Vegetation and Climate Change during Marine Isotope Stage 3 in China

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Abstract

Fossil pollen records from 45 sites across China, mostly with poor chronology and coarse resolution, were used to document MIS 3 vegetation and climate change and to understand the large-scale controls. During MIS3, vegetation type was mostly forest in the eastern part of China, and forest steppe/meadow in the north and Tibetan Plateau, while in the arid China the vegetation was steppe desert. The Vegetation scale change shows higher values in MIS3 than in LGM, especially for the period of 53-40 ka. Our results also indicate that MIS 3 vegetation was not as good as during Holocene optimum, suggesting less warm and wet climate; however, probably similar to the modern vegetation. The close relationship between vegetation and insolation and summer monsoon intensity suggests that climate variations, probably both temperature and precipitation, are the primary cause of regional vegetation change. Additional well-dated, high-resolution paleoclimate records from many locations across China will be needed, in order to understand the vegetation change on millennial and centennial scale within MIS 3 and climate control mechanisms.

Keywords: Fossil pollen; MIS 3; vegetation change; climatic controls; China

1. Introduction

MIS 3 has drawn lots of attention across the world due to its special interstadial climate during the last glacial (e.g., Brandefelt et al., 2011; Allen et al., 1999; Hughen et al., 2006; Barron and Pollard, 2002; Lambeck et al., 2002; Wright et al., 1995; Meerbeeck et al., 2009; Voelker et al., 2002; Huntley et al., 2003). Greenland ice core oxygen isotope records (Dansgaard et al., 1993; North Greenland Ice Core Project Members, 2004) indicate that climate varied between cold (stadial) and mild (interstadial) conditions during MIS 3, approximately 60-30 ka. Voelker et al. (2002) compiled global terrestrial and marine sites in order to provide an overview on the spatial distribution of centennial-resolution climate records of MIS 3 glacial. The results show that in general, climate conditions were warmer and more humid during interstadials, and colder and more arid during stadials. Based on equilibrium climate simulations, Van Meerbeeck et al. (2009) suggested that enhanced northern Hemisphere seasonality, insolation difference and freshwater forcing could have contributed to the climate difference between Marine Isotope Stage 3 and the Last Glacial Maximum. In China, many studies have revealed the possible warm and humid climate during MIS 3. Herzschuh (2006) reviewed 75 palaeoclimatic records (including 14 records covering part of MIS 3) and found MIS 3 (50-25 ka) is a relatively wetter period than MIS 2. Shi et al. (2002; 2003) and Yang et al. (2004) suggested that a warm and wet climate occurred during late MIS 3 (40-30 ka) mainly based on ice core, lacustrine sediments, pollen and paleoentology, loess/paleosol sequence and cave oxygen isotope, mostly from northwestern China and the Tibetan Plateau. Yu et al. (2002; 2007) used 19 coarse resolution pollen records at 40-30 ka and applied a biomization method to reconstruct the vegetation types. The reconstructions show that forest in southeastern China extended northwards into the present northwestern steppe region, while the northern boundary of tropical forest in southern China was shifted to the north of 24°N. However, the vegetation change during the entire MIS 3 in China and climate controls are still poorly understood due to limited records and few synthesis studies. In addition, some important questions are still not clear, mainly including: (1) When was the best vegetation period during the MIS 3? (2) Was the vegetation during MIS 3 similar to the Holocene? (3) Did precipitation change or temperature change cause the vegetation change?

In this paper, we review the pollen data from 44 sites across China (see the locations and site information in Fig. 1 and Table 1). The objectives of this paper are to document the vegetation change during MIS 3 and to understand the vegetation response to climate change and attempt to address the scientific questions above-mentioned. This synthesis would not only bring together existing pollen data but also assist the design of paleoecological and paleoenvironmental studies in the future.

2. Data sources and methods

Fourty-five pollen records of various time spans and data quality in China are available; however, in general very few records have good age controls, high temporal resolution and mostly are discontinuous. Nonetheless, we include all the data for our synthesis in this study (see Table 1 for information and reference) due to lack of the recods spanning MIS 3. We chose 7 pollen records with relatively good age controls and continuous sediments for detailed description. Pollen data of these 7 sites were digitized from pollen diagrams in the publications.

For each site, we attempted to recalibrate radiocarbon dating with the program Calib Rev 6.1.0 using IntCal09 calibration data set (Reimer et al., 2009). Our calibration shows that the calibrated age is usually 300-500 years older than radiocarbon age during the MIS 3 stage. Some Thermoluminescence (TL) and Optical Stimulated Luminescence (OSL) ages at some sites were also used in this study, which were indicated in Table 1. Unfortunately, the chronologies for most sites are based on only one radiocarbon date or through regional correlation, which caused lots of uncertainties.

We review the pollen data by seven regions: South China, Southwestern China, Central China, North China, Loess Plateau, Northwestern China and the Tibetan Plateau, based on the modern vegetation types (Hou, 2001) and for the conveniences of discussion. For each site, we assigned a vegetation score from 1-3 based on the different vegetation types inferred from pollen data, some of which are only based on the description of the original papers due to the lack of detailed figures. We generated a synthesized curve by averaging for the interval of every 2000 years.

3. Pollen records of vegetation changes

We here present seven records in detail for various regions in China. We also describe other records in general in each region.

3.1. South China

Tianyang Lake provides a representative pollen record (Zheng and Lei, 1999) in South China. The pollen assemblages were dominated by *Castonopsis* and *Quercus* at >47,770–29,000 ^{14}C yr BP (>48.4-33.2 ka; 1 ka=1000 cal yr BP) and the vegetation was evergreen forest with montane conifers and then temperate forest elements. The pollen zone is characterized by a strong increase in Poaceae (28–55%) and *Artemisia* (7–10%) at ca. 29,000–15,000 ^{14}C yr BP (33.2-19 ka), indicating dense forests were transformed to grassland or savanna vegetation. <15,000 ^{14}C yr BP (19 ka), the pollen assemblage show the resurgence of montane forest typified by Taxodiaceae, *Pinus* and *Altingia* and the disappearance of savanna.

Pollen records from Shenzhen (Zhang and Yu, 1999), Caitang (Zheng Z., 1990; cite from Huang et al., 2003), Henglan (Huang et al., 1982; cite from Huang et al., 2003), Lingtingyang (Chen et al., 1994) and Hongkong in South China (Yan, 1998) revealed that the pollen assemblages were mostly dominated by *Cyathea*, evergreen *Quercus*, *Castanopsis* and *Elaeocarpus* and tropical *Sonneraia* at ca. 40-30 ka, though the age controls were very poor and pollen data information was fragmentary for these records. The pollen data suggest the vegetation around these sites was tropical evergreen forest at MIS 3. However, a core from Continental shelf of the South China Sea (Sun et al., 2000), which had three radiocarbon dates to bracket MIS 3 stage shows that the pollen assemblages were dominated by *Pinus*, montane conifers (*Picea*, *Abies* and *Tsuga*) and herb *Artemisia* pollen at 40-18 ka (cal.) and Late MIS 3 (40-28.8 ka) and LGM are quite similar in climate.

Another feature of vegetation change inferred from pollen data in South China is the distribution change of *Dacrydium*, which is an indicator of warmer climate. The Chinese mainland flora today is totally devoid of *Dacrydium*, except that a single species (*D. pierrei*) is represented in the montane rainforests of Hainan Island (extreme southern of China). Zheng (1991) reviewed the distribution of *Dacrydium* during the late Quaternary and found that the fossil pollen grains, morphologically comparable to that of *D. pierrei*, were discovered from the Tertiary and Quaternary sediments in an extensive area of China. Even in the last interglacial of Wurm (40-20 ka), its distribution might extend to 22 º -24 º north latitude.

3.2. Southwestern China

Tang (1992) presented the results from two lakes in Menghai Region, Yunnan. At Manyang Lake Section, at 42000-38000 14C yr BP (>42-42 ka), pollen assemblages were dominated by evergreen tree pollen (Fig. 2), including Castanopsis, Cyclobalanopsis, llex, Myrica, Myrtaceae, Rutaceae, with deciduous Quercus, Salix, Euphorbiaceae, Alnus. At 38000-29000 14C yr BP (42-33.2 ka), Dacrydium appeared and pollen included evergreen Cyclobalanopsis, Myrica, llex, Rulaeeae, Rhododendron, Engelhardtia and deciduous Alnus, Betula, Ulmus, Salix, Quercus, while herb decreased. At 29-27 (33.2-31.6 ka), evergreen tree was still dominant, but decreased. At Manxing Lake core, at 27000-25000 14C yr BP (32.1- 24.7 ka), evergreen Cyclobalanopsis, Castanopsis and Quercus pollens were dominant. At 20700-11900 14C yr BP (24.7-13.8 ka), Pinus increased. The pollen data show that vegetation changed from evergreen tropical and subtropical forest at 42000-20700 14C yr BP (>42-24.7 ka) to evergreen and deciduous forest at 20700-11900 14C yr BP (24.7-13.8 ka).

The pollen records from Heqing (Yang et al., 1998), Tengchong (Qin, 1992), Dianchi Lake (Wu et al., 1991) and Dianchang Mountian (Kuang et al., 2002) in the southwestern China only had one radiocarbon date or no date during the MIS 3. In general, the pollen assemblages are dominated by *Keteleeria*, *Castnopsis*, evergreen *Quercus* with conifer *Tsuga*, *Picea* and *Pinus* around 45 ka. The vegetation changed from evergreen dominated forest at MIS3 to conifer and broad-leaved mixed forest at LGM.

3.3. Central China

There are three pollen records from Central China. In Poyang Lake region, there are 3 TL age (67.7±8.3ka; 44.8±4.5ka and 9.5±2.5ka) for PHZ section (Wu et al., 1997). At 76-55 ka, the pollen assemblages were dominated by *Artemisia* and Poaceae. At around 55-25 ka, more evergreen tree pollen appeared, mainly from *Quercus*, *Castaneae*, *Cyclobalanopsis*, and *Castanopsis*. At 25-16 ka, tree pollen decreased whileas herb pollen *Artemisia* increased. After 16 ka, evergreen tree pollen disappeared. Vegetation changed from evergreen and deciduous mixed forest at MIS 3 to deciduous forest at LGM.

At Tai Lake region, a coarse resolution pollen record for a 101.8 m long core was shown by Zhou et al. (2001). There is one radiocarbon date at 23098±1770 ^{14}C yr BP (ca. 27.3 ka). Evergreen tree of *Quercus*, Castaneae, *Pterocarya*, *Ulmus*, *Carpinus* was abundant during approximately MIS 3 period. After 27 ka, herb pollen dominated. Two peat sites at Fujian seaside for pollen analysis has one radiocarbon date (41745±4 955 ^{14}C yr BP , ca. 43.5 ka; 31430±l 510 ^{14}C yr BP, ca. 36.1 ka) respectively during MIS 3 (Yang, 1992). Tree pollen, mainly broad-leaved *Quercus* and Fagaceae covered 77-95% of the total pollen assemblages at 45-35 ka. At 21 740±520 ^{14}C yr BP (26.2 ka), the pollen assemblages were dominated by herbs (44.2%) with fewer subtropical trees, with some *Pinus*, *Ulmus*. Both the lake and peat sites show that vegetation changed from evergreen and deciduous mixed forest to forest steppe.

3.4. North China

There are few MIS 3 pollen records in north China. The pollen data in the Beijing area since 30000 ^{14}C yr BP (34.2 ka) show the vegetation change (Kong and Du, 1980). About 30000 years ago (34.2 ka), the coniferous forests (*Picea* and *Abies*) grew on the plain of Beijing; during the period 23000-12000 ^{14}C yr BP (27.5-14 ka), the vegetation was dominated by *Artemisia*, Chenopodiaceae, Poaceae, suggesting a cold dry steppe.

In the Songnen desert land between Songhua River and Nen River, Jie and Lu (1995) used the relationship between surface pollen and climate and reconstructed the precipitation based on the fossil pollen records in this region. Their results show that during MIS 3, the precipitation reached 660 mm, but decreased to 370 mm at LGM; however, the age was not well constrainted. The pollen record from the sediment core in the Yellow River Mouth has no age bracket for MIS 3 (Xu et al., 2006). Based on the extrapolation age, at MIS 3 the pollen assemblages were dominated by *Pinus*, *Quercus* and *Artemisia*, while by *Pinus*, *Picea* and Chenopodiaceae at LGM, indicating the vegetation transition from mixed forest steppe to coniferous forest steppe.

3.5. Loess Plateau

There are more high-resolution pollen records with good age controls in the Loess Plateau. The age model for Suancigou Section has been constructed based on 13 AMS dates (Feng et al, 2007). At 47210-33370 14C yr BP (ca. >47 ka-38.3 ka), the pollen assemblages were dominated by Pinus and Picea (up to 80%). The herb component (e.g., Chenopodiaceae, Artemisia, Asteraceae, Poaceae and Cyperaceae) accounted for 20% of the pollen sum with a very small amount of deciduous tree pollen. At 33370-28280 14C yr BP (ca. 38.3-32.5 ka), Pinus and Picea (up to 90%) were dominant, with very low herb component. At 28280-22480 14C yr BP (32.5-27.1 ka), the pollen assemblages were characterized by a rise in the herb pollen percentage as well as by a marked increase in the deciduous tree pollen percentage (e.g., Betula, Quercus, Rosaceae and Ulmaceae). At 22480-13090 14C yr BP (27.1-15.8 ka), both herb pollen (up to 70%) and in the deciduous tree pollen (up to 30%) increased greatly at the expense of the coniferous tree pollen percentage. The pollen data from Suancigou show that vegetation changed from a coniferous woodland at 47210-33370 14C yr BP (ca. >47 -38.3 ka) and 33370-28280 14C yr BP (ca. 38.3-32.5 ka) (with very low herb), forest steppe at 28280-22480 14C yr BP (32.5-27.1 ka), to steppe at 22480-13090 14C yr BP (27.1-15.8 ka).

Fanjiaping Loess Section (Jiang et al., 2011) and Weinan Section (Sun et al., 1997) provide other two relatively higher resolution pollen records from the Loess Plateau. The pollen data from Fanjiaping show that the vegetation changed from deciduous-conifer mixed forest at 60.6-46.0 ka, conifer-dominated forest at 46-39 ka, to steppe forest at 39-27 ka. At Weinan, the vegetation changed from steppe with sparse forest at 65.3-54.5 ka, meadow-steppe at 54.5-34.1 ka, Artemisia dominated steppe at 34.1-25.0 ka, steppe with Corylus woodland at 25.0-21.1 ka, to Asteraceae steppe at 21.2-13.7 ka.

Pollen records from Luochuan (Li and Sun, 2004), Fu County (Ke, 1993), Qishan (Zhao, 1995), Beizhuang (Ke, 1991) and Linxia (Tang, 1991) sections in the Loess Plateau suggest that the vegetation changed from steppe at 75-54 ka, through forest steppe at 54-36 ka, steppe 36-32 ka, forest steppe at 32-23 ka, to dry steppe at 23-13 ka. The pollen assemblages from a paleosol layer (paleosol#6) on the floor of a loess gully from Loess Plateau (Li et al., 1988) dated to 35390±1600 yr BP (39.8 ka) mainly included Pinus (48%), Picea (23%) and Abies (3%), suggesting conifer forest. Another pollen sequence from Yuanbao in the Loess Plateau (Ma et al., 1995; Tang et al., 1998) shows that the vegetation changed from mixed forest of coniferous and broad-leaved trees at 53-36 ka to coniferous forest at 23-15 ka.

3.6. Northwestern China

Pollen records covering MIS 3 are rare in northwestern China. Duantouliang Section provides a high-resolution pollen record in this region (Ma et al., 1998; Zhang et al., 2002). The chronology was controlled by 8 radiocarbon dates of organic matter between 42000 and 18000 ^{14}C yr BP (~47-22 ka). Three major pollen zones were identified on the basis of pollen assemblages. At ca. 40,500–34,660 ^{14}C yr B.P (44.6-39.5 ka), the most abundant taxa were Cupressaseae, *Juniperus*, *Nitraria*, and Chenopodiaceae. Needle-leaf tree pollen accounted for 12.4% to 46.2% of the total sum, and the percentage of broadleaf tree pollen was low. At ca. 34,660–21,260 ^{14}C yr B.P (39.5-25.3 ka), pollen concentration in this zone was generally high, and the number of species was the highest in the entire DTL section. At ca. 21,260–19,010 ^{14}C yr B.P. (25.3-22.6 ka), the percentages for both needle-leaf and broadleaf trees were lower than in the previous period and the number of species, especially the taxa of broadleaf trees and shrubs, also decreased. The herbs, such as *Artemisia* and Chenopodiaceae, dominated the pollen assemblages during this period. The pollen record from Duantouliang indicates that the vegetation on the mountains changed from coniferous forest dominated, to coniferous-broad leaf mixed forest and steppe forest at ca. 40,500–34,660 ^{14}C yr B.P (44.6-39.5 ka) , ca. 34,660–21,260 ^{14}C yr B.P (39.5-25.3 ka) and ca. 21,260–19,010 ^{14}C yr B.P (25.3-22.6 ka).

Pollen data from Manas Lake (Rhodes et al., 1996), Chaiwopo Lake (Shi and Qu, 1989) and Lop Nor (Yan et al., 1998) in Xinjiang are fragmentary. Vegetation was desert or steppe-desert at ca. 42-30 ka, but with more *Artemisia*, while vegetation was desert with more Chenopodiaceae or *Ephedra* during LGM. Pollen from Milanggouwan Section, Salawusu in Inner Mongolia (Wen et al., 2009) show that the vegetation landscape can be interpreted as warm-humid sparsely wooded steppe at late MIS3 (around 29 ka) changed to a cool – temperate steppe at LGM.

3.7. Tibetan Plateau

Shen et al. (2005) showed a pollen sequence for the last 180 ka at the Zoige Basin in the Tibetan Plateau. There are three radiocarbon dates to bracket MIS 3: 21600±1500, 33140±2350 and >40000 ^{14}C yr BP. At 60-43 ka, the pollen assemblages were dominated by

Cyperaceae, with some Poaceae, Asteraceae and Ranunculaceae. Tree pollens were mainly from *Picea*, *Pinus*, *Abies*. At 43-39 ka, Cyperaceae decreased abruptly (<10%), and *Picea* became dominant, with some *Pinus*, *Abies*, *Quercus*. At 39-32 ka, Poaceae (up to 33%) and Cyperaceae (up to 21.5%) were dominant and *Picea* decreased sharply. At 32-18 ka, similar to 39-32 ka, but with a very low pollen concentration. At 18-15 ka, *Picea* and *Abies* forest appeared. At 15-7 ka, tree pollen was very high. The vegetation changed from forest meadow and meadow at early MIS 3 to steppe at 43.3-21.6 ka, forest meadow /steppe after then.

At Qinghai Lake (Shan et al., 1993), Dabuxun Lake (Chen, 1996), Gonghe (Tang et al., 1988; cited from Tang et al., 1998), Maerguo Chaka (Huang et al., 1983), Zabuye Salty Lake (Xiao et al., 1996) and Zalun Chaka (Huang et al., 1983), the vegetation inferred from pollen records showed change from conifer forest or steppe forest at MIS 3 (mostly at 40-30 ka) to steppe or desert steppe at LGM. At Banggong Co (Huang et al., 1989) and Chaerhan Lake (Du and Kong, 1983), vegetation type was desert or desert steppe at MIS 3 (44-30 ka), showing similar type to LGM; however, the desert contained more Artemisia or aquatic plants. The highstand lacustrine sediments from Nam Co and North Tibet Palaeolake (Zhu et al., 2004) provide fragmentary but in a sequence pollen data. Around 51 ka, 40 ka and 36.5 ka, tree pollen is high (up to 80-90%) dominated by Abies, Picea, Tsuga, Pinus and Betula, while tree decreased after 32.7 ka and Tsuga disappeared.

4. Synthesis and discussion

4.1. General pattern of MIS 3 vegetation and climate changes

Vegetation showed different changes in various regions during MIS 3 as inferred from pollen data. In South China, evergreen forest was abundant. In southwestern China, evergreen or mixed forest dominated. In eastern-central China, vegetation was evergreen and deciduous forest. In North China, vegetation was dominated by conifer forest or conifer and deciduous forest. On the Loess Plateau, vegetation was mostly forest steppe and conifer or mixed forest. In northwestern China, desert or steppe desert dominated the vegetation, except at Duantouliang with broadleaf and conifer mixed forest, which is related to nearby mountain vegetation origin. On the Tibetan Plateau, forest steppe and conifer forest were dominant. The MIS 3 vegetation showed difference from the other glacial period, particularly from LGM. The vegetation at LGM was conifer forest/mixed forest in the south China, evergreen and deciduous forest/conifer forest in southwestern China, deciduous forest in the eastern-central China, , steppe/conifer forest in north China, steppe in the Loess Plateau, desert in the northwestern China, and desert/steppe on the Tibetan Plateau. Although the vegetation change sequence was different in various regions, all the vegetation became worse from MIS 3 to LGM (Fig. 3). The vegetation scale shows that the vegetation at early MIS 3 was better than the later stage, suggesting warmer and wetter climate (Fig. 4). The tree percentages from almost all the sites, except in extremely arid regions with very low tree percentages, show obviously higher values during the entire MIS 3 or fragmentary periods (see examples in Fig. 2).

The different vegetation features at MIS 3 from glacial period have also revealed by numerous paleoclimatic records across the world. Voelker et al. (2002) used a database of global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3, including pollen data and concluded that in general, climate conditions were warmer and more humid during interstadials, colder and more arid during stadials. Huntley et al. (2003) synthesized the pollen data from Europe and found that the inferred vegetation differs in character and spatial pattern from that of both fully glacial and fully interglacial conditions and exhibits contrasts between warm and cold intervals, consistent with other evidence for stage-3 palaeoenvironmental fluctuations. The pollen record from Camel Lake, USA, showed that 40-29 ka was a time of forests with abundant pine, oak, and diverse mesic tree species, while 29-14 ka was a species-poor pine forest (Watts et al., 1992). Anderson et al. (2000) reviewed the pollen records from 7 sites in the Colorado Plateau and found that during MIS 3, mixed conifers covered middle-elevation while at MIS 2, boreal conifers replaced the mixed conifer association. Pollen records from western Oregon, Alaska and eastern Cascade Range also suggest that MIS 3 vegetation was better than MIS 2, but also with millennial variations (Anderson et al., 1994; Anderson, 1988; Whitlock and Bartlein, 1997; Anderson et al., 2000; Grigg et al., 2001). Four pollen records from equatorial mountains Africa revealed the vegetation change over the last 40 ka (Bonnefile and Chalié, 2000) and indiated arboreal pollen at 40-30 ka was generally higher than LGM. At Lake Mikata, central Japan, arboreal pollen was more abundant in MIS 3 than in LGM (Nakagawa et al., 2002). Carbon isotopes in fossil emu (*Dromaius novaehollandiae*) eggshell from Lake Eyre, South Australia demonstrate that between 45,000 and 65,000 years ago, there was an expansion of C_4 grasses, which was affected by warm-season precipitation (Johnson et al., 1999). In the meantime, these records mostly revealed the millennial vegetation change during MIS 3. However, the age control and sample resolution from the pollen records from China made it impossible to make discussion on millennial variations in vegetation and climate.

4.2. Comparison of MIS 3 vegetation and Holocene vegetation

Only 20 records since MIS 3 for this synthesis have coarse pollen data during Holocene optimum and provided a basis for the direct vegetation comparison between these two periods (Fig. 3). MIS 3 vegetation at 8 sites show similar vegetation types to the ones during Holocene optimum, only 3 sites show better vegetation, while 9 sites show worse vegetation. Compared to the present, 20 sites show similar vegetation type and 5 sites show worse vegetation, while 17 sites show slightly better vegetation. These 17 sites are mainly located on the Tibetan Plateau and Loess Plateau. Our results indicate that MIS 3 vegetation was not as good as during Holocene optimum, suggesting less warm and wet climate; however, probably similar to the modern vegetation, but with uncertainties.

Herzschuh (2006) reviewed 75 palaeoclimatic records (including 14 records covering part of MIS 3) and found MIS 3 (50-25 ka) is a relatively wetter than MIS 2. 42-37 ka is the wettest period, during which moisture is still lower than Holocene optimum, but probably higher than the late Holocene. The reconstruction of the late Quaternary climate changes around Lake Mikata, central Japan, shows that the summer and winter temperatures were 5ºC lower than the present around 40 ka (uncalibrated) (Nakagawa et al., 2002). The pollen records from Colorado Plateau suggest that MIS 3 was warmer than MIS 2, but colder than the present (Anderson et al., 2000). In northwestern Alaska, mixed woodland was established during

Holocene, different from the shrub tundra at MIS 3 (Anderson, 1988). In northwestern Florida, oak-dominated forest developed during the Holocene, while pine-dominated forest in MIS 3 (Watts et al., 1992). The vegetation scale inferred from pollen data from Carpe Lake from Cascade Range show that the forest value was higher during the entire Holocene than MIS 3. The reconstructed precipitation in MIS 3 in the equatorial highlands of Africa, based on pollen data, was ca. 150 mm dryer than the Holocene (Bonnefille and Chalié, 2000). However, the Australian monsoon was most effective between 45,000 and 65,000 years ago, least effective during the Last Glacial Maximum, and moderately effective during the Holocene (Johnson et al., 1999). Therefore, more pollen records with higher resolution and good control across different regions are required to understand whether the climate is warmer and wetter in MIS 3 than during late Holocene.

4.3. Possible forcing mechanisms for MIS 3 vegetation change

The vegetation scale change in China generally agrees with the oxygen isotope from Hulu Cave, with lower values in MIS 3, which indicates the summer monsoon intensity (Wang et al., 2001), which followed summer insolation. The oxygen isotope from Guliya ice core aslo shows that temperature at 60-30 ka was higher (Thompson et al., 1997). Our review on peat initiation age in China demonstrates that 45-25 ka was a period with high peat initiation frequency, suggesting ideal climate (Zhao et al., in preparation). At MIS 3, the biogenic Silica from Baikal Lake, which is influenced by westerlies, shows relatively high values at 60-40 ka and 35-20 ka. Furthermore, the north Atlantic SST and benthic oxygen isotope of LR04 marine stack both indicate the higher temperature during MIS 3. The correlation between vegetation change and the above-mentioned proxies suggest that probably both temperature and precipitation contributed to the MIS 3 vegetation change in China.

The notion that the MIS 3 vegetation change was driven by large scale climate change was confirmed by the evidence from America and Europe. Pollen data from Carp Lake from the eastern Cascade Range disclose alternations of forest and steppe that are consistent with variations in summer insolation and global ice-volume, and vegetational transitions correlate well with the marine isotope-stage boundaries (Whitlock and Bartlein, 1997). The close relationship between vegetation and climate beyond LGM provides evidence that climate variations are the primary cause of regional vegetation change on millennial timescales, and that non-climatic controls are secondary. In Europe, the pollen-inferred vegetation was compared with vegetation simulated using the BIOME 3.5 vegetation model for climatic conditions simulated using a regional climate model (RegCM2) nested within a coupled global climate and vegetation model (GENISS-BIOME) (Huntley et al., 2003). The results show that European vegetation appears to have been an integral component of millennial environmental fluctuations during MIS 3 and vegetation responded to this scale of environmental change, mainly induced by insolation, SST, ice volume and through feedback mechanisms may have had effects upon the environment.

Based on syntheses of geological evidence and the AGCM+SSiB modeling, Yu et al. (2007) presented climate simulations focused on 35 ka for East China, using forcing of insolation, glaciation and land surface conditions (Yu et al., 2007) and made some preliminary concluding remarks that a decreased heat gradient from the Pacific Ocean to East Asia would reduce vapor transport from sea to land and lead to both winter and whole year precipitation decreases in East Asian lowlands. However, where the temperature gradient between inland Asia and low latitude sea was enlarged, vapor transport rate from the sea to the continent would strengthen; thus increasing precipitation for inland China, e.g., northwestern China and Tibetan Plateau, during late MIS 3, which was revealed by Shi et al. (2002; 2003).

In the mean time, CO_2 at MIS 3 was averagely ca. 20 ppmv higher than LGM. Probably CO_2 also contributed to the vegetation change, especially in northwestern China and Tibetan Plateau, which is limited by moisture. Lower CO_2 during LGM could amplify the effect of an arid climate on plants through their effects on leaf conductance and water-use efficiency, as suggested by the modeling study in tropical Africa (Wu et al., 2007). Herzschuh et al. (2011) proposed that the replacement of drought-resistant alpine steppes (that are well adapted to lowe CO_2 concentrations) by mesic *Kobresia* meadows on the Tibetan Plateau can, at least, be partly interpreted as a response to the increase of CO_2 concentration since 7000 years due to fertilization and water-saving effects, based on BIOM4 global vegetation model. The higher CO_2 could also amplify the vegetation change, especially in northwestern China and Tibetan Plateau. At most sites, vegetation became worse at 40-30 ka; however, the vegetation in the northwestern China and the Tibetan Plateau was still relatively prosperous. In these two moisture limited regions, still high CO_2 at that time might have contributed to the vegetation growth, though summer insolation decreased. However, our hypothesis needs to be based on more high-resolution pollen records to investigate the millennial change in MIS 3 and further to be testified by climate modeling.

5. Concluding remarks

(1) Vegetation during MIS3 in China shows different types from LGM, suggesting the vegetation is better than the other periods of last glacial over the last 60 ka. During MIS3, vegetation type was mostly forest in the eastern part of China, and forest steppe/meadow in the north and Tibetan Plateau, while in the arid China the vegetation was steppe desert. The Vegetation scale change shows higher values in MIS3 than in LGM, especially for the period of 53-40 ka. Our results also indicate that MIS 3 vegetation was not as good as during Holocene optimum, suggesting less warm and wet climate; however, probably similar to the modern vegetation.

(3) Vegetation change in MIS 3 based on fossil pollen data correlates well with insolation, sea surface temperature, monsoon intensity, ice core oxygen isotope and peat initiation. The close relationship between vegetation and climate provides evidence that climate variations, probably both temperature and precipitation, are the primary cause of regional vegetation change. CO_2 probably also contributed to the vegetation change, especially in northwestern China and Tibetan Plateau, where vegetation is limited by moisture.

(3) Our review and synthesis indicate that high-resolution records with robust chronology for vegetation and climate reconstructions are lacking across the entire China. There were almost no high quality (with continuous sediment, good age control and high analysis resolution)

pollen records covering the entire 60 ka. Our review only provides a general framework of MIS 3 vegetation change. Future work will require additional well-dated, high-resolution paleoclimate records from many locations across China, in order to understand the vegetation change on millennial and centennial scale within MIS 3 and climate control mechanisms .

Acknowledgements

We thank Wenwei Zhao and Huan Li for digitizing pollen data and plotting some figures. This research was supported by the National Natural Science Foundation of China (Grants #41125006 and 41071126), the National Basic Research Program of China (973 Program, grant #2012CB956102 and 2010CB950202), and 100 Talents Programme of the Chinese Academy of Sciences.

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Figure captions

Figure 1. Map showing the location of fossil pollen sites in China reviewed in this paper (see Table 1 for site information and reference).

Figure 2. Selected pollen curves at seven typical sites in various vegetation regions across China.

Figure 3. Summary of vegetation types derived from fossil pollen records in China. **A.** MIS 3 optimum; **B.** LGM; **C.** Holocene optimum; **D.** The present. The vegetation types show the optimum intervals during these four periods.

Figure 4. Correlation of vegetation scales with summer insolation and other paleoclimatic records. **A.** Vegetation scales inferred from fossil pollen records; **B.** $\delta^{18}O$ of Hulu Cave (Wang et al., 2001); **C.** $\delta^{18}O$ of Guliya ice core (Thompson et al., 1997); **D.** Summer insolation at 30°N and 60°N latitudes (Berger and Loutre, 1991); **E.** SST at Northern Atlantic (Bard, 2002); **F.** Benthic $\delta^{18}O$ of marine LR04 stack (Lisieki and Raymo, 2005); **G.** Biogenic Silica percentage at Baikal Lake; **H.** Global CO_2 concentrations (Monnin et al., 2004);