Palaeogeography, Palaeoclimatology, Palaeoecology 289 (2010) 44–61

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Palaeovegetation in China during the late Quaternary: Biome reconstructions based on a global scheme of plant functional types

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ARTICLE INFO

Article history:
Received 31 July 2009
Received in revised form 4 February 2010
Accepted 6 February 2010
Available online 11 February 2010

Keywords:
Biome
Biomization
China
Last glacial maximum
Mid-Holocene
Plant functional types (PFTs)
Pollen
Vegetation shift

ABSTRACT

Two previous reconstructions of palaeovegetation across the whole of China were performed using a simple classification of plant functional types (PFTs). Now a more explicit, global PFT classification scheme has been developed, and a substantial number of additional pollen records have become available. Here we apply the global scheme of PFTs to a comprehensive set of pollen records available from China to test the applicability of the global scheme of PFTs in China, and to obtain a well-founded reconstruction of changing palaeovegetation patterns. A total of 806 pollen surface samples, 188 mid-Holocene (MH, 6000 ^{14}C yr BP) and 50 last glacial maximum (LGM, 18,000 ^{14}C yr BP) pollen records were used to reconstruct vegetation patterns in China, based on a new global classification system of PFTs and a standard numerical technique for biome assignment (biomization). The biome reconstruction based on pollen surface samples showed convincing agreement with present potential natural vegetation. Coherent patterns of change in biome distribution between MH, LGM and present are observed. In the MH, cold and cool-temperate evergreen needleleaf forests and mixed forests, temperate deciduous broadleaf forest, and warm-temperate evergreen broadleaf and mixed forest in eastern China were shifted northward by 200–500 km. Cold-deciduous forest in northeastern China was replaced by cold evergreen needleleaf forest while in central northern China, cold-deciduous forest was present at some sites now occupied by temperate grassland and desert. The forest–grassland boundary was 200–300 km west of its present position. Temperate xerophytic shrubland, temperate grassland and desert covered a large area on the Tibetan Plateau, but the area of tundra was reduced. Treeline was 300–500 m higher than present in Tibet. These changes imply generally warmer winters, longer growing seasons and more precipitation during the MH. Westward shifts of the forest–shrubland–grassland and grassland–desert boundaries imply greater moisture availability in the MH, consistent with a stronger summer monsoon. During the LGM, in contrast, cold-deciduous forest, cool-temperate evergreen needleleaf forest, cool mixed forests, warm-temperate evergreen broadleaf and mixed forest in eastern China were displaced to the south by 300–1000 km, while temperate deciduous broadleaf forest, pure warm-temperate evergreen forest, tropical semi-evergreen and evergreen broadleaf forests were restricted or absent from the mainland of southern China, implying colder winters than present. Strong shifts of temperate xerophytic shrubland, temperate grassland and desert to the south and east in northern and western China and on the Tibetan Plateau imply drier conditions than present.
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1. Introduction

Large-scale palaeovegetation reconstruction benefits not only the better understanding of vegetation change in the past and for the future, but also the evaluation of model experiments in order to better investigate the dynamics and interactions of past climate and vegetation changes, and the responses of climate to external forcing (CLIMAP Project Members, 1981; COHMAP Members, 1988; Wright et al., 1993; Prentice and Webb, 1998; Prentice et al., 2000). Since the 1980s, palaeo-scientists have made major efforts to reconstruct the continental and global vegetation patterns in the late Quaternary, based on data syntheses. The Cooperative Holocene Mapping Project (COHMAP Members, 1988; Wright et al., 1993) was the first attempt in 1980s to summarize the palaeovegetation data in the forms of regional syntheses. In the 1990s, the Global Palaeovegetation Mapping Project (BIOME 6000) attempted to create fully-documented pollen and plant macrofossil data sets for 6000 ± 500 ^{14}C yr BP (mid-

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doi:10.1016/j.palaeo.2010.02.008

Holocene, MH) and 18,000 ± 2000 ^{14}C yr BP (last glacial maximum, LGM), and to reconstruct global maps of vegetation for these time periods (Prentice and Webb, 1998; Prentice et al., 2000), using a standard technique called biomization (Prentice et al., 1996).

The geographic patterns of MH and LGM palaeovegetation of the northern continents and Africa were established by applying the biomization method (Prentice and Webb, 1998; Prentice et al., 2000) to pollen or plant macrofossil records for Europe, Africa and the Arabian Peninsula, North America, Alaska and western Beringia, the Former Soviet Union and Mongolia, China, and Japan (see the two Special Features in the *Journal of Biogeography* in 1998 and 2000, respectively). New reconstructions in the Southeast Asia and the Pacific region (Pickett et al., 2004), Latin America (Marchant et al., 2009), and Indian Subcontinent (Sutra et al., in preparation) have helped to fill the remaining gaps, especially in the southern Hemisphere. There are also regional and local case studies based on pollen and plant macrofossil records that have used the biomization technique, e.g. for palaeobiome distribution in Colombia (Marchant et al., 2001, 2002), Holocene vegetation in Mexico (Ortega-Rosas et al., 2008), modern and late Quaternary disturbed vegetation in Japan (Gotanda et al., 2008), and vegetation in the Mediterranean–Black Sea Corridor since the LGM (Cordova et al., 2009).

China covers about 1/10 of the world's land area and possesses climate regimes ranging from perennial snow cover on the high western mountains to extreme aridity in the northwestern lowlands, and from cold climates in the northeast to warm and humid tropical climates along the southeastern coast (Zhang, 1991). The dynamics of the East Asian summer and winter monsoons, and the high uplift of the Tibetan Plateau, contribute to producing a remarkably diverse set of bioclimates and ecosystems, ranging from boreal coniferous forest in the northeast to tropical rain forest in the south, and from temperate grassland in the northern-central region to deserts in the west and tundra and alpine vegetation on the Tibetan plateau (ECVC, 1980). Pollen-based reconstructions of late Quaternary vegetation and climate have been performed by applying various data and document syntheses across the whole country and in some large regions for the Holocene (e.g. Shi et al., 1993; Ren and Beug, 2002; Feng et al., 2006) and for the last 20,000 years (An et al., 1990), in addition to a great many site-based palaeovegetation studies. Biomization was applied to reconstruct vegetation patterns across China initially based on a limited set of digitized pollen data for the MH (Yu et al., 1998) and later using additional raw pollen counts for numerous sites at MH and LGM (Yu et al., 2000). Modern reconstruction based on surface pollen samples in both studies showed good agreement between reconstructed biomes and present vegetation, both geographically and in terms of elevation gradients in mountain regions (Yu et al., 1998, 2000).

These earlier pollen-based biome reconstructions used a simple classification of plant functional types (PFTs) related to the set of PFTs used in the BIOME1 model (Prentice et al., 1992a). More recently, a more explicit, global PFT classification scheme has been developed (Harrison et al., 2009). Further, a substantial number of additional pollen records have become available in electronic form since the previous biomization studies (Yu et al., 1998, 2000). In this study, we apply the global scheme of PFTs to a comprehensive set of surface, MH and LGM pollen records from China. The modern vegetation is reconstructed from surface pollen samples in order to test the applicability of the global scheme of PFTs in China, and to demonstrate a good empirical relationship between modern vegetation and surface pollen. Then the same procedure is applied to the MH and LGM in order to obtain a well-founded reconstruction of changing palaeovegetation patterns.

2. Data and methods

2.1. Pollen data for modern, MH and LGM

The modern pollen data set comprises a total of 840 samples. We used the set of 658 raw pollen counts (Yu et al., 2000), supplemented by 41 digitized pollen records from diagrams (Yu et al., 1998), 100 raw pollen counts from the Tibetan Plateau (Yu et al., 2001a) and 41 additional raw pollen counts compiled from published and unpublished sources (Fig. 1a, see also Appendix A). The surface samples include soil samples (518), moss polsters (80), dust trap samples (81), grab samples of surface sediments (94), sediment core tops (26), and digitized samples of unspecified provenance (41). Some modern pollen samples were excluded from further analysis because of contamination, very low pollen counts, or very small numbers of reported taxa (10 samples) or because of heavy anthropogenic influence (21 samples). Three of the digitized samples used by Yu et al. (2000) were removed and replaced by full pollen counts (Miaoershan, Nanshan and Xingou). Thus, 806 pollen surface samples were finally used (Fig. 1a).

The pollen data set for the MH (6 ka BP) consists of 192 samples. In addition to the 118 raw pollen counts and 39 digitized records used by Yu et al. (2000), we compiled 35 pollen records from published and unpublished sources (Fig. 1b, see also Appendix B). Four MH samples were excluded from analysis because of either low pollen counts (Baiyangdian, Dalainuoer, and Dunde) or strong anthropogenic influence (HF). Thus, 188 MH pollen samples were used in the biomization procedure (Fig. 1b).

The pollen data set for the LGM (18 ka BP) consists of 52 samples. Most of them (37) were derived from Yu et al. (2000). A further 10 digitized records were obtained from terrestrial units within marine cores from the Chinese continental shelf (Harrison et al., 2001). Raw pollen counts were compiled from five new sites (Fig. 1c, see also Appendix B). Two LGM samples (Haerbin and Niuquanzi) were excluded from further analysis because they had low pollen counts. Thus, 50 LGM samples were used in the biomization procedure (Fig. 1c).

2.2. Biomization procedure

The method of pollen-based biome assignment (biomization) begins with a quantitative assemblage of pollen or plant macrofossil taxa and ends with an assignment of the biome most likely to have produced that assemblage (Prentice et al., 1996; Prentice and Webb, 1998). The method has five steps: (1) each pollen taxon is assigned to one or more PFTs (PFT vs. taxon matrix), on the basis of the biology and biogeography of the plant species it includes; (2) biomes are defined in terms of their characteristic PFTs (biome vs. PFT matrix); (3) the two matrices are multiplied to produce a taxon vs. biome matrix, indicating which pollen taxa may occur in which biome; (4) affinity scores for each biome are then calculated for all pollen samples. A threshold pollen percentage (0.5%) is generally defined in order to reduce the noise due to occasional pollen grains derived from long-distance transport or contamination; (5) each pollen sample is assigned to the biome having the highest affinity score, subject to a tie-breaking rule that favours the less PFT-rich biome in the case where the affinity score for two or more biomes is equal. We used this standard procedure to reconstruct the biomes from the pollen data of China. Further details on this method can be found in Prentice et al. (1996) and Prentice and Webb (1998).

2.3. PFT classification

The PFT classification is a central concept for assigning pollen taxa to biomes. PFTs are defined on the basis of traits referring to species morphology, physiology, life history, and bioclimatic tolerances (Duckworth et al., 2000). The previous assignments of pollen taxa to PFTs by Yu et al. (1998, 2000) were based on a minor extension of the very simple implicit PFT classification of Prentice et al. (1992a). Here, we use a new global PFT classification defined explicitly in terms of four traits: life form, leaf form, phenology and bioclimatic tolerances (principally related to cold-tolerance mechanisms in woody plants), on the basis of current understanding of their significance in terms of adaptation to the physical environment (Harrison et al., 2009).

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