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What caused the mid-Holocene forest decline on the eastern Tibet-Qinghai Plateau?

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ABSTRACT

Aim Atmospheric CO_2 concentrations depend, in part, on the amount of biomass locked up in terrestrial vegetation. Information on the causes of a broad-scale vegetation transition and associated loss of biomass is thus of critical interest for understanding global palaeoclimatic changes. Pollen records from the north-eastern Tibet-Qinghai Plateau reveal a dramatic and extensive forest decline beginning *c.* 6000 cal. yr BP. The aim of this study is to elucidate the causes of this regional-scale change from high-biomass forest to low-biomass steppe on the Tibet-Qinghai Plateau during the second half of the Holocene.

Location Our study focuses on the north-eastern Tibet-Qinghai Plateau. Strati-

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Location Our study focuses on the north-eastern Tibet-Qinghai Plateau. Stratigraphical data used are from Qinghai Lake (3200 m a.s.l., 36°32′–37°15′ N, 99°36′–100°47′ E).

Methods We apply a modern pollen-precipitation transfer function from the eastern and north-eastern Tibet-Qinghai Plateau to fossil pollen spectra from Qinghai Lake to reconstruct annual precipitation changes during the Holocene. The reconstructions are compared to a stable oxygen-isotope record from the same sediment core and to results from two transient climate model simulations.

Results The pollen-based precipitation reconstruction covering the Holocene parallels moisture changes inferred from the stable oxygen-isotope record. Furthermore, these results are in close agreement with simulated model-based past annual precipitation changes.

Main conclusions In the light of these data and the model results, we conclude that it is not necessary to attribute the broad-scale forest decline to human activity. Climate change as a result of changes in the intensity of the East Asian Summer Monsoon in the mid-Holocene is the most parsimonious explanation for the widespread forest decline on the Tibet-Qinghai Plateau. Moreover, climate feedback from a reduced forest cover accentuates increasingly drier conditions in the area, indicating complex vegetation–climate interactions during this major ecological change.

Keywords

Climate change, forest decline, general circulation models, Holocene, human activity, oxygen isotopes, pollen, transfer functions, Tibet-Qinghai Plateau, vegetation.

INTRODUCTION

The vast north-eastern Tibet-Qinghai Plateau (TQP) today supports vegetation predominantly of alpine meadows, grassland, shrub steppe, steppe and semi-desert. Forests of pine, spruce, juniper and birch are restricted to higher altitudes with greater annual precipitation in the Qilian and Kunlun mountains (Hou, 2001; Kürschner *et al.*, 2005). The development of the TQP with its treeless vegetation, primarily nomadic populations of yak farmers with sheep and cattle, small villages, rich flora and fauna and sustainable way of life raises important ecological questions.

Have the flora and vegetation of the TQP remained unchanged during the Holocene or was the TQP once forested? If it was forested, what factors caused the decline of forests on the TQP?

Recent palaeoecological and phylogeographical studies suggest that mainly conifer-dominated forests probably covered large areas at elevations between *c.* 2500 and 4000 m on the north-eastern TQP during the first half of the Holocene (Shen *et al.*, 2005). Meng *et al.* (2007) investigated mitochondrial DNA and chloroplast DNA of *Picea crassifolia* from several locations on the TQP and adjacent highlands. Results of their analysis suggest that the present-day disjunct populations of this species had had a common recolonization history after the glacial period, implying that the populations were once more continuous when there was early and mid-Holocene forest cover. Pollen records from the eastern TQP indicate that forests also began to decline in the mid-Holocene (Yan *et al.*, 1999; Herzschuh *et al.*, 2006; Shen *et al.*, 2006), a pattern seen through much of China (Ren, 2007). This widespread decline of forest has been attributed to human activities, especially expanding Neolithic populations (Ren, 2000, 2007; Miehe *et al.*, 2006; Kaiser *et al.*, 2007). Based on palynological and pedological results and associated ecological inferences based on peat profiles, turfs and topsoils from the eastern, southern and central TQP, Schlütz *et al.* (2007), Schlütz & Lehmkuhl (2009), Kaiser *et al.* (2007, 2008, 2009) and Miehe *et al.* (2009) have argued that nomadic people greatly influenced the vegetation during the last 8500 years by the herding of yaks and by burning and clearing of forests, and that these activities led to the expansion of dense low-growing *Kobresia pygmaea* mats at the expense of forests and alpine steppe. Their hypothesis is supported by speculations based on mitochondrial DNA analysis by Guo *et al.* (2006) that yak domestication on the TQP took place during the early Holocene. Investigations by Miehe *et al.* (2006, 2008) proposed that the occurrences of *Juniperus* forests in southern Tibet are well within their ecophysiological range but that their local re-establishment is inhibited due to strong grazing pressure. Interestingly, the highest known tree line in the Northern Hemisphere (4900 m) occurs in southern Tibet (Miehe *et al.*, deterioration) or just a lack of discoveries. The presence of a few ceramics at one of these sites (Jiangxigou, located 4.5 km south of Qinghai Lake) dating to *c.* 6500–5000 cal. yr BP clearly indicates some connection with other Neolithic cultures. The time of major forest decline is broadly consistent with expanding Neolithic populations in areas to the north-east of the TQP (Aldenderfer & Zhang, 2004; Brantingham & Gao, 2006), namely the Yangshao culture (6900–5300 yr BP) in the middle Yellow River and westward, the Majiayao culture (eastern Qinghai and western Gansu, 5300–4200 yr BP), and the Zongri culture (5600–4000 yr BP) in the upper Yellow River drainage. Remnants of these cultures may have possibly occupied mid-elevation areas such as the Qinghai Lake area (Aldenderfer & Zhang, 2004). In contrast to these comparatively well-investigated Neolithic sites in the western foreland of the plateau, the expansion of the 'Neolithic package' on the north-eastern TQP is mostly unknown. Aldenderfer (2007) proposes that the Tibetan Neolithic culture was focused on riverine habitats, at least in the beginning. Su *et al.* (2000) argue, based on human chromosome analysis in East Asia, that proto-Tibeto-Burman speakers moved from Qinghai onto the central TQP.

Besides human activity, regional climate change is the other major factor that could result in such a major broad-scale vegetation change. Palaeoclimatic records independent of palaeovegetation reconstructions (e.g. Gasse *et al.*, 1991; Fontes *et al.*, 1996; Thompson *et al.*, 1997; Wang *et al.*, 2002; Hong *et al.*, 2003; Wu *et al.*, 2006; Ji *et al.*, 2009; Zhang & Mischke, 2009) indicate that the climate of the TQP was warmer and wetter in the early Holocene, and moisture availability decreased later (Herzschuh, 2006; Shen *et al.*, 2008; Zhu *et al.*, 2008). This general pattern is seen at almost all sites within the East Asian Summer Monsoon realm. It is widely explained as a response to decreasing Asian monsoon activity due to declining summer insolation at northern latitudes in the mid-Holocene (Kutzbach, 1981).

There are thus two competing hypotheses to explain the observed decreases in tree pollen in mid-Holocene pollen stratigraphies from the TQP: (1) the mid-Holocene forest on the TQP declined as a result of human activity; and (2) the mid-Holocene forests declined as a result of regional climate change. Elucidating the likely cause of this widespread forest decline is important

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2007).

Archaeological data from the TQP are very sparse (Aldenderfer & Zhang, 2004; Brantingham & Gao, 2006). Three Epipalaeolithic sites (i.e. exhibiting the features of Palaeolithic cultures but of Holocene age) indicate that the margins of the north-eastern TQP were at least seasonally visited by humans for hunting and gathering (Brantingham *et al.*, 2007; Rhode *et al.*, 2007) during 9000–5000 calibrated years before present (cal. yr BP). Faunal remains from these sites (including gazelle, deer and sheep) are most likely to be of exclusively wild animal origin and no indications of a pastoral lifestyle were found. Rhode *et al.* (2007) related the expansion of the Epipalaeolithic culture to the Holocene climatic optimum. The lack of archaeological sites in the Qinghai Lake area until at least 2000 cal. yr BP could thus reflect a limited occupation (probably as a result of climate

in relation to understanding the global increase of atmospheric CO_2 concentrations since *c.* 8000 cal. yr BP measured in Antarctic ice cores. Ruddiman (2003) ascribed this CO_2 increase partly to the loss of terrestrial biomass as a result of extensive forest decline in Eurasia; the eastern TQP, however, was not particularly mentioned in his study.

We present pollen-based quantitative reconstructions of Holocene annual precipitation from a large lake in the north-eastern TQP, an oxygen-isotope record based on ostracod valves in the same core, and annual precipitation broad-scale hindcasts for the area from a general circulation model and an Earth system model of intermediate complexity. These analyses are designed to test the hypothesis of critical climate change on the north-eastern TQP in the mid-Holocene at the time of widespread forest decline.

STUDY AREA

Qinghai Lake, the largest saline lake in China (*c.* 4400 km^2 3200 m a.s.l, 36°32′–37°15′ N, 99°36′–100°47′ E) (Fig. 1), is situated in a closed intermontane basin. About 50 perennial streams exceeding 5 km in length discharge into the lake from a catchment area of about 30,000 km^2. Among them, the Buha River (located in the west of Qinghai Lake) accounts for 50% of the total inflow (Henderson & Holmes, 2009). The lake lies in a semi-arid area, where 75% of the annual precipitation (P_{ann}) falls between June and September, mostly from the East Asian Summer Monsoon (Xu *et al.*, 2007). P_{ann} is < 250 mm in the east and > 400 mm in the nearby Qilian Mountains (Zhang *et al.*, 2000; Hou, 2001). Annual potential evaporation is 800–1000 mm. Plant growth and vegetation are strongly limited by moisture availability and palaeovegetation records can thus provide important insights into regional changes in moisture availability. Vegetation near the lake today is temperate steppe in the south, desert in the west and alpine meadows and steppe above 3200 m in the surrounding mountains (Hou, 2001). Forests [dominated by *Sabina przewalskii* and *Picea crassifolia* (where P_{ann} > 370 mm; Zhao *et al.*, 2006)] are rare, being mainly restricted to the Qilian Mountains and the northern margin of the Kunlun Mountains (Kürschner *et al.*, 2005). *Pinus tabulaeformis* and *Betula platyphylla* are restricted to the wetter easternmost Qilian Mountains (P_{ann} > 400 mm). Qinghai Lake (catchment area *c.* 29,660 km^2), has a huge potential pollen-source area. Pollen spectra from the lake give a 'small-scale satellite photo' view (Jacobson, 1988) of 10,000 km^2 or more of the surrounding vegetation. Its sediments have been previously studied (e.g. Lister *et al.*, 1991; Henderson *et al.*, 2003; Xu *et al.*, 2007; Henderson & Holmes, 2009; Ji *et al.*, 2009) and are part of a recent International Continental Scientific Drilling Program (ICDP) drilling activity. Gaining quantitative palaeoclimate data from this key site is thus important for anyone interested in the climate history and dynamics of central Asia (e.g. Chen *et al.*, 2008; Zhao *et al.*, 2009).

MATERIALS AND METHODS

A 795-cm sediment core (QH-2000) was recovered from the south-eastern part of Qinghai Lake (water depth 22.3 m) in July

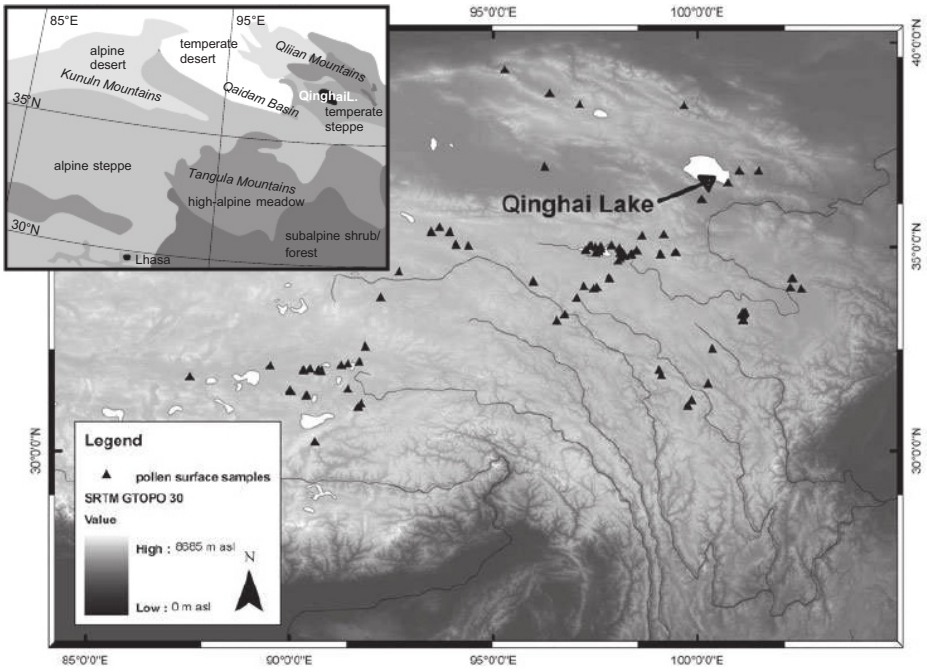

Figure 1 Sketch map showing the location of Qinghai Lake and the 108 lakes on the eastern Tibet-Qinghai Plateau (TQP) used to develop the modern pollen–precipitation transfer function. The rough distribution of the main vegetation types on the eastern TQP are shown in the inset map.