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REVIEW

Vegetation and climate reconstructions on different time scales in China: a review of Chinese palynological research

Yan Zhao[1,2]

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Abstract
This paper reviews vegetation and climate reconstructions for different time scales based on palynological studies in China. It discusses examples of significant developments in palynological research topics within China: (1) Modern pollen—a modern pollen database (East Asia Surface Pollen Database) has been established through the collaboration of Chinese palynologists. Based on these data, modern pollen distributions and their quantitative relationship with vegetation and climate have been thoroughly studied. (2) Pre-Quaternary vegetation and climate dynamics—scientists have mapped pollen and palaeobotanical data from the Palaeogene. The vegetation distributions confirm a north–south zonal pattern during the Palaeogene that changed to an east–west monsoonal pattern during the Miocene and Pliocene. These results provide key evidence for understanding monsoon evolution. (3) Late-Quaternary vegetation—biome reconstructions based on fossil pollen data show spatial and temporal changes in vegetation since the Last Glacial Maximum, permitting a better understanding of climate change across China. (4) Quantitative climate reconstructions—some reconstructions have successfully detected Holocene climate variability thereby providing insights into monsoon history. At present, there are no comprehensive spatial reconstructions. Major possible future developments should focus on: (1) long-term vegetation reconstructions from lakes to study Asian monsoon dynamics at orbital scales; (2) quantitative reconstructions of vegetation and climate change to help stronger integration with palaeoclimate models and dynamic vegetation models; (3) land-cover and land-use change across China over the last 6,000 years to understand human impacts and provide empirical data for climate modellers; and (4) integration of pollen data with vegetation and climate modelling to understand the CO_2-vegetation relationship and climate dynamics.

Keywords Palynological research · China · Vegetation · Climate · Time scales

Introduction

Pollen analysis was introduced into China in the early 1950s, almost 40 years after the first diagram by Lennart von Post. The first palynological laboratory was established at Nanjing in 1953 by Professor Ren Xu, who was the pioneer of palynology in China (Wang 2009). In 1979, the Association of Chinese Palynology was established. Since then pollen analysis has been widely applied in the field of earth sciences across China.

Over the past six decades, much progress has been made in many fields, for example, pollen–spore morphology, palynostratigraphy, modern processes, quantitative climate reconstructions, past land-cover reconstructions, and applications in sedimentology and oil exploration. In particular, palynological studies have made important contributions to our understanding of vegetation and climate changes at different time scales in China, as well as the underlying mechanisms. This review presents some brief histories and discusses major findings in the fields of palaeoecology and palaeoclimatology. It outlines some studies and concludes with some future insights.

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✉ Yan Zhao
zhaoyan@igsnrr.ac.cn

1 Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

2 University of Chinese Academy of Sciences, Beijing 100049, China

Pollen-vegetation-climate relationship studies in China

In studies of pollen-vegetation relationships, many traditional qualitative and semi-quantitative efforts have been made. In the 1980s and 1990s, research focused on comparisons between pollen and vegetation percentage data. The R-value approach was introduced to calibrate quantitative pollen percentages for major taxa (e.g. Li and Yao 1993; Zhao and Herzschuh 2009). In recent years, the Landscape Reconstruction Algorithm (LRA) model has been applied to data from northern China to refine the quantitative pollen–vegetation relationship by quantifying pollen productivity (e.g. Xu et al. 2014a, b; Li et al. 2015). For pollen–climate relationships, quantitative studies mainly started in the late 1990s (e.g. Sun et al. 1996; Song et al. 1997; Shen et al. 2006; Lu et al. 2011; Zheng et al. 2014). For example, the response surface method was introduced in China by Sun et al. (1996) to study the relationship between major taxa and climate in northern China. Since 2000, multivariate calibration-functions, modern analogue matching, and the coexistence approach have been applied (e.g. Jiang et al. 2006; Li et al. 2007; Qin et al. 2011; Lu et al. 2011; Zheng et al. 2016). Multivariate numerical methods (e.g. discriminant analysis, principal components analysis, redundancy analysis, boosted regression trees) have been widely used to aid exploring patterns in data and to understand the quantitative relationships.

To date, more than 5,000 surface pollen samples have been obtained and include data in the East Asian surface pollen database (Fig. 1; Zheng et al. 2014), modern pollen data on the Tibetan Plateau (Lu et al. 2011), and the Western China pollen database (http://www.cpdw.net) (Fig. 1). In addition, there are ca. 3,000 additional published modern pollen datasets from a number of researchers. Such research and associated databases provide an important foundation for pollen-based qualitative and quantitative vegetation and climate reconstructions in China at different time scales.

Palaeovegetation and climate at different time scales

Beyond orbital-scale vegetation and monsoon changes

There are many fewer pre-Quaternary pollen records than for the Quaternary period. Most pre-Quaternary pollen records have low to moderate resolution, discontinuous sedimentation, or partially uncertain chronological controls (Wang 2011), which limit detailed vegetation and climate reconstructions to a great degree. However, these pollen studies do provide key evidence for a number of important palaeovegetation and palaeoclimate issues. These mainly include the following.

The onset of the modern Asian monsoon climate and the formation of the Asian inland desert are important features from a palaeoclimatic viewpoint. Loess studies provide temporal evidence about the onset of the modern Asian monsoon climate and formation of the Asian inland desert. A series of loess–palaeosol sections indicates that the modern

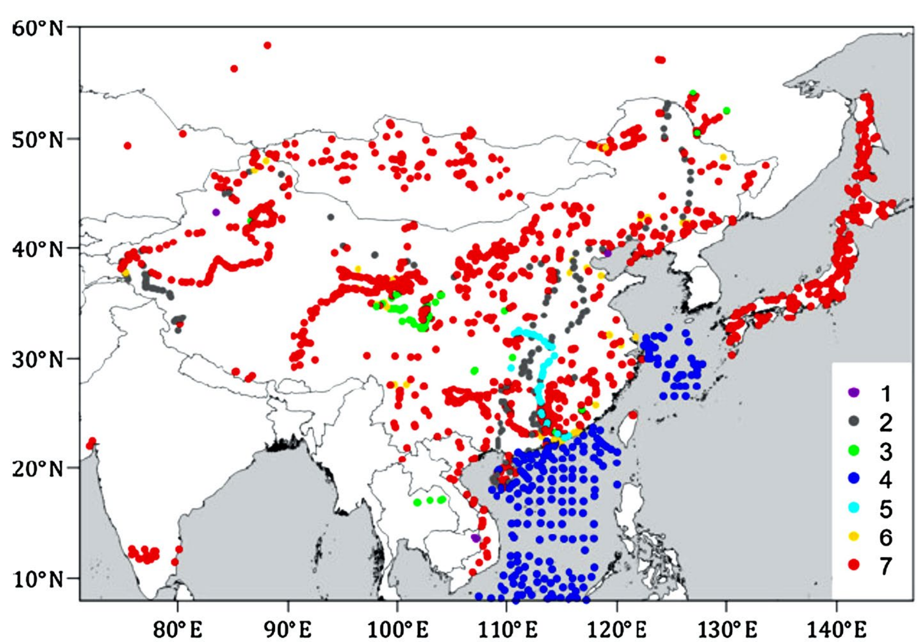

Fig. 1 Locations of the 2,858 sites in the East Asian Pollen Database (EAPD) (from Zheng et al. 2014). Numbers denote: 1-moss bog samples; 2-dust samples; 3-sea-bed surface sediments; 4-core top and profile top; 5-soil samples collected around cultivated land; 6-terrestrial lake and swamp surface sediments; 7-surface soil and sand

monsoon system started at least 22 Ma ago (Guo et al. 2002). However, spatial evidence is essentially lacking. A palynological synthesis based on 125 pollen records over China shows that the vegetation pattern in the Palaeogene in China was zonal from south to north (Sun and Wang 2005). A major reorganisation of this vegetation pattern occurred near the boundary of the Oligocene and Miocene, from a zonal to a belt pattern (forest/steppe/desert) trending east to west. This is very consistent with the loess evidence, providing more solid data for understanding the onset of the Asian monsoon-dominated climate and the formation of the inland desert during the Miocene (Fig. 2; Guo et al. 2008).

Marine oxygen isotopes provide the framework of climate trends for the Cenozoic (Zachos et al. 2001), but how terrestrial climate responded needs better documentation. Chinese palynologists have reconstructed temperature changes based on pollen data, showing the general declining trend that is roughly consistent with the marine oxygen-isotope records, suggesting land-sea coupled changes (Yang et al. 2007; Li et al. 2009; Qin et al. 2011; Wang 2011). However, data of higher resolution and with better spatial coverage are needed for more reliable reconstructions.

Palynological studies have also provided insights for understanding climate–biological evolution. For example,

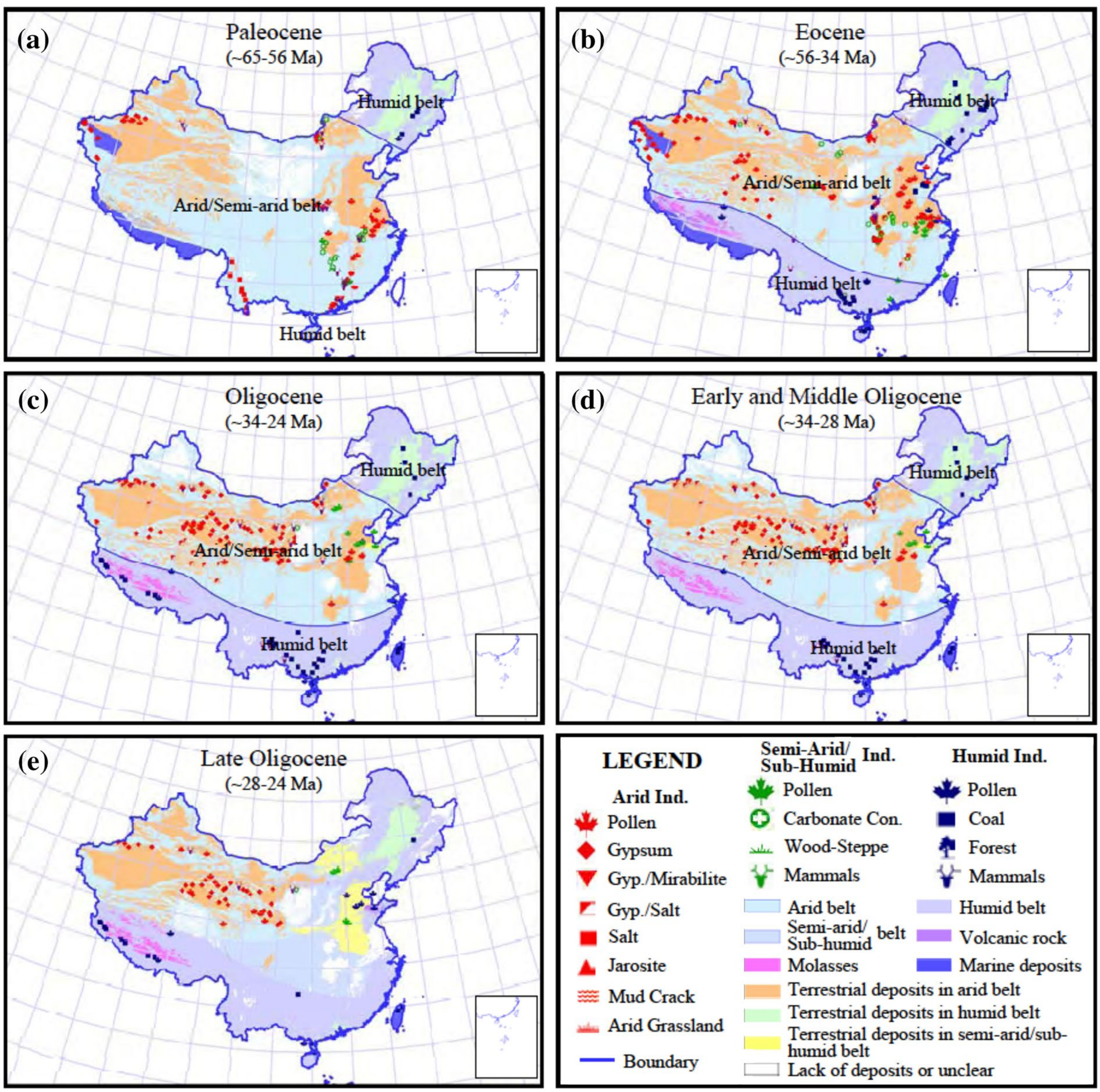

Fig. 2 Palaeogene environmental patterns in China (from Guo et al. 2008). **a** Paleocene; **b** Eocene; **c** Oligocene; **d** early and middle Oligocene; **e** late Oligocene. Gyp represents gypsum

the pollen record on the south-east margin of the Tibetan Plateau provided insights into why the last hominoid (*Lufengpithecus lufengensis*) lived in that region. Chang et al. (2015) presented pollen data from a 16-m thick section from Shuitangba, south-western China, containing the remains of this hominoid in the terminal Miocene. The results indicated that, at the Miocene termination, evergreen oak pollen dominated the pollen assemblages and vegetation diversity was relatively great, implying a warmer and more humid climate compared to present day. The diverse vegetation and suitable climate might have favoured the last hominoid's survival.

Orbital-scale vegetation and climate changes

High-resolution data able to resolve the full spectra of orbital-scale vegetation changes are scarce, but those that are available provide insights into orbital-scale climate features and mechanisms in China, particularly the Asian summer monsoon.

One example is from the Tianyang palaeolake in the south-eastern Asian monsoon region (Zheng and Lei 1999). The pollen record shows that the vegetation was not only influenced by low-latitude summer insolation with a cycle of ca. 20 ka (1 ka = 1,000 cal year BP), but also bears strong ca. 100 ka glacial–interglacial signals. This is radically different from the stalagmite oxygen isotope data that suggest a predominant role of low-latitude insolation with an associated precession signal on the south-eastern Asian monsoon. Zheng and Lei (1999) provided evidence for further understanding the eastern Asian monsoon mechanism.

Another example of high-resolution Quaternary pollen records is from the Heqing Palaeolake Basin, in south-western monsoonal China. *Tsuga* pollen percentages, which are regarded as a temperature indicator in this region, show clear variability. The intervals with low or zero values are associated with cold glacials, whereas those with high *Tsuga* percentages correspond to warm interglacials (An et al. 2011). The decrease in south-western monsoon strength inferred from pollen and other proxies in this core show that the transition from peak interglacials into glacials is not linearly related to increases in ice volume. This glacial–interglacial pattern and its timing suggest that the South Asian monsoon might also be controlled by the Antarctic ice-sheet.

On the Tibetan Plateau, there are also a few long palynological time series, but with coarse sample resolution. They provide some useful information about changes in surface conditions on the Plateau with glacial–interglacial signals, for example the record from Coer Lake (Lu et al. 2001). However, high-resolution pollen data are urgently needed to document the orbital-scale vegetation history on the Plateau, as surface conditions strongly influence monsoon circulation.

Vegetation and climate reconstruction since Last Glacial Maximum

Pollen records covering the last 20 ka have a much better spatial coverage in China (Cao et al. 2013). There are more than 200 pollen records starting in the Last Glacial Maximum (LGM), mostly covering the Holocene period, but less than 60 of them have a resolution better than 200 years per sample and > 4 dates (Fig. 3). Data with millennial-centennial scale resolution are therefore insufficient. Nevertheless, these data provide good evidence of the broad temporal and spatial changes of vegetation and climate over the past 20 ka.

Pollen records with continuous sediments, relatively good chronology, high sample resolution, with limited pollen-preservation problems, and that show the impacts of multi-millennial to millennial climate change can be found. One high-resolution record covering the LGM is from Qinghai Lake in the currently semi-arid region on the Tibetan Plateau (Shen et al. 2005). The pollen assemblages imply that vegetation around Qinghai Lake changed from steppe before 11 ka and in the early Holocene, through steppe forest at 8.5–4 ka, to *Artemisia*-dominated steppe. This vegetation shift suggests a dry climate before the Holocene, a wet climate in the early and middle Holocene, and a dry climate in the late Holocene. The pattern suggests good links between summer insolation and summer monsoon changes.

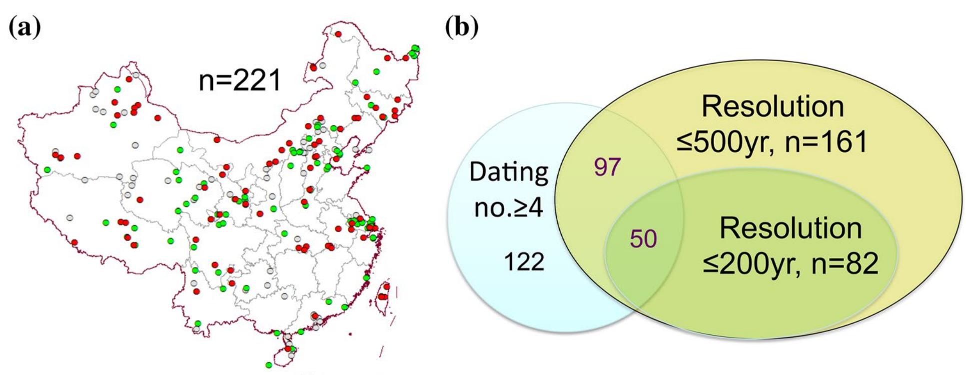

Fig. 3 Late Quaternary fossil pollen records in China. **a** Locations of fossil pollen sites (from Cao et al. 2013), red dots show the sites with < 200 year resolution and green dots indicate the sites with < 500 year resolution; **b** The quality of the fossil records indicated by dating levels and sampling resolution

Three high-resolution pollen records, each with 20 dates, from the semi-humid Zoige Basin on the Tibetan Plateau (Zhao et al. 2011; Sun et al. 2017) show consistent vegetation change. Tree pollen (mainly *Picea*) mostly reflects temperature change in this region; it has variable values (from 3 to 34%) during the early Holocene, reaches peak values during the middle Holocene at 6.5 ka, and then decreases until 2 ka. The cooling trend since the middle Holocene inferred from the *Picea* percentages probably reflects the influence of the decreasing solar insolation.

The pollen assemblages from Bayanchagan Lake in semi-arid Innner Mongolia show that vegetation around the lake changed from steppe at 12.5–9.2 ka, through a *Betula*/*Pinus*-dominated steppe forest at 9.2–6.7 ka, and back to steppe after 6.7 ka (Jiang et al. 2006). The steppe/forest shift suggests that a relatively humid climate during the early to middle Holocene favoured the development of forest.

A ~ 20-year resolution pollen record from Gonghai Lake in the eastern part of China, charts the detailed changes of the East Asian Summer Monsoon (EASM) since the last deglaciation (Xu et al. 2016). From 14.7 to 11.1 ka, forest and mountain meadow dominated the surrounding area, suggesting a weak EASM with less precipitation. At 11.1–7.3 ka, the vegetation was gradually replaced by mixed broadleaf/conifer forest, implying an enhanced EASM. At 7.3–5 ka, the mixed broadleaf/conifer forest further expanded, indicating the strongest EASM. Conifers increased from 5 to 1.6 ka, suggesting a recession of the EASM. Since 1.6 ka, forest sharply decreased, probably due to deforestation and land use.

Another high-resolution 5,350-year pollen record from Lake Xiaolongwan, an annually-laminated maar lake in north-eastern China, reflects the regularity of temperature change (Xu et al. 2014). Spectral analysis on pollen percentages/concentrations of *Pinus* and *Quercus* reveals 500-year quasi-periodic cold–warm fluctuations, which could be related to solar activity and Greenland temperature changes. This centennial cyclic temperature trend is hypothesised as partially slowing down anthropogenic global warming.

Some syntheses based on pollen records from across China provide further insights into the general pattern of change, regional differences, and large-scale controls (e.g. Zhao et al. 2009a, b; Zhao and Yu 2012; Herzschuh 2005). Zhao et al. (2009b) synthesised 31 fossil pollen records with relatively reliable chronologies and high-resolution data from the monsoonal region of China. They semi-quantitatively reconstructed moisture histories based on the pollen data, showing that a humid climate generally characterised the early and middle Holocene, and a drier climate prevailed during the late Holocene (Fig. 4). This pattern of moisture change is similar to those inferred from other independent climate proxies. However, gradual vegetation changes in the early Holocene lagged about 1,000 years behind the summer

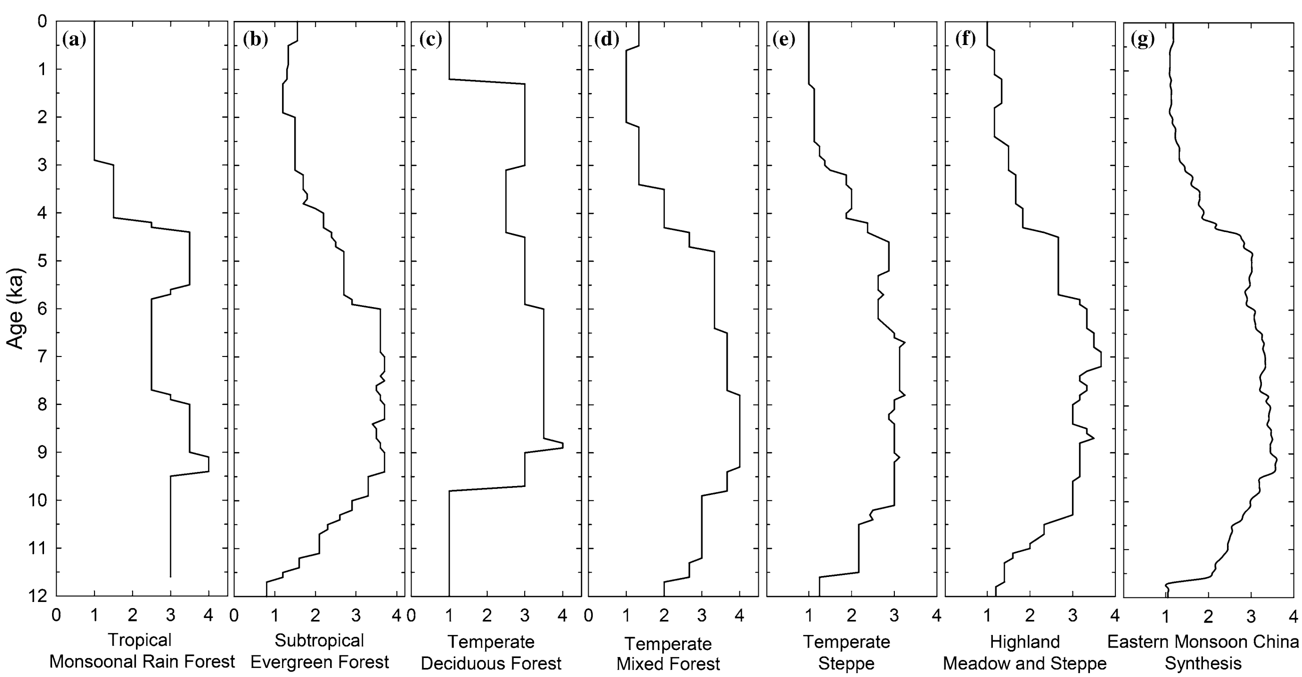

Fig. 4 Synthesised time series of relative moisture changes as inferred from fossil pollen data across eastern monsoonal China (from Zhao et al. 2009b). **a** Tropical monsoonal rain forest; **b** subtropical evergreen forest; **c** temperate forest; **d** temperate mixed forest; **e** temperate steppe; **f** highland meadow and steppe; **g** eastern monsoonal China. The moisture conditions are 100 year averages and coded into four classes: 1-dry; 2-moderately dry; 3-moderately wet; and 4-wet

monsoon maximum, as indicated by speleothem isotope records from Dongge Cave (Wang et al. 2005).

The synthesis of pollen data from 30 sites in arid and semi-arid regions of China indicates spatial differences in vegetation and climate change during the Holocene (Zhao et al. 2009a). Vegetation at most sites in eastern Inner Mongolia switched between forest, forest steppe, and typical steppe, implying maximum moisture conditions before 6 ka and a dry climate after ~ 6 ka. Vegetation on the north-western Loess Plateau changed between desert steppe, forest steppe, and steppe, suggesting wet-dry oscillations, from dry to wet climate at ~ 9–4 ka and then back to a dry climate. On the northern Tibetan Plateau, vegetation was characterised by steppe desert, steppe, or desert, implying a wetter climate in the early and middle Holocene until 6–4.5 ka. In western Inner Mongolia and Xinjiang, pollen assemblages show changes between desert, steppe desert, and steppe, with a wet period occurring during 8.5–5.5 ka at most sites. All the regions in the north-western region show a drying trend during the late Holocene. Herzschuh (2005) also reveals similar spatial differences. These complex climate patterns suggest that regional climate was controlled by interactions of competing factors, including the monsoons, westerlies, and topographically-induced regional atmospheric dynamics.

Abrupt vegetation and climate change

Stalagmite records from China reveal perfectly the abrupt changes in monsoonal China (e.g. Wang et al. 2005). How the vegetation responded to these abrupt changes remains unclear. The datasets for resolving millennial and centennial scale vegetation changes are still insufficient. However, there are some high-resolution pollen data that clearly show abrupt changes in vegetation, for example, large vegetation shifts during the Younger Dryas and the Holocene 8.2 and 4.2 ka cold or drought events.

A broad-scale abrupt shift in vegetation is well documented for the Sahara–Sahel ecosystem. Whether such a non-linear response to climate is universal remains to be seen. Zhao et al. (2017) explored the vegetation–climate relationships in central Asia based on a compilation of 38 high-quality pollen records (mostly from China). The results indicate that Holocene vegetation experienced two major abrupt shifts: an establishing shift in the early Holocene and a collapsing shift in the late Holocene. The timing of these shifts in various regions is asynchronous, and cannot currently be explained by any known abrupt climate shifts, but may be strongly related to local precipitation change (Fig. 5). Zhao et al. (2015, 2017) hypothesise that the vegetation shifts are attributable to threshold effects of orbitally-induced gradual climate changes.

Pollen evidence for Younger Dryas changes is found at some sites, for example, Huguangyan Lake in southern China (Wang et al. 2007), Moon Lake in north-eastern China (Wu and Liu 2012), Zoige peatland (Zhou et al. 2010) and Qinghai Lake on the Tibetan Plateau (Shen et al. 2005), and the Dahu peatland in southern China (Zhou et al. 2004). Vegetation deteriorated at these sites during this period, but the timing, the temperature-moisture association, and the features of centennial changes within the Younger Dryas remain to be understood.

Due to the short duration of the 8.2 ka cold event, poor sample resolution, and chronological uncertainty, there is little solid pollen evidence to confirm this event across China. A few sites show decreases in tree pollen assemblages or an increase in cold-tolerant taxa at ca. 8.2 ka, for example, at Hulun Lake, Qinghai Lake, Xuguo Co, Kuhai, and Zigetang (Shen et al. 2005; Herzschuh et al. 2006; Wen et al. 2010; Wischnewski et al. 2011). They are mostly situated on the Tibetan Plateau, probably reflecting a magnified temperature decrease.

Palynological evidence for the 4.2 ka drought event has been mostly found in the arid and semi-arid regions of northern China due to their dry climate. There was a major shift from forest steppe to steppe or from steppe to desert at 4.2 ka that was characterised by drought, for example, at Manas Lake (Sun et al. 1994), Dahai Lake (Xiao et al. 2004), Bayanchagan palaeolake (Jiang et al. 2006) and Wulungu Lake (Liu et al. 2008). After this event, the vegetation never recovered. This could be attributed to two main causes: vegetation response to an abrupt climate event or threshold effects associated with orbital-scale climate changes. In some cases, an abrupt climate event and a "threshold event" may have co-acted in modulating the vegetation change. The cold and dry event is thought to play an important role in the "Hongshan" culture decline (Jin and Liu 2002).

Quantitative reconstructions of biome and climate change

The first biome reconstruction for selected time-slices since the LGM for the whole of China was conducted in the late 1990s (Yu et al. 1998). It generally shows that steppe and desert expanded eastward and the forest vegetation zone in the east moved southward during the LGM, while forest expanded northward in the middle Holocene. There are now more improved biome reconstructions based on the modified global plant functional type (PFT) classification scheme (e.g. Chen et al. 2010; Ni et al. 2010; Fig. 6). The general patterns since the LGM based on this new scheme are similar to the first reconstruction, but have more detail in terms of spatial coverage.

In terms of quantitative climate reconstructions, pollen-based studies during the pre-Quaternary period are relatively few. Qin et al. (2011) estimated the temperature of Zhangcun

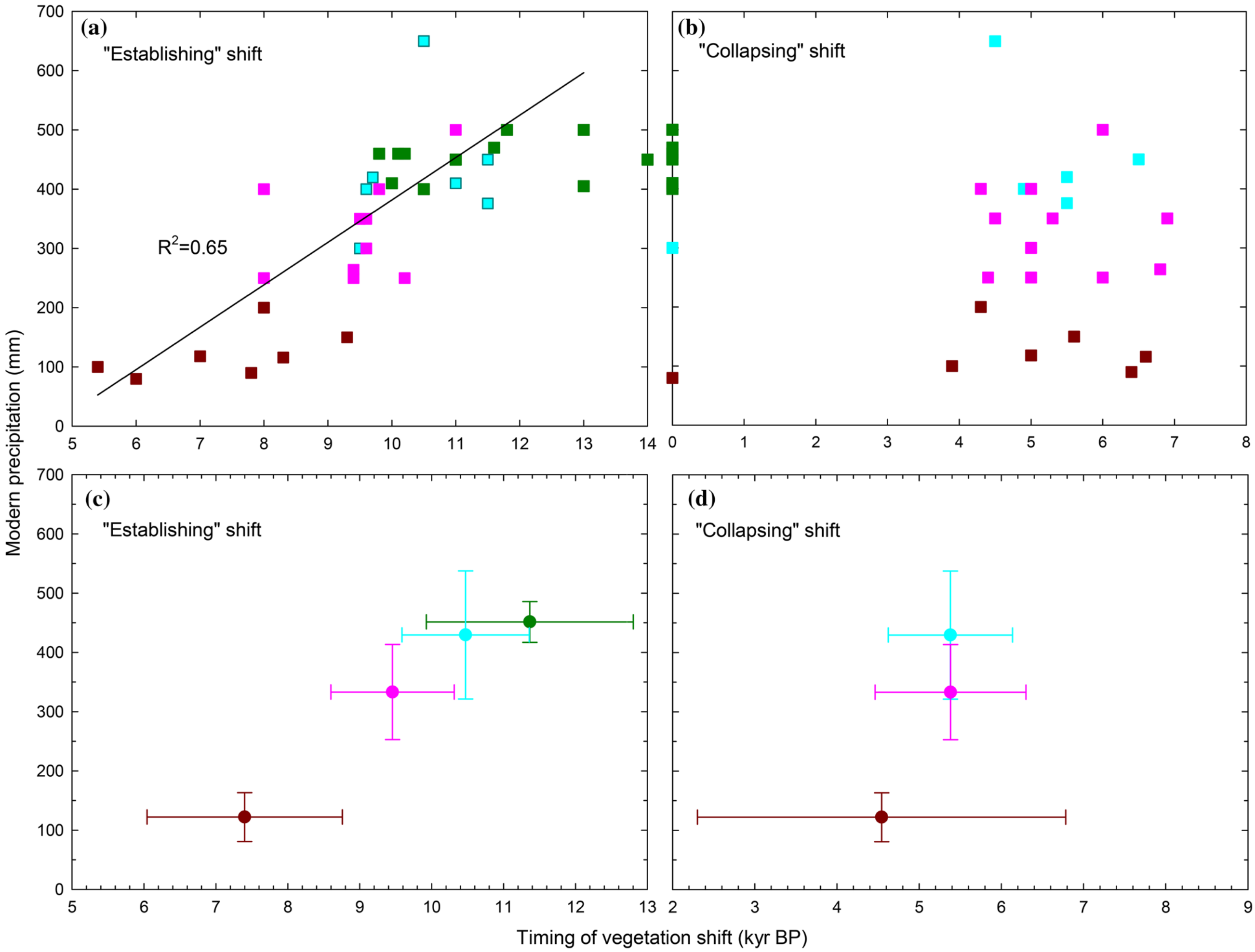

Fig. 5 Timing of the vegetation shifts during the late deglaciation and the Holocene across central Asia (modified from Zhao et al. 2017). The abrupt vegetation change was identified by both biome and principal component analyses. **a** Timing of the establishing shift (Shift I). **b** Timing of the collapsing shift (Shift II). **c** The mean and standard deviation of the timing of Shift I for different vegetation types. **d** The mean and standard deviation of the timing of Shift II for different vegetation types. The different colours in **a**–**d** represent various vegetation types: green-forest; blue-forest steppe; pink-steppe; brown-desert

in northern China during the late Pliocene by using the coexistence approach. They synthesised the records from northern China covering the early Miocene (Li et al. 2009), the middle Miocene (Yang et al. 2007), and the late Pliocene (Qin et al. 2011), and reconstructed temperature change through the Cenozoic. The reconstruction indicated a warming climate from the early to middle Miocene, then a cooling trend from the middle Miocene to the late Pliocene. The Neogene climate in northern China exhibited a general cooling and drying trend. The mean annual temperature dropped by ca. 1 °C in northern China, which agrees with the general trend of global mean annual temperature fluctuations (e.g. Zachos et al. 2001). The mean annual precipitation increased by ca. 470 mm from the early to middle Miocene and then dropped by ca. 550 mm from the middle Miocene to the late Pliocene, but with large uncertainties.

So far, there are less than 50 Quaternary pollen records that have quantitative climate reconstructions in China, most of which focus on the Holocene [with some exceptions for the last 400 ka and the last part of the last Glacial (e.g. Zheng and Lei 1999; Wang et al. 2014)]. The commonly used approaches in these studies are multivariate calibration-functions and the modern analogue technique. In some cases, the reconstructions show high uncertainties due to data and/or methodology problems (Zheng et al. 2016). At present, there are no regional time-series climate reconstructions for the whole of China, which limits data input for climate modelling and data–model comparison.

Some examples of quantitative reconstructions covering the Holocene period are given here. From the semi-arid regions of northern China, Jiang et al. (2006) used a pollen sequence from Bayanchagan in Inner Mongolia to

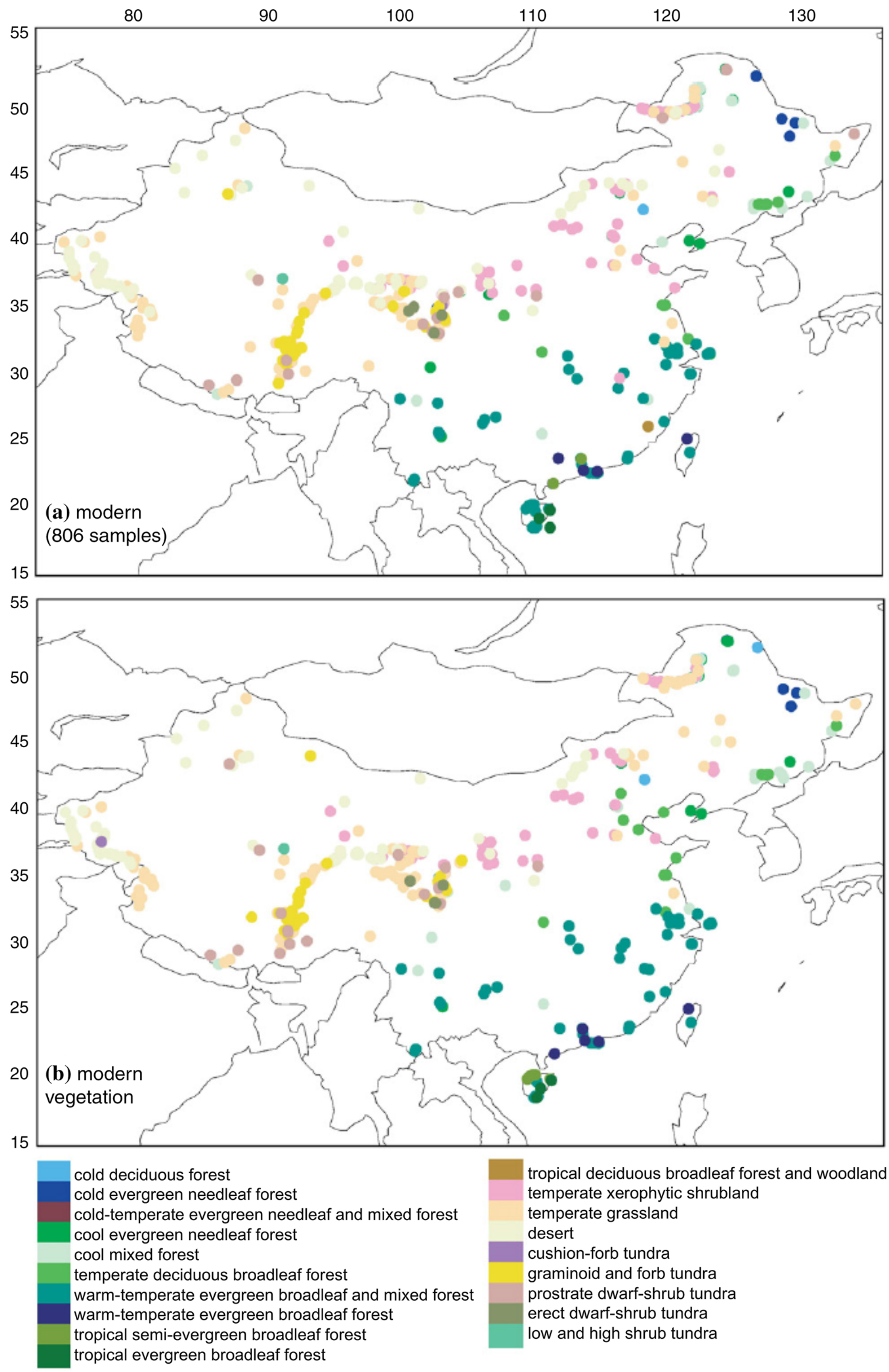

Fig. 6 Biomes in the middle Holocene (**a**) and at the Last Glacial Maximum (**b**) reconstructed from pollen records in China (from Ni et al. 2010)

reconstruct climate changes using the modern analogue technique on the basis of 211 surface pollen samples. The reconstructions using both individual pollen taxa and the plant functional type affinity scores indicate that a cold and dry climate prevailed before 10.5 ka. The wettest climate occurred between 10.5 and 6.5 ka, when annual precipitation was up to 30–60% higher than the present day. These results imply that in the early to middle Holocene, the monsoon extended to more northerly latitudes.

In the typical monsoon region of northern China, a quantitative precipitation reconstruction from Gonghai Lake using a transfer function shows a gradually intensifying monsoon from 14.7 to 7.0 ka, a maximum monsoon (30% higher precipitation than present) from ~ 7.8–5.3 ka, and a rapid decline since ~ 3.3 ka (Chen et al. 2015; Xu et al. 2016). The precipitation reconstruction is quite different from the cave record in terms of monsoon intensity timing (Wang et al. 2005). The reason for the contradiction is still to be explained.

In the Tibetan Plateau region, Herzschuh et al. (2010b) developed a modern pollen–climate calibration set based on lake sediments from 112 lakes. Transfer functions for P_{ann}, T_{ann} and T_{July} were developed with weighted averaging partial least squares. They then applied the calibration models to fossil pollen spectra covering the last ca. 50 ka for Luanhaizi Lake in the Qilian Mountains on the north-eastern Tibetan Plateau. The reconstructed T_{ann} and P_{ann} values are similar to the present for late Marine Isotope Stage 3, have minimum values (ca. 300 mm and 2 °C below present) for the Last Glacial Maximum, and maximum values (ca. 70 mm and 0.5 °C greater than present) for the early Holocene. Another example is the quantitative reconstruction from Chen Co (Lu et al. 2011). Locally-weighted weighted averaging (LWWA) was applied to reconstruct mean annual precipitation, July mean precipitation and humidity, based on surface soil samples collected at 1,202 sites across the Tibetan Plateau. The results indicate that precipitation is the most important variable and that LWWA is a robust calibration method in the study region.

Zheng et al. (2016) reviewed the annual temperature and precipitation anomaly based on the limited pollen records across China. The results show that the early Holocene at ~ 10–7 ka is a transitional stage into the optimum period, with strong oscillations and large differences among regions. The average values for mean annual temperature during the early to middle Holocene are generally 1–1.5 °C higher than the present day. Data integration for standardised annual precipitation indicates inconsistent changes among various sites. These reconstructions yield great uncertainties due to the unequal quality of the various pollen records.

In the past decade, inverse vegetation modelling has been applied to deal with inconstancy of the vegetation–climate relationship under non-analogous environmental conditions. Wu et al. (2017) have preliminarily used inverse vegetation modelling to reconstruct mid-Holocene climate in China. Climate modelling has developed quickly to simulate past climates in China. For example, Jiang et al. (2013a, b) selected 36 models out of the climate models used in the Paleoclimate Modeling Intercomparison Project (PMIP) for LGM and Holocene climate simulations. These approaches show promising potential; however, they require further detailed pollen data and rigorous modelling comparison for verification in the future.

Human impacts

Pollen data can provide robust qualitative and quantitative reconstructions of human impacts on vegetation. For example, many pollen records from monsoonal China indicate that strong human impact mostly started there around 2–1 ka (Zhao et al. 2009b). A quantitative reconstruction of the Human Impact Index on the Loess Plateau based on fossil pollen and a modern transfer function shows a great increase since 2 ka, suggesting intensified human impacts on vegetation (Li et al. 2014).

Past land-cover is another important way of revealing human impact. It almost constitutes a research gap in China, although Herzschuh et al. (2010a) made an initial attempt using pollen records of four lakes (Hurleg Lake in the Qaidam Basin; Qinghai Lake on the north-eastern Tibetan Plateau; Zigetang Lake on the central Tibetan Plateau and Koucha Lake on the eastern Tibetan Plateau), which represent different regions and vegetation types on the Plateau today. The results show strong regional differences in inferred vegetation change in terms of timing, strength, and the nature of change. The greatest changes in compositional turnover and leaf area index are found in the Qinghai Lake record, indicating that forests were replaced by steppe vegetation in a step-wise fashion since the middle Holocene, probably related to both natural factors and human activities. More efforts on quantitative reconstructions of land-cover for the whole of China since 6 ka are urgently needed. Furthermore, integration with quantitative prehistoric land-use model (PLUM) research (Yu et al. 2016) is required, in order to distinguish human impacts from climate changes.

Summary and perspectives

The major contributions of palynological research in China in the fields of palaeoecology and palaeoclimatology include: setting up a Chinese modern pollen database; providing firm evidence for understanding palaeomonsoon patterns and mechanisms; establishing the framework of climate change for the late Quaternary; quantitatively reconstructing biome changes since the LGM; and identifying human impact on vegetation.

Pollen studies in China are still poorly represented in many topics. In other words, there are many possible development opportunities for the Chinese palynological community including:

1. Long-term vegetation reconstructions from lakes to study Asian monsoon dynamics at orbital scales. As

discussed above, pollen records for orbital scales are very few, which limits our insights into monsoon mechanisms. Even though quantification of monsoon-vegetation feedbacks by means of proxy data alone will be difficult, reconstructions of past land and vegetation cover are indispensable to test model-derived hypotheses and may aid in the improvement of the parameterisation of land-surface models.

2. High-resolution and high-quality pollen records to track vegetation response to abrupt change and the response threshold to climate. This will enhance our understanding of present-day vegetation responses and mechanisms under global warming.
3. Quantitative reconstruction of vegetation and climate change. China obviously lags behind many other countries in this field, especially in open-access modern pollen databases and reconstruction approaches adapted to the Chinese environment. Quantitative reconstructions have only been conducted at a few sites and a large spatial reconstruction of past climate across China is urgently needed.
4. Palaeovegetation and CO_2 mechanisms. In previous palaeovegetation reconstructions based on pollen data, little attention was paid to vegetation responses to CO_2 (but see Herzschuh et al. 2011), which led to a large error range in the quantitative climate reconstructions. Future reconstructions should take CO_2 into account with the aid of modelling.
5. Land-cover and land-use change to understand human impacts and provide empirical data for climate modellers is highly urgent, first to reconstruct the spatial and temporal changes, and then to incorporate these with modelling to understand vegetation feedbacks.
6. Integration with dynamic vegetation and palaeoclimate models. This is almost a research blank in China, with only a couple of studies. Based on fossil pollen data, data-model comparison and integration should move forward greatly to understand climate dynamics better (Birks et al. 2010).

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