in this area.

Technical developments in recent years enable high-resolution palynological studies of loess sequences and thus the reconstruction of vegetation and climate histories in this area since the Late Pleistocene[10—19]. There have been a few high-resolution pollen records constrained by numerous $^{14}C$ dates. An example is the 100 ka-long pollen record from Weinan in Shannxi Province[10, 11]. This section has an average time resolution of 930 years. The Holocene section (about 150 cm thick) was controlled by two $^{14}C$ dates. The vegetation and climate histories in the desert-loess transition zone, studied by Zhou et al.[14] and Li et al.[15, 16], have been extended back to the Lateglacial. The Holocene section is nearly 1000 cm thick, and was constrained by more than 10 AMS $^{14}C$ dates. In addition, using phytolith and molecular fossils to explore vegetation succession on the loess plateau is promising. However, compared with studies elsewhere, systematic and high-resolution palynological studies of the Loess Plateau are rare. Moreover, studying the structure of the primitive vegetation on the Loess Plateau has important implications for ecological restorations in NW China. At present, there are many conflicting views on the natural vegetation of the Loess Plateau during the Holocene. Some researchers believe that the Loess Plateau was covered with forests and forests-steppes in the Holocene, while others think that steppe vegetation was the climax community. Still others suggest that there were different vegetation types in different landforms and regions[21, 22]. High-resolution palynological studies will be helpful in reconstructing vegetation history, which are also important for better understanding of the history of natural environments that would be useful for landscape management.

Here, we present detailed palynological studies of five Holocene loess sections in Dingxi and Qin'an of the loess region of central Gansu, including analysis of more than 400 fossil pollen samples and 174 surface pollen samples from the studied area and its vicinity. This work reveals the succession of Holocene vegetation on the Loess Plateau of Central Gansu Province. The chronology of the five sections was controlled by a total of 16 AMS $^{14}C$ dates. Samples were taken at 2—5 cm intervals, yielding an average time resolution of 20—200 years. We improved the

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methods for the treatments of loess pollen samples. For most samples, more than 300 pollen grains were identified and counted. This quantity ensures a well representation of pollen assemblages and thus reduces potential errors in the reconstruction of past vegetation.

## 1 The modern vegetation in the studied area

The studied area is situated in the central Gansu Loess Plateau region, west of Liupanshan and east of Lanzhou, where the climate condition is semi-arid. Modern vegetation is characterized by forest steppes composed of thermophilic and xerophilous components of east Asia[23]. The vegetation of the studied area exhibits a strong vertical zonation. The forest belt is found mainly on the Xinglong and Mahan mountains. It is divided into several subzones, including *Picea* conifer forest at 2400—3000 m a.s.l., *Betula-Populus* broad-leaved forest at 2200—2400 m a.s.l., and brushwood at 1800—2200 m a.s.l.

## 2 Site description and methods

We studied five Holocene natural sections in central Gansu Province. From east to west, they are Dadiwan, Maying, Jiantan, Dingxi, and Sujiawan. The Dadiwan (DDW) section (35°00′N, 105°54′53.3″E, 1400 m a.s.l.) is situated at the first terrace on the southern bank of the Qingshui River, a tributary to the Hulu River in Qin'an, and has an outcrop of 500 cm thick. The upper part (0—120 cm) of the section is eolian loess; from 120 to 160 cm is a marsh facies of pedogenically modified sediments; from 160 to 350 cm is a wetland-alluvial complex; from 350 to 404 cm are marsh-wetland deposits underlain by fluvial loess. A total of 250 pollen samples were collected from the section at an average interval of 2 cm.

The Maying (MY) section (35°20′18.2″N, 104°59′23.2″E, 1800 m a.s.l.) is located on the southern bank of a tributary of the upper Liugu River. The studied section is stream-eroded with a thickness of 300 cm. From 300 to 290 cm is a slightly loose soil structure. From 290 to 170 cm is leached paleosol with pellet structure and root holes. From 170 to 50 cm is a weak paleosol with blocky structure. Above 50 cm is loess and surface soil with numerous root holes.

The Jiantan (JT) section (35°20′18.2″N, 104°59′23.2″E, 1889 m a.s.l.) is a stream-eroded outcrop of 450 cm thick. Below 380 cm is grey, blocky marsh-wetland soil. From 380 to 370 cm is blocky weak soil; from 370 to 40 cm is loess interbedded with alluvium, and the top 40 cm is modern cultivated soil.

The Dingxi (DX) section (35°32′53.1″N, 104°36′33.5″E, 1750 m a.s.l.) is located beside the Academy of Agriculture Sciences in the south of Dingxi City. It is of 465 cm thick. The upper 60 cm is the arable soil layer. The 150—60 cm and 450—400 cm are loess, 300—150 cm is a paleosol and the 400—300 cm is bug soil.

The Sujiawan (SJW) section (35°32′20″N, 104°31′22″E, 1700 m a.s.l.) lies at the first terrace of a tributary of the Guanchuan River in Dingxi of Gansu, with an outcrop of 450 cm thick. Above 300 cm are 3 layers of loess alternating with 3 layers of soil. From 300 to 400 cm are bedded marsh-wetland facies, and the underlying 400—450 cm is loess. A total of 85 samples were collected from the section at an average interval of 5 cm.

The ages of these sections were dated using the AMS (accelerator mass spectrometry) $^{14}C$ technique in the $^{14}C$ AMS laboratory of Arizona University. A total of 15 AMS $^{14}C$ dates were obtained on charcoal from the Dadiwan, Tianan, and Sujiawan section (Fig. 1). Dates from the Dadiwan section ranged within 12—3.8 ka BP. The theoretical resolution of each sample is 20—50 yr. The Sujiawan section has a $^{14}C$ date of 10.9—0 ka BP. Eighty-five samples were analyzed for this section, with the theoretical resolution of 200—300 yr. Five $^{14}C$ AMS dates (Fig. 1) were attained using organic matter for the Dingxi and Maying section.

Palynological studies of loess samples are very difficult because of low pollen abundance. In order to obtain a sufficient number of pollen grains per sample (e.g. $>$ 300 grains), we employed the following methods. A total of 20—40 g bulk samples were washed repeatedly with 5%—10% HCL, and then treated with HF. After this treatment, most of the samples were counted to more than 300 pollen grains. In order to calculate the pollen concentration, two *Lycopdium* tablets were added.

A number of samples were taken from the sections for grain-size, organic-matter and snail analyses. Organic matter was measured using the chemical titration method, and grain size using a Master Sizer 2000 laser grain-size analyzer.

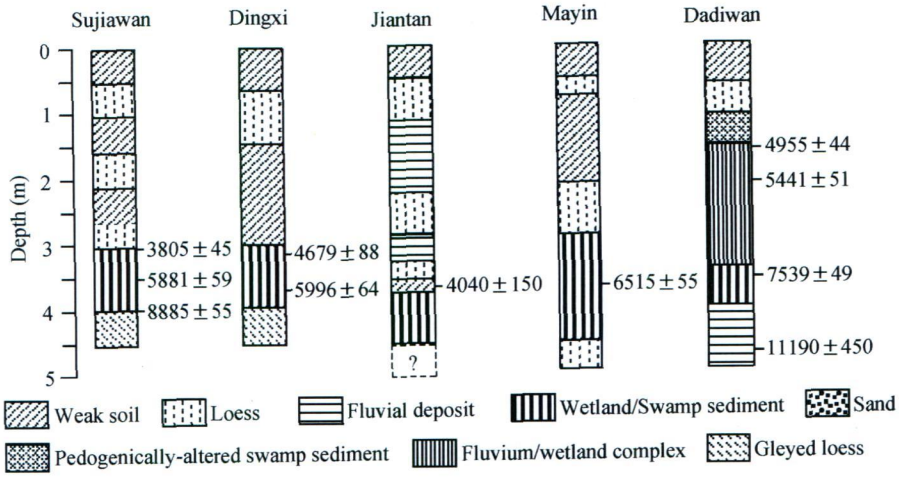


Fig. 1. Strata and AMS $^{14}C$ dates of five Holocene loess sections in central Gansu Province.

## 3 Pollen assemblages

### 3.1 Surface pollen samples

In order to give a better explanation of the conifer pollen content in the Holocene strata and the possible existence of the coniferous forests in the studied area, we collected 174 surface samples from the studied area and its vicinity (Fig. 2). Of which 71 were obtained from forests, 63 from grassland meadow, 28 from desert (grassland), 9 from brush land, and 3 from forest steppe. The results of the conifer tree species contained in these surface samples are listed in Table 1. Conifers, especially *Pinus* and *Cunninghamia*, are most abundant in forests, with the highest percentage of 21.6%—83.6%, especially *Pinus* pollen accounting for as high as 76.2% of the coniferous vegetation. In *Picea* forest, *Picea* pollen may reach 83.6%, whereas in mixed deciduous broad-leaved forests, the average value of *Pinus* pollen is 36.6%, *Picea* 8.3%; in deciduous broad-leaved forest, *Pinus* pollen reaches 37.6%, *Picea* 3.2%; *Abies* and *Tsuga* pollen is lower than *Pinus*, and *Picea* exceeds 20%. Forest grassland is the transitional type between forest and grassland vegetation, of which the content of *Pinus* and *Picea* pollen also more or less exhibits such a transitional character. *Pinus* pollen may reach as high as 55% in content, while *Picea* pollen does not exceed 20%.

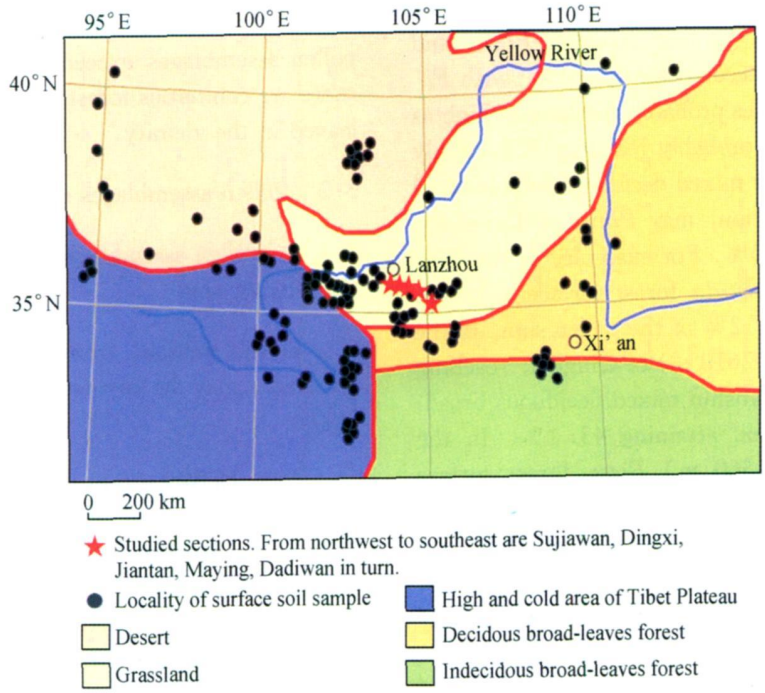


Fig. 2. Distribution of modern surface pollen samples in the study area and its neighboring area.

Table 1. Coniferous tree pollen percentages of the 174 modern surface soil samples from the study area and its surrounding area.

| Modern vegetation in the sampling spots | Sample number | Coniferous tree pollen percentages (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Pinus* | | *Abies* | *Picea* | | Tsuga | Larix |
| | | Highest | Average | Highest | Highest | Average[a)] | Highest | Highest |
| Coniferous forests | 34 | 76.2 | 20.2 | 19.3 | 83.6 | 35.5 | 4.4 | 28.3 |
| Mixed deciduous broad-leaved forests | 12 | 67.1 | 36.6 | 1.7 | 54.1 | 8.3 | 2.0 | 0 |
| Deciduous broad-leaved forests | 25 | 83.1 | 37.6 | 16.6 | 21.6 | 3.2 | 3.4 | 16.5 |
| Forest steppe | 3 | 55.0 | 5.3 | 0 | 18.6 | 0 | 0 | 0 |
| Shrubs | 9 | 25.0 | 9.0 | 2.2 | 4.5 | 2.6 | 0 | 3.0 |
| Grassland | 25 | 17.1 | 8.4 | 8.5 | 17.1 | 1.1 | 0 | 0 |
| Meadow | 38 | 22.6 | 3.6 | 0.8 | 7.7 | 0.5 | 0.8 | 0 |
| Desert (grassland) | 28 | 37.5 | 5.1 | 0 | 41.2 | 5.3 | 0 | 0 |

a) The averages of *Abies*, *Tsuga*, and *Larix* are not calculated because of their small quantities.

Our results indicate that the percentages of *Pinus*, *Picea*, *Abies*, and *Tsuga* pollen from grassland, meadow, and forest (steppe) vegetation will not exceed 10%. Only in the surface soil of the forest grassland, *Pinus* and *Picea* pollen exceed 35%, and the average of *Abies* and *Tsuga* pollen is less than 10%. Deciduous *Pinus* only appears in deciduous *Pinus* forest surface soil samples. In most surface samples of forest grassland or brush land vegetation, neither *Pinus* or *Cunninghsmia*, nor *Abies* or *Tsuga* pollen exceeds 10%, but a few samples may contain as much as 20%; but in the total pollen spectra, there should be many tree species.

Surface soil pollen from China's west and northern arid regions[24—26], the grasslands, meadows or deserts of Gansu, Qinghai and Xizang, *Pinus* and *Picea* pollen generally account for 0—10%, with *Pinus* pollen in few samples probably reaching as high as 33% and *Picea* pollen probably reaching 32%. Only in the conifer forests or mixed deciduous broad-leaved forests or shrub vegetation, may *Pinus* or *Cunninghamia* pollen exceed 30%. For example, in the Qinling (1500 m) *Pinus-Betula* forest surface soil, *Pinus* pollen makes up 41.2% of the pollen sum, in the surface soil of Zhajian (2610 m) of Qinghai, reaching 58.3%, and in the Tianshui mixed deciduous broad-leaved forest surface soil attaining 43.1%. In the Xinglong Mountain (2360 m) *Picea* forest surface soil, *Picea* pollen makes up 33.5%, and *Pinus* pollen 13.5%. In the Maxian mountain (3100 m) shrub surface soil, *Pinus* pollen is 31.5%. In the Badong *Quercus* forest surface soil of Liziyuan (1567 m) of Jingning, Gansu, *Pinus* pollen is 65%, *Picea* pollen 0.5%. Below the *Picea* forest (2240 m) of Qilian Mountain, *Picea* pollen is 49.6%, *Pinus* pollen 5.4%. In the forest surface soil of the Altay Mountain, *Picea* is certainly abundant. For instance, the *Picea* pollen in the Sanjiaocheng surface soil of the Zhongluhu region of the Shiyang River may reach as high as 50%[27]. A large amount of surface soil, climatic response surface in north China, shows that in the humid region where the mean July temperature is 10—15 ℃ and the annual precipitation is more than 600 mm, the pollen percentage is, in general, higher than 40%. If the annual precipitation is 100—400 mm and the mean July temperature is 0—20 ℃, the value may be increased to lower than 30%[26]. It may be regarded as, in this way, that in the Loess Plateau where the annual rainfalls are less than 500 mm, *Picea* forests are impossible to grow there. On the contrary, if the conifer tree pollen values of the pollen assemblages exceed 30%, it is for sure that there are coniferous forests or mixed deciduous broad-leaved in the vicinity.

### 3.2 Pollen assemblages of the Holocene section

#### 3.2.1 Pollen assemblages of the Dadiwan section in the Qin'an area

In this section, from bottom to top, pollen assemblages may be divided into nine zones (Fig. 3 (a)):

Zone DDW9 (500—454 cm, 12.0—9.5 ka BP). This zone is dominated by herbaceous pollen, such as Compositae (20%—60%) and *Artemisia* (30%—70%). The pollen concentrations of both reach 1000 grains/g, Woody plant pollen are *Pinus*, and *Ulmus*, with extremely low pollen concentrations (< 20 grains/g).

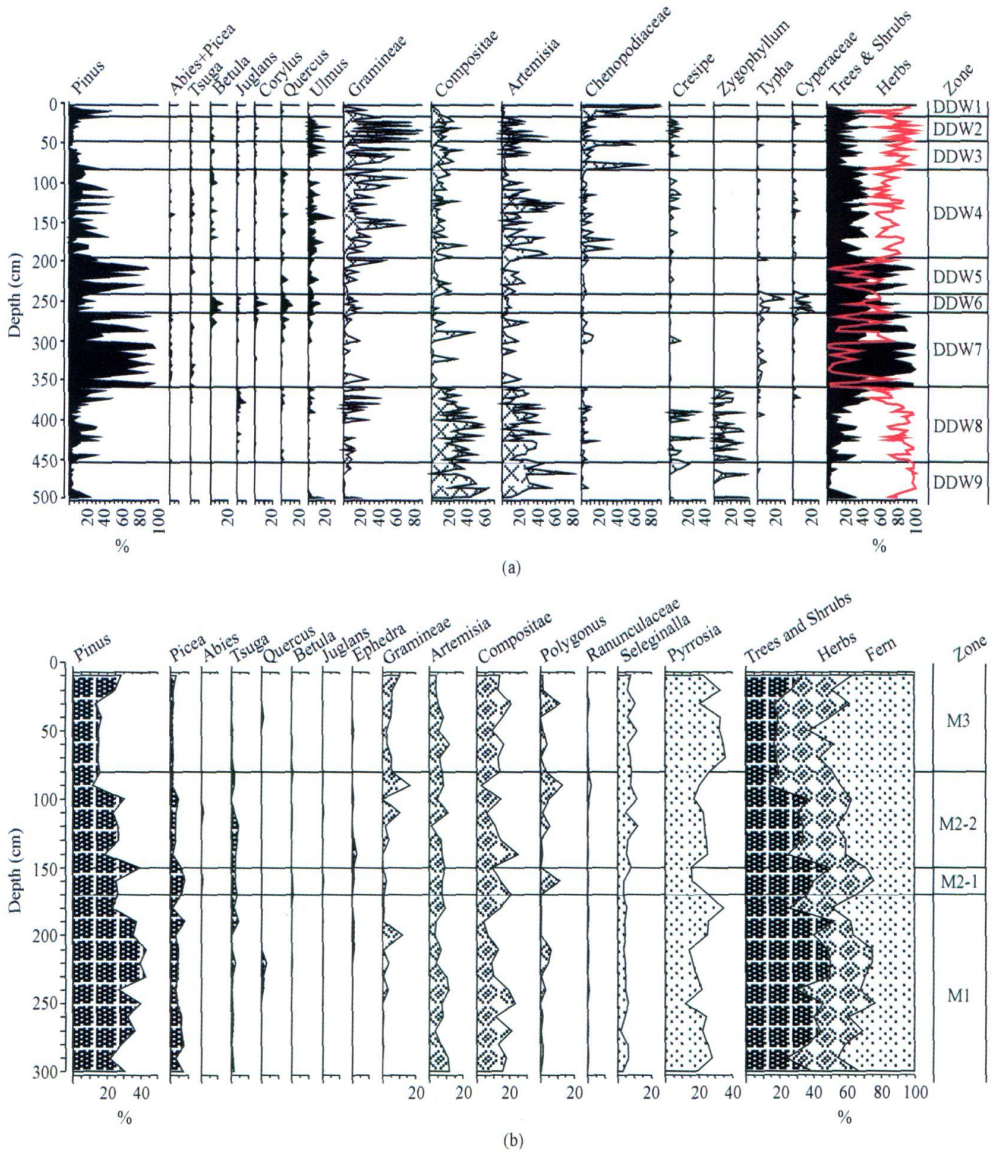


Fig. 3. Pollen diagram of the DDW (a) and M Y (b) section of Qin' an.

Zone DDW8 (454—359 cm, 9.5—7.6 ka BP). In this zone, woody plant pollen are more abundant. The concentrations of *Pinus*, *Sabina*, Cupressaceae, *Juglans*, *Ulmus* and *Nitraria* do not exceed 100 grains/g. Herbaceous plant pollen including Compositae and *Artemisia* remains at high values. Gramineae, Ranunculaceae, *Cresipe*, and *Zygophyllum* are also present.

Zone DDW7 (359—265 cm, 7.6—6.5 ka BP). This zone is dominated by conifer pollen such as *Pinus*, *Picea*, *Abies*, *Tsuga*, Cupressaceae, and *Sabina*. Deciduous broad-leaved tree species such as *Betula*, *Quercus*, *Corylus*, *Ulmus*, and *Juglans* occur in the upper part of this zone. The total concentration of the woody plant pollen reached 200—400 grains/g. Herbaceous plant pollen was mainly Gramineae, Compositae, and Chenopodiaceae with percentages not exceeding 20%. *Typha* and *Cyperaceae* also occur.

Zone DDW6 (265—242 cm, 6.5—5.9 ka BP). This zone is characterized by the increase of deciduous broad-leaved tree species, and by occurrences of hydrophilous herbaceous plant pollen. Total pollen concentration reached as high as 3000—6000 grains/g, including woody plant pollen mainly from *Betula* (10%), *Corylus* (5%—15%), *Quercus* (10%), *Ulmus* (15%), Rosaceae, *Celtis*, *Salix*, *Alnus*, *Pinus* (20%—30%), *Picea* (5%—10%), *Tsuga*, and Cupressaceae. Herbaceous plant pollen is mainly from *Typha* and Cyperaceae, with pollen percentages

making up 10%—25% and 5%—25%, respectively. Other herbaceous plant pollen includes Gramineae (5%—20%), *Artemisia* (15%), Compositae (5%), Chenopodiaceae (5%), and *Humulus*.

Zone DDW5 (242—196 cm, 5.9—5.4 ka BP). Compared with DDW6, pollen of deciduous broad-leaved woody plants in this zone decreased, while some herbaceous plants, such as Gramineae, Compositae, and *Artemisia* increased, but *Typha* and Cyperaceae pollen is less abundant than that in Zone DDW6.

Zone DDW4 (196—83 cm, 5.4—3.5 ka BP). This zone is dominated by herbaceous plant pollen (over 60%), mainly from *Artemisia* (20%—60%), Gramineae (20%—50%), Compositae (15%—30%), Chenopodiaceae (5%—20%), *Polygonum* (0—15%), *Humulus*, *Cresipe*, *Talictrum*, Ranunculaceae, Cyperaceae, and *Typha*. Woody plants are mostly *Pinus* and *Ulmus*, respectively, making up 10%—30% and 5%—20%; others are woody trees and shrubs, such as *Picea*, *Tsuga*, Cupressaceae, *Betula*, *Corylus*, *Juglans*, *Elaeagnus*, and *Nitraria*.

Zone DDW3 (83—47 cm, 3.5 ka BP—?). This zone is also dominated by the herbaceous plant pollen, especially Chenopodiaceae, which reached 10%—60%. The abundance of *Artemisia* is less than that in zone DDW4, but Gramineae (10%—50%) and Compositae (5%—25%) remain the same values. Woody plant pollen is rare, most of which are from *Ulmus* (2%—15%) with a few *Pinus* Cupressaceae, *Betula*, and *Elaeagenus*.

Zone DDW2 (47—16 cm). As a whole, the total concentrations and percentage values of pollen in this zone are similar to those in zone DDW3, but pollen from Gramineae, *Artemisia*, *Cresipe* and Cyperaceae increased. *Ulmus* pollen is fairly abundant.

Zone DDW1 (16—0 cm). This zone is characterized by a sharp increase in Chenopodiaceae (25%—85%), and the rapid decrease in Gramineae, and Compositae. Woody plant pollen is scarce, with only a small amount of *Pinus*, *Rhammus* and *Salix*.

### 3.2.2 Pollen assemblage of the Maying section

In this section, the pollen concentration is lower than that in the Dadiwan section, with only 120—200 grains/g (Fig. 3(b)).

Zone MY1 (300—180 cm, 7.5—5.5 ka BP). This zone corresponds to zone DDW7, predominated by woody plant pollen. *Pinus* is dominant (20%—40%), along with *Picea*, *Tsuga*, and *Abies*. The pollen from a small number of deciduous broad-leaved trees occurs in company with the conifer pollen, such as *Quercus*, *Betula*, and *Tsuga*. Herbaceous plant pollen is mainly from Compositae (5%—20%) and *Artemisia* (5%—10%).

Zone MY2 (180—80 cm, 5.5—1.2 ka BP). The pollen (50%—80%) in this zone is more abundant than that in zone MY1. Compositae (5%—25%), *Artemisia* (10%), Gramineae (0—15%), *Polygonum* (2%—15%), and Ranunculaceae all occurred abundantly. Conifer tree pollen has a tendency to decrease, but values of deciduous broad-leaved trees increased. The pollen assemblage zones of this zone are similar to zones DDW3-2.

Zone MY3 (80—10 cm, 1.2 ka BP—?). Herbaceous plant pollen maintains high values, higher than that in Zone MY2. However, at the late stage, owing to the increase in *Pinus* and *Picea* pollen (perhaps transported by winds from remote localities), the deciduous broad-leaved tree species pollen is reduced.

The Jiantan section is near the Maying section. Lithologically, they are similar. Here, the sampling intervals were rather coarse (10 cm). The pollen analyses are used as a complement to the Maying section. The results show that the part above 400 cm can be correlated to Zone MY2 and MY 3.

### 3.2.3 Pollen assemblages of the Sujiawan section

Zone SJW1 (450—410 cm, 10.9—9 ka BP). Herbs and shrubs are equivalent in this zone, although shrub pollen was very scarce at the early stage. *Pinus* pollen tended to increase at the late stage (rising from 5% to about 50%). Herbs were dominated by Compositae, *Artemisia*, and Gramineae. Pollen concentrations of this zone are very low (<500 grains/g) (Fig. 4).

Zone SJW2 (410—365 cm, 9.0—5.9 ka BP). Shrub pollen reaches 60%—85%, of which *Pinus* plays an absolutely dominant role, followed by *Picea*, *Abies*, *Tsuga*, *Juglans*, *Ulmus*, and *Quercus*. Herb pollen, such as Compositae, Gramineae, and

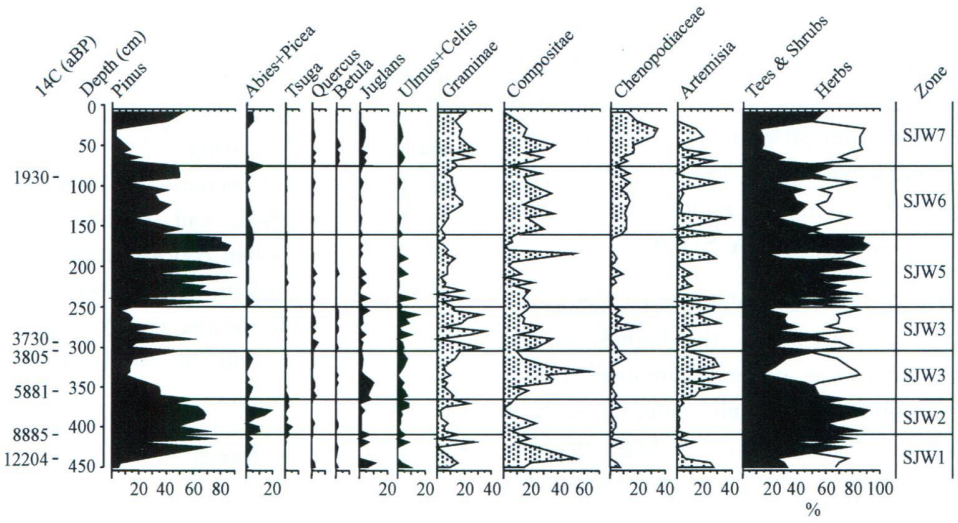


Fig. 4. Pollen diagram of the Sujiawan section.

*Typha*, is relatively scarce, with pollen concentrations of $6.5\times10^3$ grains/g.

Zone SJW3 (365—305 cm, 5.9—3.8 ka BP). This zone is dominated by herb pollen (40%—80%), mainly from Compositae (20%—60%), *Artemisia* (20%—50%), Gramineae (10%), and Ranunculaceae. Woody pollen began to decrease to 20%, and then rose slightly to nearly 40%. In addition to *Pinus*, there were *Juglans* (5%—10%), *Ulmus* (5%), *Quercus*, and Rosaceae. Pollen concentration in this zone is $1-3\times10^3$ grains/g.

Zone SJW4 (305—250 cm, 3.8—3.3 ka BP). Shrub pollen continued to decrease (20%—30%). Herb pollen is 30%—70% of the total, mainly from Compositae, *Artemisia*, Gramineae, and Chenopodiaceae with percentage ranging between 10% and 20%. In addition, *Typha* begins to increase (about 10%), along with *Humulus*, and Ranunculaceae. The pollen concentration is $1-2\times10^3$ grains/g.

Zone SJW5 (250—160 cm, 3.3—2.5 ka BP). This zone is characterized by few changes in the pollen assemblage. However, frequent fluctuations of pollen percentage values between 10% and 60% were present in *Pinus* Compositae, and *Artemisia*. Pollen concentrations fluctuated within $1-3\times10^3$ grains/g.

Zone SJW6 (160—75 cm, 2.5—1.7 ka BP). Woody pollen had a tendency to decrease, especially *Pinus*, with values generally between 10% and 25%. The pollen values of *Quercus*, *Corylus*, and *Ulmus* also decreased. Herb pollen values, mainly from Compositae, *Artemisia*, Chenopodiaceae, Gramineae, and Leguminosae reached 30%—65%. The total pollen concentrations were $1-2\times10^3$ grains/g.

Zone SJW7 (75—0 cm, 1.7 ka BP—). This zone is dominated by herb pollen (40%—70%), mainly Chenopodiaceae, Compositae, *Artemisia*, Gramineae, *Polygonum*, *Humulus*, and Leguminosae. Woody pollen was scarce at the early stage (10%) and then increased to 45% at the late stage, due to large increases in *Pinus* pollen. Other woody pollens were *Juglans*, *Ulmus*, and *Quercus*, not exceeding 50%. The pollen concentration of this zone decreased to 200 grains/g.

### 3.2.4 Pollen assemblage of the Dingxi section

The pollen assemblage of this section is similar to that of the zones SJW6-7 of the Sujiawan section (about 3.5 ka BP), and may be divided into four zones.

Zone DX1 (250—230 cm, about 3.5—3.3 ka BP). The pollen species of this zone is not diverse, dominated by herb pollen (60%), especially by *Artemisia* (10%—45%). Woody pollen is dominated by *Pinus*, which increased gradually from 20% to 50%, corresponding to the zone SJW4 of the Sujiawan section.

Zone DX2 (230—130 cm, 3.3—2.5 ka BP). Woody pollen, especially *Pinus*, has fairly high values (30%—60%), while *Picea*, and *Cunninghamia* pollen reached 0—5%, together with *Ulmus*, and *Juglans*; Compositae increased (about 15%), while *Artemisia* decreased. This zone is similar to zone

SJW5.

Zone DX3 (130—55 cm, 2.5 ka BP—). Woody pollen, especially *Pinus*, and *Picea*, decreased from 60% to 15%, and from 30% to 0%, respectively. Values of Compositae reached 20%—30%. Chenopodiaceae pollen occurred in the middle part of this zone. This zone is similar to zone SJW6.

Zone DX4 (55—10 cm). Values of Chenopodiaceae pollen increased to 50%, the highest of the whole section. Gramineae pollen maintained 10%. Other pollen also presents in small amounts, such as Ranunculaceae, *Polygonum*, Leguminosae, *Pimpinella*. *Pinus*, and *Picea* occurred abundantly for a time in the middle and upper parts of this zone, reaching as high as 50%. Spores decreased and finally vanished. This zone corresponds to zone SJW7.

### 3.3 Other proxies

#### 3.3.1 Organic matter and grain size

Regional biomass and vegetation cover are reflected by the amount of organic matter. In semi-arid regions, they are controlled by water availability. Thus, we can regard organic matter as a proxy of biomass. In the study of loess, coarse fraction, part of grain size analysis, is an indicator of winter monsoon. Eolian loess only occurs in the upper part. However, grain size also reflects the amount of eolian loess, and the degree of water erosion in swamp sediment. When vegetation is scarce and erosion is accordingly strong, many coarse materials are washed into the swamp. The sections from central Gansu Province have relatively low content of organic matter, low percentage of fine ($<2$ μm) fractions, and high percentage of coarse ($>63$ μm) fractions between 12 and 9 ka BP, in phase with low pollen concentrations. During 9—5.9 ka BP (6.5—4.5 ka BP in the MY section; 6—5 ka BP in the DX section), organic matter increased. The percentage of coarse fractions decreased, while fine fractions increased sharply. During 5.9—3.8 ka BP, the content of organic matter was still high, and the grain size was similar to that of 9—5.9 ka BP. This stage is in accord with low pollen percentage of trees and shrubs. In phase with the predominance of herbaceous pollen, the content of organic matter decreased rapidly (wave-like decreases at DDW), with high percentage of coarse fraction (up to 30% at DDW) and low percentage of fine fraction occurred between 3.8 and 3.3 ka BP. In phase with the increased herbaceous pollen, the content of organic matter fluctuated frequently, with low percentage of coarse fraction and high percentage of fine fraction occurred between 3.3 and 2.5 ka BP. During 2.5—1.7 ka BP, the content of organic matter decreased. The percentage of coarse fractions decreased, and the fine fraction increased. With the low pollen concentration and predominance of herbaceous pollen, the content of organic matter increased, while the percentage of coarse fraction decreased sharply, and the fine fraction decreased after 1.7 ka BP.

#### 3.3.2 Mollusc fossils

Mollusc fossils occur mainly in the SJW section and the DDW section, especially in the SJW section. Intact mollusk fossils did not present in the SJW section before 9 ka BP, and only *Vallonia tenera* (Reinhardt) was found in the DDW section. Genera of the SJW section were *Gyraulus*, *Galba*, and *Vallonia*. Six aquatic mollusk fossils appeared in SJW section, namely *Gyraulus sibiricus* (Dunker), *Gyraulus heuderi* (Clessin), *Planorbarius sp.*, and *Polypyris hemisphaercula* (Benson). Many cold/dry mollusk fossils presented in the DDW section between 5.5 and 3.8 ka BP. Both aquatic and terrestrial mollusk fossils were present during 3.8—3.5 ka BP, whereas no mollusk fossils occurred between 3.5 and 3.3 ka BP. *Vallonia* and *Pupilla* only occurred during 3.3—2.0 ka BP, while terrestrial mollusk fossils occasionally occurred after 2.0 ka BP.

#### 3.3.3 Charcoal

The total amount of charcoal reflects not only the influence of human activity and climate, but also biomass. In the DDW section, charcoal concentration was relatively low ($<2\times10^5$ grains/g), without distinct change during 12—9 ka BP in phase with predominance of terrestrial herbs and low pollen concentration. The charcoal concentration increased gradually and reached the high, making up over $2\times10^5$ grains/g between 9 and 7.5 ka BP in phase with dominance of trees and shrubs. During 2.5—3.8 ka BP charcoal increased successively with an average of $1.5\times10^5$ grains/g. The pollen percentage of terrestrial herbs increased at the same time. After 3.8 ka BP, charcoal concentration arrived at the minimum value, and then decreased. It is consistent with the pollen zone dominated by terrestrial herbs (Fig. 5).

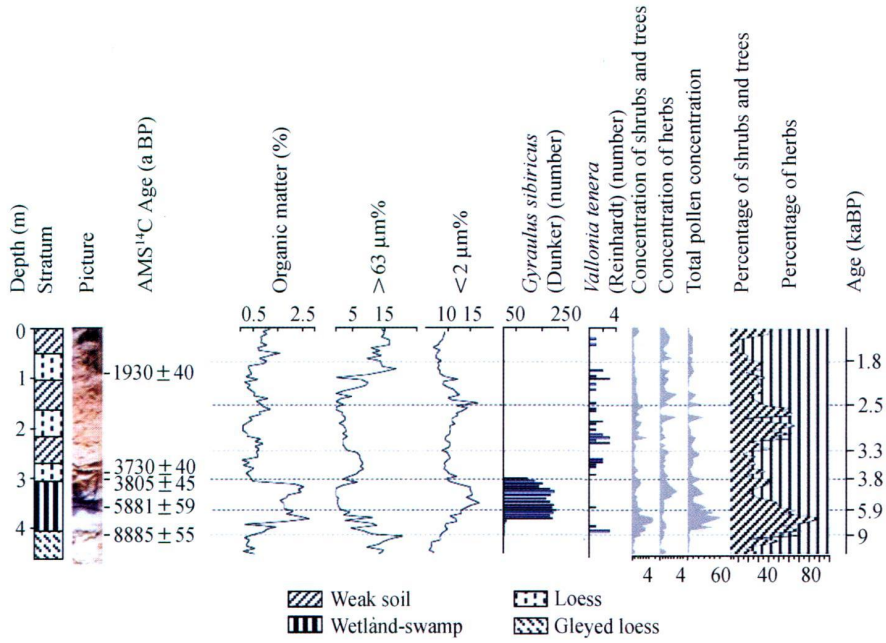


Fig. 5. Variations of proxies in the Sujiawan section.

## 4 Vegetation and climate changes

According to pollen and other proxies, the regional vegetation and climate experienced the following major stages during the Holocene.

Desert grassland stage (12.2—8.8 ka BP). Vegetation was dominated by herbs, mainly including *Artemisia*, Chenopodiaceae, Compositae, with low pollen concentrations, indicating a probably lateglacial cold arid climate at the late stage. However, woody plants began to increase, indicating a gradual increase in temperature and humidity.

Steppe stage (8.8—7.5 ka BP). Woody plants began to increase, in particular, *Pinus*; deciduous broad-leaved tree species occurred sporadically. Herbs, for example, *Artemisia*, Chenopodiaceae, and Compositae, though decreased, were still abundant, indicating a temperate cool and slightly arid climate as a whole, with a steppe or forest grassland landscape.

Conifer forest stage (7.5—6.2 ka BP): Woody plants increased rapidly at this stage, including mainly *Picea*, *Pinus*, *Ulmus*, *Betula* and *Quercus*, with a high pollen concentration. A conifer forest vegetation was developed in this period.

Temperate deciduous broad-leaved forest stage (6.2—5.8 ka BP). Woody plants and shrubs are equivalent to herbs in percentage values. Deciduous broad-leaved trees were relatively abundant, indicating a temperate deciduous broad-leaved landscape. In the Dadiwan section, some hydrophytic and hygrophilous herbs appeared, indicating a temperate and humid climate.

Forest grassland stage (5.8—3.8 ka BP). At the early stage, the deciduous broad-leaved components decreased, and herbs pollen increased, along with the decreases of hydrophytic and hydrophilous plants, presenting a forest grassland landscape. After 5.0 ka BP, woody plant components decreased. *Pinus* especially made a gradual retreat, and herbaceous *Artemisia* expanded. The proportion of the Woody and herbaceous plants were similar, with small numbers of deciduous broad-leaved tree species appearing in the forest grassland. The climate was temperately cool and slightly dry.

Grassland stage (3.8—3.5 ka BP). Woody plants decreased, while herbs dominated, including Compositae, *Artemisia*, Chenopodiaceae, Gramineae, and other components of grassland, indicating a temperate grassland landscape.

Forest grassland stage (3.5—3.1 ka BP). At this stage, woody and shrub plants were equivalent to herbs in values, with a high pollen concentration, indicating forest grassland.

Grassland stage (3.1—2.9 ka BP). Herbs dominated with abundant *Pinus*. The vegetation of this stage was similar to that of the 3.8—3.5 ka BP

stage, being temperate grassland vegetation.

Forest grassland stage (2.9—2.5 ka BP). Herbs dominated the landscape. *Artemisia*, and Chenopodiaceae sometimes occurred abundantly. Pollen concentrations are low, possibly equivalent to the northern edge of the China's modern forest grassland, indicating a very dry climate.

Grassland stage (2.5—2.0 ka BP). Herbaceous *Aremisia*, Gramineae, Compositae, and Chenopodiaceae were abundant, with some *Nitraria*. Endemic vegetation is similar to the northern edge of China's present temperate grassland.

Forest grassland stage (2.0—1.0 ka BP). The landscape was absolutely dominated by herbs, with some deciduous broad-leaved tree species and few *Pinus*. Vegetation is similar to the landscape of the northern edge of the present forest grassland.

## 5 Discussion and conclusions

### 5.1 Holocene vegetation history in the Loess Plateau of central Gansu Province

Pollen records reveal that the Holocene vegetation of the studied area experienced many occasions of rapid change from grassland, forest grassland, coniferous forest to desert grassland. The Holocene palynofloras from Dingxi and Qin'an indicate that forest vegetation was developed in the shade-slopes during the period of good moisture conditions in the studied area. The vegetation types were mainly temperate *Cunninghamia*- and *Pinus*-dominated coniferous forests, sometimes accompanied by a few other woody plants. In the middle Holocene, in addition to the coniferous tree species such as *Picea* and *Pinus*, some warm temperate deciduous broad-leaved tree species such as *Betula*, *Ulmus*, and *Quercus* also appeared. However, there were grasslands and forest grasslands including *Artemisia*, Compositae, Gramineae, Chenopodiaceae, and Ranunculaceae, with very low pollen concentrations in these sections. It may be seen that at that time, the coverage of the grassland and desert grassland vegetation was not high. Pollen was very rare, reflecting that the climate was worse, and vegetation cover was sparse.

According to the succession of vegetation types in the section, these changes were rapid, especially in the lateglacial. Transitions between grassland and desert grassland were over short intervals, e.g. the shortest interval is only 700 years and generally lasted about 1000 years. This indicates that since the LGM (Last Glacial Maximum), vegetation never became stable but changed rapidly and often. During the middle Holocene (about 7.5—6.2 ka BP) when the climatic conditions were good, coniferous forests appeared but lasted only 1300 years. During 6.2—5.8 ka BP, the temperate deciduous broad-leaved forests developed, only lasting 400 years, showing that the Holocene climatic changes in the studied area were very sharp.

### 5.2 Variability of Holocene climate conditions in Dingxi and Qin'an

The palynogical records of the Sujiawan and Dadiwan sections show that the vegetation flourished and the climate was rather humid during 8.8—3.8 ka BP. About from 10 ka BP onwards, *Picea* pollen began a gradual nonlinear increase to 7.5 ka BP and then decreased after 5.0 ka BP, with an increased pollen concentration during this period. Appearances of peak *Picea* pollen values and concentrations at 9.7 ka BP, 9.2 ka BP, 8.8 ka BP, 7.5 ka BP, and 5.8 ka BP indicate high effective moisture in the studied area. In the semi-humid and semi-arid Loess Plateau region of central Gansu Province, water content has greater effects on plants than temperature does, which is advantageous to forest development. During 7.5—6.2 ka BP and 6.2—5.8 ka BP, *Picea* increased, along with increases of woody plants, indicating forest or forest grassland vegetation.

During 10—7 ka BP organic matter was high, showing that at this time, vegetation coverage was high. Moreover, during 9—6.5 ka BP in the Sujiawan section[28, 29], a large amount of hydrophytic and hygrophilous snails presented, and a number of hydrophytic and hygrophilous plants also occurred in the Dadiwan section. In addition, pollen from the Dadiwan cultural site reveals that coniferous forests presented during 8.5—7.8 ka BP[30]. According to archaeological studies of the first terrace of the Hulu river, Qin'an, moist climate led to the appearance and development of the Dadiwan civilization during 8—7 ka BP[31]. The palaeosol magnetic susceptibility of western Gansu recorded five stages of soil development, of which during 7.7—5.7 ka BP, the warmest period occurred[32]. In the Sajiaocheng section at Zhongluhu of the Shiyang River *Picea* pollen values reached as high as 80% during 9.2—7.25 ka BP and 7.25—6.3 ka BP, indicating well-developed vegeta-

tion in the river basin[27]. During 8.5—7.5 ka BP, two peaks of pollen concentrations indicate that the Shiyang river basin had high vegetation coverage, especially by alpine vegetation[33, 34]. At that time, the mountain forest grassland was developed on a black loam. During 10—7.5 ka BP, Liushuwan of northern Shanxi experienced a warm and humid climate[15].

However, pollen records show that the humid stages were highly variable. In fact, the entire Holocene is marked by rapid changes in climate. It is inferred from pollen assemblages and the changes of pollen concentrations in the Sujiawan and Dadiwan sections that several dry events happened in the central Gansu area. We use the high values of *Picea* pollen, the abundance values of coniferous tree pollen, and high pollen concentrations in general to indicate humid stages, and use very low pollen concentrations of mountain vegetation components, and even the pollen-poor belt to indicate dry stages. Taken together, these factors revealed that there were 11 dry stages appearing in the two sections.

The earliest dry event (D11) took place before or after 10.9 ka BP, probably being correlated with Fang[36] earliest cold event (10 ka BP) and dry stage D9[34] in the Minqin basin during China's Holocene millennium-scale climatic changes. D10—D5 are six dry events that occurred at 9.4, 8.8, 8.0, 6.8, 5.6, and 5.0 ka BP, respectively. These dry events lasted for a short time. As indicated by pollen analysis, all of these dry events happened abruptly during the time when coniferous trees were well developed, which turned the forests or forest grassland to open grassland or desert grassland. Event D10 happened before or after 9.4 ka BP, being the dry event before the Holocene climate optimum stage. This event was equivalent to the dry event during 9.7—8.5 ka BP at the Dadiwan site, the dry event during 9.8—9.2 ka BP in the Sanjiaoyu section at the Shiyang river and the dry cold event during about 10.2—10 ka BP at Liushuwan corresponding to the cold event at 9.7 ka BP at Dunde ice core and at 9.5 ka BP at Ruoergai. D9 and D8 happened at 8.8 and 8.0 ka BP, respectively, corresponding to the cold event of the secondary glacier advance at Dunde ice core, and equivalent to the D7 and D8 at Sanjiaocheng, the Minqin Basin. At 8.0 ka BP, there was a cold event occurring not only in China, but also in the North Atlantic and Western Africa, further supporting the existence of this cold event in central Gansu Province. D7 (6.8 ka BP) was a very particular abrupt dry event during the flourishing of forest vegetation, with which no corresponding dry event in the neighboring area may be compared. It was possibly related to the cold event of Dunde ice core at 6.5 ka BP, perhaps only occurring in Qin'an and Dingxi. During this time period, especially in Qin'an, coniferous tree pollen values were reduced from 90% to about 5% and organic material became low. Those of $<2$ μm grain size reduced from 20% to about 5%. D6, at 5.6 ka BP, was equivalent to the D4 dry stage at Sanjiawan, the Minqin Basin, and can be correlated to the cold event of Dunde ice core at 5.4 and 5.6 ka BP and three low moisture events at Hongshui river at 5.66, 5.56, and 5.38 ka BP, respectively. This event can also be correlated to the North Atlantic cold event at 5.4 ka BP. D5 occurring at 5.0 ka BP (5.2—4.1 ka BP) was a dry event during the Holocene climate optimum, lasting for 900 years in the Dadiwan section, corresponding to the D4 (4.7 ka BP) dry event of Sanjiaocheng of Minqin and cold events of Ruoergai (at 4.4 ka BP) and Dunde ice core (at 4.6 ka BP). It is also chronologically close to the dry event of western Gansu (4.9—3.0 ka BP) and Dadiwan site (5.0—4.0 ka BP).

The pollen and other proxies of the Qin'an and Dingxi sections indicate that since 3.5 ka BP, the climate had a tendency to become drier. D4 occurred at 3.5 ka BP. D1, D2, and D3 occurred at 0.8, 1.7 and 2.6 ka BP, respectively, corresponding to the cold stage of China's historic time, also to the Nos. 0, 1, and 2 cold stage climate changes in China[42].

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