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Negative impacts of afforestation and economic forestry on the Chinese Loess Plateau and proposed solutions

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ABSTRACT

Severe loss of soil and water on the Chinese Loess Plateau (CLP) has caused enormous pressure on social and economic development. To restore the ecological environment and boost the economy, the government has invested heavily in afforestation programmes and encouraged local farmers to plant trees that are economically productive. Although these measures have led to considerable increases in the economic value of forests and some farmers' income, negative effects on the environment, such as deep soil desiccation, soil erosion, and environmental pollution, have increased over time. Our field observations show that non-native forests are not well suited to controlling soil erosion unless a protective ground herb cover is also present. To identify the natural vegetation type on the CLP, pollen records from various topographic units were collected and synthesized. The results show that herbs, mainly from the Poaceae and Asteraceae families, were dominant during both the cold-dry period and warm-humid period. The reason for the dominance of these species is that the moisture in the surface soil is insufficient to sustain forests in the CLP where rainwater infiltrates quickly into the thick, loose loess. The ecological restoration of herbs from the Poaceae and Asteraceae families on the CLP should be considered a priority, and trees can grow well only in areas covered by thin loess deposits with efficient underlying water-resisting layers and a high underground water table. Because Asteraceae are such an important source of medicines, the CLP has great potential to be an important centre for Chinese medicinal herb production. We therefore recommend an expansion of the cultivation of medicinal herbs at the expense of high-value economic trees and pasture grasses, both of which consume large quantities of water.
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1. Introduction

The Chinese Loess Plateau (CLP) has an arid and semi-arid climate and suffers from some of the most severe soil erosion problems anywhere in the world (Zhang and Liu, 2005). The plateau covers an area of ~650 000 km^2, with an erodible region of ~470 000 km^2 (NDRC et al., 2010). Every year, ~16.4 billion tonnes of sediments from the main body of the CLP are transported along the Yellow River, raising the riverbed downstream, thereby causing frequent flooding, which not only hinders sustainable economic and societal development but also threatens the lives of many in the region (Fan et al., 2012). To address this problem, the Chinese government has been investing heavily in programmes of afforestation ever since the late 1950s (Wang et al., 2007; Chen et al., 2008a).

There are ~70 million peasant farmers living on the CLP. In a bid to develop the rural economy, economically important species have been widely planted, including apple, walnut, jujube, apricot, pear, persimmon, and chestnut. Because these species are high-investment and high-yield, their planting area has been growing since the 1980s (Zhang et al., 2004).

The massive afforestation associated with these high-yield species has resulted in some considerable achievements: an increase both in forest resources (by ~6–8% between 2000 and 2006, Xin et al., 2008) and in some farmers' incomes. However, the negative impacts on the environment have increased over time, such as low survival rate (Guo et al., 2001; Wang et al., 2007), deep soil desiccation (Huang et al., 2001; Liu et al., 2004; McVicar et al., 2007; Chen et al., 2008b), soil erosion (Normile, 2007; Wang et al., 2010), and environmental pollution (Wu et al., 2008; Zhang et al., 2009; Tables 1 and 2).

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Table 1
Negative impacts of planted forests and pasture.

Planting type	Negative impact	References
Ecologic forest	• High water consumption	Li et al., 1991; Wang et al., 2009
	• Exacerbated water shortages	Cao et al., 2009a
	• Low survival rate	Guo et al., 2001; Wang et al., 2007
	• Low growth rate (widespread small-aged trees)	Hou et al., 1991; Chen et al., 2008b
	• Decreased vegetation cover	Cao et al., 2009a
	• Increased soil erosion	Normile, 2007; Wang et al., 2010
	• Desiccation of deep soil	McVicar et al., 2007; Chen et al., 2008b
	• Disturbed regional water cycle	Li, 2001; Chen et al., 2008a
Economic forest	• High water consumption	Wang et al., 2009
	• Desiccation of deep soil	Huang et al., 2001; Liu et al., 2004
	• Disturbed regional water cycle	Huang et al., 2001; Liu et al., 2004
	• Pollution from the overuse of chemical fertilizers and pesticides	Wu et al., 2008; Zhang et al., 2009
Planted pasture	• High water consumption	Wang et al., 2009

Table 2
Survival rates of planted forests.

Region/Project	Date	Planting type	Total planted	Alive	Survival rate (%)	References
Qingyang, Gansu Province		*Pinus tabuliformis*	6600 ha	~1320 ha	~20	Zhao, 2002
Wuhai, Inner Mongolia Autonomous Region	2000	*Platycladus orientalis*	26.67 ha	0	0	Jing and Sheng, 2001
Qingjian, Shaanxi Province	1999	*Pinus tabuliformis*	400 000 trees	~100 trees	~0.025	Guo et al., 2001
Qingjian, Shaanxi Province		*Caragana microphylla*	22 000 ha	2667 ha	~12.1	Shi and Yang, 2002
Mizhi, Shaanxi Province	2000	*Pinus tabuliformis*	Several thousand trees	0	0	Guo et al., 2001
Xiao Bian Gou watershed, Yanan, Shaanxi Province	1997–2006	*Prunus persica*			38.6	Cao et al., 2008
		Prunus simonii			32.8	
		Prunus davidiana			36.6	
		Prunus armeniaca			33.4	
		Pyrus bretschneideri			60.3	
		Acer truncatum			64.3	
		Ziziphus jujuba			4.6	
		Armeniaca mandshurica			32.6	
		Platycladus orientalis			43.2	
Jingbian, Ansai, Baota, Yanchang, and Luochuan, Shaanxi Province	1998–2005	*Robinia pseudoacacia*			68.2	Cao et al., 2009a
		Prunus armeniaca			11.4	
		Hippophae rhamnoides			61.8	
		Platycladus orientalis			12.7	
		Caragana korshinskii			67.2	
		R. pseudoacacia, *C. korshinskii*			15.3	
Three North Shelterbelt Development Programme	1949–1999	Ecologic and economic forests	1.5×10^8 ha	0.3×10^8 ha	20	Su, 2004

Previous studies have suggested that natural regeneration without human intervention is the best means of ecological recovery (Jiao et al., 2012; Wang et al., 2012). While this idea carries some theoretical merit, it is unrealistic in practice given that the CLP supplies food for some 70 million people. Therefore, affirmative measures must be taken to achieve sustainable development, the aim being to develop the economy while simultaneously protecting the environment. Here we first summarize the negative effects of afforestation and the cultivation of high-value tree species on the CLP. Using pollen records, we then reconstruct the main vegetation

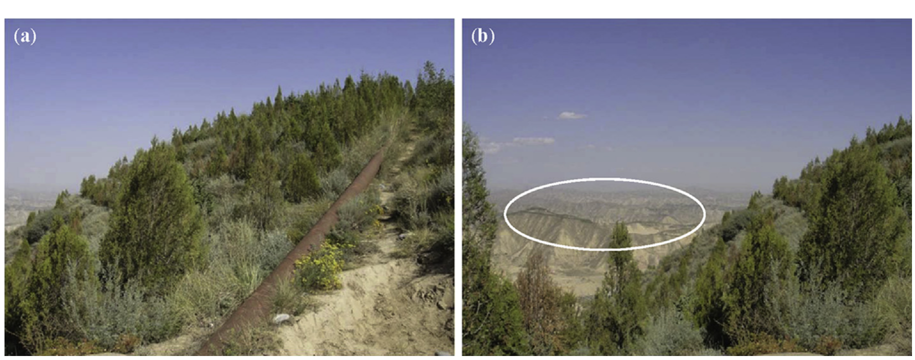

Fig. 1. Contrast in landscape between (a) irrigated afforestation on Jiuzhoutai Mountain and (b) herbaceous vegetation on adjacent loess hills without irrigation (shown in the white oval) in summer. Note that the planted trees on Jiuzhoutai Mountain are maintained by water piped from the Yellow River (550 m below the mountain top).

Fig. 2. A stretch of planted trees on the northern Loess Plateau (note that the roots are exposed to air as a result of rain and wind erosion).

types of various topographic units for the Last Glacial Maximum and the Holocene Optimum. Finally, we suggest plant types suitable for ecological restoration and discuss the related prospects of economic development in the Chinese Loess Plateau.

2. Negative impacts of large-scale tree, shrub and pasture grass planting on the Loess Plateau

Loess is a wind-blown, generally silt-sized material (Liu, 1985; Yang and Ding, 2004). In the CLP, the thick loess deposits cover the old strata, forming various landforms – "yuan" (a high tableland consisting of thick loess), "liang" (flat ridges covered by thick loess) and "mao" (round hills with a loess cap) (Liu, 1985). At present, the climatic conditions of the CLP vary significantly between regions, with ~250 mm mean annual rainfall and a mean annual temperature of ~8 °C in the northwest and ~650 mm mean annual rainfall and a mean annual temperature of ~14 °C in the southeast.

Current greening programmes in the Chinese Loess Plateau compensate farmers for the loss of their farmlands. Each farmer will receive 300 Chinese Yuan and 1500 kg of grain per year for converting 1 ha of farmland into grassland and forests (Cao et al., 2009b). Most of the planted species popular in afforestation programmes are drought-tolerant trees and shrubs, such as black locust (*Robinia pseudoacacia*), peashrub (*Caragana korshinskii*), river locust (*Amorpha fruticosa*), Chinese pine (*Pinus tabuliformis*), aspen (*Populus davidiana*), elm (*Ulmus pumila*) and sea buckthorn (*Hippophae rhamnoides*) (Table 2). These species share the common characteristics of rapid growth, high rates of transpiration, and large root systems (Mu et al., 2003). For example, the roots of black locust, sea buckthorn and peashrub can reach a depth of ~10 m in soil (Mu et al., 2003), and the mean annual rate of transpiration of afforestation plots is four to eight times higher than that of barren land (Li et al., 1991).

It has been found that planted forests grow well only in areas with favourable moisture conditions (e.g., river valleys and floodplains). Their survival rates are relatively low in areas converted from croplands such as barren hills, "liang", and "mao". In some places, survival rates have been close to zero (Guo et al., 2001; Table 2).

The reason for the low survival rates is that moisture in the surface soil is insufficient to maintain the rapid growth of trees and shrubs, which have to absorb groundwater from deep soil. This process exacerbates problems of water scarcity and leads to the

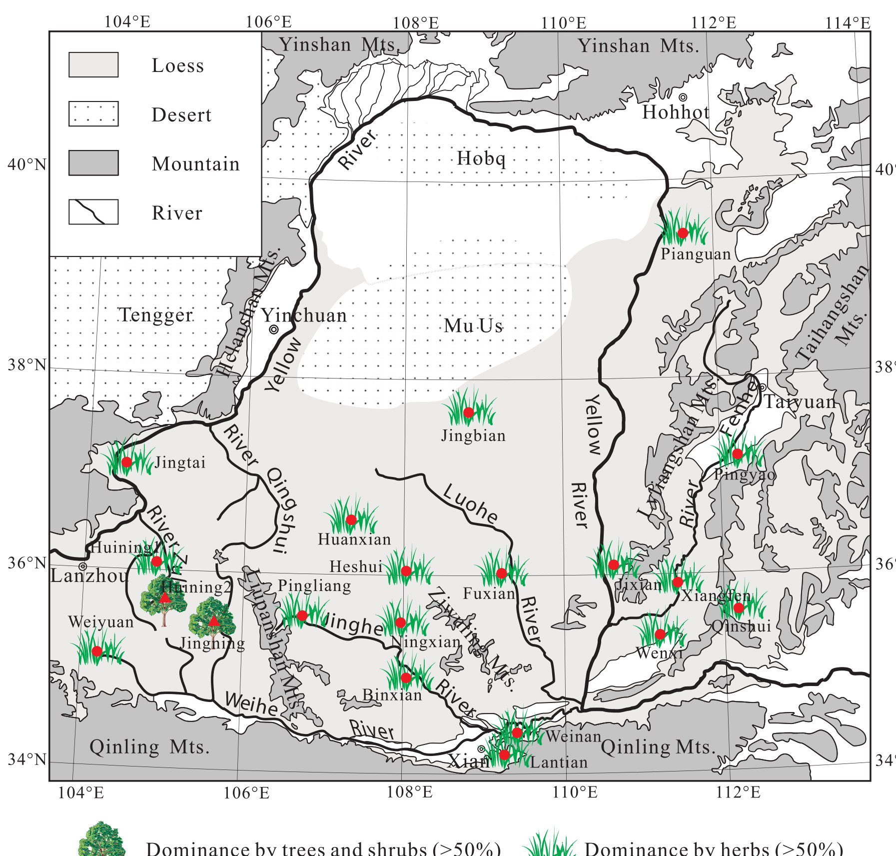

Fig. 3. Major plant types on the Chinese Loess Plateau during the LGM. The map showing the distribution of loess in the middle reaches of the Yellow River is adapted from Liu (1964).

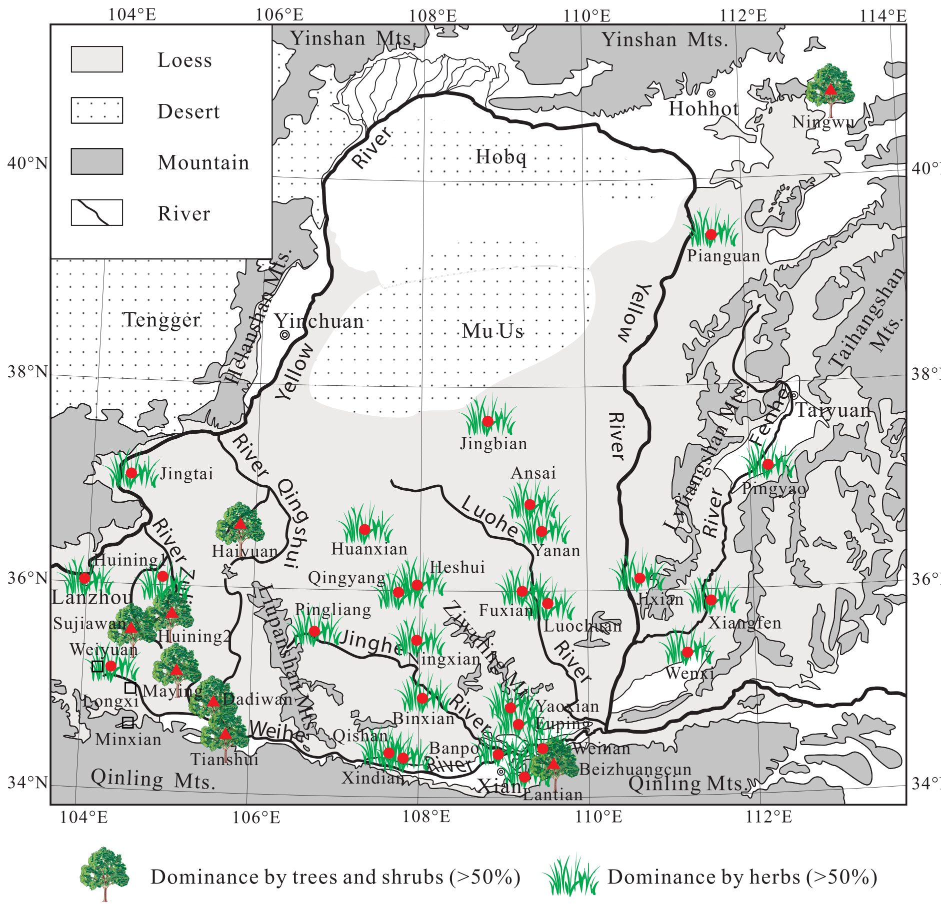

Fig. 4. Major plant types on the Chinese Loess Plateau during the Holocene Optimum. Squares indicate areas where medicinal herbs are planted. The map showing the distribution of loess in the middle reaches of the Yellow River is adapted from Liu (1964).

drying of soil layers (McVicar et al., 2007; Chen et al., 2008b), which both prevents rainwater from penetrating into the ground (Li, 2001; Chen et al., 2008a) and cuts the supply of groundwater to plants, thereby having a considerable effect on the water cycle in the soil–vegetation–atmosphere system. Although some trees and shrubs may grow well soon after planting, their growth rate may decline significantly at a later stage. As a result, low-productivity and stunted planted trees (3–5 m high), so-called "small-aged trees", are commonly seen on the Loess Plateau (Hou et al., 1991). In addition, large-scale tree mortality occurs in drought years (Chen et al., 2008b).

To maintain tree growth, some local governments have installed expensive irrigation systems (Shen et al., 2003). For example, in Lanzhou, 660 million Chinese Yuan has been spent on the North and South Mountains Greening Project. A pipe network of ~3000 km has been installed to supply water to the planted trees, whereas in adjacent areas without irrigation, only sparse vegetation is seen (Fig. 1).

The fact that non-native trees and shrubs cannot grow well on the CLP due to moisture stress raises another question: is this vegetation effective in controlling erosion? As shown in Fig. 2, on the northern part of the CLP, the land surface beneath the trees is eroded by rain and wind, and tree roots are exposed because of the lack of a protective ground herb cover. The reasons for this are: 1) the in-situ herbaceous vegetation is generally cleared in order to avoid competition for moisture prior to planting trees (Cao et al., 2009a); and 2) even if native herbs are not removed, the deeply rooted trees lose large quantities of water due to transpiration, thereby lowering the groundwater table (Normile, 2007) and causing the native vegetation to die off gradually. Therefore, the presence of a protective ground herb cover is crucial for controlling soil erosion.

High-yield herbs have also been introduced to the Loess Plateau, including the leguminous plants *Medicago sativa*, *Melilotus suaveolens*, *Onobrychis viciaefolia* and *Astragalus adsurgens*, and the graminaceous plants *Elymus dahuricus*, *Bromus inermis* and *Agropyron cristatum* (Shi and Yang, 2002). The question of how effective this measure is must be addressed. Recently, non-native forests (mainly Chinese pine), planted grassland (mainly peashrub and alfalfa) and natural grassland have been evaluated in terms of the effects of soil water consumption and ecological restoration (Wang et al., 2009, 2012). The results showed that the average soil moisture content in the top 3 m is higher in natural grassland than it is in non-native forests and grassland (Wang et al., 2009). Moreover, the physical properties of the soil are significantly better in natural grassland (Wang et al., 2012), indicating that Chinese pine, peashrub, and alfalfa consume large amounts of water and readily cause soil degradation. They are therefore not suitable for ecological restoration.

In general, the extensive planting of trees and shrubs on the CLP is not appropriate. Although the planting of herbs was suggested as early as the 1970s (Xue and Gao, 1979; Ma, 1981; Xiong, 1983; Ai et al., 1986), the idea originally received little attention. Furthermore, it remains unclear what types of herbs should be planted. The identity of the prehistoric vegetation of the CLP provides critical clues to help answer this question, given that the native vegetation of the plateau has been destroyed by human activities over the past several thousand years (Liu et al., 1996; Yang et al., 2015).

3. Natural vegetation of the Loess Plateau since the Last Glacial Maximum and implications for vegetation restoration

On the Chinese Loess Plateau, the loess deposits consist of alternating layers of loess and soil. Yellowish loess beds were deposited during cold-dry glacials, and reddish soils developed in warm-humid interglacials. More than thirty loess (L)–soil (S) couplets have been found in complete Pleistocene loess deposits, providing evidence of large-scale oscillations between glacial and interglacial conditions (Kukla, 1987; Ding et al., 2002; Yang and Ding, 2003, 2010).

Over the last 26 ka, the Loess Plateau has experienced a cold extreme (the Last Glacial Maximum: LGM, ~26.5–18 ka) and a warm period (the Holocene Optimum, ~11–3 ka) (Liu et al., 1994; Ding et al., 2002; Huang et al., 2006; Lu et al., 2007). We collected vegetation records on the Loess Plateau for the period since the LGM (Tables 3 and 4). The main vegetation types for the cold and warm periods are shown in Figs. 3 and 4, respectively.

Table 3
Pollen assemblages on the Chinese Loess Plateau during the LGM. yuan: a high table-land consisting of thick loess; liang: a flat ridge covered by thick loess.

Sites	Morphological units	Sediments	Trees and shrubs (%)	Herbs (%)	Trees and shrubs	Herbs	References
Weiyuan	River terrace	Loess	<42	>58	*Picea*, *Pinus*, *Abies*, *Ephedra*, *Betula*, *Corylus*	*Artemisia*, *Echinops*-type, Poaceae	Yang et al., 2015
Jingtai	Yuan	Loess	<35	>65	*Picea*, *Ephedra*, *Abies*, *Pinus*, *Tsuga*, *Corylus*	*Artemisia*, *Echinops*-type, Chenopodiaceae, Poaceae, *Aster*	Yang et al., 2015
Huining 1	Yuan	Loess	<28	>72	*Picea*, *Ephedra*, *Abies*, *Pinus*, *Tsuga*	Artemisia, Chenopodiaceae, Poaceae	Yang et al., 2015
Huining 2	River valley	Lacustrine–fluvial–loess	40–100	0–60	*Picea*, *Abies*, *Pinus*	*Anthemis*-type, *Polygonum*, Plumbaginacea	Wu et al., 2009
Jingning	River valley	Lacustrine-wetland	30–60	40–70	*Pinus*, *Picea*, *Ulmus*, Cupressaceae	Asteraceae, *Artemisia*, Poaceae, Chenopodiaceae, Polygonaceae, Ranunculaceae	Li et al., 2006 Tang et al., 2007 Feng et al., 2007
Jingbian	Liang	Loess	<20	>80	*Pinus*, *Quercus*, *Carpinus*	*Artemisia*, *Taraxacum*-type, Chenopodiaceae, *Echinops*-type	Jiang et al., 2013, 2014
Pingliang	Yuan	Loess	<5	>95	*Quercus*, *Pinus*, Oleaceae, *Corylus*, *Carpinus*	*Artemisia*, *Taraxacum*-type, *Echinops*-type, Chenopodiaceae	Jiang et al., 2013, 2014
Heshui	Yuan	Loess	<10	>90	*Corylus*, *Pinus*, Caprifoliaceae	*Artemisia*, Chenopodiaceae, *Taraxacum*-type, *Echinops*-type	Jiang et al., 2013, 2014
Fuxian	Yuan	Loess	<2	>98	*Pinus*, *Ephedra*, *Betula*, Caprifoliaceae	*Artemisia*, *Echinops*-type, *Taraxacum*-type, Chenopodiaceae	Jiang et al., 2013, 2014
Jixian	Yuan	Loess	<18	>82	*Pinus*, *Forsythia*, *Corylus*	*Artemisia*, Chenopodiaceae, *Echinops*-type	Jiang et al., 2013, 2014
Xiangfen	River terrace	Loess	<10	>90	*Pinus*, Oleaceae, *Forsythia*, *Betula*	*Artemisia*, *Echinops*-type, *Taraxacum*-type, Poaceae, Chenopodiaceae	Jiang et al., 2013, 2014
Lantian 1	Yuan	Loess	<1	>99	*Ephedra*, *Corylus*, *Juglans*	*Artemisia*, *Echinops*-type, Chenopodiaceae, *Aster*, *Taraxacum*-type	Jiang et al., 2014
Lantian 2	Yuan	Loess	~20	~80	*Ulmus*, *Pinus*, *Quercus*	*Artemisia*, Chenopodiaceae, Asteraceae, Poaceae, Polygonaceae	Jiang and Ding, 2005
Weinan	Yuan	Loess	<40	>60	*Pinus*, *Tsuga*, *Abies*, *Picea*	*Artemisia*, Poaceae, Brassicaceae, Fabaceae	Sun et al., 1997
Qinshui	Yuan	Loess	~10	~90	*Pinus*, *Quercus*, *Ailanthus*	*Artemisia*, Chenopodiaceae, Poaceae, *Humulus*	Shi, 2000
Binxian	Yuan	Loess	~20	~80	*Carpinus*, *Ulmus*, *Pinus*, *Picea*, *Abies*	*Artemisia*, Asteraceae, Chenopodiaceae, *Polygonum*, Poaceae	Jiang and Ding, 2005
Ningxian	Yuan	Loess	~3	~97	*Juglans*, *Carpinus*	*Artemisia*, Brassicaceae, Asteraceae, Poaceae	Jiang and Ding, 2005
Huanxian	Yuan	Loess	~1	~99	*Pinus*, *Picea*, *Abies*	*Artemisia*, Gentianaceae, Chenopodiaceae	Jiang and Ding, 2005
Pianguan	Lower slopes of mountains	Loess	<10	>90	*Quercus*, *Corylus*, *Betula*	*Artemisia*, Chenopodiaceae, Fabaceae	Zhou et al., 2014
Pingyao	Lower slopes of mountains	Loess	<20	>80	*Corylus*, *Betula*	*Artemisia*, Chenopodiaceae, Fabaceae	Zhou et al., 2014
Wenxi	Loess tableland	Loess	<10	>90	*Quercus*, *Ulmus*	*Artemisia*, *Aster*, Chenopodiaceae, Fabaceae	Zhou et al., 2014

Table 4
Pollen assemblages on the Chinese Loess Plateau during the Holocene Optimum. yuan: a high table-land consisting of thick loess; liang: a flat ridge covered by thick loess.

Sites	Morphological units	Sediments	Trees and shrubs (%)	Herbs (%)	Trees and shrubs	Herbs	References
Lanzhou	River valley	Fluvial–loess	8	92	*Salix*, *Pinus*	*Artemisia*, Chenopodiaceae, *Reaumuria*, Asteraceae, Poaceae	Wang et al., 1991
Weiyuan	River terrace	Loess	<5	>95	*Betula*, *Corylus*, Oleaceae	*Artemisia*, *Taraxacum*-type, *Echinops*-type, Chenopodiaceae, *Aster*	Yang et al., 2015
Jingtai	Yuan	Loess	<2	>98	*Betula*, *Ephedra*, *Corylus*	*Artemisia*, Chenopodiaceae, Taraxacum-type, *Aster*	Yang et al., 2015
Huining 1	Yuan	Loess	<4	>96	Oleaceae, *Ephedra*, *Betula*, *Picea*, *Pinus*, *Abies*	*Artemisia*, Chenopodiaceae, *Taraxacum*-type, Brassicaceae	Yang et al., 2015
Huining 2	River valley		~65–90	~10–35			Wu et al., 2009

(continued on next page)

Table 4 (*continued*)

Sites	Morphological units	Sediments	Trees and shrubs (%)	Herbs (%)	Trees and shrubs	Herbs	References
		Lacustrine–fluvial–Loess			*Pinus*, *Picea*, *Abies*, *Quercus*, *Ulmus*, *Corylus*, *Betula*, *Juglans*	Chenopodiaceae, *Artemisia*, Poaceae, *Anthemis*-type	
Maying	River valley	Wetland–swamp-Loess	<60	>40	*Pinus*, *Picea*, *Tsuga*	Asteraceae, *Artemisia*, Poaceae, *Polygonum*	Tang and An, 2007
Sujiawan	River valley	Wetland–swamp-Loess	<80	>20	*Pinus*, *Picea*, *Abies*, *Tsuga*	*Artemisia*, Asteraceae, Poaceae, Fabaceae	An et al., 2003 Feng et al., 2006 Tang and An, 2007
Dadiwan	River valley	Wetland–swamp-Loess	~40–80	~20–60	*Pinus*, *Picea*, *Abies*, *Betula*, *Juglans*, *Corylus*, *Quercus*, *Ulmus*	*Artemisia*, Asteraceae, Poaceae, Fabaceae	Xia et al., 1998 An et al., 2003 Feng et al., 2006 Tang and An, 2007
Haiyuan	River terrace	Wetland–Swamp-Loess	44–86	14–56	*Pinus*, *Picea*, *Tsuga*, *Quercus*, *Betula*, *Ulmus*, *Salix*	Chenopodiaceae, *Artemisia*, Poaceae, Liliaceae	Sun et al., 2007
Tianshui	Rocky mountains	Soil	~75	~25	*Quercus*, *Betula*, *Pinus*, *Ulmus*	*Artemisia*, Poaceae	Ju and Chen, 1998
Xindian	River terrace	Loess	<40	>60	*Pinus*, *Castanea*, *Tsuga*, *Ulmus*, *Carpinus*	*Artemisia*, Chenopodiaceae, Poaceae, *Thalictrum*	Shang and Li, 2010
Qishan	River terrace	Loess	<10	>90	*Quercus*, *Pinus*, *Carpinus*, *Corylus*, *Juglans*, *Alnus*, *Castanea*, *Toxicodendron*	*Artemisia*, Asteraceae, Chenopodiaceae, Poaceae, Brassicaceae, Ranunculaceae	Zhao et al., 2003
Banpo	River terrace	Loess	<24.2	>75.8	*Pinus*, *Picea*, *Abies*, *Betula*, *Ailanthus*, *Carpinus*	*Artemisia*, Chenopodiaceae, Asteraceae, *Selaginella sinensis*	Li and Sun, 2005
Lantian 1	River terrace	Fluvial	<50.5	>49.5	*Quercus*, *Corylus*, *Ulmus*, *Carpinus*, *Betula*	*Artemisia*, Chenopodiaceae, Asteraceae, *Selaginella sinensis*	Li and Sun, 2005
Lantian 2	Yuan	Loess	<5	>95	Oleaceae, *Ephedra*, *Betula*, Rhamnaceae	*Artemisia*, Chenopodiaceae, *Taraxacum*-type, Polygonaceae, *Aster*, *Selaginella sinensis*	Jiang et al., 2014
Lantian 3	Yuan	Loess	~10	~90	*Pinus*, *Ulmus*, *Tsuga*	*Artemisia*, Chenopodiaceae, Asteraceae, *Polygonum*, Brassicaceae, *Selaginella sinensis*	Jiang and Ding, 2005
Beizhuangcun	River terrace	Loess	<58	>42	*Pinus*, *Tsuga*, *Picea*, *Abies*, *Betula*	*Artemisia*, Poaceae, Chenopodiaceae, Fabaceae	Shang and Li, 2010
Fuping	River terrace	Fluvial	<20	>80	*Pinus*, *Quercus*, *Corylus*, *Betula*	*Artemisia*, Asteraceae, Ranunculaceae, Poaceae	Li and Wang, 2009
Ansai	River terrace	Loess	~15	~85	*Quercus*, *Pinus*, *Tsuga*, *Acer*	*Artemisia*, Cyperaceae, Ranunculaceae, *Polygonum*, Brassicaceae	He et al., 2004
Yan'an	River terrace	Loess	20–30	70–80	*Pinus*, *Quercus*, *Betula*, *Carpinus*	*Artemisia*, Chenopodiaceae, Poaceae, Brassicaceae	He et al., 2000
Jingbian	Liang	Loess	<~2	>~98	*Quercus*, *Pinus*	*Artemisia*, Chenopodiaceae, *Echinops*-type, Poaceae	Jiang et al., 2013, 2014
Pingliang	Yuan	Loess	<5	>95	*Corylus*, *Pinus*, *Carpinus*, Oleaceae	*Artemisia*, Chenopodiaceae, *Echinops*-type, Poaceae	Jiang et al., 2013, 2014
Heshui	Yuan	Loess	<~20	>~80	*Corylus*, *Pinus*, *Carpinus*	*Artemisia*, *Echinops*-type, Poaceae, *Fagopyrum*	Jiang et al., 2013, 2014
Fuxian	Yuan	Loess	<14.5	>88.5	*Corylus*, *Nitraria*, *Quercus*	*Artemisia*, Chenopodiaceae, Fabaceae, *Fagopyrum*, *Selaginella sinensis*	Jiang et al., 2013, 2014
Jixian	Yuan	Loess	<~20	>~80	*Pinus*, *Corylus*, *Quercus*, *Pterocarya*, *Betula*	*Artemisia*, Chenopodiaceae, Poaceae, *Echinops*-type, *Selaginella sinensis*	Jiang et al., 2013, 2014
Xiangfen	River terrace	Loess	<28	>72	*Pinus*, *Corylus*, *Quercus*, *Ulmus*, *Betula*, *Alnus*	Chenopodiaceae, Polygonaceae, *Artemisia*, *Selaginella sinensis*, Poaceae, *Taraxacum*-type	Jiang et al., 2013, 2014
Weinan	Yuan	Loess	6–25	75–94	*Pinus*, *Tsuga*, *Betula*, *Ulmus*, *Corylus*	Asteraceae, Brassicaceae, Poaceae, Cyperaceae, Fabaceae	Sun et al., 1997
Yaoxian	Yuan	Loess	<38	>62	*Pinus*, *Picea*, *Abies*, *Quercus*	*Polygonum*, Labiatae, *Artemisia*, Chenopodiaceae	Li et al., 2003
Ningwu	Dry lake	Lacustrine	<80	>20	*Betula*, *Pinus*, *Quercus*	Asteraceae, Liliaceae, Cyperaceae	Meng et al., 2007
Binxian	Yuan	Loess	~20	~80	*Pinus*, *Picea*, *Abies*, *Ulmus*	*Artemisia*, Brassicaceae, Asteraceae, Chenopodiaceae, *Polygonum*	Jiang and Ding, 2005
Ningxian	Yuan	Loess	~40	~60	*Corylus*, *Carpinus*, *Betula*	*Artemisia*, Asteraceae, Brassicaceae	Jiang and Ding, 2005
Qingyang	Yuan	Loess	~2	~98	Tamaricaceae, *Quercus*, *Ulmus*	*Artemisia*, *Polygonum*, Asteraceae, Chenopodiaceae, Poaceae	Jiang and Ding, 2005
Huanxian	Yuan	Loess	~1	~99	*Pinus*	*Artemisia*, Asteraceae, *Polygonum*, Gentianaceae	Jiang and Ding, 2005
Luochuan	Yuan	Loess	<~15	>~85	*Pinus*	*Artemisia*, Chenopodiaceae, Asteraceae, *Polygonum*, Ranunculaceae, *Fagopyrum*	Wei, 1996
Pianguan	Lower slopes of mountains	Loess	<5	>95	*Corylus*, *Betula*	*Artemisia*, Chenopodiaceae, Fabaceae	Zhou et al., 2014
Pingyao	Lower slopes of mountains	Loess	<20	>80	*Corylus*, *Betula*, *Picea*	*Artemisia*, Chenopodiaceae	Zhou et al., 2014
Wenxi	Loess tableland	Loess	<40	>60	Cupressaceae, *Quercus*	*Artemisia*, *Taraxacum*-type, Poaceae	Zhou et al., 2014

The results show that during both the warm and cold periods, the vegetation at most of the studied sites was dominated by herbs. Specifically, vegetation on the CLP since the LGM mainly consisted of *Artemisia*, Poaceae, *Taraxacum*-type plants, *Echinops*-type plants, Chenopodiaceae, Brassicaceae, Liliaceae, Labiatae, Solanaceae, Fabaceae and Apiaceae (Tables 3 and 4). There was a low incidence of trees and shrubs. Ferns and algae were also present. Almost all pollen assemblages were dominated by the Asteraceae family (mainly *Artemisia*, *Taraxacum*-type and *Echinops*-type), with an abundance of as high as 95% at a few sites (Jiang et al., 2013, 2014). In general, the content of Poaceae pollen was in the range 2–20%, indicating a high biomass of Poaceae on the plateau given its low pollen productivity (Liu et al., 1999; Li et al., 2005). Moreover, pollen of *Juglans* and *Corylus* and spores of *Selaginella sinensis* occurred in Holocene soil on the southeastern CLP.

The sites dominated by herbs share one common characteristic, in that they all have very thick loess deposits (60–300 m). Because Chinese loess is mainly composed of loose silt (Liu, 1985; Yang and Ding, 2008), rainwater infiltrates rapidly (Chen et al., 2008a; Yang et al., 2012), and so moisture in the surface soil is insufficient to maintain forests in areas covered by thick loess deposits (e.g., "yuan", "liang", "mao" and high river terraces). The pollen records show that trees thrived in the riparian zones of the Yellow River and its tributaries (e.g., floodplains and low river terraces) that contain thin loess deposits and a high underground water table (Figs. 3 and 4; Tables 3 and 4). However, in the semi-arid Loess Plateau, the riparian zones are very limited, and most areas are covered by thick loess (>20 m) (Liu, 1985). Therefore, herbs are more suitable for cultivation in most loess areas on the plateau. It should be noted that in the CLP a number of both natural and non-native forests are found in rocky mountainous areas. The reason for this is that these areas are usually covered by thin surface soils formed through weathering of bedrock, and bedrock itself can serve as an efficient water-resisting layer, allowing the surface soil to retain sufficient rainwater to support forests.

Both the physical characteristics of loess and the prehistoric plant types indicate that herbs (mainly from the families Asteraceae and Poaceae) dominated most areas of the CLP. In light of this, we make the following suggestions:

(1) Herbs from the Poaceae and Asteraceae families should be considered a priority for ecological restoration on the CLP.
(2) Only in areas with a high water table, such as the riparian zones of large rivers (e.g., the Weihe River) and deep valleys covered with thin loess, should some trees and shrubs be considered candidate species.
(3) The species *Juglans* and *Corylus* could serve as useful candidate species for the south-eastern CLP or at other sites with efficient irrigation systems.

4. The potential of the CLP as a centre for Chinese medicinal herb production: a future perspective

The native vegetation of the CLP contains plant families that include many species of medicinal use. The pollen records show that herbs from the Asteraceae family bloomed on the CLP in both the cold-dry period and the warm-humid period (Tables 3 and 4). Asteraceae is an important source of medicines: more than 300 species in this family have medicinal value (Dharmananda, 2012). For example, artemisinin, the most effective antimalarial drug, is extracted from *Artemisia annua* (a member of that family) (Covello, 2008). Other important medicinal source materials from the Asteraceae family include *Arctium lappa*, *Eclipta prostrata*, *Bidens biternata*, *Cirsium japonicum* and *Senecio scandens*, which are currently in short supply in Chinese herbal medicine markets (http://www.zyctd.com). In addition, the families Labiatae, Ephedraceae and Solanaceae, which are common in the pollen records (Tables 3 and 4), also contain some urgently needed medicinal plants such as *Perilla frutescens*, *Agastache rugosa*, *Scrophularia ningpoensis*, *Datura metel*, *Viscum album*, *Elsholtzia splendens* and *Ephedra sinica* (http://www.zyctd.com). Furthermore, during the Holocene Optimum, *Selaginella sinensis* and *Corylus* occurred in the south-eastern CLP (Tables 3 and 4). *Selaginella sinensis*, a native species of fern, is a traditional Chinese medicine for the treatment of hepatitis, cholecystitis, eczema and burns. *Corylus*, a genus of deciduous trees or shrubs, provides seeds for the food industry as well as leaves and nutshells used as source material for the extraction of paclitaxel (an expensive anti-cancer drug) (Ottaggio et al., 2008). We therefore believe the CLP has great potential to be a centre for Chinese medicinal herb production.

The CLP has many advantages in the race to develop the Chinese herbal medicine industry. First, the climatic conditions of the various morphological units may favour different types of medicinal herbs. Second, medicinal herbs generate more income per hectare than crops. For example, the income derived from *Angelica sinensis*, *Codonopsis pilosula*, and *Astragalus membranaceus* is much higher than that from wheat and potato (Wan et al., 2011). Third, there have already been some successful examples of cases in which medicinal herbs have helped to boost the local economy. Minxian, Longxi and Weiyuan counties (Fig. 4) in Gansu Province have been important production areas for *Angelica sinensis*, *Codonopsis pilosula* and *Astragalus membranaceus*, respectively, with each contributing ~25% of local revenue (He et al., 2005).

Extensive planting of medicinal herbs may have two negative consequences: 1) problems resulting from planting a single species, and 2) pollution from the overuse of chemical fertilizers and pesticides. The former problems can be avoided through combination of different species, and the latter problem through development of organic medicinal herb production.

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