



## Higher recent peat C accumulation than that during the Holocene on the Zoige Plateau



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### ABSTRACT

In order to understand the carbon fate of alpine peatlands under climate change, this study aimed to measure carbon accumulation in recent decades and that during the Holocene at seven representative peat sites on the Zoige Plateau using empirical peat core data (<sup>14</sup>C and <sup>137</sup>C<sub>5</sub>) and modeling approaches. The observed apparent carbon accumulation rate over the past 50 years was 75 (35–123) g C m<sup>-2</sup> yr<sup>-1</sup>, nearly four times that of 19 (7–30) g C m<sup>-2</sup> yr<sup>-1</sup> over the whole Holocene. With decomposition history included in consideration by using modeling approaches, the average expected peat carbon accumulation rate was still nearly 1.6 times that of the modeled net carbon uptake rate of peats accumulated over the whole Holocene, though exceptions were found for Denahequ and Hongyuan peat cores with extremely low water table levels. The newly accumulated peat carbon of the Zoige Plateau amounted to 0.4 Tg C yr<sup>-1</sup> (1 Tg = 10<sup>12</sup> g) during recent decades. Overall, the effect of climate warming on recent C accumulation of peatlands on the Zoige Plateau is dependent on their water conditions. The peat C storage on the alpine Plateau is threatened by human activities (drainage) and continuous climate change with increasing temperature and decreasing precipitation which cause dryness of peatlands.

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### 1. Introduction

Peatlands are a type of wetland where a thick layer about 30–40 cm of incompletely decomposed organic matter, or peat exist (Wieder et al., 2007) and the estimated area of global undisturbed peatlands is 400 Mha, occupying an area of approximately

3% of the earth's land surface (Wieder and Vitt, 2006). Peatlands are carbon (C) rich ecosystems, with the organic C storage of about 455–600 Pg (Gorham, 1991; Yu et al., 2010), amounting to nearly one-third of the global soil C pool. Peatlands can not only sequester carbon dioxide (CO<sub>2</sub>) from atmosphere via plant photosynthesis (Flanagan and Syed, 2011; Lohila et al., 2011), but also emit CO<sub>2</sub> and methane (CH<sub>4</sub>) through aerobic and anaerobic respiration (Wieder and Vitt, 2006; Jauhainen et al., 2012; Brown et al., 2014; Budishchev et al., 2014; Treat et al., 2014; Zheng et al., 2014), acting as large sources of particulate and dissolved organic carbon (DOC) to downstream ecosystems (Armstrong et al., 2013; Olefeldt and Roulet, 2014). The carbon balance of peatlands is determined by the joint effect of frequently changing biogeochemical processes of

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photosynthesis and respiration, so the peat carbon sequestration often shows great fluctuation over a wide range of timescales. Peat core data indicated that carbon accumulation rate varies over millennial (Frolking and Roulet, 2007; Yu et al., 2010), centennial (Craft and Richardson, 1998; Malmer and Wallén, 2004; Ali et al., 2008) and decadal timescales (Craft and Richardson, 1998; Wieder, 2001; Gao et al., 2010; Loisel and Yu, 2013), which can be attributable to many factors, such as climate change (Ise et al., 2008; Cai et al., 2010; Yu, 2011), geological and human disturbances (Yu et al., 2010; Hooijer et al., 2010), landscape morphology (Belyea and Baird, 2006) and self-regulation mechanisms (Wu, 2012). Overall, climate change, which is ubiquitous in the whole world, turns out to be a crucial element in determining carbon accumulation rate of peatlands over different timescales (Friedlingstein et al., 2006; Cai et al., 2010; Yu et al., 2010). A large area of northern peatlands is considered to be severely affected by climate warming (Kettles and Tarnocai, 1999) and water table drawdown during the growing season (Solomon et al., 2007). The changed temperature and precipitation can radically alter the carbon cycle processes of peatland ecosystems (Conant et al., 2008; Dise and Phoenix, 2011; Turetsky et al., 2011).

Undisturbed peatlands serve as persistent carbon sink and are estimated to sequester approximately 20–30 g C m<sup>-2</sup> yr<sup>-1</sup> over thousands of years (Turunen et al., 2002; Roulet et al., 2007; Yu et al., 2010), mainly due to their extremely low decomposition rate of organic matters under the waterlogged and extremely cold soil conditions (Wieder and Vitt, 2006), which makes the organic matter inputs through assimilation exceed the outputs via mineralization. In this regard, the carbon sequestration capacity of peatlands is very sensitive to alterations of temperature and precipitation. Carbon balance can be challenged under projected climate change, further influencing regional C budget and climate system, with the magnitude of such feedback still uncertain.

Understanding the response of carbon cycling of peatlands to climate change is crucial for predicting their feedback to future alterations of climate systems. In northern peatlands, flux measurements and models suggested that climate warming can reduce the carbon accumulation of peatlands by accelerating respiration from surface and subsurface soils (Dorrepaal et al., 2009; Wu, 2012), stimulating the export of DOC from peatlands (Freeman et al., 2001; Frey and Smith, 2005) and enhancing CH<sub>4</sub> emission,

especially in growing season (Ward et al., 2013). On the other hand, other studies suggested that warming can promote carbon sequestration in peatlands through elongation of growing season and increase in nutrient availability (Ali et al., 2008; Klein et al., 2013). Overall, the diverse responses of peatlands to climate warming make it challenging to predict whether the increased primary production induced by climate change can be offset by corresponding enhanced carbon release through respiration.

Compared to low altitude/latitude regions, high altitude/latitude ones have experienced more pronounced climate change (Solomon et al., 2007). The Qinghai–Tibetan Plateau (QTP), as the ‘third pole’ of the Earth, is the largest (2.5 million km<sup>2</sup>) and highest (4000 m a.s.l.) plateau in the world. In the past 50 years, the whole QTP has experienced a significant warming (with an increase of 0.2 °C per decade) and an overall slight decrease in precipitation with high inter-annual variations (Chen et al., 2013). Hitherto, many studies have focused on the long-term C sequestration of peatlands on the Zoige Plateau, the Northeast part of QTP (Sun et al., 2001; Zhao et al., 2011; Zhou et al., 2011). Very recently, some authors even have tried to identify the controlling factors for C accumulation dynamics during the Holocene (Wang et al., 2014; Zhao et al., 2014). However, limited attention has been paid to the carbon fate of modern peats. As we know, carbon stored in surface peats is exposed to climate variables and thus significantly affected by climate change. In addition, plant production and short-time peat decay largely determine the amount of carbon that eventually contributes to the long-term peat store. Therefore, to assess the impact of global warming on the structure and function of peatlands on the QTP, it is important to document the climate sensitivity of these short-term C flux terms. In this paper, we tried to determine the peat C addition and decomposition rates of seven alpine bogs on the Zoige Plateau by combining empirical peat core data (Cs<sup>137</sup> and C<sup>14</sup>) and peatland carbon dynamics modeling. We estimated the recent peat C accumulation rate and directly compared the expected recent C accumulation rate with the Holocene C addition rate at the regional scale. We hypothesized that the C accumulation rate is decreasing in recent decades. Bogs are precipitation-sensitive ecosystems since their only water source is precipitation, so they are prone to be dry in recent decades with increasing temperature and decreasing precipitation (Chen et al., 2014). We speculated that the warmer and drier climate would

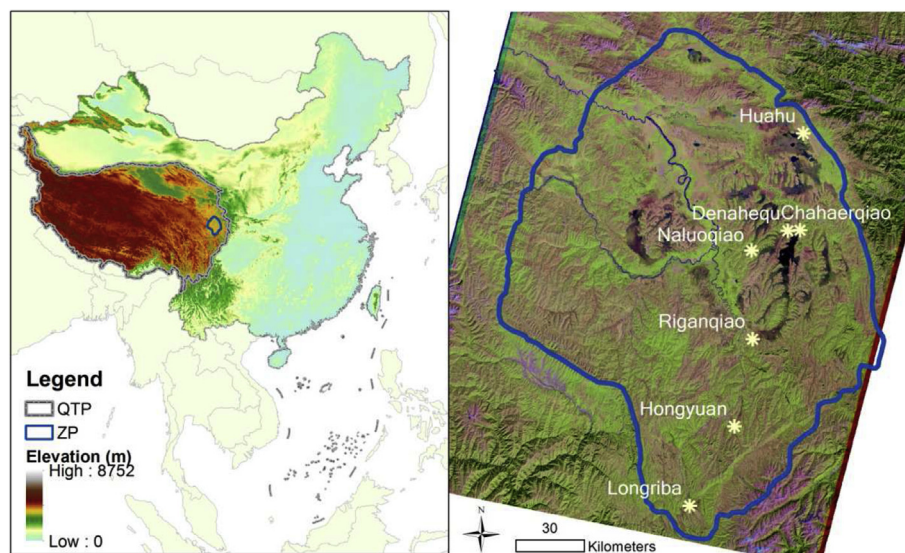


Fig. 1. Location of the sampling sites.

accelerate the peat decomposition and correspondingly diminish C sequestration directly or indirectly via exposing a lot of peats to aerobic conditions. This weaker C sequestration of the alpine peatlands would exert a positive feedback to the current warming climate systems.

## 2. Material and methods

### 2.1. Study area and selection of field sites

The Zoige Plateau (101°30′–103°30′E, 32°20′–34°00′N, 3400 m a.s.l.) covers an area of approximately 4600 km<sup>2</sup> peatlands, which are regarded as the highest and largest peatlands worldwide. This region belongs to the cold Qinghai–Tibetan climatic zone, with the mean annual temperature about 1.5 °C and the mean annual precipitation 720 mm. During the past four decades, its climate showed a significant heating and a slight drying trend (raw data from the Information Center of China Meteorological Administration [<http://www.nmic.gov.cn/>]) (Fig. 2). The detail information about this study site is described in our recently published paper (Chen et al., 2014).

During May and June 2012, we selected seven peatland sites along the altitude on the Zoige Plateau (Fig. 1). The detail of the sampling sites is available in our recent published paper (Chen et al., 2014). Among them, there are five alluvial plain peatlands, one lacustrine plain peatland and one mountain valley peatland. The water table level of these selected sites ranged from –160 to –10 cm during the sampling period. The dominant species are *Carex lasiocarpa*, *Carex muliensis*, *Carex meyeriana* for wetter peatlands (water table level above –35 cm) and *Blysmus sinocompressus*, *Kobresia tibetica* for drier peatlands (water table level below –115 cm) (Table 1).

### 2.2. Peat core sampling and analyses

For each of the seven sites we sampled at five study points along a 1.5–2.5 km transect, with the distance of between the study points as 300–500 m. A peat sampler (8 cm in diameter, 80 cm in length) was used to measure the peat depth of each study point. For analysis of <sup>137</sup>Cs activities, we collected the peat samples at 2 cm intervals in the top 30 cm soil. For <sup>14</sup>C analysis, we collected the

peat sample every 10 cm in the top 80 cm soil, and every 20 cm for peat soils below 80 cm.

### 2.3. Dating

In this study, we used 15 peat samples from each site for the analysis of <sup>137</sup>Cs activities. The peat samples were weighted (for bulk density), ground, and passed through a 2-mm mesh diameter sieve. The activity of <sup>137</sup>Cs was determined by the gamma emissions at 661.61 ke V, which was measured by a germanium dictator (2.08% efficiency, EG & G Oretec, Oak Ridge, TN) (Craft and Richardson, 1998). We chose 16 samples from centre cores for <sup>14</sup>C dating by using accelerator mass spectrometry (AMS) in Beta Analytic Radiocarbon Dating Laboratory at Florida <http://radiocarbon.com/index.htm>. AMS dating materials were root-free, handpicked and cleaned with distilled water, without any carbonates, bacterial CO<sub>2</sub> and humic/fulvic acids. A fraction of homogenized sample was used for radiocarbon dating (Piotrowska et al., 2010). Calendar-calibrated dates were generated based on the INTCAL09 database [Beta Analytic Radiocarbon Dating Laboratory: <http://radiocarbon.com/index.htm>(Talma and Vogel, 1993)].

### 2.4. Data analyses

#### 2.4.1. Carbon content and dry bulk density

All the peat core intervals were transported in zip-lock bags to the laboratory and air-dried. Contiguous subsamples of peat were analyzed for C content (Multi N/C 2100S, Jena, Germany), air-dry bulk density [dry weight (g)/field volume (cm<sup>3</sup>)] and C density (mean bulk density × C content % × 0.01). Mean bulk density and C content were calculated based on the value of all samples along the same profile.

#### 2.4.2. Accumulation rates

Recent carbon accumulation rates (RCAR) and the long-term apparent C accumulation rates (LCAR) were calculated with the following equations:

$RCAR (g C m^{-2} yr^{-1}) = [dmax/(a \times 1000)] \times n \times c$ ;  $LCAR = r/1000 \times n \times c$ . where  $r$  is peat accumulation rate (mm yr<sup>-1</sup>);  $n$  is dry bulk density (g m<sup>-3</sup>);  $c$  is C content (g C g<sup>-1</sup> dry weight);  $a$  is the

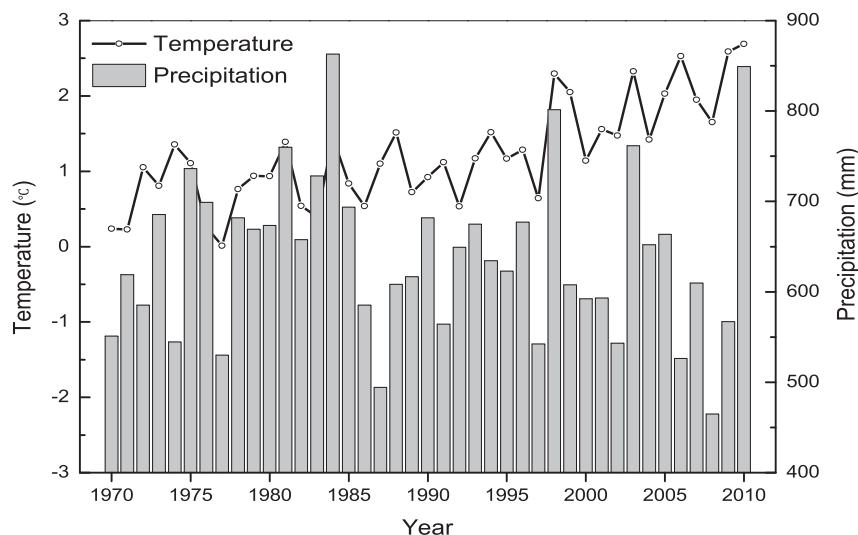


Fig. 2. Temperature and precipitation data of the study area during the last four decades.

**Table 1**  
Peat samples and characteristics of the study sites.

Study site	Location	Elevation (m)	No. of cores	No. of <sup>14</sup> C dating cores	Sample depth	<sup>14</sup> C dates (year BP)	Calibrated age (cal year BP)	Water table depth (cm)	Dominant species	Peatland type
Huahu	E102°52'08" N33°55'08"	3434	10	4	90–100	2090 ± 30	2095 (2080–2110)	–10	Carex lasiocarpa	Lacustrine plain peatland
					190–200	3650 ± 30	4055 (4050–4060)		Carex muliensis	
					280–290	5770 ± 30	6650 (6650–6650)			
Chahaerqiao	E102°51'50" N33°32'13"	3444	10	2	350–360	9440 ± 40	10,645 (10,560–10,730)	–15	Carex lasiocarpa	Old channel gully peatland
					80–90	2410 ± 30	2405 (2340–2470)		Carex muliensis,	
					150–160	4920 ± 30	5700 (5690–5710)		Carex meyeriana	
Denahequ	E102°48'24" N33°32'01"	3444	10	2	90–100	5720 ± 40	6595 (6590–6600)	–115	B. sinocompressus	Flood plain peatland
					190–200	8960 ± 40	10,155 (10,110–10,200)		K. tibetica	
Naluoqiao	E102°38'16" N33°27'12"	3469	6	2	90–100	1770 ± 30	1635 (1560–1710)	–16		Downed gully peatland
					190–200	2740 ± 30	2810 (2760–2860)			
Riganqiao	E102°39'08" N33°06'15"	3471	6	4	90–100	3840 ± 30	4340 (4330–4350)	–35	Carex meyeriana	Subsidence gully peatland
					560–570	10,700 ± 50	12,605 (12,560–12,650)			
					210–220	3400 ± 30	3625 (3560–3690)			
Hongyuan	E102°34'36" N32°45'28"	3551	4	1	300–310	4420 ± 30	4950 (4860–5040)	–135		Mountain valley peatland
					80–90	4330 ± 30	4850 (4830–4870)			
Longriba	E102°22'34" N32°26'28"	3580	10	1	170–180	12,290 ± 60	14,095 (13,980–14,210)	–160	K. tibetica, Carex meyeriana	River terraces peatlands

number of years between 1963 and 2012 (50a);  $d_{max}$  is the peat depth where the maximum value of <sup>137</sup>Cs appears.

#### 2.4.3. Models for peat accumulation and decomposition

The exponential decay model (Clymo, 1984) and the peatland C flux reconstruction model (Yu, 2011) were used to estimate the peat C fluxes during the Holocene. The exponential decay model, which is originated from the formulae of  $dM/dt = p - a \cdot M$ , can be presented as  $M = (p/a) \cdot (1 - e^{-at})$ . This model is based on the assumption that  $p$  and  $a$  remain constant over time.  $M$  is the observed cumulative carbon pool;  $t$  is the age before present;  $a$  is peat carbon decay coefficients;  $p$  is peat carbon addition rate. We used Sigma Plot version 12 to derive  $p$  and  $a$  according to the observed cumulative peat C pool. The peatland C flux reconstruction model was based on the following formulae:  $NCU_t = NCP_t / e^{-at}$ ;  $NCR_t = \sum(NCP_k / e^{-at} - NCP_k / e^{-a(t-1)})$  (Yu, 2011). We model  $NCU$  (the initial peat C input) and  $NCR$  [the summed C emission of all peat cohorts ( $k$ ) older than time ( $t$ ) over each time interval according to the observed  $NCP$  (net carbon pool) and modeled decay coefficient ( $a$ )]. The detailed definition and explanation of these peatland C flux terms is available in Yu (2011).

### 3. Results

#### 3.1. Dry bulk density and organic C content

The average air-dry peat bulk density was 0.38 (ranging from 0.28 to 0.48)  $g\ cm^{-3}$  for modern peats, comparable to the mean Holocene value of 0.39 (ranging from 0.20 to 0.50)  $g\ cm^{-3}$ . The C content of modern peats was 240 (ranging from 160 to 280)  $g\ kg^{-1}$ , higher than that of 198 (ranging from 155 to 272)  $g\ kg^{-1}$  for their Holocene counterparts (Table 2).

#### 3.2. Peat accumulation rate and C accumulation rate

The distribution of <sup>137</sup>Cs with depth revealed well-developed peaks in all seven sampling sites. The peak value of <sup>137</sup>Cs appeared at 2–8 cm (Fig. 3), consistent with that of 1963. Correspondingly, the recent peat accumulation rate ranged from 0.4 to 1.6  $mm\ yr^{-1}$ , with the mean value of 0.9  $mm\ yr^{-1}$ , higher than the 0.3  $mm\ yr^{-1}$  Holocene peat accumulation rate. The peat carbon accumulation rate over recent decades averaged 75  $g\ m^{-2}\ yr^{-1}$

(ranging from 35 to 123  $g\ m^{-2}\ yr^{-1}$ ), higher than the Holocene mean value of 19  $g\ m^{-2}\ yr^{-1}$  (ranging from 7 to 30  $g\ m^{-2}\ yr^{-1}$ ) (Table 2).

#### 3.3. Modeled litter input and peat loss patterns

Based on the exponential decay model about Huahu, the carbon addition rate ( $p$ ) was  $25 \pm 4\ g\ C\ m^{-2}\ yr^{-1}$ , with the decay coefficient ( $a$ )  $0.00007\ yr^{-1}$  over the last 10 ka (Fig. 4). The NCU rate for Huahu peat core was  $25\ g\ C\ m^{-2}\ yr^{-1}$ , ranging from 18 to 37  $g\ C\ m^{-2}\ yr^{-1}$ ; its NCR increased from 0.15 to 15.53  $g\ C\ m^{-2}\ yr^{-1}$ , indicating that nearly 16  $g$  of subsurface carbon was involved in modern carbon cycling per year in recent years (Fig. 5). Because we did not have enough data to model the decay coefficient ( $a$ ) to reconstruct accurate NCU for the other sites, we estimated their NCU by assuming that they had the same decay coefficient ( $a$ ) with Huahu peat core. The remaining modern peat masses after 25, 50 and 100 yr decomposition were assumed to be equivalent to 60%, 44.4% and 29.6%, respectively, of the initial mass (Loisel and Yu, 2013). Assuming the surface peat decay rate of QTP peatlands as  $0.0244\ yr^{-1}$  reported by Loisel and Yu (2013), we used the recent C accumulation rate obtained from peat cores, which represents the remaining C mass after 25 yr decomposition, to back calculate the initial peat C mass. Therefore, the initial peat C mass was  $125\ g\ m^{-2}\ yr^{-1}$  (ranging from 58 to 205  $g\ m^{-2}\ yr^{-1}$ ), the remaining C mass after 50 yr decomposition being  $56\ g\ m^{-2}\ yr^{-1}$  (ranging from 26 to 91  $g\ m^{-2}\ yr^{-1}$ ), and that after 100 yr decomposition being  $37\ g\ m^{-2}\ yr^{-1}$  (ranging from 17 to 61  $g\ m^{-2}\ yr^{-1}$ ), which was 5.3, 2.3 and 1.6 times respectively higher than their modeled NCU (Table 3). However, the remaining C mass after 100 yr decomposition was 0.7 and 0.8 times that of their modeled NCU for Denahequ and Hongyuan peat core, respectively (Table 3).

### 4. Discussion

#### 4.1. Peat carbon accumulation rate on the Zoige Plateau during Holocene and the recent decades

According to this study, the average peat C accumulation rate throughout Holocene ranged from 8 to 32  $g\ C\ m^{-2}$ , indicating great variations among different peat sites. Our synthesis data showed that the peat C accumulation rate in Zoige was  $33\ g\ C\ m^{-2}\ yr^{-1}$

**Table 2**  
Characteristics and peat C accumulation rate of seven sampling peatlands.

	Peat core	Bulk density ( $\text{g cm}^{-3}$ )		C Content ( $\text{g kg}^{-1}$ )		Peat accumulation rate ( $\text{mm yr}^{-1}$ )		C accumulation rate ( $\text{g m}^{-2} \text{yr}^{-1}$ )	
		Long-term	Recent	Long-term	Recent	Long-term	Recent	Long-term	Recent
Wetter peatlands	Huahu	0.40	0.48	186	160	0.37	1.6	19	123
	Chaha'erqiao	0.45	0.40	155	280	0.28	0.8	15	90
	Naluoqiao	0.34	0.40	194	250	0.72	0.8	30	80
	Riganqiao	0.20	0.37	272	240	0.52	1.2	23	107
Drier peatlands	Denahequ	0.50	0.42	165	250	0.21	0.4	23	42
	Hongyuan	0.49	0.31	204	280	0.18	0.4	16	35
	Longriba	0.37	0.28	209	220	0.12	0.8	7	49

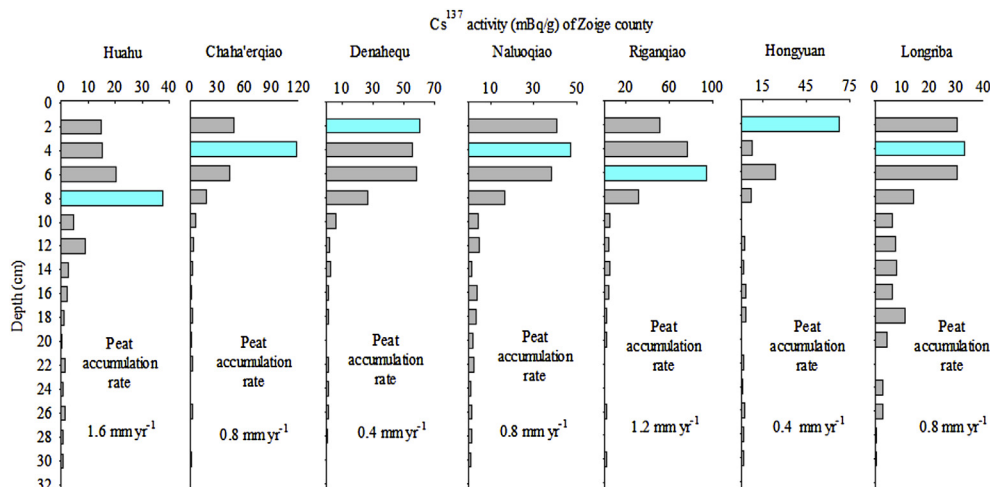
(Fig. 7C), which was comparable to the highest value in Huahu peat core ( $32 \text{ g C m}^{-2}$ ) but higher than the average value. The higher value in our synthesis result was probably because the synthesis was based on peatlands with higher C accumulation rate, and no direct bulk density or C content value was used in the estimation. The recent carbon accumulation rate ranged from 35 to  $123 \text{ g C m}^{-2} \text{yr}^{-1}$ , with a mean value of  $75 \text{ g C m}^{-2} \text{yr}^{-1}$ , which was comparable to the values of boreal peatlands (Table 4). The recent C accumulation rate was  $96.8 \text{ g C m}^{-2} \text{yr}^{-1}$  for Central Alaska (Loisel and Garneau, 2010),  $40.0\text{--}117.0 \text{ g C m}^{-2} \text{yr}^{-1}$  for peatlands in eastern Canada and  $83.5 \text{ g C m}^{-2} \text{yr}^{-1}$  for peatlands in western Canada (Turunen et al., 2004; Bauer et al., 2009), all results yielded with  $^{210}\text{Pb}$  dating technique.

In early 1970s on the Zoige Plateau, about 380 km of canals were drained for agriculture and grazing, resulting in a large area of dried peatlands (Zhang et al., 2011). The recent C accumulation rate of the drier peatlands was  $42 (35\text{--}49) \text{ g C m}^{-2} \text{yr}^{-1}$ , only 42% that of  $100 (80\text{--}123) \text{ g C m}^{-2} \text{yr}^{-1}$  for wetter peatlands, which was comparable to  $104 \text{ g C m}^{-2} \text{yr}^{-1}$  based on  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  techniques in a previous study (Gao et al., 2010). The difference of recent C accumulation between drier and wetter peatlands was attributable to the difference in water conditions. The RCAR was shown to be closely related with the water table level ( $R^2 = 0.761$ ,  $P = 0.01$ ) (Fig. 6). Thus, drainage dried peatlands and caused carbon loss from the alpine peatlands, which was similar to the conclusion of previous studies that drained peatlands were large C sources to atmosphere (Hooijer et al., 2010; Simola et al., 2012). However, a study based on eddy covariance method suggested that drainage significantly increased the  $\text{CO}_2$  uptake rate in a drained nutrient-poor peatland in southern Finland (Lohila et al., 2011). The drainage intensity was

probably an important explaining factor. Drainage has resulted in a mean water table level of  $-135 \text{ cm}$  for the peatlands on the QTP (Table 1), much lower than that of  $-40 \text{ cm}$  at Kalevansuo in the study of Lohila et al. (2011). Such small drawdown at Kalevansuo obviously enhanced the tree growth, which can offset the increased carbon loss through mineralization. However, the obvious water table drawdown in Zoige has inhibited the growth of plants due to limited available water, and resulted in a decline in the carbon sequestration in drained peatlands.

#### 4.2. Comparison between recent and past carbon sequestrations

This study found that the recent carbon accumulation rate was higher than the mean carbon accumulation rate during the Holocene, similar to the previous conclusions from boreal peatlands based on  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  techniques (Tolonen and Turunen, 1996; Craft and Richardson, 1998; Turunen et al., 2004; Ali et al., 2008; Klein et al., 2013; Loisel and Yu, 2013). Most of the previous studies attributed the relative high recent CAR to less peat decomposition of modern peat. However, Loisel and Yu (2013) demonstrated that the carbon accumulation rate over recent decades was still higher than the late-Holocene average value, even when the peat decomposition history was taken into consideration. Similarly, with decomposition of recently accumulated peats included in calculation, our results indicated that the expected peat C accumulation rate in recent decades was still higher than their counterparts during the whole Holocene. Our synthesis data showed that the average late-Holocene ( $0\text{--}4 \text{ ka}$ ) carbon accumulation rate was  $27 \text{ g C m}^{-2} \text{yr}^{-1}$ , lower than the average value of  $33 \text{ g C m}^{-2} \text{yr}^{-1}$  for the whole Holocene due to lower summer



**Fig. 3.** Depth versus radioisotope results for  $^{137}\text{Cs}$  in Zoige peatlands.

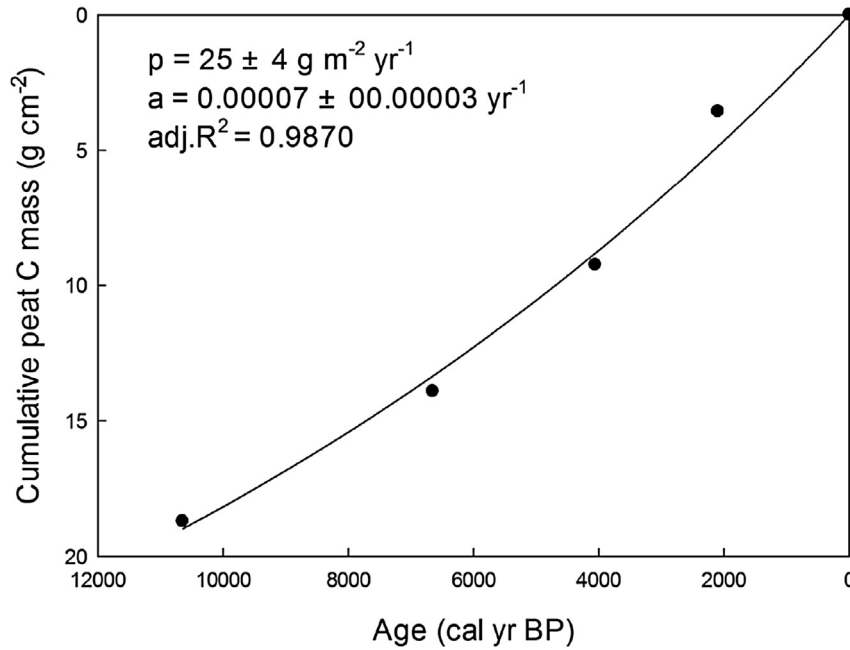


Fig. 4. Exponential decay modeling results from Huahu peat core.

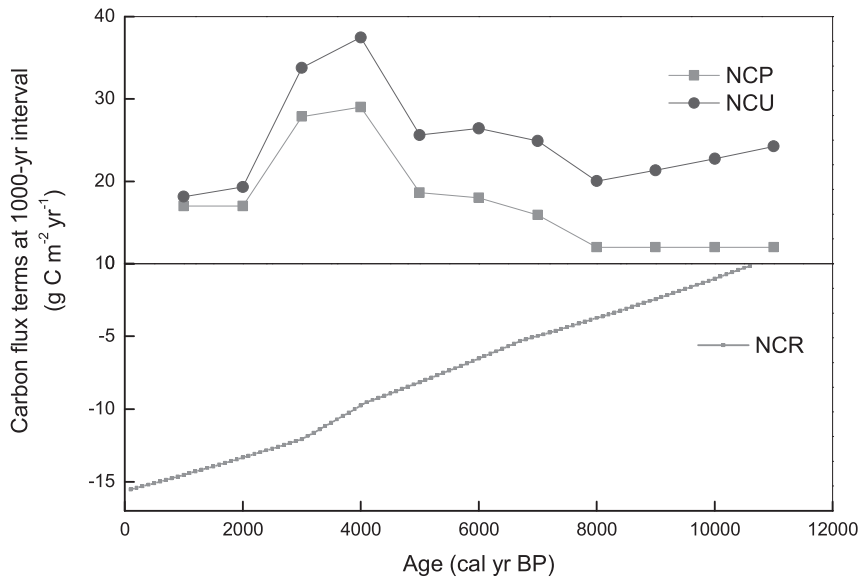


Fig. 5. Peat carbon fluxes for Huahu peat core during the Holocene, as modeled using the peatland C flux reconstruction model. The net C pool (NCP) represents today's peat stock as reconstructed peat cores; the net C uptake (NCU) represents the average annual peat C flux that entered the peat subsurface over the past 10,000 years; and the net C release (NCR) represents the summed C release of all peat cohorts over time.

insolation and weaker summer monsoon (Fig. 7) (Wang et al., 2014). Therefore, the expected carbon accumulation rate during recent decades was higher than that in the late-Holocene, probably in response to warmer climate in recent decades. Climate warming in recent decades resulted in a longer and warmer growing season (Zhang et al., 2013), which might favor peat C accumulation by promoting net primary production. It was found that throughout the northern hemisphere the peat C accumulation rate over the last millennium was positively related with the photosynthetically active radiation (PAR) and growing season length (Charman et al., 2013). Similarly, the peak peatland initiation and peat C sequestration occurred at the Holocene Thermal Maximum (HTM) period

in Zoige (Fig. 6), in line with the previous study (Sun et al., 1998; Wang et al., 2014; Zhao et al., 2014). Also, a study indicated that warming in recent decades increased the height, coverage and corresponding aboveground biomass of vegetation on the QTP (Zhou et al., 2000). Although warming may also accelerate C decomposition, the increased carbon loss through such decomposition was outweighed by the increased NPP (net primary productivity) induced by climate warming. Peatland models have similarly reported an overall positive effect of higher temperatures on peat C sequestration (Frolking et al., 2001). These results clearly indicated that recent warming-induced increase in NPP can potentially increase peat C sequestration in wetter peatlands on the

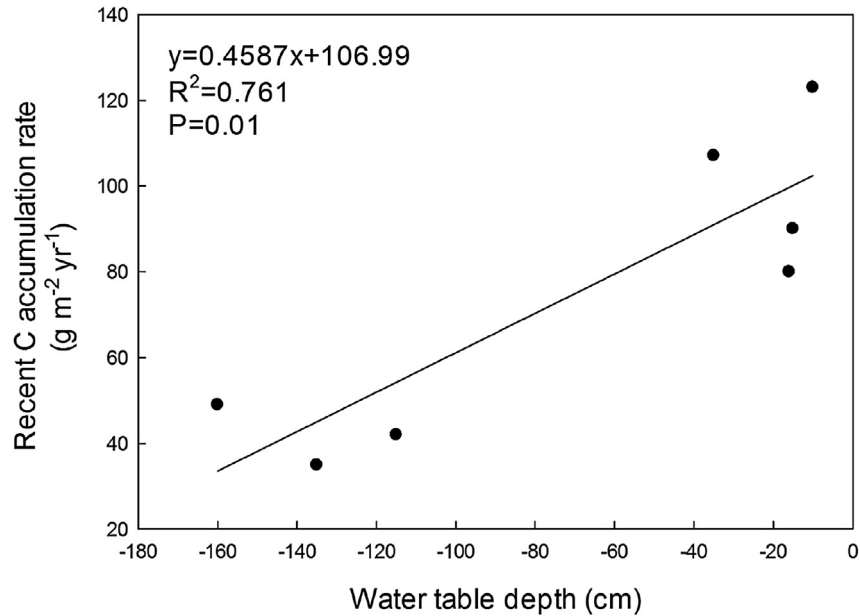


Fig. 6. Relationship between recent C accumulation rate and water table depth.

Table 3

Comparison between the expected C accumulation rate after 50–100 yr decomposition and the net peat C uptake rate (NCU).

Site	Remaining C mass ( $\text{g m}^{-2} \text{yr}^{-1}$ )			NCU ( $\text{g m}^{-2} \text{yr}^{-1}$ )
	Initial input	50 yr after	100 yr after	
Huahu	205	91	61	25
Chahaer qiao	150	67	44	18
Denahequ	70	31	21	30
Naluoqiao	133	59	39	33
Riganqiao	178	79	53	29
Hongyuan	58	26	17	20
Longriba	82	36	24	11

QTP. In addition, changes in vegetation composition induced by climate warming may be another factor contributing to the recent increase in C sequestration of the peatlands on the QTP. A warming experiment in the alpine wetland of northeastern QTP showed that warming resulted in the increase of grass and sedge species, and the corresponding decrease in forb species (Zhou et al., 2000). According to the study of Cornelissen et al. (2007), forbs decompose faster than grass and sedges do (Dorrepaal et al., 2005; Cornelissen et al., 2007). The warming-induced changes of species composition could benefit peat C accumulation on the QTP.

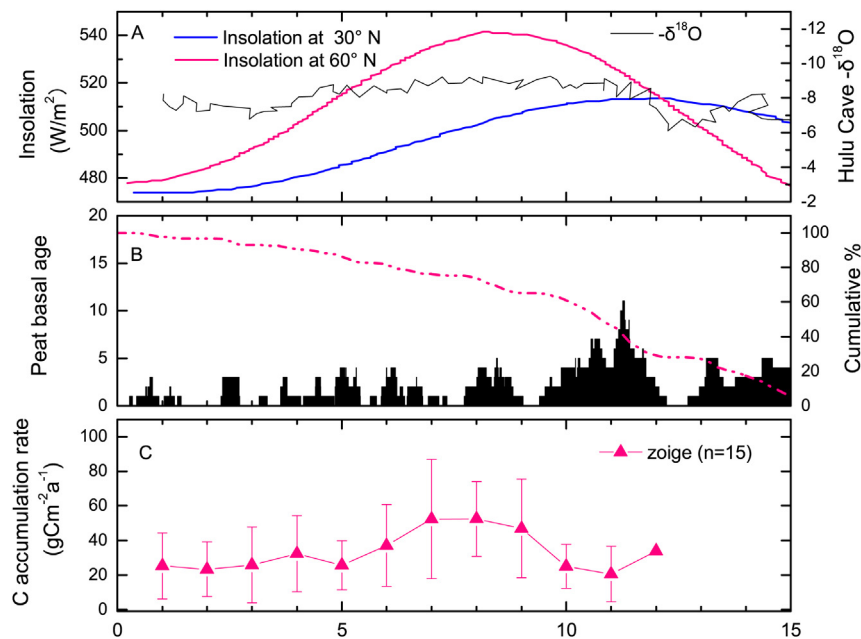


Fig. 7. Zoige peatland records since the Holocene (A) Summer insolation at  $30^{\circ} \text{N}$  (blue curve) and at  $60^{\circ} \text{N}$  (red curve) (Berger and Loutre, 1991), and the oxygen isotope record at Hulu Cave (black curve) (Wang et al., 2001). (B) Peat basal ages plotted as calibrated age frequency (bars) and cumulative percentage (dotted line) for peatlands in Zoige ( $n = 87$ ); (C) Average peat carbon accumulation rates ( $\text{g C m}^{-2} \text{yr}^{-1}$ ) at 1000-year bins (showing means of the bins from various sites in a region and standard errors of the means) for peatlands in Zoige ( $n = 15$ ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 4**  
Comparison of the recent C accumulation rate ( $\text{g C m}^{-2} \text{yr}^{-1}$ ) between Zoige and boreal peatlands.

	Location	Rerca	Dating method	Source
Alpine peatlands	Zoige	75 (35–123)	$^{137}\text{Cs}$	This study
		113	$^{210}\text{Pb}$ , $^{137}\text{Cs}$	Gao et al., 2010.
Boreal peatlands	Central	97	$^{210}\text{Pb}$	Loisel and Yu, 2013.
	Alaska			
	Eastern	40–117	$^{210}\text{Pb}$	Turunen et al., 2004.
	Canada			
	Western	83.5	$^{210}\text{Pb}$	Bauer et al. 2009.
	Canada			

In contrast to that of wetter peatlands, the C accumulation rate decreased in recent decades at the Hongyuan and Denahequ peat sites with extremely low water table level due to drainage for agriculture and grazing nearly 40 years ago (Zhang et al., 2011). Drainage draws down the water table, exposing a quantity of peats to oxygen conditions, directly causing large amount of C loss from peat soil by accelerating peat decomposition (Zhang et al., 2011). In addition, drainage can also lead to decrease in peat C sequestration indirectly by making peatlands much more available for grazing. A quick expansion of the livestock population, quadrupling from  $5.8 \times 10^5$  to  $2.3 \times 10^6$ , was found during 1958 and 2002 (Zhang et al., 2011). It was suggested that over-grazing can reduce peat C sequestration mainly by decreasing organic matter input (Liu and Bai, 2006). Several works suggested that overgrazing caused obvious decline of plant production and corresponding organic matter input to the soil (Nieveen et al., 2005; Ward et al., 2007). Besides, climate warming can also affect peat C sequestration in dried peatlands (Hu et al., 2012). The changed hydrology condition after drainage probably causes limited water availability for plant growth, thereby making the drained peatland more sensitive to climate warming. Although climate warming can elongate growing season (Zhang et al., 2013), it can also increase evaporation, aggravating water depletion of heavily drained peatlands and thus suppress plant growth due to water deficit (Xiao et al., 2009). Overall, the positive effect of high temperature and solar radiation cannot balance the negative effect caused by water limit, thereby resulting in a reduction of peat C accumulation rate. Our result indicated that the increase or decrease in peat C accumulation rate depended heavily on the water regime of peatlands, which was in line with the conclusions that warming can enhance the C sink of ecosystems in good water condition but decrease the C sequestration of water-limited ecosystems (Zhang et al., 2013).

#### 4.3. Carbon sequestration of peatlands over recent decades

Peatlands on the Zoige Plateau cover a total area of 4605  $\text{km}^2$  (Sun, 1992) and the pristine one accounts for about 3179  $\text{km}^2$  (Chen et al., 2014). Therefore, the area of degraded one was 1426  $\text{km}^2$ . According to our calculation based on soil bulk density and carbon concentration, the pristine (wetter) and degraded (drier) peatlands have accumulated 17 Tg C and 3 Tg C respectively since 1963. Thus the total Zoige peat C accumulation was 20 Tg C in recent decades, comprising 4% of the total peat carbon stock (0.477 Pg) in Zoige. The newly accumulated peat C on the Zoige Plateau was 0.4 Tg C  $\text{yr}^{-1}$  in recent decades. However, it is still uncertain whether peatlands have acted as carbon sink or source in recent decades, since we failed to consider the C decomposition of older peats from sub-surface. Moreover, climate change may challenge the C sequestration potential of peatlands. Warming can enhance the potential evapotranspiration and potentially reduce water supply from

glacier melting of peatlands (Zhang et al., 2013). Meanwhile, the QTP may experience a decrease of precipitation, receiving less rain in the future (Solomon et al., 2007). Thus, the drying tendency may lead to degradation of an increasing area of peatlands. In that case, the decrease in carbon sequestration of drier peatlands may outweigh the increase in the remaining wetter peatlands, probably resulting in a decrease in the peat C sequestration. Therefore, in order to accurately estimate and predict the present and future carbon sequestration of peatlands in Zoige under the projected climate change and human activities, much more detailed studies are needed. Firstly, how alterations of temperature and precipitation affect the hydrological condition of peatlands should be studied to estimate the area change of drier peatlands caused by climate change, and to further predict the carbon sequestration on the whole plateau. Future work also should be focused on the microbial enzyme activities related to the C cycle of peatlands (Turner and Joseph Wright, 2014). Also worth of research are the variations of vegetation community which can influence the carbon cycle of peatlands by determining the quality and quantity of organic matter into peat soils for decomposition (Weltzin et al., 2000; Strack et al., 2006).

## 5. Conclusions and implications

This is the first study estimating the regional carbon accumulation rate during recent decades and directly comparing it with the Holocene long-term accumulation estimate for the same peatlands on the Zoige Plateau based on detailed field measurements at representative sites. The C accumulation rate of peatlands on the Zoige Plateau during the recent decades ranged from 35 to 123  $\text{g C m}^{-2} \text{yr}^{-1}$ , with a mean value of 75  $\text{g C m}^{-2} \text{yr}^{-1}$ , nearly four times the average of 19 (ranging from 7 to 30)  $\text{g C m}^{-2} \text{yr}^{-1}$  throughout the whole Holocene. Even when taking into consideration the decomposition of peats accumulated in recent decades and during the Holocene, the average peat C accumulation for the recent decades was still higher than that for the whole Holocene. Moreover, the water table level influences recent peat C accumulation, resulting in heterogeneous peatland responses to climate warming, indicating that peatland hydrology is a primary control on recent C accumulation rates. Overall, recent climate warming may increase carbon sequestration of wetter peatlands but decrease that of drier ones. Therefore, human activities like drainage which alter the peatland water regime may have significant effect on the carbon sequestration capacity of peatlands.

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