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Chinese Loess Plateau vegetation since the Last Glacial Maximum and its implications for vegetation restoration

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Summary

1. China has been investing heavily in afforestation programmes to control soil erosion on the vast Chinese Loess Plateau (CLP). This massive afforestation has led to a considerable increase in forest and a decrease in dust-storm activity in some areas. However, there have also been some negative outcomes, including low tree survival rate, increased soil erosion, exacerbated water shortages and deep soil desiccation. One important explanation for these is the use of inappropriate species because of a lack of knowledge of the natural vegetation in the area, which has been largely destroyed by human activities.

2. Natural vegetation in the most recent warm period (the early–mid-Holocene) can serve as an analogue for the ongoing greening programme, particularly under the global warming scenario. In this study, the natural vegetation of the CLP since the Last Glacial Maximum (LGM) was reconstructed from pollen analyses of six loess sections.

3. Our results show that herbs were dominant both in the cold–dry LGM and the warm–humid early–mid-Holocene. During the LGM, vegetation in the north-western CLP mainly consisted of *Artemisia*, *Echinops*-type, *Taraxacum*-type and Chenopodiaceae, and vegetation in the south-eastern CLP was characterized by the same types but with a slightly higher incidence of Poaceae. During the early–mid-Holocene, vegetation was more diverse, with Poaceae, *Artemisia*, *Echinops*-type and Chenopodiaceae dominant in the north-west, and *Pinus*, *Corylus*, Poaceae, *Artemisia* and *Selaginella sinensis* dominant in the south-east.

4. *Synthesis and applications*. The ecological restoration of herbs should be considered a priority, although trees and shrubs have been prioritized previously. To balance environmental conservation and farm-income support objectives, we suggest planting *Corylus*, *Juglans* and *Selaginella sinensis* in the south-eastern Chinese Loess Plateau (CLP) because of their edible value or medicinal properties. Given the considerable prevalence of *Selaginella sinensis* and the Asteraceae family in the pollen records, and their useful medicinal effects, the CLP has great potential to be a centre for Chinese medicinal herb production.

Key-words: arid and semi-arid climate, herb, Holocene, Last Glacial Maximum, loess, natural vegetation, pollen records

Introduction

Loess, a wind transported accumulation derived from arid inland areas, covers an area of ~440 000 km^2 on the Loess Plateau in north-central China (Liu 1985). The main body of the Chinese Loess Plateau (CLP) is found in the middle reaches of the Yellow River (Fig. 1) and is characterized by an arid and semi-arid climate. Destruction of vegetation cover on the CLP, as a result of long-term human activities, has resulted in severe soil erosion. About 1·64 billion tonnes of sediment are transported into the Yellow River each year (Liu 1985), raising the riverbed downstream and thereby causing frequent devastating floods. To tackle this issue, China has invested hundreds of billions of Yuan in

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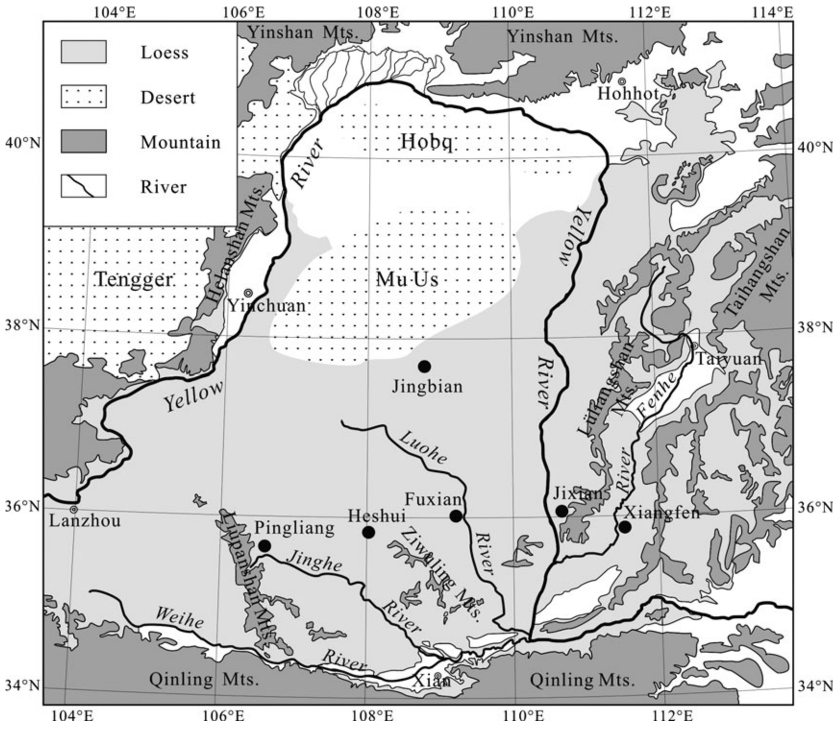

Fig. 1. Map showing the study sites (solid circles) and the distribution of loess in the middle reaches of the Yellow River (adapted from Liu 1964).

numerous afforestation campaigns since the end of 1950s (Wang *et al.* 2007; Chen, Shao & Li 2008b).

Afforestation has led to a considerable increase in forest resources and a decrease in dust-storm activity in some areas (Shen *et al.* 2003; Cao 2011). However, it has also caused environmental degradation in the arid and semi-arid regions (Cao 2008; Cao *et al.* 2011a,b), including low survival rate of trees (Guo *et al.* 2001; Wang *et al.* 2007), increased soil erosion (Normile 2007; Wang *et al.* 2010), exacerbated water shortages (Cao, Chen & Yu 2009) and deep soil desiccation (Chen, Shao & Li 2008a; Wang, Liu & Liu 2009).

To improve the tree survival rate, some local governments have adopted extreme approaches, including the digging of parallel trenches to collect slope run-off (Cao, Chen & Liu 2007); the introduction of exotic, fast-growing species (Cao, Wang & Chen 2010) and the removal of herbaceous vegetation under trees to reduce competition for moisture (Cao, Chen & Yu 2009); and installing expensive irrigation systems (Shen *et al.* 2003). For example, 660 million Chinese Yuan has been invested since 1999 in the North and South Mountains Greening Project in Lanzhou, the largest city in the upper reaches of the Yellow River (Fig. 1). Water from the Yellow River has been used to maintain an artificial forest on mountains along both sides of the valley, involving a network of ~3000 km of pipes. In contrast, herbs are only sparsely present on the adjacent, nonirrigated slopes and hills, which have a distinctly different landscape.

A major reason for the failure of afforestation is the improper selection of plant types (Cao 2011). Therefore, two questions must be asked: (i) What kind of trees or herbs should be planted under current climatic conditions and to withstand global warming? and (ii) How can sustainable alternative incomes be provided for farmers in the Loess Plateau? Knowledge of the native Loess Plateau vegetation is central to these questions, because naturally grown native plants are fully suited to the local climate and soil (Sun *et al.* 1998; Li 2001). However, the natural vegetation on the Loess Plateau has been destroyed by human activities, such as clearance, cultivation and grazing, over a long period (Liu *et al.* 1996).

The Earth's climate has varied naturally between glacial and interglacial states, driven by periodic variations in the Earth's orbit (Hays, Imbrie & Shackleton 1976; Ding *et al.* 2002; Lisiecki & Raymo 2005), and global ecosystems have continually adjusted to accommodate the changing climate, showing cyclic shifts between alternative states (Whitlock & Bartlein 1997; Yu *et al.* 2000; Shi *et al.* 2003; Jiang & Ding 2005; Ni *et al.* 2010). Warm periods in the geological past are widely used as analogues for current and future warming. For example, the global change community and the Intergovernmental Panel on Climate Change (IPCC) have taken the Holocene Optimum (~9–5 ka), Marine Isotope Stage (MIS) 5e (~130–116 ka) and MIS 11 (~420–360 ka) as analogues for evaluating the effect of different warming scenarios on various ecosystems (e.g. Kukla *et al.* 1997; Loutre & Berger 2003; Jansen *et al.* 2007; Kopp *et al.* 2009; Tzedakis *et al.* 2012).

The climate in northern China was cold and dry during glacial periods, and warm and humid during interglacials (Ding *et al.* 2002; Yang & Ding 2010). Geological records have shown that present climatic conditions are similar to those in the early Holocene (Xiao *et al.* 2004; Jiang *et al.* 2006). Although the present temperature is ~2 °C lower than the temperature in the Holocene Optimum (Shi *et al.*

Table 1. Study sites together with their geographical and climatic characteristics

Section	Latitude (°N)	Longitude (°E)	Altitude (m a.s.l.)	Mean annual temperature (°C)	Mean annual precipitation (mm)
Jingbian	37·50	108·90	1688	7·8	395
Pingliang	35·54	106·86	1514	8·6	490
Heshui	35·78	108·29	1475	9·1	562
Fuxian	36·02	109·30	1226	9·2	600
Jixian	36·11	110·64	990	10·0	580
Xiangfen	35·84	111·45	560	11·5	550

2003), if the current warming rate continues, it will rise to the Holocene Optimum temperature by AD 2100. Therefore, the vegetation present in the early–mid-Holocene is a good reference for potential natural vegetation on the Loess Plateau and will provide valuable insights into the restoration of vegetation for policy makers.

To date, native vegetation on the Loess Plateau, as derived from various records, remains controversial, and assertions have been made that it was predominantly forest (Shi 1981, 1991; An, Feng & Tang 2003; Tang & An 2007; Shang & Li 2010), forest-steppe (Zhu 1983, 1994; Liu *et al.* 1996) or steppe (Sun *et al.* 1997; Xie *et al.* 2002; Li, Zhou & Dodson 2003; Jiang & Ding 2005). At present, the climatic conditions of the Loess Plateau vary significantly between regions, with ~250 mm mean annual rainfall and a mean annual temperature of ~8 °C in the north-west and ~650 mm mean annual rainfall and a mean annual temperature of ~14 °C in the south-east. Therefore, observations at a single site or a few geological samples may not represent the whole Loess Plateau vegetation picture that well, and systematic paleovegetation studies are urgently required before a practical vegetation restoration strategy can be implemented. In this study, we present pollen records from six sites across the plateau, with the objective of identifying the natural vegetation types since the Last Glacial Maximum (LGM) and to suggest suitable plant types for vegetation restoration under global warming conditions.

Materials and methods

SITES AND STRATIGRAPHY

Loess is a wind-blown, silt-sized material. On the CLP, complete loess sequences consist of over 30 loess (L)–soil (S) couplets, which date back to ~2·8 Ma (Yang & Ding 2010). From the top to the bottom, the loess units are labelled L_1–$L_{34,}$ and the interbedded soils are labelled S_0–S_{33}. Loess beds were deposited during cold–dry glacials, whereas soils developed during warm–humid interglacials (Liu 1985; Kukla 1987). The alternation of loess and soils is evidence of cold–dry and warm–humid climate oscillations during the Quaternary (Kukla 1987; Ding *et al.* 2002; Yang & Ding 2010).

Six loess sections from different topographic and geomorphological units, located at Jingbian, Pingliang, Heshui, Fuxian, Jixian and Xiangfen, were logged (Fig. 1). The Jingbian section, near the margin of the Mu Us desert, is located on 'Liang' – a flat ridge covered by thick loess. The other five sites form a west–east transect across the middle of the CLP. The Xiangfen section is situated on the terrace of the Fenhe River, while the Pingliang, Heshui, Fuxian and Jixian sections are located on 'Yuan' – a high table-land consisting of thick loess. These six sites ensure sufficient spatial coverage and well represent various climatic conditions in the main body of the Loess Plateau. Further details for the sites and their climates are shown in Table 1.

All sections consisted of soil unit S_0 and the upper part of loess unit L_1. The Holocene soil (S_0), overlain by modern topsoil, is dark in colour because of its relatively high organic matter content. Loess unit L_1, yellowish in colour and massive in structure, was deposited during the last glacial period. L_1 can generally be subdivided into five subunits termed $L_{1\text{-}1}$, $L_{1\text{-}2}$, $L_{1\text{-}3}$, $L_{1\text{-}4}$ and $L_{1\text{-}5}$ (Yang & Ding 2008). $L_{1\text{-}2}$ and $L_{1\text{-}4}$ are weakly developed soils, and the other subunits are typical loess horizons. Previous studies have shown that $L_{1\text{-}1}$ was deposited in the MIS 2 (~28–11 ka), which includes the LGM (~26·5–19 ka), S_0 was deposited in the early–mid-Holocene (~11–4 ka), and $L_{1\text{-}2}$ was deposited in the late MIS 3 (~40–28 ka) (Kukla 1987; Ding *et al.* 2002; Lu, Wang & Wintle 2007).

All the six loess–soil sequences are well exposed in natural outcrops along the walls of gullies. In the field, the loess and soil layers are readily recognizable and laterally traceable for long distances. At each site, a ~1·2-m-wide vertical trench was first excavated along the gully wall, and fresh samples (~400 g each) were then taken at 5–10-cm intervals. To ensure that we used a complete cold–warm cycle for vegetation reconstruction, all the sections were sampled down to loess unit $L_{1\text{-}2}$, and a total of 498 samples were collected.

MEASUREMENTS AND ANALYSES

For stratigraphic correlation and pollen sample selection, grain size was first measured for all samples using a SALD-3001 laser diffraction particle analyser (Shimadzu Corporation, Kyoto, Japan). Ultrasonic pretreatment, with the addition of 20% $(NaPO_3)_6$ solution, was used to disperse the samples prior to particle size determination. The analytical procedures used were as detailed by Ding *et al.* (1999). Results showed that soil unit S_0 and the weakly developed soil $L_{1\text{-}2}$ are consistently finer grained than loess unit $L_{1\text{-}1}$ (Fig. 2). The correlation of the lithostratigraphy (Fig. 3) and grain-size curves (Fig. 2) between sections indicates the continuity of the loess deposits.

A total of 97 samples were selected for pollen analysis (Fig. 2). Samples from the coarse-grained unit $L_{1\text{-}1}$ represent deposition during a cold and dry glacial period, while those from the

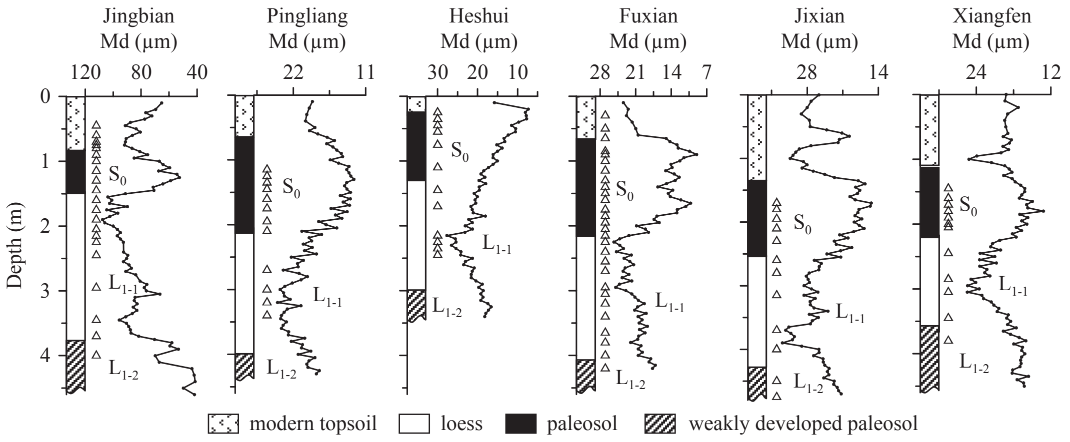

Fig. 2. Stratigraphic column and median grain size (Md) for the six loess sections. The stratigraphic positions used for pollen analyses are marked in triangles in each section.

fine-grained soil units (S_0 and $L_{1\text{-}2}$) represent deposition during relatively warm and humid interglacial intervals. Pollen grains were extracted using the heavy-liquid method (Li *et al.* 2006) and identified at ×400 magnification using a Nikon ECLIPSE 50i microscope (Nikon Corporation, Tokyo, Japan). For each sample, 80–400 land pollen grains were counted. Percentages of pollen, spores and algae were calculated relative to the sum of all land pollen counted. Pollen diagrams were drawn using the Psimpoll 4·25 program (Bennett 2005) (Queen's University Belfast, UK).

Results

The major pollen assemblages found in the loess and soil units in each loess section are detailed below.

JINGBIAN SECTION

$L_{1\text{-}2}$: Arboreal pollen (AP) percentages are low. *Taraxacum*-type pollen dominates herbaceous pollen (HP) assemblages (Fig. 4a).

$L_{1\text{-}1}$: a decrease in *Taraxacum*-type pollen. An increase in pollen of *Artemisia*, *Echinops*-type, Chenopodiaceae and Caryophyllaceae.

S_0: *Artemisia* pollen predominates (80–90%). A decrease in Chenopodiaceae and a slight increase in Fabaceae.

Modern topsoil: an increase in the pollen of *Pinus*, Oleaceae, Brassicaceae and *Fagopyrum*.

PINGLIANG SECTION

$L_{1\text{-}1}$: AP (<5%) includes *Pinus*, *Ephedra*, *Betula*, *Corylus*, *Quercus*, *Juglans*, Oleaceae, *Ulmus* and *Nitraria* (Fig. 4b). Pollen of *Artemisia*, *Echinops*-type and *Taraxacum*-type dominates the spectrum.

S_0: AP is rare. *Artemisia* pollen still dominates. Pollen of *Echinops*-type and *Taraxacum*-type decreases to <5%. Small amounts of *Selaginella sinensis* and Zygnema.

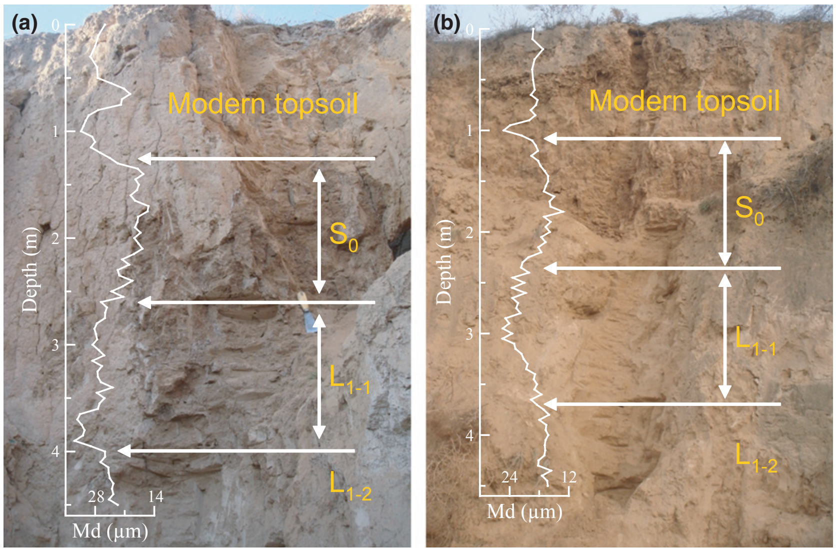

Fig. 3. Correlation of the lithostratigraphy and median grain size (Md) between the Jixian (a) and Xiangfen (b) sections.

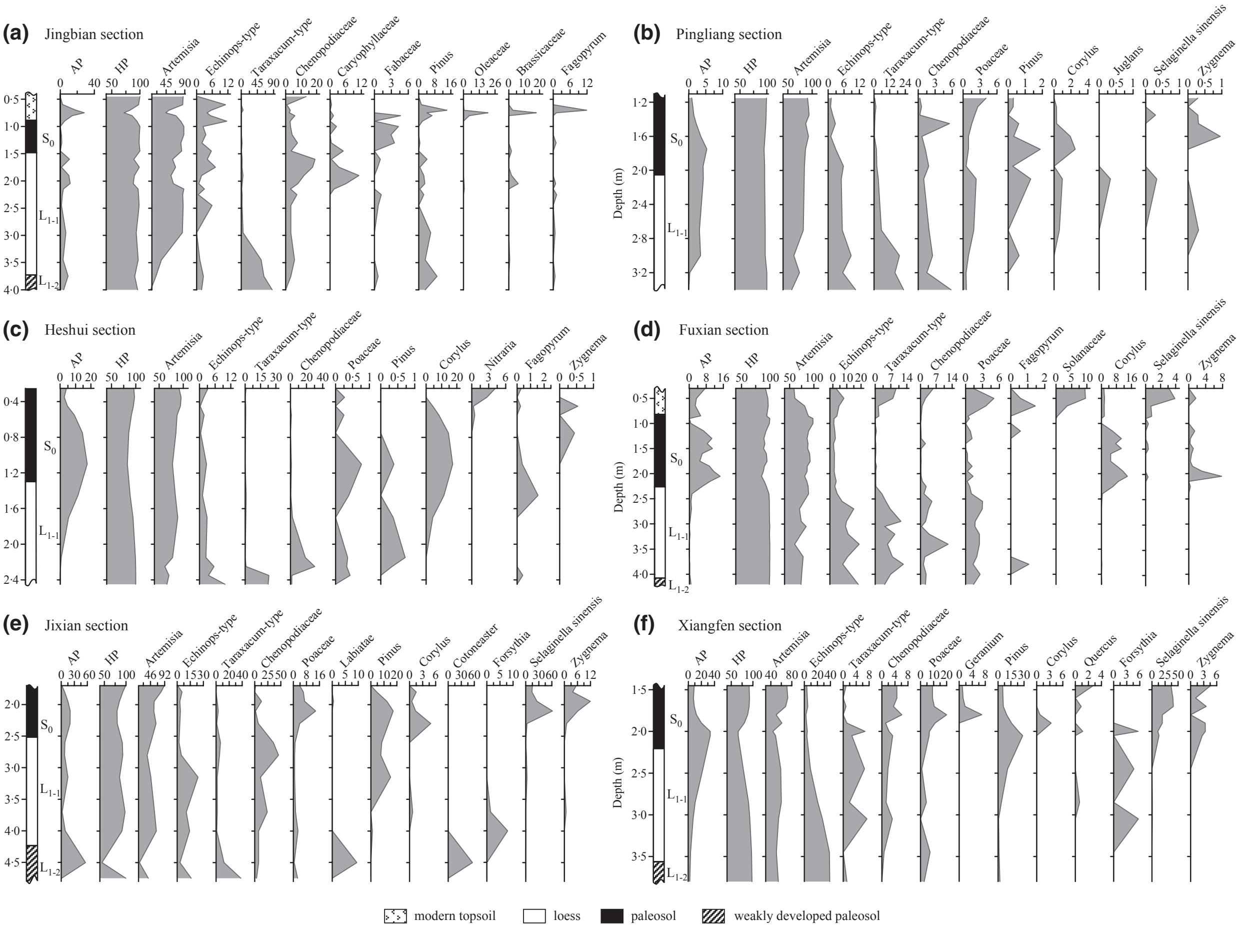

Fig. 4. Pollen percentage diagrams for major pollen types and stratigraphic columns at Jingbian (a), Pingliang (b), Heshui (c), Fuxian (d), Jixian (e) and Xiangfen (f).

HESHUI SECTION

$L_{1\text{-}1}$: AP is rare (Fig. 4c). Pollen of *Artemisia*, *Taraxacum*-type, *Echinops*-type and Chenopodiaceae dominates the spectrum.

S_0: *Corylus* pollen increases to 17%, making a large contribution to AP. *Artemisia* pollen dominates HP. A decrease in the pollen of *Echinops*-type, *Taraxacum*-type and Chenopodiaceae.

FUXIAN SECTION

$L_{1\text{-}2}$ and $L_{1\text{-}1}$: AP <2% (Fig. 4d). HP predominates, including mainly *Artemisia*, *Echinops*-type, *Taraxacum*-type, Chenopodiaceae and Poaceae.

S_0: AP increases to 14·5%, mainly because of an increase in *Corylus* (to 13·8%). *Artemisia* pollen increases to 80%. Pollen of *Echinops*-type, *Taraxacum*-type and Chenopodiaceae decreases. Ferns and algae are also seen, including Polypodiaceae, *Selaginella sinensis* and Zygnema.

Modern topsoil: A decrease in the pollen of *Corylus* and *Artemisia*. An increase in *Echinops*-type, *Taraxacum*-type, Chenopodiaceae, Poaceae, *Fagopyrum* and Solanaceae pollen, and *Selaginella sinensis* spores.

JIXIAN SECTION

$L_{1\text{-}2}$: AP is as high as 55%, mainly derived from *Cotoneaster* (Fig. 4e). HP consists mainly of *Artemisia*, *Echinops*-type, *Taraxacum*-type, Chenopodiaceae and Labiatae.

$L_{1\text{-}1}$: *Cotoneaster* pollen disappears. Increase in pollen of *Pinus*, *Corylus* and *Forsythia*. HP content increases because of increases in *Artemisia*, *Echinops*-types and Chenopodiaceae.

S_0: AP increases, mainly because of an increase in *Pinus*. *Artemisia* pollen dominates HP. Poaceae pollen increases to 13%. Pollen of *Echinops*-types and Chenopodiaceae decreases. Large increase in both *Selaginella sinensis* and Zygnema.

XIANGFEN SECTION

$L_{1\text{-}2}$: AP is low (<5%), and includes *Pinus* and Oleaceae (Fig. 4f). Pollen of *Artemisia* and *Echinops*-type dominates the spectrum.

$L_{1\text{-}1}$: Slight increase in AP thanks to increases in *Pinus*, *Quercus*, Oleaceae and *Forsythia*. *Artemisia* pollen dominates the spectrum. Decrease in *Echinops*-type pollen.

S_0: AP increases in both diversity and abundance. Its content increases to 28%, mainly because of an increase in *Pinus*. In total, twelve AP types may be identified. Increase in *Artemisia* and Poaceae pollen and *Selaginella sinensis* spores to 72%, 20% and 41%, respectively. Fall in *Echinops*-type pollen to 4%.

A total of 54 pollen types may be identified in the six loess sections. It is notable that *Artemisia* pollen dominates all the spectra. A detailed comparison of the pollen assemblages between $L_{1\text{-}1}$ (from a cold and dry period) and S_0 (from a warm and humid period) is given in Table 2.

Natural vegetation in the geological past

VEGETATION IN THE COLD–DRY PERIOD ($L_{1\text{-}1}$)

All sections from the CLP show a similar pollen assemblage for the cold–dry period, characterized mainly by *Artemisia*, together with other significant pollen types including *Taraxacum*-type, *Echinops*-type and Chenopodiaceae. These data indicate the presence of steppe vegetation on the CLP during the LGM.

Spatial differences in pollen assemblages can also be observed. First, the content of Chenopodiaceae generally decreases from 20 to 30% in the north-west (Jingbian and Heshui) (Fig. 4a, c) to 5–12% in the south-east (Fuxian and Xiangfen) (Fig. 4d, f). Second, the Poaceae content increases significantly in a south-easterly direction. In northern China, Chenopodiaceae species predominates in desert shrub, and Poaceae are dominant in steppe (Editorial Committee of Vegetation Map of China, Chinese Academy of Sciences 2007). We therefore infer that during the LGM, there was a desert steppe in the north-west of the CLP and dry steppe in the south-east.

VEGETATION IN THE WARM–HUMID PERIOD (S_0)

Pollen types were much more diverse during the warm–humid period than during the cold–dry period. There was a greater incidence of AP, and less HP. *Artemisia* was still dominant in pollen assemblages. The incidence of *Taraxacum*-type, *Echinops*-type and Chenopodiaceae pollen decreased, while Poaceae pollen became more prevalent. In addition, the percentages of *Selaginella sinensis* and Zygnema increased. In general, steppe vegetation still prevailed on the CLP during the early–mid-Holocene.

The spatial differences in pollen assemblages are distinct. The AP content increases to the south-east, and HP decreases accordingly. In the Jingbian and Pingliang sections in the north-western CLP, although the AP consists of about ten pollen types (*Pinus*, *Betula*, *Quercus*, etc.), its incidence is very low (<10%) (Fig. 4a, b). In the middle part of the CLP (Heshui and Fuxian), AP (mainly *Corylus*) has a percentage of ~15% (Fig. 4c, d), but this increases to 17–30% (mainly *Pinus*) in the south-east (Jixian and Xiangfen) (Fig. 4e, f). Hygrophilous ferns and algae, such as *Selaginella sinensis* and Zygnema, are rare in the north-west (Jingbian, Pingliang and Heshui) (Fig. 4a–c), but their incidence increases to as high as 10–50% in the south-east (Fuxian, Jixian and Xiangfen)

Table 2. Pollen results from the six loess sections

Site	Dry and cold period ($L_{1\text{-}1}$)	Warm and humid period (S_0)
Jingbian	AP (<20%) mainly includes *Pinus* and *Quercus*. HP (>80%) mainly consists of *Taraxacum*-type, *Artemisia* and Chenopodiaceae.	Small amounts of AP (mainly *Pinus* and *Quercus*). *Artemisia* is predominant. Chenopodiaceae decreases and Fabaceae increases slightly.
Pingliang	AP (<5%) includes *Pinus*, *Ephedra*, *Betula*, *Corylus*, *Quercus*, *Juglans*, Oleaceae, *Ulmus* and *Nitraria*. HP mainly consists of *Artemisia*, *Echinops*-type and *Taraxacum*-type.	AP is rare. *Artemisia* still dominates. Both *Echinops*-type and *Taraxacum*-type decrease.
Heshui	Few AP types. *Artemisia* is dominant. Other HPs mainly consist of *Taraxacum*-type, *Echinops*-type and Chenopodiaceae.	*Corylus* content rises to 17% (a large contribution to the AP). *Artemisia* still dominates. *Taraxacum*-type, *Echinops*-type and Chenopodiaceae decrease.
Fuxian	AP (<2%) consists of *Pinus*, *Ephedra*, *Betula*, *Corylus*, Caprifoliaceae, *Nitraria* and *Ulmus*. HP is predominant, mainly including *Artemisia*, *Echinops*-type, *Taraxacum*-type, Chenopodiaceae and Poaceae.	AP increases to 14·5%, mainly due to a rise in *Corylus* (up to 13·8%). *Artemisia* content is up to 80%. *Echinops*-type, *Taraxacum*-type and Chenopodiaceae decrease. Polypodiaceae, *Selaginella sinensis* and Zygnema also occur.
Jixian	AP (<18%) includes *Pinus*, *Corylus* and *Forsythia*. *Artemisia* is dominant. Other HPs mainly consist of *Echinops*-types, *Taraxacum*-type and Chenopodiaceae.	AP increases, mainly due to a rise in *Pinus*. *Artemisia* still dominates. Poaceae increases. *Echinops*-types and Chenopodiaceae decrease. Both *Selaginella sinensis* and Zygnema increase rapidly.
Xiangfen	AP (<10%) includes *Pinus*, *Quercus*, Oleaceae, *Forsythia* and *Sorbaria*. HP consists of high percentages of *Artemisia* (50–60%) and *Echinops*-type (20–40%), and small amounts of *Taraxacum*-type, Chenopodiaceae and Poaceae.	Twelve AP types. AP increases to 28%, mainly due to a rise in *Pinus*. *Artemisia*, Poaceae and *Selaginella sinensis* increase to 72%, 20% and 41%, respectively. *Echinops*-type drops to 4%.

AP, Arboreal pollen; HP, Herbaceous pollen.

(Fig. 4d–f). It is therefore clear that during the warm–humid period, meadow-steppe vegetation dominated the south-eastern CLP, while dry steppe prevailed in the north-west.

Discussion

Our study sites represent a range of geomorphological units and are characterized by different climatic conditions (Table 1), but they all have very thick loess deposits (60–300 m). Chinese loess is mainly composed of loosely cemented silt (Liu 1985; Yang & Ding 2008), which allows rainwater to infiltrate quickly (Chen, Shao & Li 2008b; Yang *et al*. 2012). In areas with thick loess, therefore, the water in the surface soil is insufficient to maintain forests. Only in areas of thin loess underlain by bedrocks (e.g. deep gullies, incipient floodplains and low river terraces), where the underground water table is relatively high, can trees and shrubs grow under the appropriate conditions.

Our pollen results all show that herbs, rather than trees or shrubs, were dominant on the Loess Plateau in both the cold–dry period and the warm–humid period, which is consistent with pollen data from many other loess sections (Sun *et al*. 1997; Li, Zhou & Dodson 2003; Jiang & Ding 2005; Tang & An 2007; Shang & Li 2010). It should be noted that the pollen records from several sections in river valleys indicate that trees were abundant in the Holocene (An, Feng & Tang 2003; Wu *et al*. 2009; Shang & Li 2010). However, these sections are all located in the riparian zones of first-order tributaries of the Yellow River. In the semi-arid Loess Plateau, these riparian zones cover a very limited area.

Most areas in the Loess Plateau are covered by thick loess (>20 m) (Liu 1985); therefore, our records, together with pollen data from many other sites (Sun *et al*. 1997; Li, Zhou & Dodson 2003; Jiang & Ding 2005; Tang & An 2007; Shang & Li 2010), may well be representative of the entire loess area. Because of this, it appears that priority should be given to planting herbs rather than trees or shrubs in current and future greening programmes.

Most plants selected for past and present afforestation programmes have been trees or shrubs tolerant to arid conditions, including *Robinia pseudoacacia*, *Caragana intermedia*, *Amorpha fruticosa*, *Pinus tabuliformis*, *Populus davidiana*, *Ulmus pumila* and *Hippophae rhamnoides* (Shi & Yang 2002; Cao 2008). However, these species are rare in the natural vegetation record, except for a few species of *Pinus* and *Ulmus*. Our results show that the native vegetation species on the CLP in the past were mainly from the Poaceae and Asteraceae families, which are well adapted to arid and semi-arid climates and to various topographic and geomorphological units in the loess area. For example, *Agropyron cristatum*, a perennial species from the Poaceae family, is very tolerant of drought, cold and grazing and produces high herbage yields in early spring (a season when feed is in short supply). It also has a fibrous root system that stabilizes disturbed soil. Members of the Poaceae and Asteraceae families are, therefore, likely to be ideal candidate species for ongoing greening programmes. Choosing the most appropriate species is an urgent task for ecologists.

At present, more than 70 million farmers live on the CLP. Any ecological restoration must therefore be combined with income generation for local farmers, to promote sustainable development. According to the early–mid-Holocene pollen records, we suggest *Juglans*, *Corylus* and *Selaginella sinensis* as candidate species for the ongoing greening programmes in areas south-east of Heshui and Fuxian (Fig. 1). *Juglans* (walnut) and *Corylus* (hazelnut) seeds are important in the food industry. In a recent study (Ottaggio *et al*. 2008), taxanes, including 10-deacetylbaccatin III, baccatin III, paclitaxel C, and 7-epipaclitaxel, were found in *Corylus* shells and leaves. Paclitaxel is a popular and expensive anticancer drug, so *Corylus* can be used as a medicinal source material. *Selaginella sinensis*, a native species of fern, is a traditional Chinese medicine for the treatment of hepatitis, cholecystitis, eczema and burns. In addition, the Asteraceae family, which flourishes on the CLP in both cold and warm conditions, is an important source of medicines (Dharmananda 2012). For example, the most effective antimalarial drug artemisinin is derived from *Artemisia annua* (a member of the Asteraceae family) (Covello 2008). The Loess Plateau, therefore, has tremendous potential to be a source of medicinal plants, and this prospect deserves serious consideration in the greening programme.

In summary, as reviewed by Cao (2011), excessive reliance on afforestation has caused significant negative environmental impacts in northern China. According to our pollen records, priority should be given to herbs (especially the Poaceae and Asteraceae families), rather than trees or shrubs, in current and future greening programmes. Only in the deep valleys, with very thin loess and the riparian zones of large rivers, should some trees and shrubs be considered as candidate species. To combine ecological restoration with economic growth, *Juglans*, *Corylus* and some medicinal plants (e.g. *Selaginella sinensis*) should also serve as useful candidate species for the south-eastern Loess Plateau.

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