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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 heavil 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 activit in some areas. Ho ever, there have also been some negative outcomes, including lo tree survival rate, increased soil erosion, e acerbated ater shortages and deep soil desiccation. One important e planation for these is the use of inappropriate species because of a lack of kno ledge of the natural vegetation in the area, hich has been largel destro ed b human activities.

2. Natural vegetation in the most recent arm period (the earl –mid-Holocene) can serve as an analogue for the ongoing greening programme, particularl under the global arming scenario. In this stud , the natural vegetation of the CLP since the Last Glacial Ma imum (LGM) as reconstructed from pollen anal ses of si loess sections.

3. Our results sho that herbs ere dominant both in the cold–dr LGM and the arm–humid earl –mid-Holocene. During the LGM, vegetation in the north- estern CLP mainl consisted of *Artemisia*, *Echinops*-t pe, *Taraxacum*-t pe and Chenopodiaceae, and vegetation in the south-eastern CLP as characteri ed b the same t pes but ith a slightl higher incidence of Poaceae. During the earl –mid-Holocene, vegetation as more diverse, ith Poaceae, *Artemisia*, *Echinops*-t pe and Chenopodiaceae dominant in the north- est, 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 priorit , although trees and shrubs have been prioriti ed previousl . To balance environmental conservation and farm-income support objectives, e 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 famil 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 Ma imum, loess, natural vegetation, pollen records

Introduction

Loess, a ind 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 bod of the Chinese Loess Plateau (CLP) is found in the middle reaches of the Yello River (Fig. 1) and is characteri ed b 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 Yello River each ear (Liu 1985), raising the riverbed do nstream and thereb causing frequent devastating oods. To tackle this issue, China has invested hundreds of billions of Yuan in

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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 activit in some areas (Shen *et al*. 2003; Cao 2011). Ho ever, it has also caused environmental degradation in the arid and semi-arid regions (Cao 2008; Cao *et al*. 2011a,b), including lo survival rate of trees (Guo *et al*. 2001; Wang *et al*. 2007), increased soil erosion (Normile 2007; Wang *et al*. 2010), e acerbated ater 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 govern-

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Table 1. Stud sites together ith 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
Fu ian	36·02	109·30	1226	9·2	600
Ji ian	36·11	110·64	990	10·0	580
Xiangfen	35·84	111·45	560	11·5	550

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

To date, native vegetation on the Loess Plateau, as derived from various records, remains controversial, and assertions have been made that it as predominantl 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 var signi cantl bet een regions, ith ~250 mm mean annual rainfall and a mean annual temperature of ~8 °C in the north- est 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 fe geological samples ma not represent the hole Loess Plateau vegetation picture that ell, and s stematic paleovegetation studies are urgentl required before a practical vegetation restoration strateg can be implemented. In this stud , e present pollen records from si sites across the plateau, ith the objective of identif ing the natural vegetation t pes since the Last Glacial Ma imum (LGM) and to suggest suitable plant t pes for vegetation restoration under global arming conditions.

Materials and methods

SITES AND STRATIGRAPHY

Loess is a ind-blo n, silt-si ed material. On the CLP, complete loess sequences consist of over 30 loess (L)–soil (S) couplets, hich 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 ere deposited during cold–dr glacials, hereas soils developed during arm–humid interglacials (Liu 1985; Kukla 1987). The alternation of loess and soils is evidence of cold–dr and arm–humid climate oscillations during the Quaternar (Kukla 1987; Ding *et al.* 2002; Yang & Ding 2010).

Si loess sections from different topographic and geomorphological units, located at Jingbian, Pingliang, Heshui, Fu ian, Ji ian and Xiangfen, ere logged (Fig. 1). The Jingbian section, near the margin of the Mu Us desert, is located on 'Liang' – a at ridge covered b thick loess. The other ve sites form a est–east transect across the middle of the CLP. The Xiangfen section is situated on the terrace of the Fenhe River, hile the Pingliang, Heshui, Fu ian and Ji ian sections are located on 'Yuan' – a high table-land consisting of thick loess. These si sites ensure suf cient spatial coverage and ell represent various climatic conditions in the main bod of the Loess Plateau. Further details for the sites and their climates are sho n in Table 1.

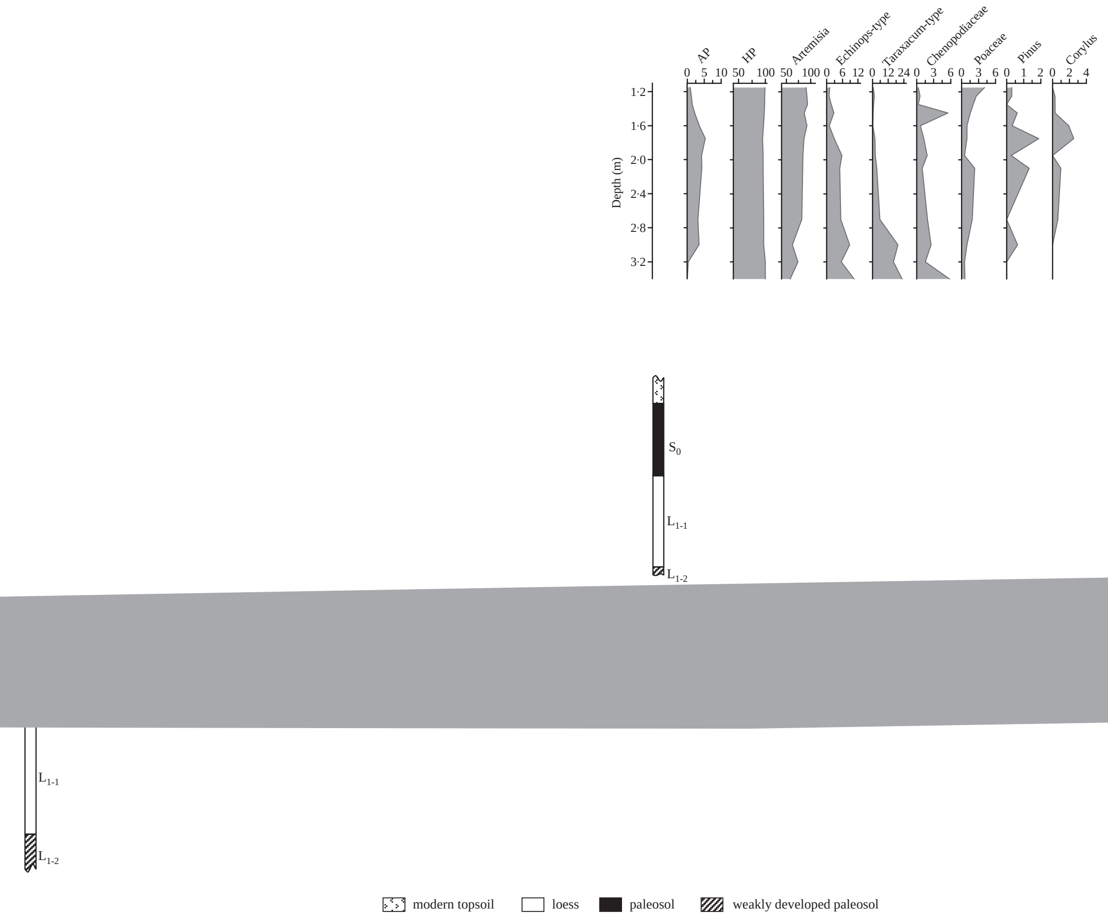
All sections consisted of soil unit S_0 and the upper part of loess unit L_1. The Holocene soil (S_0), overlain b modern topsoil, is dark in colour because of its relativel high organic matter content. Loess unit L_1, ello ish in colour and massive in structure, as deposited during the last glacial period. L_1 can generall be subdivided into ve 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 eakl developed soils, and the other subunits are t pical loess hori ons. Previous studies have sho n that $L_{1\text{-}1}$ as deposited in the MIS 2 (~28–11 ka), hich includes the LGM (~26·5–19 ka), S_0 as deposited in the earl –mid-Holocene (~11–4 ka), and $L_{1\text{-}2}$ as deposited in the late MIS 3 (~40–28 ka) (Kukla 1987; Ding *et al.* 2002; Lu, Wang & Wintle 2007).

All the si loess–soil sequences are ell e posed in natural outcrops along the alls of gullies. In the eld, the loess and soil la ers are readil recogni able and laterall traceable for long distances. At each site, a ~1·2-m- ide vertical trench as rst e cavated along the gull all, and fresh samples (~400 g each) ere then taken at 5–10-cm intervals. To ensure that e used a complete cold– arm c cle for vegetation reconstruction, all the sections ere sampled do n to loess unit $L_{1\text{-}2}$, and a total of 498 samples ere collected.

MEASUREMENTS AND ANALYSES

For stratigraphic correlation and pollen sample selection, grain si e as rst measured for all samples using a SALD-3001 laser diffraction particle anal ser (Shimad u Corporation, K oto, Japan). Ultrasonic pretreatment, ith the addition of 20% $(NaPO_3)_6$ solution, as used to disperse the samples prior to particle si e determination. The anal tical procedures used ere as detailed b Ding *et al.* (1999). Results sho ed that soil unit S_0 and the eakl developed soil $L_{1\text{-}2}$ are consistentl ner grained than loess unit $L_{1\text{-}1}$ (Fig. 2). The correlation of the lithostratigraph (Fig. 3) and grain-si e curves (Fig. 2) bet een sections indicates the continuit of the loess deposits.

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



HESHUI SECTION

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

FUXIAN SECTION

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

S_0: AP increases to 14·5%, mainl because of an increase in *Corylus* (to 13·8%). *Artemisia* pollen increases to 80%. Pollen of *Echinops*-t pe, *Taraxacum*-t pe and Chenopodiaceae decreases. Ferns and algae are also seen, including Pol podiaceae, *Selaginella sinensis* and Z gnema.

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

JIXIAN SECTION

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

S_0: AP increases, mainl because of an increase in *Pinus*. *Artemisia* pollen dominates HP. Poaceae pollen increases to 13%. Pollen of *Echinops*-t pes and Chenopodiaceae decreases. Large increase in both *Selaginella sinensis* and Z gnema.

XIANGFEN SECTION

$L_{1\text{-}2}$: AP is lo (<5%), and includes *Pinus* and Oleaceae (Fig. 4f). Pollen of *Artemisia* and *Echinops*-t pe 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*-t pe pollen.

S_0: AP increases in both diversit and abundance. Its content increases to 28%, mainl because of an increase in *Pinus*. In total, t elve AP t pes ma be identi ed. Increase in *Artemisia* and Poaceae pollen and *Selaginella sinensis* spores to 72%, 20% and 41%, respectivel . Fall in *Echinops*-t pe pollen to 4%.

A total of 54 pollen t pes ma be identi ed in the si loess sections. It is notable that *Artemisia* pollen dominates all the spectra. A detailed comparison of the pollen assemblages bet een $L_{1\text{-}1}$ (from a cold and dr period) and S_0 (from a arm 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 sho a similar pollen assemblage for the cold–dr period, characteri ed mainl b *Artemisia*, together ith other signi cant pollen t pes including *Taraxacum*-t pe, *Echinops*-t pe 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 generall decreases from 20 to 30% in the north- est (Jingbian and Heshui) (Fig. 4a, c) to 5–12% in the south-east (Fu ian and Xiangfen) (Fig. 4d, f). Second, the Poaceae content increases signi cantl in a south-easterl direction. In northern China, Chenopodiaceae species predominates in desert shrub, and Poaceae are dominant in steppe (Editorial Committee of Vegetation Map of China, Chinese Academ of Sciences 2007). We therefore infer that during the LGM, there as a desert steppe in the north- est of the CLP and dr steppe in the south-east.

VEGETATION IN THE WARM–HUMID PERIOD (S_0)

Pollen t pes ere much more diverse during the arm–humid period than during the cold–dr period. There as a greater incidence of AP, and less HP. *Artemisia* as still dominant in pollen assemblages. The incidence of *Taraxacum*-t pe, *Echinops*-t pe and Chenopodiaceae pollen decreased, hile Poaceae pollen became more prevalent. In addition, the percentages of *Selaginella sinensis* and Z gnema increased. In general, steppe vegetation still prevailed on the CLP during the earl –mid-Holocene.

The spatial differences in pollen assemblages are distinct. The AP content increases to the south-east, and HP decreases accordingl . In the Jingbian and Pingliang sections in the north- estern CLP, although the AP consists of about ten pollen t pes (*Pinus*, *Betula*, *Quercus*, etc.), its incidence is ver lo (<10%) (Fig. 4a, b). In the middle part of the CLP (Heshui and Fu ian), AP (mainl *Corylus*) has a percentage of ~15% (Fig. 4c, d), but this increases to 17–30% (mainl *Pinus*) in the south-east (Ji ian and Xiangfen) (Fig. 4e, f). H grophilous ferns and algae, such as *Selaginella sinensis* and Z gnema, are rare in the north- est (Jingbian, Pingliang and Heshui) (Fig. 4a–c), but their incidence increases to as high as 10–50% in the south-east (Fu ian, Ji ian and Xiangfen)

Table 2. Pollen results from the si loess sections

Site	Dr and cold period ($L_{1\text{-}1}$)	Warm and humid period (S_0)
Jingbian	AP (<20%) mainl includes *Pinus* and *Quercus*. HP (>80%) mainl consists of *Taraxacum*-t pe, *Artemisia* and Chenopodiaceae.	Small amounts of AP (mainl *Pinus* and *Quercus*). *Artemisia* is predominant. Chenopodiaceae decreases and Fabaceae increases slightl .
Pingliang	AP (<5%) includes *Pinus*, *Ephedra*, *Betula*, *Corylus*, *Quercus*, *Juglans*, Oleaceae, *Ulmus* and *Nitraria*. HP mainl consists of *Artemisia*, *Echinops*-t pe and *Taraxacum*-t pe.	AP is rare. *Artemisia* still dominates. Both *Echinops*-t pe and *Taraxacum*-t pe decrease.
Heshui	Fe AP t pes. *Artemisia* is dominant. Other HPs mainl consist of *Taraxacum*-t pe, *Echinops*-t pe and Chenopodiaceae.	*Corylus* content rises to 17% (a large contribution to the AP). *Artemisia* still dominates. *Taraxacum*-t pe, *Echinops*-t pe and Chenopodiaceae decrease.
Fu ian	AP (<2%) consists of *Pinus*, *Ephedra*, *Betula*, *Corylus*, Caprifoliaceae, *Nitraria* and *Ulmus*. HP is predominant, mainl including *Artemisia*, *Echinops*-t pe, *Taraxacum*-t pe, Chenopodiaceae and Poaceae.	AP increases to 14·5%, mainl due to a rise in *Corylus* (up to 13·8%). *Artemisia* content is up to 80%. *Echinops*-t pe, *Taraxacum*-t pe and Chenopodiaceae decrease. Pol podiaceae, *Selaginella sinensis* and Z gnema also occur.
Ji ian	AP (<18%) includes *Pinus*, *Corylus* and *Forsythia*. *Artemisia* is dominant. Other HPs mainl consist of *Echinops*-t pes, *Taraxacum*-t pe and Chenopodiaceae.	AP increases, mainl due to a rise in *Pinus*. *Artemisia* still dominates. Poaceae increases. *Echinops*-t pes and Chenopodiaceae decrease. Both *Selaginella sinensis* and Z gnema increase rapidl .
Xiangfen	AP (<10%) includes *Pinus*, *Quercus*, Oleaceae, *Forsythia* and *Sorbaria*. HP consists of high percentages of *Artemisia* (50–60%) and *Echinops*-t pe (20–40%), and small amounts of *Taraxacum*-t pe, Chenopodiaceae and Poaceae.	T elve AP t pes. AP increases to 28%, mainl due to a rise in *Pinus*. *Artemisia*, Poaceae and *Selaginella sinensis* increase to 72%, 20% and 41%, respectivel . *Echinops*-t pe drops to 4%.

AP, Arboreal pollen; HP, Herbaceous pollen.

(Fig. 4d–f). It is therefore clear that during the arm–humid period, meado -steppe vegetation dominated the south-eastern CLP, hile dr steppe prevailed in the north- est.

Discussion

Our stud sites represent a range of geomorphological units and are characteri ed b different climatic conditions (Table 1), but the all have ver thick loess deposits (60–300 m). Chinese loess is mainl composed of loosel cemented silt (Liu 1985; Yang & Ding 2008), hich allo s rain ater to in ltrate quickl (Chen, Shao & Li 2008b; Yang *et al.* 2012). In areas ith thick loess, therefore, the ater in the surface soil is insuf cient to maintain forests. Onl in areas of thin loess underlain b bedrocks (e.g. deep gullies, incipient oodplains and lo river terraces), here the underground ater table is relativel high, can trees and shrubs gro under the appropriate conditions.

Our pollen results all sho that herbs, rather than trees or shrubs, ere dominant on the Loess Plateau in both the cold–dr period and the arm–humid period, hich is consistent ith pollen data from man 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 valle s indicate that trees ere abundant in the Holocene (An, Feng & Tang 2003; Wu *et al.* 2009; Shang & Li 2010). Ho ever, these sections are all located in the riparian ones of rst-order tributaries of the Yello River. In the semi-arid Loess Plateau, these riparian ones cover a ver limited area.

Most areas in the Loess Plateau are covered b thick loess (>20 m) (Liu 1985); therefore, our records, together ith pollen data from man other sites (Sun *et al.* 1997; Li, Zhou & Dodson 2003; Jiang & Ding 2005; Tang & An 2007; Shang & Li 2010), ma ell be representative of the entire loess area. Because of this, it appears that priorit 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). Ho ever, these species are rare in the natural vegetation record, e cept for a fe species of *Pinus* and *Ulmus*. Our results sho that the native vegetation species on the CLP in the past ere mainl from the Poaceae and Asteraceae families, hich are ell adapted to arid and semi-arid climates and to various topographic and geomorphological units in the loess area. For e ample, *Agropyron cristatum*, a perennial species from the Poaceae famil , is ver tolerant of drought, cold and gra ing and produces high herbage ields in earl spring (a season hen feed is in short suppl). It also has a brous root s stem that stabili es disturbed soil. Members of the Poaceae and Asteraceae families are, therefore, likel 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. An ecological restoration must therefore be combined ith income generation for local farmers, to promote sustainable development. According to the earl – mid-Holocene pollen records, e suggest *Juglans*, *Corylus* and *Selaginella sinensis* as candidate species for the ongoing greening programmes in areas south-east of Heshui and Fu ian (Fig. 1). *Juglans* (alnut) and *Corylus* (ha elnut) seeds are important in the food industr . In a recent stud (Ottaggio *et al.* 2008), ta anes, including 10-deacet lbaccatin III, baccatin III, paclita el C, and 7-epipaclita el, ere found in *Corylus* shells and leaves. Paclita el is a popular and e pensive 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, cholec stitis, ec ema and burns. In addition, the Asteraceae famil , hich ourishes on the CLP in both cold and arm conditions, is an important source of medicines (Dharmananda 2012). For e ample, the most effective antimalarial drug artemisinin is derived from *Artemisia annua* (a member of the Asteraceae famil) (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 summar , as revie ed b Cao (2011), e cessive reliance on afforestation has caused signi cant negative environmental impacts in northern China. According to our pollen records, priorit should be given to herbs (especiall the Poaceae and Asteraceae families), rather than trees or shrubs, in current and future greening programmes. Onl in the deep valle s, ith ver thin loess and the riparian ones of large rivers, should some trees and shrubs be considered as candidate species. To combine ecological restoration ith economic gro th, *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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