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Quantitative woody cover reconstructions from eastern continental Asia of the last 22 kyr reveal strong regional peculiarities

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ABSTRACT

We present a calibration-set based on modern pollen and satellite-based Advanced Very High Resolution Radiometer (AVHRR) observations of woody cover (including needleleaved, broadleaved and total tree cover) in eastern continental Asia, which shows good performance under cross-validation with the modern analogue technique (all the coefficients of determination between observed and predicted values are greater than 0.65). The calibration-set is used to reconstruct woody cover from a taxonomically harmonized and temporally standardized fossil pollen dataset (including 274 cores) with 500-year resolution over the last 22 kyr. The spatial range of forest has not noticeably changed in eastern continental Asia during the last 22 kyr, although woody cover has, especially at the margin of the eastern Tibetan Plateau and in the forest-steppe transition area of north-central China. Vegetation was sparse during the LGM in the present forested regions, but woody cover increased markedly at the beginning of the Bølling/Allerød period (B/A; ca. 14.5 ka BP) and again at the beginning of the Holocene (ca. 11.5 ka BP), and is related to the enhanced strength of the East Asian Summer Monsoon. Forest flourished in the mid-Holocene (ca. 8 ka BP) possibly due to favourable climatic conditions. In contrast, cover was stable in southern China (high cover) and arid central Asia (very low cover) throughout the investigated period. Forest cover increased in the north-eastern part of China during the Holocene. Comparisons of these regional pollen-based results with simulated forest cover from runs of a global climate model (for 9, 6 and 0 ka BP (ECHAM5/JSBACH ~1.125° spatial resolution)) reveal many similarities in temporal change. The Holocene woody cover history of eastern continental Asia is different from that of other regions, likely controlled by different climatic variables, i.e. moisture in eastern continental Asia; temperature in northern Eurasia and North America.

1. Introduction

Today, climate change and human activities are known to strongly affect woody cover, especially in arid and semi-arid areas where arboreal taxa are growing at the edge of their climatic niche (Tarasov et al., 2007; Liu and Tian, 2010; Ni et al., 2014). Broad-scale quantitative reconstructions of past woody cover based on palynology are necessary for understanding the present-day distribution of forests and for disentangling their driving forces, and they can also provide a useful benchmark for assessing the results of vegetation modelling research. Broad-scale changes in Quaternary woody cover in North America (Williams, 2003; Williams et al., 2011) and northern Eurasia (Tarasov et al., 2007; Williams et al., 2011) have been reconstructed using continental and regional pollen databases combined with satellite-based Advanced Very High Resolution Radiometer (AVHRR) observations of woody cover (DeFries et al., 1999) that find the closest analogues for fossil pollen samples from modern pollen datasets. AVHRR data provide a powerful tool to reconstruct woody cover gradients using analogue-based approaches (Williams and Jackson,

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2003). Williams (2003) and Tarasov et al. (2007) suggest that climate is the major driver of woody cover change. Having similar data on past land-cover changes for eastern continental Asia (mainly China, Mongolia, and southern Siberia) is of particular interest because of their more complicated climate and vegetation systems, but to date, few studies on land-cover change in this region have been made. Ren (2007) presents changes in forest cover in China during the Holocene using a greater than 40% arboreal pollen limit, but the various arboreal pollen taxa have different pollen representation factors (e.g. Xu et al., 2007; Cao et al., 2015). Zheng et al. (2010) established a pollen calibration-set for woody cover reconstruction. Tarasov et al. (2007) reconstructed the spatial pattern of woody cover for the last glacial maximum (LGM: ~21 ka BP) in northern Eurasia (mainly Siberia and Mongolia) and the temporal changes of woody cover during the late glacial and Holocene using four selected fossil pollen records. Liu et al. (2013) reconstructed regional vegetation cover changes quantitatively based on 15 fossil pollen spectra for north-central China. Ni et al. (2014) reconstructed biome changes in China over the last 22 kyr based on numerical pollen data. These studies provide some primary information on the broad-scale vegetation changes in eastern continental Asia; however, for a more accurate picture of woody cover change, large spatial-scale quantitative studies are necessary.

In this study, we employ a taxonomically harmonized and temporally standardized fossil pollen dataset (Cao et al., 2013) covering the last 22 kyr with 500-year temporal resolution, focusing on eastern continental Asia. We reconstruct needleleaved, broadleaved and total tree cover densities based on a modern pollen dataset (Cao et al., 2014) and AVHRR data, by quantifying the relationship between the palynological and AVHRR-estimates of woody cover, and test the accuracy of regional woody cover reconstructions. We apply the Modern Analogue Technique (MAT) to fossil pollen records to reveal the spatial and temporal changes of woody cover since 22 ka BP; and validate the reconstructions with simulation results from a global climate model for 9, 6 and 0 ka BP (Dallmeyer et al., 2013). The model is also used to detect the potential driving forces of any changes. Our aims are to (1) evaluate the quality of the calibration and reliability of the reconstructions; (2) characterize the overall woody cover change for certain intervals; (3) extract regional differences in the temporal evolution of woody cover; (4) identify the major driver of woody cover change; and (5) compare our reconstruction to general trends of woody cover change from other (sub-)continents.

2. Study area

In the study area (eastern continental Asia, 18°–55°N, 70°–135°E), vegetation follows a south-east–north-west precipitation gradient, changing from a moist coastal forest zone, via steppe, to desert. The eastern part of the study area reflects the influence of the East Asian Summer Monsoon (Fang et al., 1996), allowing dense forest to develop. The natural forest type in the eastern part of the study area consists of tropical rainforest and seasonal rainforest (south of ~23°N; mean annual temperature (T_{ann}): 21–26 °C; mean annual precipitation (P_{ann}): 1200–2200 mm), subtropical evergreen broadleaved forest (23°–32°N) and warm-temperate deciduous forest (32°–40°N) (T_{ann}: 14–21 °C; P_{ann}: 1000–1800 mm), temperate mixed conifer-deciduous broadleaved forest (40°–50°N; T_{ann}: 0–14 °C; P_{ann}: 500–1000 mm), and boreal conifer forest (north of ~50°N; T_{ann}: −5 to −1 °C; P_{ann}: 400–600 mm). In the north-western part of the study area, which is dominated by westerlies, the alpine coniferous forests are limited to mountainous areas. Many plains in the eastern part of the study area are farmed, and forests have only survived in mountainous areas. Deciduous broadleaved taxa (e.g. *Quercus*, *Betula*, *Alnus*, *Ulmus*, *Juglans*) and evergreen needleleaved taxa (e.g. *Picea*, *Pinus*, *Abies*) are regionally widespread, while evergreen broadleaved taxa (e.g. *Castanopsis*, *Cyclobalanopsis*, *Fagus*) are restricted to the tropical and subtropical areas.

3. Data and methods

3.1. Modern and fossil pollen data

The modern pollen dataset used here consists of 2626 pollen spectra from China and Mongolia (Fig. 1) compiled by Cao et al. (2014). We excluded 117 samples from marine (and coastal areas) and 98 samples from lakes with an area larger than 1 km^2 (as neither have local vegetation, but might have high arboreal pollen percentages), following the experience of previous studies (e.g. Williams, 2003; Tarasov et al., 2007), leaving us with 2411 spectra.

A fossil pollen dataset (Cao et al., 2013) with 271 records was employed to reconstruct past woody cover changes since 22 ka BP at a 500-year resolution in eastern continental Asia. For the 271 records, pollen percentages were standardized, pollen names harmonized, an age-depth model re-established, and pollen abundance interpolated for each 500-year interval. Further details are described in Cao et al. (2013). In this study, we added three new records with raw pollen percentage data: Lake Donggi Cona (35.5°N, 98.5°E, 4090 m a.s.l.; Wang et al., 2014) from the eastern part of the Tibetan Plateau, Lake Sumxi Co (34.6°N, 84.2°E, 5059 m a.s.l.; Campo and Gasse, 1993) from the western margin of the Tibetan Plateau, and Lake Bayan Nuur (90.9°N, 48.8°E, 1576 m a.s.l.; Krengel, 2000) from north-west Mongolia. These 274 pollen records evenly cover the major vegetation zones of the study area (Fig. 1).

3.2. AVHRR data

The modern estimates of four cover types (needleleaved, broadleaved, deciduous and evergreen tree cover) were produced from AVHRR observations for 1992 to 1993 (DeFries et al., 2000) in which each 1 × 1 km pixel was described as a percent mixture of several vegetation-cover categories, varying from 0% to 80%. For data extraction, Williams and Jackson (2003) suggest that search window half-widths between 25 and 100 km can best capture the pollen and AVHRR forest cover estimates, which is also consistent with studies of pollen source areas for lakes and mires (Bradshaw and Webb, 1985; Jackson, 1990; Sugita, 1993; Xu et al., 2012). In our study, we used a square search window with a half-width of 50 km to assign AVHRR-based estimates and modern pollen data by centring the window on each modern-pollen site and averaging AVHRR-based estimates from all pixels within the window using ArcGIS 10 software. We recalculated the total tree cover by summing the broadleaved and needleleaved tree cover for each modern pollen site. Due to a strong correlation between broadleaved and deciduous cover, and between needleleaved and evergreen cover (Appendix 1), we only present and discuss the results for broadleaved, needleleaved and total tree cover, while the results for deciduous and evergreen tree cover are in the supplementary material (Appendix 2 and 3).

3.3. Numerical analysis

In our modern pollen dataset, 1180 sites (ca. 49% of the 2411 sites) have ≤5% total tree cover. As an uneven distribution of sites along a gradient will strongly impact transfer function performance (Telford and Birks, 2011), we established a subset of modern pollen comprising 1531 sites including 1231 sites with total tree cover >5% plus 300 sites randomly selected from the 1180 sites with cover