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ESTIMATING VEGETATION SENSITIVITY TO CLIMATE CHANGE AND HUMAN DISTURBANCE: EVIDENCE FROM MODERN VEGETATION PATTERN AND PALAEOVEGETATION DEVELOPMENT

ОЦЕНКА ЧУВСТВИТЕЛЬНОСТИ РАСТИТЕЛЬНОСТИ К ИЗМЕНЕНИЯМ КЛИМАТА И АНТРОПОГЕННЫМ НАРУШЕНИЯМ: СВИДЕТЕЛЬСТВА, ОСНОВАННЫЕ НА СТРУКТУРЕ СОВРЕМЕННОЙ РАСТИТЕЛЬНОСТИ И ЕЕ РАЗВИТИИ НА ПРОТЯЖЕНИИ ГОЛОЦЕНА

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In the forest-steppe ecotone in Inner Mongolia of China, different tree-species are distributed with different MAP range in the forest-steppe ecotone. Both modern vegetation pattern and the Holocene vegetation development show that Chinese pine was the most drought tolerant tree species and can resist long-term climate drying. Strong human impact on vegetation was constrained to the West Liao River basin over thousands of years of sedentary agriculture.
Key words: forest-steppe ecotone, mean annual precipitation (MAP), vegetation dynamic, Pacific monsoon, Inner Mongolia (China), the Holocene.

В пределах лесостепного экотона Внутренней Монголии (Китай) различные виды деревьев распространены в соответствии с границами распределения среднегодового количества осадков. Как структура современной растительности, так и ее развитие на протяжении голоцена, показывают, что из числа деревьев китайская сосна (*Pinus tabulaeformis*) является наиболее толерантным к засухе видом, способным выдерживать долговременные процессы повышения сухости климата. Значительный уровень антропогенной нагрузки был постоянным ограничивающим фактором для растительности бассейна р. Западный Ляо (юго-восток Внутренней Монголии) на протяжении тысяч лет ведения оседлого сельского хозяйства.
Ключевые слова: лесостепной экотон, среднегодовые осадки, динамика растительности, тихоокеанский муссон, Внутренняя Монголия (Китай), голоцен.

INTRODUCTION

It is generally regarded that modern forest distribution at the forest-steppe ecotone is very sensitive to climate change and human disturbance. As marginal distribution of forest at its drought limitation, even small change in climate is regarded to cause great shifting in forest distribution and structure as well (Shen et al., 2009). Current forest dieback has been widely observed in marginal forest at different parts of the world (Allen et al., 2009), which will accelerate desertification in semi-arid to semi-humid regions. In central North America, global warming is expected to cause the existing prairie-forest border to shift to the northeast; a substantial area of currently forested lands will change to savannas or grasslands (Freilich and Reich, 2008). What will happen in the Inner Asian forest-steppe ecotone remains unclear.

Concerning climate change and vegetation response in the forest-steppe ecotone, we have to know how the modern climate shape distrbution of tree species within the ecotone and how different tree species respond to long-term climate change, particularly during the Holocene period with distinct climatic phases. In addition, the forest-steppe ecotone in the West Liao River basin is considered one of three cradles of ancient agriculture in China (An, 1998). Primitive agriculture occurred during the years 8,150–7,350 BP (Before Present) and sedentary agriculture began in 7,150 BP. in the West Liao River basin (Yan, 1992; Linduff et al.,

2002). Archeological evidence also indicated that agriculture development in this region was disrupted by climate changes (Shelach, 2002). To predict future climate-driven vegetation development relies on how to distinguish the roles of climate change and human impact on vegetation development.

In this paper, we present modern vegetation pattern and palaeovegetation development reconstructed from pollen analysis in southeastern Inner Mongolia of China. How climate pattern shapes tree species distribution and how climate change and human disturbance drive the Holocene migration of tree species within the ecotone is emphasized. We aimed at providing evidence for predicting the future dynamics of the forest-steppe ecotone in northern China.

STUDY AREA AND METHODS

Mean annual precipitation (MAP) in continental East China decreases from the southeast to the northwest, associated with weakening of the Pacific monsoon intensity. As a boundary between semi-humid to semi-arid climates, the 400-mm isohyet passes through the southeastern edge of the Inner Mongolia Plateau (Fig. 1).

One hundred and forty-eight relevés were made in randomly selected 71 sites in the forest-steppe ecotone. Species composition and topological features of both forest and steppe relevés were recorded. Forest relevés were classified according to dominant tree species and further linked to precipitation. Thirteen pollen sequencies were collected from previous publication, of which eight were completed by the authors (see Fig. 1). Eight sequencies spanning the entire Holocene were selected to show establishment and recession time of four dominant taxa, *Pinus, Picea, Quercus* and *Betula.*

RESULTS

Regional climate and vegetation patterns

The temperatures were relatively higher in the valley and lower on the high peaks of the mountainous areas; however, there was no marked variation across the Plateau. Mean Annual Precipitation (MAP) had a NW-SE gradient (see Fig. 1). From the mountains and the edge of the Inner Mongolia Plateau in the southeast to the inner surface of the Plateau, MAP decreased from more than 450 mm to less than 200 mm. MAP had a significant correlation with longitude, latitude and altitude ($p < 0.01$):

$$MAP = -878.918 - 56.657 laitude + 31.676 longitude - 0.008 altitude$$

$n = 31$, $R^2 = 0.74$.

With the increase of latitude and the decrease of longitude, MAP decreased, which was identical to the above pattern.

At sites where MAP exceeded 450 mm, continuous closed-canopy forests were found. Ninety-five percent of the forest in the ecotone distributed where MAP ranged between 370-450 mm, with an average of 424 mm. Fragments of closed forest existed on shady slopes where soil water condition was favorable. The majority (95 %) of the elm woodland scattered on steppe where MAP is between 346–409 mm, with an average MAP of 378 mm. There were no significant differences in MAP between elm woodland and steppe ($p >> 0.1$). The range of MAP variations for elm woodland was significantly smaller than the range for sites where closed broad-leaf forest distributed ($p < 0.01$). When MAP declined to about 200 mm, *Caragana microphylla* Lam. replaced elm woodland, as in the west of Otindag sandy land, with no woody patch left.

Forest community type and MAP gradient were tightly linked (Fig. 2). By comparing field results, remote sensing interpretation and interpolated climate data, we found that precipitation range differed for different forest (woodland) types. Mean annual precipitation for forest (woodland) types dominated by *Ulmus pumila* L., *Picea meyeri* Rehder & E.H. Wilson, *Populus davidiana* Dode and *Pinus tabulaeformis* Carrière are lower than those dominated by *Quercus mongolica* Fisch. ex Ledeb., *Betula platyphylla* Sukacz., *Betula davurica* Pall. and *Larix gmelinii* var. *principis-rupprechtii* (Mayr) Pilger. Poplar forest was the most drought-tolerant among broad-leaved forests, followed by oak and birch forest.

Reconstructed vegetation dynamics in the forest-steppe ecotone

Table below shows the establishment and recession of different tree species in the forest-steppe ecotone during the Holocene. It is evident that *Picea* and *Betula* as cold resistant species, established earlier in the current forest-steppe ecotone. As dominant broadleaf forest species, *Quercus* arrived at 8,500–5,500 yr BP (Before Present) at the northern sites (HLK, XNC,

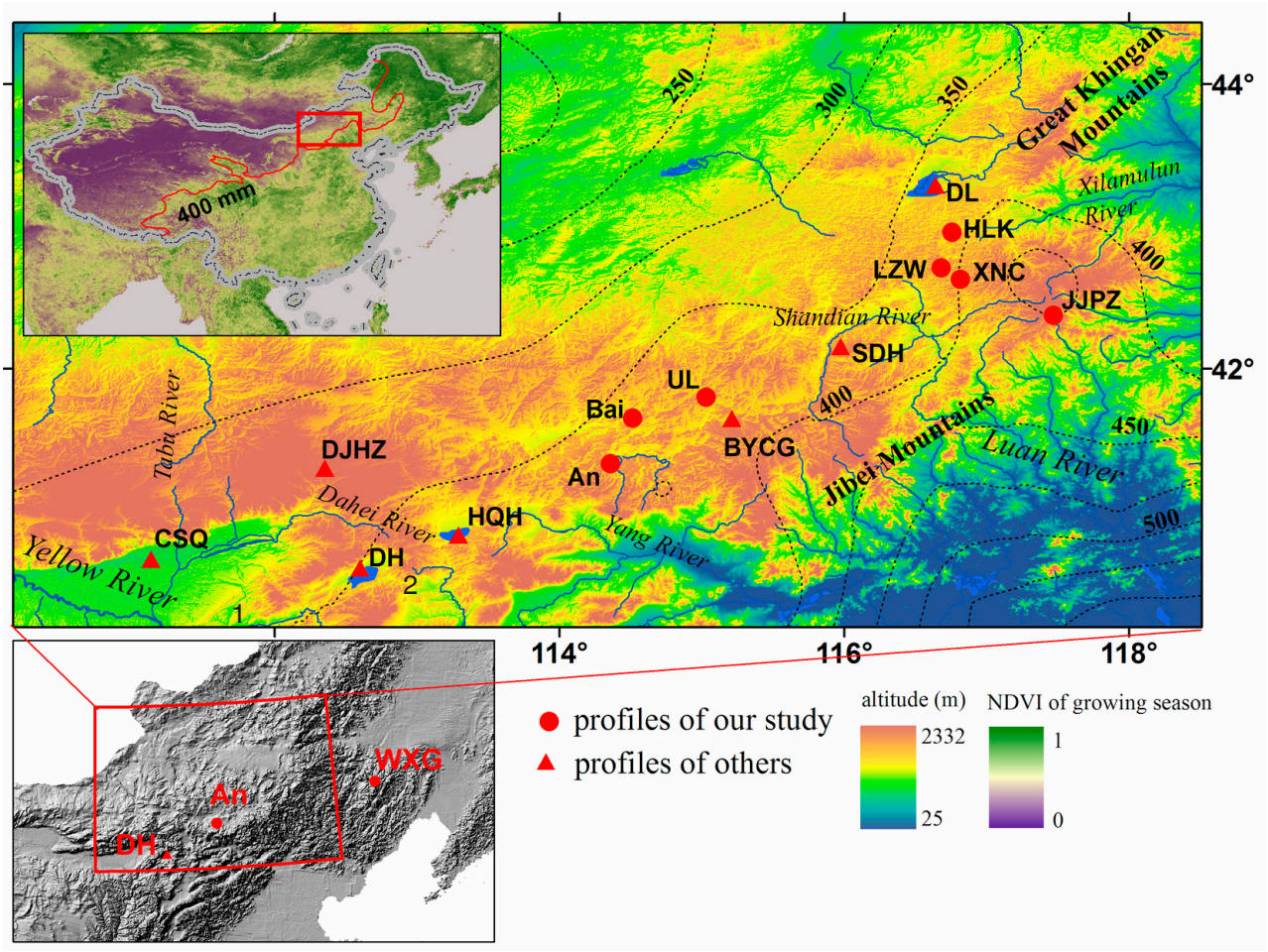

Fig. 1. Map of the study area. Dashed lines represent the isohyet of MAP (mm). Red dots show sediment sequences investigated by the authors of this paper and red triangles sediments sequencies by other researchers. The symbol 1 represents Inner Mongolia Plateau and 2 West Liao River basin

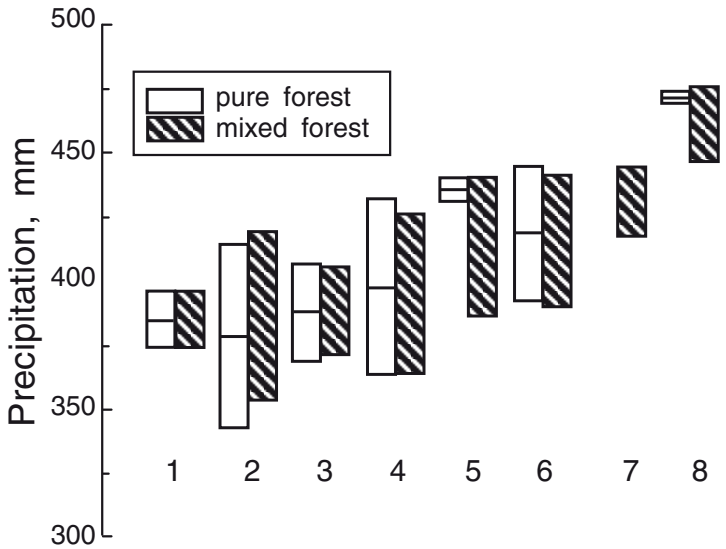

Fig. 2. Forest types along precipitation gradient, and the number stands for edificators: 1 — *Ulmus pumila*, 2 — *Picea meyeri*, 3 — *Populus davidiana*, 4 — *Pinus tabulaeformis*, 5 — *Quercus mongolica*, 6 — *Betula platyphylla*, 7 — *Betula dahurica* and 8 — *Larix gmelinii* var. *principis-ruprechtii*. *Ulmus pumila* forms so-called elm woodland and *Betula dahurica* has no pure forest

LZW, JJPZ) during the middle Holocene, but at the beginning of the Holocene at the southern sites (BYCG, DJHZ, An, DH). Similar situation was also found for *Pinus.*

Co-existence of these dominant taxa existed for most sites although their establishment and recession time differs. There are only a few cases of dominant taxa replacement, for example, *Picea* was replaced by *Pinus* at LZW, and *Betula* was replaced by *Quercus* at JJPZ. *Pinus* recessed from the ecotone much later than other taxa at LZW and JJPZ, but at about the same time as other taxa at most sites.

Establishment and recession time (yr BP) of four dominant tree taxa in the forest-steppe ecotone during the Holocene

	Pinus	*Picea*	*Betula*	*Quercus*
HLK	9,000~0	11,000~0	11,000~0	8,500~3,000
XNC	8,500~3,000	11,000~3,000	11,000~3,000	8,500~3,000
LZW	7,400~1,300	11,000~7,400	11,000~1,300	7,400~1,300
JJPZ	9,000~0	11,000~4,500	11,000~5,500	5,500~0
BYCG	11,000~2,100	11,000~2,100	11,000~2,100	11,000~2,100
DJHZ	11,000~2,000	11,000~4,000	11,000~0	11,000~2,800
An	11,000~2,100	11,000~2,100	11,000~0	11,000~2,100
DH	11,000~1,800	8,000~1,800	11,000~5,700	11,000~1,800

DISCUSSION

Climate sensitivity of forests in the forest-steppe ecotone

We observed species changes along precipitation gradient in our study region. H. Bugmann (1996) proposed a plant functional type (PFT) scheme in temperate and boreal forests based on distribution of tree species in Europe. He sorted different types of woody plants along a combined bioclimatic gradient of temperature and drought occurrence and suggested that a combination of high temperature and low moisture might lead to a "drought limit" of the forest distribution, and he listed *Pinus* as the forest species in the drought limit in the temperate zone. This classification was verified in our study region, but there are more species, including *Ulmus pumila, Picea meyeri*, *Populus davidiana* and *Pinus tabulaeformis* distributed near the forest limit.

The reason that broadleaf trees' survival at the drought limit of forest distribution might depend on the landform-regulated soil moisture pattern, the primary factor used to explain changes in woody cover in African savannas (Sankaran et al., 2005). A remarkable characteristic in our study area is that MAT (Mean Annual Temperature) varied little whereas MAP varied markedly. In our study region, sunny slopes received more solar radiation which led to greater evaporation, so that shadow area formed by mountain topography had strong impact on solar effective radiation and led to marked reduction of evaporation on shady slopes. The landform differences seem to be the key for greater available soil water on steep shady slopes to allow the occurrence of montane forest.

The vegetation pattern observed in our study region also occurs in the Loess Plateau in China, and southern Siberia. For example, along a precipitation gradient in southern Siberia, *Pinus sylvestris* L. replaces *Larix sibirica* Ledeb. This observation, combined with the knowledge that *Pinus sylvestris* is more drought-tolerant species than *Larix sibirica* (Tchebakova et al., 2006), implying that the mechanism underlying the vegetation pattern observed in our study region may also apply to other temperate forest-steppe ecotones.

Our study highlighted the role of drought on forest recession. The reconstructed climate change suggested a drying trend since about 5,000 yr BP (Peng et al., 2005; Zhao et al., 2009). Replacement of broadleaf trees (*Quercus, Tilia*) by *Pinus* as indicated by their relative cover was evident when climate is becoming dry after about 5,000 yr BP (Liu et al., 2002), but the exact time depends on the location of the site. However, final recession of different tree taxa from one site concurred in most sites, most likely that diversified local habitat (mountain slopes, sandy dunes) benefited coexistence of tree species under climatic deterioration. Diversified habitat at site level can also explain the individuallistical response of tree taxa (Delcourt, Delcourt, 1991). Although it is difficult to quantify the sensitivity of different tree taxa, *Pinus* can be regarded as the most sensitive one among all tree taxa.

Human impacts and forest dynamics

Most archeological findings have been concentrated on the southern edge of West Liao River plain (Hu and Cui, 2002). However, the Inner Mongolia Plateau region has experienced only a very short history of agricultural cultivation during the past 100 years, as recorded in historical documents, and nomadic pasture prevailed before that time (Cui et al., 2004). Sedentary agriculture is scattered and its distribution is limited.

Weed and crop pollen in the Wang-Xiang-Gou (WXG, 119°55'E, 42°04'N, 751 m a.s.l.) from the West Liao River basin section clearly declare the historical human impact on vegetation development (Li et al., 2006). However, there is no pollen evidence of human cultivation in the sections located in the Inner Mongolia Plateau. The observed tree pollen decrease

could also be caused by human logging, which is difficult to be identified from tree pollen evidence itself. *Corylus mandschurica* Maxim. and *Ostryopsis davidiana* Decaisne are two common shrub species which form a narrow belt between forest patch and steppe in the forest-steppe ecotone. However, they expanded very fast at sites where forests were destroyed. Therefore, we can distinguish the role of climate and human from the pollen assemblages (Liu, Li, 2009). Decrease of tree pollen percentage followed by high percentages of *Corylus* and *Ostryopsis* pollen might indicate human logging whereas their low percentages with no obvious decrease of tree pollen might indicate forest recession under climate deterioration. For example, in Anguli Nuur (An in Fig. 1), *Pinus* pollen percentages decreased since 2.1 ka BP, but changes in *Corylus* and *Ostryopsis* pollen is not evident, we therefore conclude it as climate-forced forest recession. In WXG section, in contrary, changes of *Corylus* and *Ostryopsis* pollen percentage were converse to those of tree (*Betula*) pollen percentages (Li et al., 2006), implying human impact on vegetation composition.

CONCLUSIONS

We found that, in the forest-steppe ecotone in Inner Mongolia of China, different tree-species are distributed with different MAP range in the forest-steppe ecotone. Both modern vegetation pattern and the Holocene vegetation development show that Chinese pine was the most drought tolerant tree species and can resist long-term climate drying. Strong human impact on vegetation was limited to the West Liao River basin with thousands years of sedentary agriculture.

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