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Holocene fire and forest histories in relation to climate change and agriculture development in southeastern China

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Four cores (GY1, LTY, SZY, GT-2) taken from lowland to mountain sites in southeastern subtropical China were studied. Charcoal and pollen analyses were conducted to examine the regional Holocene fire history and discuss its possible relationship with both climatic changes and anthropogenic activities. Our results show extremely low charcoal influxes between 9.5 and 3.5 cal ka BP, revealing low fire frequency. Meanwhile, high proportions of arboreal pollen demonstrated expansion of subtropical evergreen broadleaf forest. This phase is consistent with heavy precipitation during the early-mid Holocene. After 3.5 cal ka BP., the abrupt increases in fire frequency revealed by core GY1 and LTY were closely related to gradual drying towards the late Holocene, possibly due to the Asian Summer Monsoon weakening and activation of the El Niño Southern Oscillation. Our pollen records also reveal this drying trend after the mid-Holocene, demonstrating a regional retreat of subtropical evergreen forests and local development of *Glyptostrobus*-dominated wetland community around the LTY and GY1 sites. However, the intensified fires after 3.5 cal ka BP probably resulted mainly from increasing human activities during the Shang-Zhou Bronze age. Pollen results show severe damage of forest by fires, indicated by notable decrease of arboreal pollen and increase of *Dicranopteris* and herbs. After 2.0 ka, obvious growth of Poaceae, *Dicranopteris* and *Pinus* recorded in the GY1 and LTY cores demonstrate agriculture development in low-altitude plains and hills, coinciding with the first human population boom and big progress in agricultural technology during the Warring States to Western Han Dynasty period. Signs of profound human impacts and extensive agriculture in South China appeared after 1.0 cal ka BP, which is revealed by frequent local fires and intensified anthropogenic impact around the mountains sites (SZY and GT-2). Generally, our results reveal a gradual expansion of anthropogenic activities into elevated areas.

1. Introduction

Fire is acknowledged as both a natural phenomenon and a human tool that has been used for instance to clear or exploit forest since at least the Early Neolithic. In recent decades, paleo-fire studies in various parts of Europe, North America, and East Asian have illuminated general patterns of Holocene fire-climate-vegetation-human interactions (Whitlock et al., 2007; Kaal et al., 2011; Rius et al., 2011; Whitlock et al., 2011; Han et al., 2012; Inoue et al., 2012; Tan et al., 2013, 2015). These studies demonstrate that Holocene fire history was closely related to climate variations, as well as the spatial and temporal distributions of anthropogenic activities.

According to past and present global fire records, fires have repeatedly occurred in subtropical areas, and even tropical forests, causing profound disturbance of ecosystems. Fire regimes are closely related to reductions in the supply of moisture to the land surface from the atmospheric circulation system, which can be caused by for example weakened monsoonal circulation or El Niño events (Kershaw et al., 1997; Sun et al., 2000; Haberle and Ledru, 2001; Huang et al., 2014; Xue et al., 2015).

Southeastern China is an area of great climatological interest. The Asian summer monsoon (ASM) controls precipitation regimes

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in this region and has prominent impacts on effective moisture and fuel availability. In addition, during summer, precipitation in this region is modulated by the number of typhoons passing nearby, which are originated in the western Pacific and closed related to El Niño southern oscillation (ENSO) variation. Thus, knowledge of Holocene fire history in this region (obtained from charcoal records) could enhance understanding of past climate variability and ecosystem responses. Previous study in monsoon-influenced and monsoon-margin region demonstrate that their fire histories are closely associated with ASM variabilities (Huang et al., 2006; Li et al., 2006; Jiang et al., 2008; Tan et al., 2013, 2015). However such paleo-fire records from southeastern subtropical China are limited. Furthermore, Neolithic history in South China, in comparison to the central part and Yangtze area in China, is far from systematically understood, especially regarding the start of extensive agriculture in the region (Chi and Hung, 2010). Linking archaeological and palaeoecological records is crucial for elucidating the timing and extent of anthropogenic modification of vegetation during the Holocene. Here too, charcoal signals could provide significant information about the regional fire history, including both natural and anthropogenic fires in the palaeoenvironment. In combination with palynological records, such information could provide detailed indications of changes in forests, natural and anthropogenic land cover changes, and the history of agricultural practices in the region.

In this study, we analysed charcoal and pollen records in four cores collected at different geographical locations in southeastern subtropical China in efforts to reconstruct the regional Holocene fire history, and elucidate effects of climate changes and human activities on the fire regimes.

2. Study area and sites

Cores GY1, LTY, SZY and GT-2 were collected from four peat bogs in southeastern subtropical China. The regional climate is dominated by the ASM, with high (>1000 mm) average annual precipitation (Fig. 1). These sites covered both high and low altitudes, representing deposits under various geographical conditions including delta and mountainous areas. A brief description of the four sites is as followed.

Core GY1 (22°54.072′N, 112°20.427′E; 29 m a.s.l.) was collected from a buried peatlands in Gaoyao County, located at the edge of Pearl River Delta. This area is part of the south subtropical climatic region, with average annual temperature and precipitation of 22 °C and 2000 mm, respectively (Peng et al., 2015). The local natural vegetation is south subtropical monsoon evergreen broadleaved forest. The dominant tree taxa are tropical species mainly from Fagaceae, Lauraceae, Theaceae and Hamamelidaceae, including *Castanopsis concinna*, *C. carlesii*, *C. tonkinensis*, *Lithocarpus fenestrarus*, *Rhodoleia championii*, *Machilus thunbergii*, *M. kwangtungesis*, *Artocarpus styracifolius*, *Schima superba*, *Artocarpus styracifolius* etc. (Institute of Botany, Academy Sinica (IBAS), 1960).

Core LTY (28°26.040′N, 119°18.849′E; 902 m a.s.l.) was taken from the Lantianyan peat bog in a valley of the Xianxia Mountains in the northern edge of the Wuyi Mountain chains, where the average annual temperature is 19 °C and annual precipitation varies from 1500 to 1900 mm. The local natural vegetation is dominated by evergreen broadleaved trees, with an admixture of deciduous taxa. The characteristic taxa of evergreen broadleaved trees are primarily from many genuses of Fagaceae (mostly *Cyclobalanopsis*, *Castanopsis*, *Lithocarpus* etc.), Lauraceae, Theaceae, Moraceae, Elaeocarpaceae and Hamamelidaceae. Some deciduous broadleaved trees mainly occur in the mountains that frequently include *Carpinus*, *Corylus, Fagus*, *Acer*, *Tilia* and *Pterocarya*. Conifers are also found in some areas including *Taxus chinensis*, *Tsuga longibracteata*, *Keteleeria fortunei* and *Torreya grandis*. Wetland vegetation communities around the LTY site include species of Cyperaceae, Poaceae, Araceae, Rosaceae, Ericaceae and *Alnus*, among others (Ma et al., 2016a).

Core SZY (26°46′N, 119°02′E; 1007 m a.s.l.) was taken from the subalpine Shuizhuyang peat bog in Jiufeng Mountains, where the mean annual temperature and precipitation are about 14–15 °C and 1900 mm, respectively. The local natural vegetation is subtropical evergreen broadleaved forest dominated by *Castanopsis*, *Quercus*, *Lithocarpus*, *Cinnamomum*, *Machilus*, *Schima*, *Ilex* etc. Some coniferous taxa such as *Tsuga chinensis* and *Pinus taiwanensis* are popular in some mountain ranges (Yue et al., 2012).

Core GT-2 (26°5′16″N, 110°21′56″E; 1677 m a.s.l.) was taken from the Gutian wetland, located in the hinterland of the Yuecheng Mountains, one of the major mountain ranges in the western Nanling Ranges. The annual mean temperature and precipitation here are about 12–13 °C, and 1800 mm, respectively. The local mountainous forest communities are composed of a certain proportion of deciduous broadleaf species such as *Fagus*, *Liquidambar*, and *Acer*, often mixed with evergreen broadleaved trees containing *Cyclobalanopsis*, *Castanopsis*, *Quercus, Schima etc*. Conifers including *Tsuga chinensis* and *Pinus* spp. are present in some high elevation habitats (Li, 1985).

3. Materials and methods

The chronological frames for cores GY1, LTY, SZY and GT-2 were established using ^{14}C accelerator mass spectrometry (AMS) dating. AMS ^{14}C dates of core samples of these sites are listed in Table 1. All ^{14}C dates were calibrated using IntCal13 (Reimer et al., 2013). The age models for the four cores (Fig. 2) are based on linear interpolation between the nearby two calibrated ^{14}C dates, and constructed using the Clam 2.2 software package (Blaauw, 2010).

Method of pollen extraction in the cores of GY1, LTY, SZY, and GT-2 is based on zinc chloride ($ZnCl_2$) dense-media separation (Nakagawa et al., 1998). To estimate pollen and charcoal concentrations, a tablet containing a known quantity of *Lycopodium* spores (27,637 ± 563) was added to each sample (Stockmarr, 1971; Maher, 1981). *Pollen Flora of China* (Wang et al., 1995) and *Tropical and Subtropical Angiosperm Pollen Morphology* (IBSCIBAS, 1982) were consulted for pollen taxa identification. Usually, at least 300 pollen grains were counted per sample. Pollen taxa percentages were calculated using the total sum of pollen, including pollen from trees, shrubs, and herbs. Percentages of ferns were calculated using the total sum of pollen and spores.

Charcoal particles were obtained during the pollen preparation process. We consider charcoal particles smaller than 125 μm as microscopic charcoal, and those bigger than 125 μm as macroscopic charcoal. Both microscopic charcoal and macroscopic charcoal were counted for each sample. Particles smaller than 10 μm were not counted. The number of charcoal particles was treated as charcoal concentration (grains/cm^3), and charcoal influxes (grains/cm^2 yr) were calculated by multiplying the charcoal concentrations by the sedimentation rate (cm/yr).

4. Results and interpretation

Theoretical models of charcoal particle transport, as well as researches of charcoal deposition based on modern fires, allow us to understand the processes of charcoal production, transport, and deposition (Swain, 1978; Tolonen, 1986; Patterson et al., 1987; Clark, 1988, 1990; Whitlock and Millspaugh, 1996). Macroscopic charcoal particles are not transported far from the margins of fire before settling, thus providing a record of local fires. Microscopic charcoal particles can be carried aloft to great heights and

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