J Paleolimnol (2016) 56:267–274
DOI 10.1007/s10933-016-9896-0

ORIGINAL PAPER

# Holocene controls on wetland carbon accumulation in the Sanjiang Plain, China

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Received: 21 May 2015 / Accepted: 7 June 2016 / Published online: 19 September 2016


**Abstract** Understanding the response of carbon (C) accumulation to past climate changes can provide useful insights for predicting the fate of C in a future, warmer world. Here, we present data from three well-dated peat cores that reveal the history of wetland C accumulation in the Sanjiang Plain (China), and its links to Holocene climate and environmental changes. Regional C accumulation was largely governed by monsoon-driven depositional conditions. Before ~4400 cal year BP, the strong summer monsoon favored development of lakes with relatively slow and stable C accumulation rates, ~20 g C $m^{-2}$ $year^{-1}$. Thereafter, with the sharp decline in summer monsoon precipitation, peatlands began to form at the expense of the paleolakes, leading to a roughly sixfold increase in the C accumulation rate. This was a consequence of the higher primary production in peatlands compared to lakes. During the interval from 4400 to 500 cal year BP, the gradually increasing C accumulation rate responded to the decreasing strength of the summer monsoon. The decline in C accumulation rate over the past 500 years is attributed to both the strengthened summer monsoon and intensified human influences.

**Keywords** Wetlands · C accumulation · Sanjiang Plain · Holocene · Summer monsoon

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## Introduction

Wetlands are considered optimal natural environments for sequestering carbon (C) from the atmosphere and thus play an important role in the global carbon cycle and climate change (Bridgham et al. 2006; Mitsch et al. 2013). It is estimated that 20–30 % of the Earth's soil C is stored in wetlands, which comprise only 5–8 % of the terrestrial land surface (Mitsch et al. 2013). Under the influence of ongoing global changes, wetlands are now considered one of the biggest unknowns of the near future, with respect to their degradation and organic matter decomposition (Updegraff et al. 1995; Leavit 1998). The fate of these large C reservoirs in a future, warmer world has thus drawn widespread attention.

Understanding the responses of these C-rich ecosystems to past climate change can provide useful insights into the fate of wetland C in the future. It is generally accepted that increased climate seasonality will lead to higher C accumulation rates (Moore and Dalva 1993), because warmer conditions during the growing season favor higher primary production, and colder conditions during winter help prevent the oxidation of C (Bridgham et al. 2006; Carroll and Crill 1997). This contention is supported by the middle-to-high-latitude distribution of northern peatlands, where the climate is characterized by remarkable seasonality (Yu et al. 2001). Additionally, local moisture conditions may influence C accumulation. It has been documented that wetter conditions favor C accumulation in modern wetlands, as a higher water table leads to both higher primary production and lower C decomposition (Frolking et al. 2001). These findings were mainly derived from experimental models that spanned relatively short timescales, but other studies that covered longer periods show varying C responses to climate change. For example, C deposits in Alaskan peatlands accumulated more rapidly under drier conditions (Gorham et al. 2003), and numerous peatlands developed globally during the Last Glacial Maximum, a relatively cold and dry interval (Adams et al. 1990; Yu et al. 2010). Thus, the impact of climate change on C accumulation in wetlands is complex, and high-resolution records of C sequestration from climatically sensitive locations are needed to provide additional information.

The Sanjiang Plain contains the largest and most concentrated wetland area in China (Chen 1995) and covers middle-high latitudes and marginal areas influenced by the East Asian Monsoon. Therefore, this geographic setting lies in a climatically sensitive region that is ideal for analyzing the response of C accumulation in wetlands to Holocene monsoon variations (An 2000). In this paper, we present three well-dated peat/mud profiles that reveal the C accumulation history in wetlands and discuss possible links between long-term C burial and East Asian Monsoon variations during the Holocene.

### Regional setting

The Sanjiang Plain (129°11′–135°05′E, 43°49′–48°27′N), located in northeastern China, is a low alluvial plain crossed by the Heilong, Songhua and Wusuli Rivers (Fig. 1). The plain has a total area of $10.9 \times 10^4$ km$^2$, an altitude of <200 m and a slope of <1:10,000. A temperate, humid-to-sub-humid continental monsoon climate dominates the Sanjiang Plain. Mean annual temperature ranges from 1.4 to 4.3 °C, with an average maximum of 22 °C in July and average minimum of −18 °C in January. Mean annual precipitation is 500–650 mm, and 80 % of rainfall occurs between May and September (Fig. 2; Liu 1995). The months with greatest precipitation and warmest temperatures generally coincide, and characterize the typical monsoon climate of the modern plain. In addition to the highly seasonal climate conditions on the Sanjiang Plain, the low relief is favorable for wetland development. Over 70 % of the plain is dominated by freshwater wetlands situated along ancient riverbeds and water-logged depressions that formed during pingo development throughout the last glacial stage (Song and Xia 1988).

## Materials and methods

### Sampling and lithology

Three well-preserved wetlands, located approximately in the southern, central, and northern regions of the plain, were selected as study areas. One sediment core was extracted with a Russian Peat Corer from each study area. A 195-cm-long sediment core was extracted from site SH (46°34.864′N, 130°39.873′E, 165 m a.s.l.), in the southern region of the plain. Located 238 km to the northeast is site HE (47°35.096′N, 133°30.006′E, 71 m a.s.l.), where a 160-cm core was taken. A 100-cm-long core was extracted from northernmost site HX (48°20.096′N, 134°42.006′E, 36 m a.s.l.), located 137 km from HE. Lithologically, each core can be divided into two sections: blackish-grey mud overlain by brownish peat layers with high organic content (Fig. 3).

### Laboratory analysis

In the laboratory, the sediment cores were sliced into 1-cm-thick intervals, for a total of 455 samples. Volumetric samples of ~2 cm$^3$, taken at every 1-cm interval, were prepared for organic matter analysis by loss-on-ignition (LOI). The samples were dried at 100 °C in a drying oven for ~12 h and combusted at 500 °C in a muffle furnace for ~4 h to estimate dry weight and organic matter content, respectively. The bulk density of each sample was calculated from the sample volume, dry weight, and organic matter

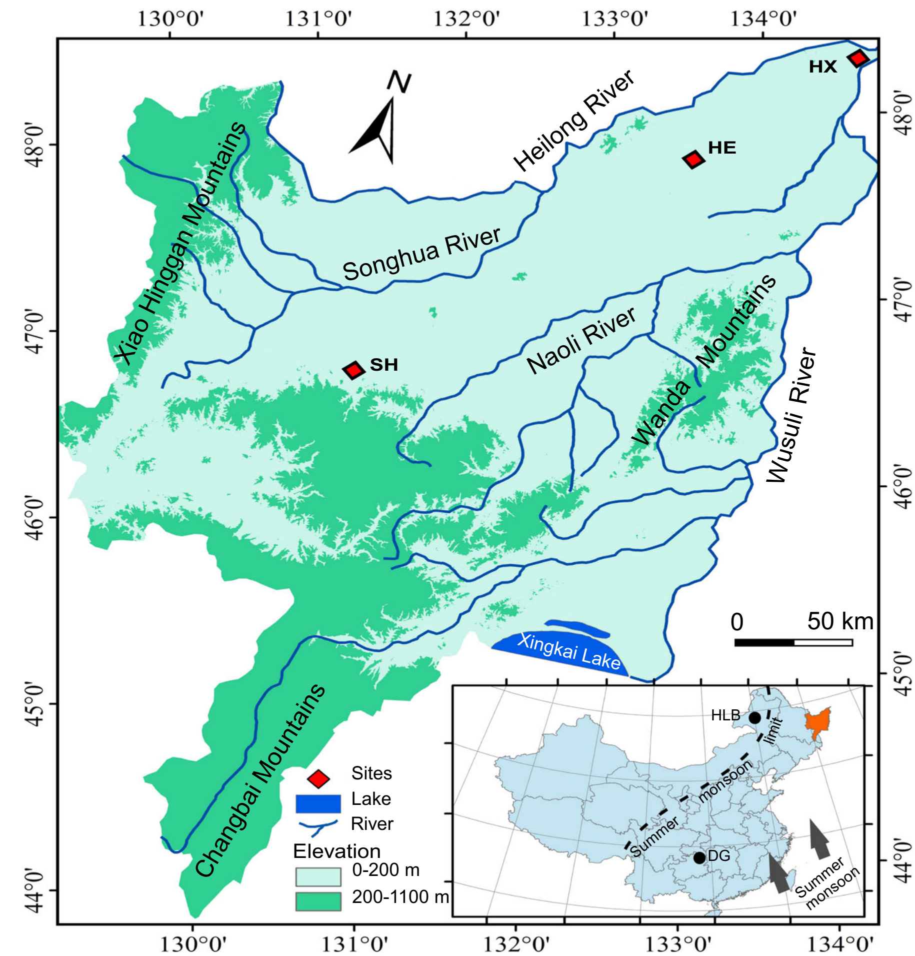


**Fig. 1** Digital elevation model of the Sanjiang Plain. The *solid red diamonds* indicate the sampling sites. The current northern limit (*dashed line*) of the East Asian summer monsoon and its direction (indicated by the *black arrows*), along with the locations of the Sanjiang Plain (highlighted in *orange*), the Hulun Buir Desert (HLB) and Dongge Cave (DG) (*solid circles*) are shown in the *inset*. (Color figure online)

contents, following the method described by Zhao et al. (2011) (Fig. 3). Average net C accumulation rates for each core were calculated at 200-year intervals, using calibrated $^{14}C$ ages, ash-free bulk density measurements, organic matter content, and carbon content of organic matter, assuming C is 52 % of organic matter (Vitt et al. 2000). Mean C accumulation rates (Fig. 4) in the three studied cores reveal the C accumulation history in wetlands of the Sanjiang Plain.

Twenty samples were selected from roughly equal intervals and dated by accelerator mass spectrometry (AMS) at the Institute of Earth Environment, Chinese Academy of Sciences. For peat samples, plant detritus was picked and chosen for dating, whereas in mud sections, total organic matter was used. The AMS $^{14}C$ dates were calibrated to calendar ages before present (cal year BP, 0 year BP = 1950 AD) with the CALIB 7.0.1 program, using the IntCal13 calibration curve (Stuiver and Reimer 2006; Table 1). Core chronologies were established based on a third-order polynomial, using the mean 2σ range values of the calibrated ages (Fig. 3). Historical population information for Heilongjiang Province, where the Sanjiang Plain is situated, is from data compiled by the Northeast Culture Community (1931).

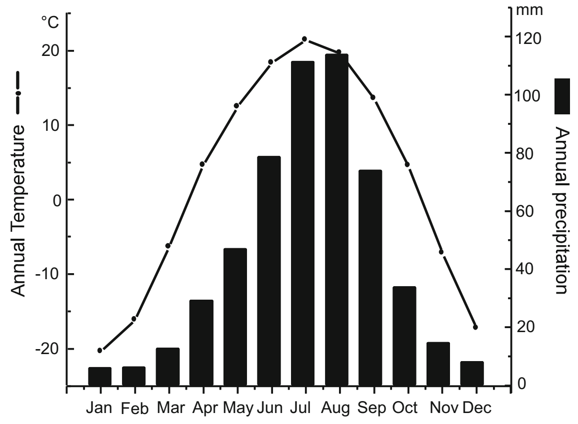


**Fig. 2** Climate diagram showing monthly temperature and precipitation in the Sanjiang Plain. Data were collected from meteorological stations in the Sanjiang Plain from 1957 to 2000

## Results

The age-depth models indicate that the studied profiles cover the last ~7800 (SH), ~6200 (HE), and ~9000 (HX) years, and the peat layers began to accumulate around ~4400 cal year BP. Both organic matter content and ash-free bulk density show a sharp increase above the mud-peat lithologic boundary (Fig. 3). The mean C accumulation rates for the three studied profiles cover the last ~9000 years. A sharp increase occurred at ~4400 cal year BP, with low and stable values before and relative high values, with a gradual increasing trend, thereafter, except for slightly lower values during the last 500 years (Fig. 4).

## Discussion

### Holocene environmental changes in the Sanjiang Plain

It has been documented that C accumulation in wetlands is a function of the balance between the rate of primary production and the rate of organic matter decay, with both processes governed by regional temperature and moisture (Belyea and Malmer 2004). The litho-facies of local strata is a direct indicator of paleoenvironmental conditions. Blackish-grey mud layers with laminar structures were found in the lower parts of the sediment cores (Fig. 3). These layers are characterized by low and stable linear sediment accumulation rate (~0.5 cm/100 year) and organic matter content (~7 %). Such values for the mud layers are consistent with lacustrine deposits throughout China's monsoon regions (Xiao et al. 2004; Xue et al. 2003), indicating that shallow lakes had developed in the Sanjiang Plain before ~4400 cal year BP. Thereafter, peat deposition, defined by high organic matter content (>50 %), began, suggesting a transition from a lacustrine to a peatland environment. At the mud/peat boundary at ~4400 cal year BP, both organic matter content and ash-free bulk density increased sharply, indicating a rapid rise in the C accumulation rate.

Such a lake-peatland transition could be related to autogenic infilling processes or changes in external water supply. During lake development, autogenic

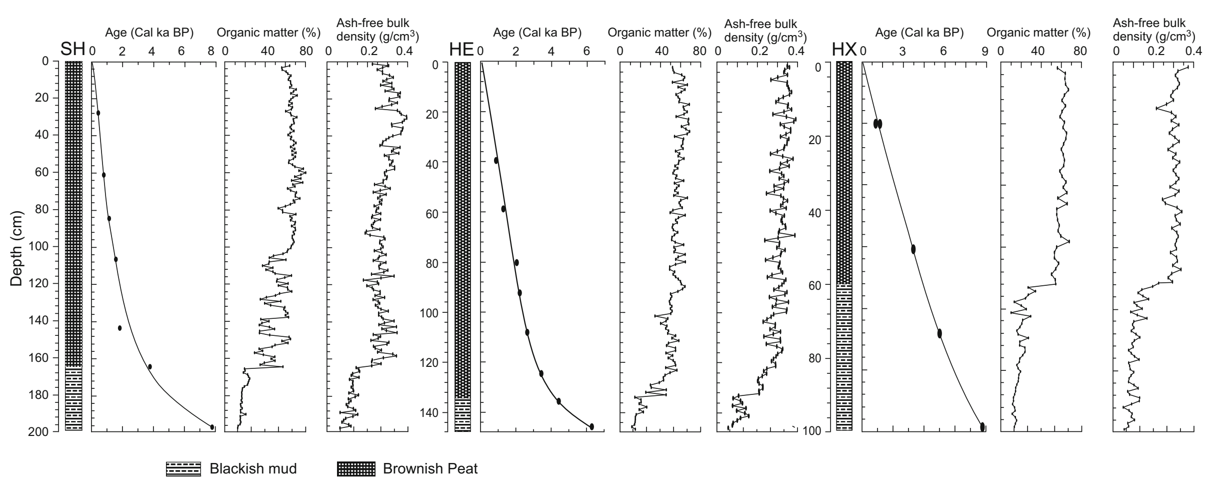


**Fig. 3** Lithology, age model, organic matter content and ash-free bulk density of the sediment cores

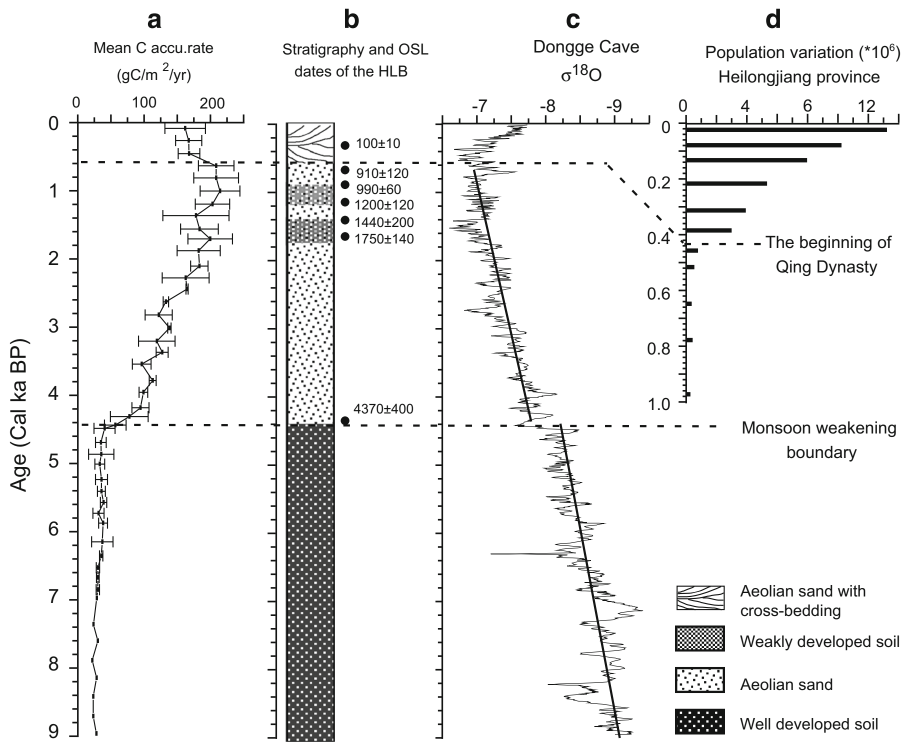


**Fig. 4** Mean C accumulation rate with standard deviation in 200-year intervals of the three studied cores (**a**), Holocene climate changes recorded in the HLB (**b**) and DG (**c**) (see locations in Fig. 1), and historical population variation of Heilongjiang province (**d**) are shown

depositional processes would lead to gradual terrestrialization (Fang 1991). Such infilling is widely considered to be a lengthy process, often spanning multiple millennia (Rhodes et al. 1996), much longer than the abrupt lake-wetland transition that occurred within a few decades in the Sanjiang Plain. Alternatively, a sudden decline in water supply can cause the rapid extinction of a lake. In these wetlands, most water is provided directly or indirectly by atmospheric precipitation (Liu 1995).

East Asian monsoon rainfall is linked to the interaction between warm moist southerly air masses and cold northerly airflows (An 2000). A stronger summer monsoon would lead to northerly migration of the rainfall belt and increased precipitation in middle- and high-latitude regions. Recent studies indicate a period of enhanced summer monsoon conditions during the early-middle Holocene (Hong et al. 2001; Li et al. 2007; Sun et al. 2006; Wang et al. 2005; Wen et al. 2010; Xiao et al. 2004; Zhao et al. 2011). In low-middle latitudes of China, stalagmite $\delta^{18}O$ has been used widely as a climate-sensitive proxy for monsoon variation. Values decrease when the summer monsoon intensifies, whereas values increase when the system weakens (Wang et al. 2005). In northeastern China, alternation between sand accumulation and paleosol development in desert regions is a direct indicator of past monsoon variations (Sun et al. 2006; Li et al. 2007). Two high-resolution and well-dated monsoon records from Dongge Cave (DG) (Wang et al. 2005) in southern China and the Hulun Buir Desert (HLB) (Li et al. 2007) in northeastern China (Fig. 1), were analyzed to reveal relationships between Holocene C accumulation and monsoonal variation in the Sanjiang Plain.

## Holocene climate controls on C accumulation

The three sediment cores all display a remarkable increase in C accumulation rates associated with the lake-wetland transition at ~4400 cal year BP. This increase corresponds well with the East Asian summer monsoon variations during the Holocene, indicating a potential climate control on C accumulation in the

**Table 1** AMS radiocarbon dates for 20 samples from the three studied sediment profiles, Sanjiang Plain, China

| Site# | Lab number | Depth (cm) | Dated material | $\delta^{13}C$ (‰) | AMS $^{14}C$ age ($^{14}C$ year BP) | Calibrated $^{14}C$ age ($2\sigma$) (cal year BP) |
|---|---|---|---|---|---|---|
| SH | XA7553 | 27 | Plant residues | −37.7 | 550 ± 24 | 520–560 |
| SH | XA7592 | 60 | Plant residues | −38.6 | 1088 ± 24 | 940–1010 |
| SH | XA7542 | 84 | Plant residues | −30.3 | 1381 ± 26 | 1280–1340 |
| SH | XA7543 | 107 | Plant residues | −24.5 | 1673 ± 32 | 1520–1630 |
| SH | XA7555 | 145 | Plant residues | −34.3 | 1731 ± 30 | 1560–1710 |
| SH | XA7570 | 165 | Plant residues | −30.1 | 3542 ± 26 | 3810–3900 |
| SH | XA7571 | 195 | Organic matter | −48.9 | 6982 ± 90 | 7660–7980 |
| HE | XA7572 | 38 | Plant residues | −32.1 | 606 ± 23 | 580–650 |
| HE | XA7573 | 60 | Plant residues | −30.9 | 1243 ± 24 | 1170–1270 |
| HE | XA7574 | 80 | Plant residues | −31.5 | 2295 ± 25 | 2310–2350 |
| HE | XA7575 | 94 | Plant residues | −41.6 | 2535 ± 30 | 2490–2900 |
| HE | XA7576 | 108 | Plant residues | −29.8 | 2759 ± 28 | 2780–2930 |
| HE | XA7577 | 125 | Plant residues | −30.4 | 3335 ± 25 | 3550–3640 |
| HE | XA7560 | 135 | Organic matter | −29.3 | 4491 ± 31 | 4460–4521 |
| HE | XA7578 | 148 | Organic matter | −31.7 | 6092 ± 100 | 5992–6192 |
| HX | XA7520 | 30 | Plant residues | −25.7 | 1625 ± 28 | 1470–1570 |
| HX | XA7521 | 30 | Plant residues | −23.9 | 1597 ± 26 | 1410–1550 |
| HX | XA7525 | 51 | Plant residues | −27.8 | 3508 ± 27 | 3700–3860 |
| HX | XA7526 | 74 | Organic matter | −26.0 | 5070 ± 28 | 5750–5900 |
| HX | XA7527 | 100 | Organic matter | −21.3 | 8062 ± 32 | 8970–9030 |

Sanjiang Plain. Before ~4400 cal year BP, the summer monsoon was strong, suggested by well-developed soil sections in the HLB and relatively low $\delta^{18}O$ values in the DG record (Fig. 4). The strong summer monsoon would have triggered a northerly migration of the rainfall belt and therefore increased precipitation in the Sanjiang Plain (Zhang et al. 2014). Greater precipitation would, in turn, have raised the water table in depressions, ultimately forming lakes or ponds, as indicated by the lacustrine mud deposits in the sediment cores. Although the paleolakes in the Sanjiang Plain served as C sinks, C accumulation rates were relatively low and stable, despite gradual weakening of the summer monsoon, as indicated by the stalagmite $\delta^{18}O$ records in DG before 4400 cal year BP (Fig. 4).

Subsequently, there was a sharp decline in monsoon strength, resulting in a dry event at ~4400 cal year BP. Evidence of regional monsoon weakening during the middle Holocene has been documented in cave deposits (Wang et al. 2005), lake sediments (Xiao et al. 2004; Wen et al. 2010), aeolian deposits (Sun et al. 2006), accretionary soils (An 2000), and peat accumulations (Hong et al. 2001; Zhao et al. 2011). The sharp decline in strength of the summer monsoon and the associated decrease in precipitation abruptly lowered the water table in the paleolakes of the Sanjiang Plain, causing them to dry completely. Elimination of the paleolakes enabled initiation of peatlands after 4400 cal year BP (Figs. 3, 4). Notably, the lacustrine mud layers provided a nutrient-rich base and a water-retaining layer, vital to the initiation of peatlands.

Peatlands are favorable for C accumulation because primary production is much higher than in lakes. The C accumulation rates during the peatland stages were roughly six times higher than during the lake phases (Fig. 4). Even during the weak summer monsoon after 4400 cal year BP, the C accumulation rate gradually increased from ~100 to ~180 g C $m^{-2}$ $year^{-1}$. This trend correlates well with the gradual decline of the East Asian summer monsoon, indicated by increasing $\delta^{18}O$ values in the DG record, and suggests that relatively dry conditions favored C accumulation in peatlands of the Sanjiang Plain. Since the peatlands of the Sanjiang Plain formed at the expense of paleolakes, their development likely occurred in relatively deep water, which could support few aquatic plant types. With the decline of the summer monsoon and decrease in precipitation, the hydrogeologic conditions would have favored a greater range of wetland plant types, causing higher primary production and consequent increased C accumulation in the peatlands. Extremely dry conditions, however, may have caused a decrease in primary production and an increase in C decomposition, which would likely have resulted in a lower C accumulation rate.

During the last 500 years, the mean C accumulation rate has decreased, which may be a result of the gradually strengthened summer monsoon, indicated by the decreasing stalagmite $\delta^{18}O$ values in the DG record. This period also corresponds to the time of intensive land use, a consequence of the sharply rising human population. Since the beginning of the Qing Dynasty (1616 AD), thousands of people gradually migrated to northeastern China to strengthen security along the border (Northeast Culture Community 1931). The population in Heilongjiang Province, where the Sanjiang Plain is situated, quickly increased to several million during the last 400 years. Such a large population residing in the low-relief plains would have influenced regional primary productivity. The peatlands of the Sanjiang Plain were ideal environments for agriculture, and farmers historically burned local vegetation, which would have resulted in significant loss of accumulated C. Thus, we suggest that the combination of a strengthened summer monsoon and intensified human disturbance was critical in driving the changes in C accumulation during the last 500 years in the Sanjiang Plain.

## Conclusions

Holocene C accumulation in wetlands of the Sanjiang Plain was largely controlled by variations in strength of the East Asian summer monsoon. The strong monsoon before 4400 cal year BP led to the lacustrine environments in low-lying areas of the plain, associated with a relatively low and stable mean C accumulation rate. With the sudden mid-Holocene decline of the summer monsoon, a lake-peatland transition occurred, with a significant increase in the C accumulation rate. We attribute this change in C accumulation to the higher primary production in peatlands, compared to lakes. From about 4400–500 cal year BP, the gradual increase in C accumulation rate resulted from high primary production, a consequence of the decreasing strength of the summer monsoon. The lower C accumulation rate over the last 500 years is attributed to the strengthened summer monsoon and intensified human disturbance.

**Acknowledgments** We thank Dr. Thomas Bianchette and two anonymous reviewers for their constructive comments on a previous version of the manuscript. This study was supported by the National Natural Science Foundation of China (Nos. 41271209 and 41271205) and the State Key Laboratory of Lake Science and Environment (2014SKL007).

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