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The carbon stock of alpine peatlands on the Qinghai–Tibetan Plateau during the Holocene and their future fate

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ABSTRACT

Most studies about carbon dynamics of peatlands have been focused on boreal, subarctic and tropical peatlands. However, there is limited data about carbon dynamics of alpine peatlands, like Zoige peatlands on the Qinghai–Tibetan Plateau (QTP), which are sensitive to climate change and human disturbance. We studied the role of these peat deposits on the Zoige as a C reserve and sink by measuring peat depth, radiocarbon age and peat and C accumulation rates at 7 sites. The peat depths of the sample sites ranged from 0.20 to 6.0 m; the basal age on the plateau varied from 1635 to 14095 cal yr BP; the peat accumulation rates ranged from 0.12 to 0.85 mm yr^{-1}, and the C accumulation rates from 5 to 48 g m^{-2} yr^{-1}. Based on data of field studies and remote sensing, we regarded that with 3179 km^2 of intact peatlands, about 1426 km^2 of degraded peatlands, and the total area of Zoige peatlands was 4605 km^2. The current peat C stock of Zoige peatlands was0.477 Pg (ranging from 0.206 to 0.672 Pg). We also estimated that peatlands covered an area of about 5091 km^2on the QTP and sequestered 0.543 Pg C, 88% in Zoige and the rest in other parts of the plateau. Human activities, together with the ubiquitous warming on the plateau (temperature increased by 0.2 °C per decade over the past 50 years) not only shrank the area of intact peatlands, but also caused substantial carbon releasing from peatlands.

1. Introduction

Though covering only 3% of the Earth's land surface, peatlands stores 15–30% of the total world soil carbon pool(Gorham, 1991; Turunen et al., 2002; Limpens et al., 2008), accumulating more than 600 Pg carbon since the Last Glacial Maximum(Yu et al., 2010). Undisturbed peatlands are presently a consistent sink of carbon dioxide (CO_2) (Roulet, 2000), a source of methane (CH_4), approximately 10% of the global CH_4 sources (Roulet, 2000; Mikaloff Fletcher et al., 2004) and at the same time sources of particulate

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and dissolved organic carbon to the nearby watershed landscape (Billett et al., 2004, 2011, 2012). However, if peatlands were destabilized by climate warming, land use change, or other disturbances (e.g. fires), the proportion of carbon stored in them would be emitted to the atmosphere (Page et al., 2002; Ward et al., 2007, 2012). As a result, though peatlands have contributed to global cooling for millennia (Roulet et al., 2007), it is uncertain whether their cooling function will continue or even shift to warming. The cooling or warming role of peatlands depends on their carbon balance under intensified global change and anthropogenic activities (Moore et al., 1998; Limpens et al., 2008). For a very long time most of studies about carbon dynamics have been focused on boreal and subarctic peatlands (Gorham, 1991; Moore et al., 1998; Turunen et al., 2002; Roulet et al., 2007; Billett et al., 2011; Yu, 2012), though during the last decade carbon dynamics of tropical peatlands have also become an issue of global importance (Page et al., 2002, 2011; Jauhiainen et al., 2012; Lähteenoja et al., 2012). However, there is limited data about carbon dynamics of alpine peatlands, like peatlands on the Qinghai–Tibetan Plateau (QTP), which are sensitive to climate change and human disturbance. Due to great uncertainties in carbon dynamics and limited data for some specific peatlands worldwide, peatlands are not explicitly included in global climate models (Solomon et al., 2007; Wu, 2012).

As the "third pole" of the Earth (average elevation 4000 m a.s.l.) and the world's largest plateau, with a size of about 2.5 million km^2 (a quarter of the area of China), the QTP and its peatlands receive much less attention than their counterparts in the boreal and tropical regions. Though the world's highest peatland was found in Zhongba (4600 m a.s.l.) on the plateau (Song et al., 1985), most previous studies on peatlands of QTP were usually located on the Zoige Plateau (av. 3400 m a.s.l., Fig. 1), which is a complete and orbicular plateau surrounded by a series of alpine mountains, covering an area of 28,000 km^2. The plateau belongs to the northeastern part of the QTP, which was a relative sinking region during the intensive uplift of the QTP since the Quaternary Period(Xu, 1988; Sun et al., 2001), harboring up to 10 m thick minerotrophic peatlands (Sun, 1992), which have accumulated since the early Holocene (Xiang et al., 2009).Moreover, during the Kunhuang (Kunlun-Huanghe) Movement(1.2–0.6 Ma B.P.), the Yellow river cut back into the QTP (Li et al., 2001). Consequently, peat accumulation was affected by lateral movements of river channels of the Yellow river system and substantial peats were found to deposit in the ancient channel valleys of the Yellow river (Sun and Zhang, 1987; Sun, 1992). However, there would be substantial peat erosion as well as development in such a river valley system. The Zoige peatlands have been suggested to cover up to 46 00 km^{2}and regarded as one of the largest alpine peatlands in the world (Sun, 1992; Xiang et al., 2009). Together with ubiquitous warming and intensified anthropogenic activities on the plateau, the C dynamics of Zoige peatlands may be of research importance.

In the 1960's, Cai and Jin (1963) firstly discussed the classification of Zoige peatlands (Cai and Jin, 1963) and Lang et al. (1963) described their vegetation types (Lang et al., 1963). During the following decades, studies were focused on peat deposition (Sun et al., 2001), peatland coverage (Fan, 1987), and peat storage (Sun, 1992; Wang et al., 1992), *etc*. Recently, many studies tried to discuss Holocene climate change of the QTP based on peat records of Zoige (Wang, 1987; Schlütz and Lehmkuhl, 2009; Zhao et al., 2011; Zheng et al., 2011; Ferrat et al., 2012; Yu et al., 2012; Guo et al., 2013). Previous studies estimated that Zoige peatlands deposited 1.9–2.9 Pg peat (Sun, 1992; Wang et al., 1992), not including the buried peat. To the best of our knowledge, there is so far no study estimating the carbon storage of Zoige peatlands based

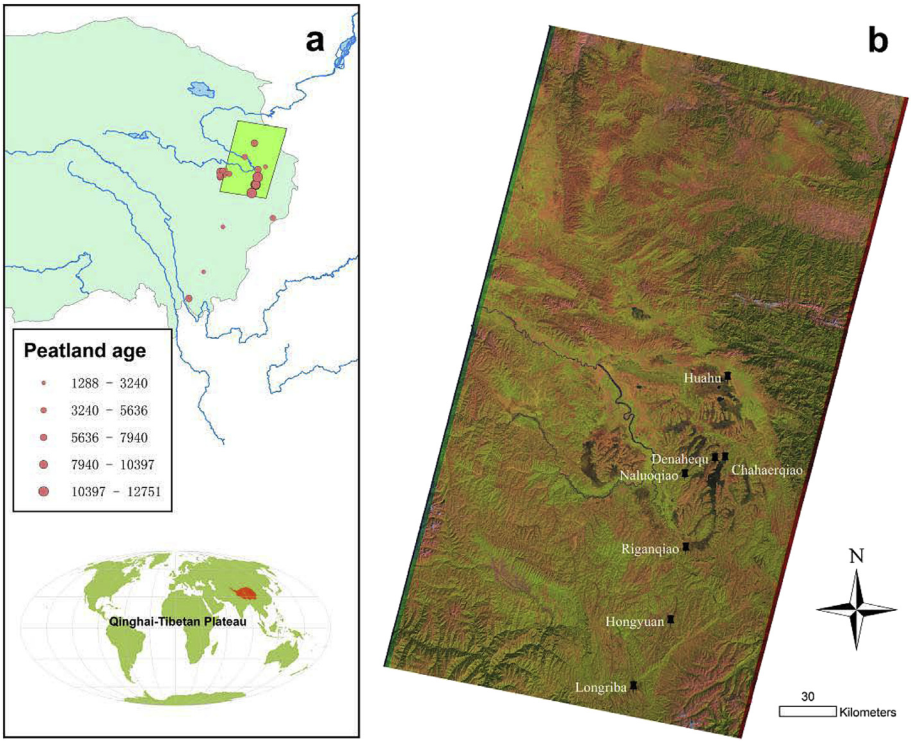

Fig. 1. Location of the study area (a) and sampling sites (b) in the Qinghai–Tibetan Plateau. a: Different ages of each peatland on our study area; different circle size represents different peatland age. b: The seven sampling sites in our study area. A mosaic of two Landsat TM satellite images (Orthorectified, WRS-2, path 131, row 36 and path 131, row 37) acquired in 21st, Sep, 2000 was selected for least cloud coverage. A false color composite was used. Band 5, 4, 3 was assigned to red, green, blue respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on detailed fieldwork. Therefore, in this study, we aimed to answer the following questions: 1) What are the peat depths, peat and C accumulation rates in Zoige peatlands? 2) What is the area of the peatlands covering Zoige Plateau? 3) How much C is stored in Zoige peatlands?

2. Materials and methods

2.1. Study area and selection of field sites

The field work was undertaken during May and June 2012 on the Zoige Plateau (av.3400 m a.s.l.), located between 101°30′-103°30′E and 32°20′-34°00′N, on the upper reaches of the Yellow River in the northeastern portion of the QTP. Black River and White River are two branches in the right bank of the Yellow River on the Zoige Plateau. This region belongs to the cold Qinghai–Tibetan climatic zone. During the past four decades, its mean annual temperature was 1.5 °C and mean annual precipitation approximately 720 mm (raw data from the Information Center of China Meteorological Administration [http://www.nmic.gov.cn/]), showing a significant heating and a slight drying trend since 1970.

For the field sampling, we selected 7 accessible peatland sites from north to south of the Zoige Plateau, which were defined as different peatland types on the basis of their distinctive characteristics (Sun, 1992). The seven sites are all bogs of three major peatland kinds on the plateau: one of lacustrine plain peatland, five of alluvial plain peatland and one of mountain valley peatland. Lacustrine plain peatland is mainly located in the northern part of the Zoige Plateau. The Huahu sampling site belonged to this kind of peatland. Alluvial plain peatlands are formed on the basis of the alluvial plain mainly distributed in the mid-lower reaches of the Yellow River, Black River and White River as well as their tributaries. The five sites of this type of peatland in our study were Chaha'erqiao, Denahequ, Naluoqiao, Riganqiao and Longriba. Mountain valley peatlands are distributed in the valleys of Black River and White River. The Hongyuan site of our field research belonged to this type.

2.2. Peat depth, field description and sampling

The sites were located in the field using a hand-held GPS receiver. For each site we established a sampling transect along the straight line from the edge to the center of the site. The length of these transects varied from 1.5 to 2.5 km. One study point was set every 300–500 m along each transect, so that 5 study points were determined for each transect. Peat depth was determined with a peat sampler (8 cm in diameter, 80 cm in length) at each of the study point. The peat sampler was driven downwards from the surface until sand and mud visually appeared. At each study point, we collected peat samples from two cores collected about a few meters apart. The peat samples were taken at 10 cm intervals in the top 80 cm soil, and at 20 cm intervals from 80 cm below the peat surface until sand and mud appeared visually. Then the peat samples were sealed in polyethylene ziplock bags for later analyses.

2.3. C content and dry bulk density

The collected samples were transported in ziplock bags to the laboratory and air-dried on brown paper. Soil samples for C analysis were passed through a 75 micron mesh sieve. Then approximately 0.1 g was taken to measure C content with a CN Analyzer (Multi N/C 2100S, Jena, Germany). The dry bulk density was decided as [dry weight (g)/field volume (cm^3)] and C density as (mean bulk density × C content % × 0.01).

2.4. Radiocarbon dating

A total of 16 samples were dated using the AMS radiocarbon dating method in the Beta Analytic Radiocarbon Dating Laboratory at Florida, USA. These samples were collected from the central part of the peat core, since the outer layer of the core might be contaminated when the sampler was drawn out. Root remains were removed from the samples in the laboratory before drying, and double checked before dating. Then, the sample was treated to eliminate secondary carbon components using acid washes method (method used in BETA analytic radiocarbon dating. Wood and Wells, 1996). The samples were first dispersed in H_2O by agitation. They were then progressively wet sieved through a 250 micron and then a 180 micron sieve to remove any root hairs until no separable plant or other macrofossils were found. The samples were then treated with 90 °C, 0.5 M HCl (Hydrochloric Acid) leaches for about 4 h to remove any carbonates that might have been present. When all carbonates present were removed, the samples were then rinsed neutral with deionized H_2O at 90 °C. Once neutral, the samples were then dried in an oven at 70 °C until all moisture was removed (this is typically 8–16 h). The dried samples were then placed under a microscope and inspected for any remaining foreign matter. If any, the remaining foreign matter was removed by hand-picking until the sample was clean. The sediment was then thoroughly homogenized and a small sub-sample was tested with concentrated 18 M HCl to observe if there was any reaction to the acid. This step was to ensure that no carbonate resistant substance (like Dolomites) remained. If no reaction to the acid was observed, a fraction of the sample was then analyzed for radiocarbon content in an accelerator mass spectrometer. The final data was reported as a calendar-calibrated date. Beta Analytic Radiocarbon Dating Laboratory using the INTCAL09 database calibrate radiocarbon age to calendar years (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the ^{14}C activity of the National Institute of Standards and Technology (NIST) oxalic acid (SRM 4900C) and calculated using the Libby ^{14}C half – life (5668 years). [Beta Analytic Radiocarbon Dating Laboratory : http://radiocarbon.com/index.htm(Talma and Vogel, 1993)].

2.5. Accumulation rates

Peat accumulation rates (mm yr^{-1}) were calculated for peat layers between the dated depths of the profiles, and C accumulation rates were obtained from the following equation (Lähteenoja et al., 2012).

$$\mathrm{CA} = r/1000 \times n \times c$$

where CA is C accumulation rate (g m^{-2} yr^{-1}); r is peat accumulation rate (mm yr^{-1}); n is dry bulk density (g m^{-3}); c is C content (g C g^{-1} dry weight).

2.6. Estimating the carbon storage in Zoige peatlands

To estimate the distribution and carbon storage of the Zoige peatlands, we combined field survey with remote sensing method. We acquired 2 Landsat 5 TM scenes (path 131, row 36 and path 131, row 37) on 21st Sep 2000, orthorectified and projected to UTM Zone 48N from USGS (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/TM). All 6 bands except thermal band were used to perform supervised classification under ENVI 4.8 (ITT Visual Information Solutions). Supervised classification is a method based on machine learning to analyze remote sensing images. It uses pre-known land cover type on the image (known as "training area") to build a discriminant function, which is then applied to the whole study area. In our study the 7 field study sites were used as training area. The number of 30 m*30 m peatland pixels was then extracted from supervised classification, after which the total area was calculated.

The total carbon storage in Zoige peatlands was calculated using area data mentioned above and *in situ* observations including peat depth, bulk density, and carbon content. Investigation showed statistical negative correlation ($p < 0.01$) between bulk density and carbon content ($r = -0.707$, $n = 381$). Therefore, we introduced in calculation the carbon content in cubic volume (carbon bulk density) () to significantly reduce the confidence interval by 65.2%. The carbon storage was calculated using peatland area, average peat depth as well as mean carbon bulk density:

$$\mathrm{C\ stock(Gt)} = 0.001 * \mathrm{A} * \overline{\mathrm{h}} * \rho$$

Where A stands for peatland area (km^2), $\overline{\mathrm{h}}$ for average peat depth (m), ρ for carbon bulk density (g cm^{-3}). The maximum and minimum carbon bulk density was introduced in the quotation to estimate the range of carbon stock.

3. Results

3.1. Peat depths, peat accumulation rates, basal ages and carbon accumulation rates

In the present study, the peat depths were recorded as the lengths of extracted column from the surface layer of peat to the minerogenic sediments (mud, sand, etc.). The peat depths of the sample sites ranged from 0.20 to 6.0 m (Table 1 and Fig. 2), with a mean depth of about 1.39 m. Our study found the basal age varied from 1635 to 14095 cal yr BP (Fig. 2), and carbon concentrations of samples from 9.99% to 38.91%, with an average concentration of 19.80% (Table 1 and Fig. 3). Based on their variable bulk density and carbon contents (Fig. 3), we calculated peat accumulation rates and carbon accumulation rates. The peat accumulation rates on the plateau was found to be from 0.12 to 0.85 mm yr^{-1} (mean about 0.39 mm yr^{-1}), and the C accumulation rates from 5 to 48 g m^{-2} yr^{-1} (mean about 20.4 g m^{-2} yr^{-1}) (Table 2). We also found that C accumulation rates increased with the increase of peat depth in four sites (Huahu, Denahequ, Naluoqiao and Riganqiao) when the peat depth is below 200 cm. For the other three sites, however, probably due to lack of data, we did not find any significant change in C accumulation with peat depth.

3.2. The extent and carbon stock of peatlands

The present study decided, through supervised classification, that the area of intact peatlands was about 3179 km^2 (Fig. 4). Based on the previous detailed field investigation during the 1980s (Sun, 1992), we regarded that about three fifths of the total peatland area on the plateau was intact peatland, and the other two fifths was degraded peatlands of about 1426 km^2. Therefore, the total area of Zoige peatlands was 4605 km^2. According to our calculation with soil bulk density and carbon concentration (Table 1 and Fig. 3), the intact Zoige peatlands reserved 0.329 Pg C (ranging from 0.142 to 0.464 Pg) and the degraded peatlands reserved about 0.148 Pg C (ranging from 0.064 to 0.208 Pg). In summary, the total Zoige peat C stock was 0.477 Pg (ranging from 0.206 to 0.672 Pg).

4. Discussion

4.1. Peat accumulation on the Qinghai–Tibetan Plateau

Our field measurements and remote-sensing results strongly suggested that peat accumulation is extensive on the Zoige Plateau (Fig. 1 and 2). In our study, the mean peat depth is about 1.39 m, which is shallower than tropical (Page et al., 2011; Lähteenoja et al., 2012), boreal and subarctic peatlands (Gorham, 1991; Yu et al., 2010; Yu, 2012), but comparable with previous study results (0.5–10 m) on the same plateau (Sun, 1992; Schlütz and Lehmkuhl, 2009; Guo et al., 2013).

Our results about basal ages again proved that peat deposits initiated on the QTP in the early Holocene (Sun, 1992; Sun et al., 2001), similar with northern peatlands but much later than tropical peatlands (Yu et al., 2010), probably attributable to a relatively warmer and wetter climate since the early Holocene on the QTP, similarly as documented by paleoclimate records of aeolian deposits (Liu et al., 2013). Tropical peatlands initiated before 20 ka, much earlier than Tibetan peatlands and northern peatlands, probably induced by a warm climate during the Antarctic Thermal Maximum in the South Ocean region (Barker et al., 2009; Yu et al., 2010). Integrating peat ages from other studies on the plateau (Fig. 1), we found that most peatlands deposited more than 6000 years ago, similarly with the formation pattern of northern peatlands (Yu, 2012), indicating that peat accumulation and peatland expansion on the QTP, especially the monsoon-influenced eastern part (Sun et al., 2001), reached its peak in the Holocene Thermal Maximum, similar with the results of previous studies (Song et al., 1985; Sun, 1992; Sun et al., 2001). The peat accumulation peak was probably initiated and sustained by the maximum summer

Table 1
Core depth and characteristics of the study sites.

Study site	Location	Elevation (m)	No of cores	Mean core depth cm	Range of core depth cm	Mean bulk density (g cm^{-3})	Range of the bulk density (g cm^{-3})	Mean C content %	Range of the C content %	C content per cm^3 g.cm^{-3}	Range of C content per cm^3 g.cm^{-3}
Huahu	E102°52′08″ N33°55′08″	3434	10	240	60–360	0.396	0.176–0.842	18.64	10.59–32.70	0.067	0.021–0.112
Chaha'erqiao	E102°51′50″ N33°32′13″	3444	10	72	20–160	0.454	0.242–0.772	15.54	9.99–27.03	0.067	0.041–0.097
Denahequ	E102°48′24″ N33°32′01″	3444	10	116	40–200	0.496	0.152–0.889	16.47	10.47–29.40	0.075	0.031–0.134
Naluoqiao	E102°38′16″ N33°27′12″	3469	6	123	30–180	0.342	0.154–0.556	19.42	14.02–31.15	0.065	0.032–0.122
Riganqiao	E102°39′08″ N33°06′15″	3471	6	444	380–600	0.201	0.051–0.646	27.23	10.35–38.91	0.048	0.011–0.131
Hongyuan	E102°34′36″ N32°45′28″	3551	4	75	70–80	0.489	0.280–0.902	20.40	10.05–29.86	0.085	0.041–0.174
Longriba	E102°22′34″ N32°26′28″	3580	10	114	10–180	0.366	0.181–0.671	20.92	10.05–36.38	0.074	0.036–0.161

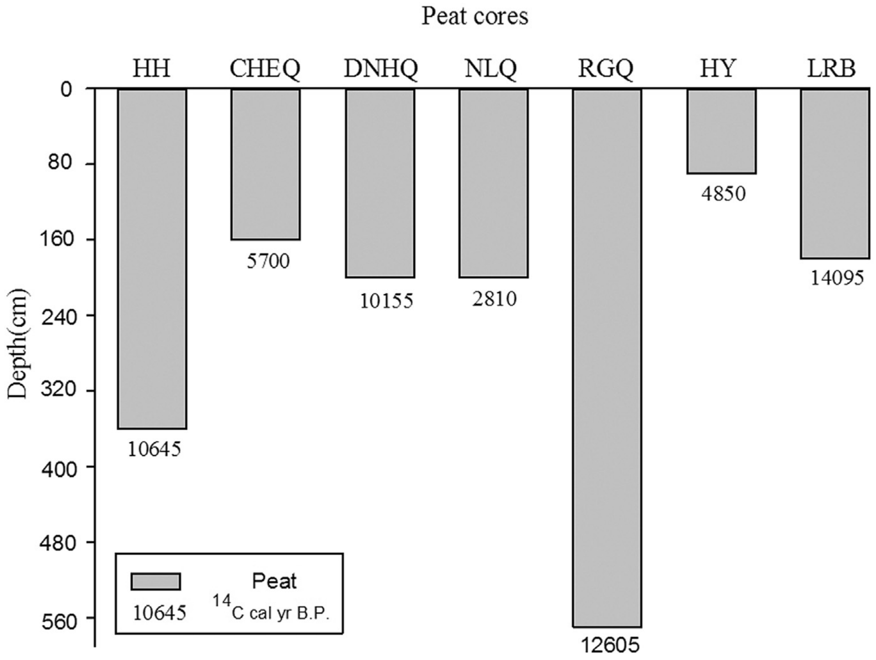

Fig. 2. Stratigraphy data of all 7 peat cores (HH, Huahu; CHEQ, Chahaer'qiao; DNHQ, Denahequ; NLQ, Naluoqiao; RGQ, Riganqiao; HY, Hongyuan; LRB, Longriba).

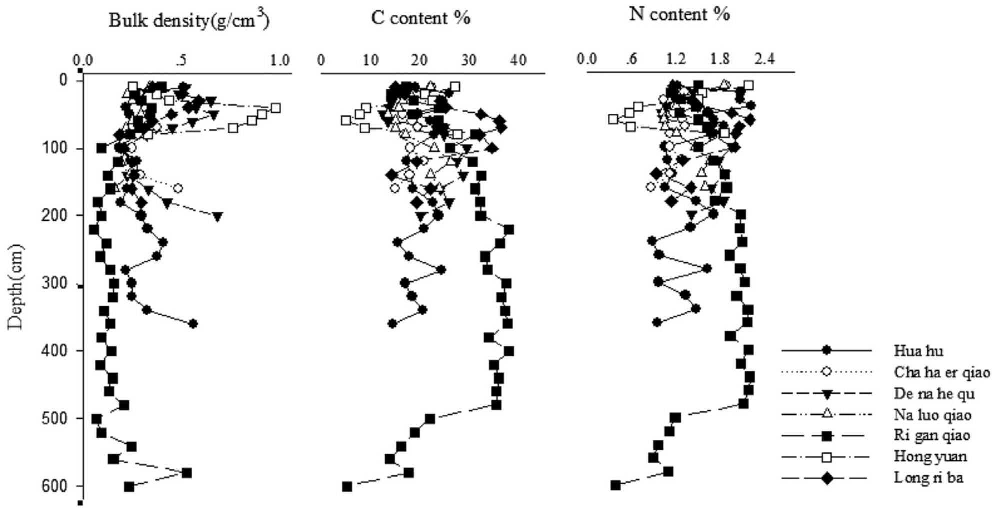

Fig. 3. Bulk density, C content and N content in the measured peat cores.

insolation and the greatest seasonality in insolation and climate at that time (Sun et al., 2001; Yu et al., 2010), since plants grew well with high summer insolation and the cold winter can slow down decomposition of organic matters.

The peatlands on the vast plateau did not begin to accumulate all synchronously, with the great variations in basal peat ages partly attributable to fragility of alpine peatlands and lateral movements of river channels of the Yellow river system, and partly to the regional climate (Sun and Zhang, 1987; Sun, 1992; Lähteenoja et al., 2012). The peat accumulation rate of 0.39 mm yr^{-1} agreed well with the 0.41 mm yr^{-1}in the study of Sun (Sun et al., 2001), while the C accumulation rates seemed to be slightly lower than those reported in previous studies about Zoige peatlands (Sun et al., 1998; Gao et al., 2010a; Zhao et al., 2011), probably owing to the lower value of C content. However, different measurements of carbon content and bulk density might also cause difference in the C accumulation rate among them. E.g. Gao et al. (2010a) calculated the C accumulation rate using organic carbon content (by the potassium-dichromate oxidation procedure) instead of the total carbon, which would slightly underestimate the C accumulation rate. Zhao et al. (2011) did not directly measure the carbon content but only calculated with the assumption of 52% carbon in peat organic matter, which probably overestimated the accumulation rate. The peat and C accumulation rates recorded in this study were higher than those of tropical peatlands and comparable to those of boreal peatlands and Southern peatlands (Yu et al., 2010). Moreover, the peat accumulation rate of Zoige was much higher than its counterpart in Sanjiang Plain, another important peatlands in China (Xia, 1988; Yang, 1990). The relative high C accumulation rate of peatlands in Zoige could be explained by the high organic matter input in relative warm and wet growing season, and low decomposition in extremely long and cold non-growing season (Ding and Cai, 2007; Tan et al., 2010). Such results indicated Zoige peatlands are an essential player in modifying regional climate as a great carbon sink.

Table 2
Radiocarbon ages and peat and C accumulation rates of the dated profile.

Study Site	Core code	Sample depth	^{14}C dates (year BP)	Calibrated age (cal year BP) Mean (Range)	Interval (cm)	C content %	Bulk density (g cm^{-3})	Peat accumulation rate (mm yr^{-1})	C accumulation rate (g m^{-2}yr^{-1})
Huahu	S1-3	90–100	2090 ± 30	2095 (2080–2110)	0–95	17.57	0.217	0.45	17
	S1-3	190–200	3650 ± 30	4055 (4050–4060)	95–195	19.74	0.290	0.51	29
	S1-3	280–290	5770 ± 30	6650 (6650–6650)	195–285	16.41	0.309	0.35	18
	S1-3	350–360	9440 ± 40	10645 (10560–10730)	285–355	15.08	0.455	0.18	12
Chaha'erqiao	S2-2	80–90	2410 ± 30	2405 (2340–2470)	0–85	17.90	0.244	0.35	15
	S2-2	150–160	4920 ± 30	5700 (5690–5710)	85–155	14.95	0.483	0.21	15
Denahequ	S3-2	90–100	5720 ± 40	6595 (6590–6600)	0–95	29.40	0.186	0.14	8
	S3-2	190–200	8960 ± 40	10155 (10110–10200)	95–195	19.94	0.676	0.28	38
Naluoqiao	S4-3	90–100	1770 ± 30	1635 (1560–1710)	0–95	22.88	0.211	0.58	28
	S4-3	190–200	2740 ± 30	2810 (2760–2860)	95–195	23.86	0.154	0.85	31
Riganqiao	S5-2	90–100	3840 ± 30	4340 (4330–4350)	0–95	26.07	0.089	0.22	5
	S5-2	560–570	10700 ± 50	12605 (12560–12650)	95–565	17.55	0.228	0.57	23
	S5-4	210–220	3400 ± 30	3625 (3560–3690)	0–215	30.01	0.089	0.59	16
	S5-4	300–310	4420 ± 30	4950 (4860–5040)	215–305	34.162	0.205	0.68	48
Hongyuan	S6-2	80–90	4330 ± 30	4850 (4830–4870)	0–85	27.47	0.327	0.18	16
Longriba	S7-2	170–180	12290 ± 60	14095 (13980–14210)	0–175	19.28	0.293	0.12	7

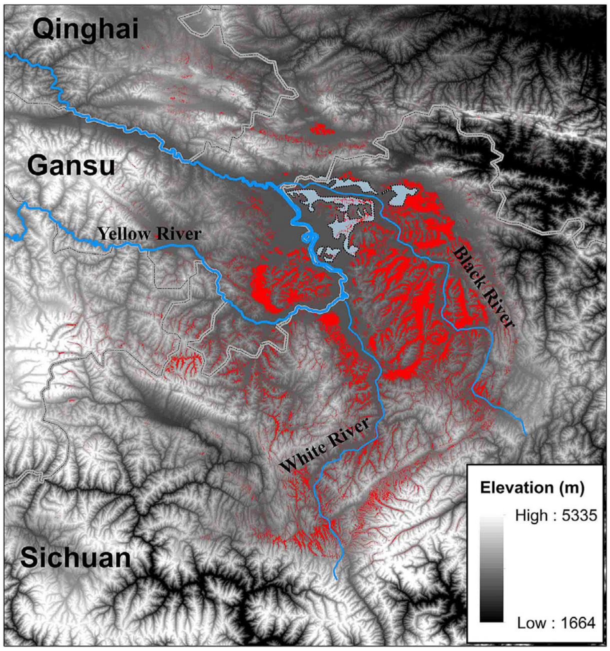

Fig. 4. The result of supervised classification of peatland on the Zoige plateau. Red parts indicate the peatland retrieved from Landsat TM images; gray parts with dashed outline are peatlands according to the field survey by Sun (1992) but not retrieved as such from remote sensed data in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. *The extent and carbon stock of peatlands on the Qinghai–Tibetan Plateau*

The present study decided, through supervised classification, that the area of intact peatlands was about 3179 km^2 (Fig. 4), much smaller than the area (4605 km^2) measured several decades ago (Sun, 1992; Sun et al., 1998). The previous studies showed that large area of peatlands in Zoige were under different degradation status with some of them even buried recently under meadows or steppes, probably due to overgrazing, draining and global warming (An et al., 2007; Zhang et al., 2011a). Besides, mining activities have even destroyed some peatlands in Zoige, cutting over 10% of their area (Zhang et al., 2011b). The above two scenario caused difficulty for satellite to identify peatlands, resulting in a large peatland (about 466.66 km^2) reported by Sun (1992) was not observed by satellite observation in this study (Fig. 4).

Based on our calculation, the total Zoige peat C stock is 0.477 Pg (ranging from 0.206 to 0.672 Pg), comparable to that of 0.63 Pg in a previous study based on limited data (Liu et al., 2012). On the plateau, there are some peatlands scattered in Qinghai, Tibet and the southern part of Hengduan Mountain, covering about 486 km^2, only about one tenth of the area of Zoige peatlands (Song et al., 1985; Sun et al., 1998; Yin, 1999). In Qinghai province, peatlands deposited about 0.093 Pg peat (Yin, 1999). A report indicated that peatlands in Tibet deposited about 0.17 Pg peat (Song et al., 1985; Yin, 1999). A previous study summarized that in the southern part of Hengduan Mountain on the QTP, buried and intact peatlands deposited 0.068 Pg peat (Sun et al., 1998). In our study, carbon concentrations of peat samples ranged from 9.99% to 38.91%, with an average concentration of 19.80% (Table 1). Assuming similar carbon concentration of peat on the plateau, we could preliminarily know that Qinghai peatlands accumulated 0.019 Pg C (ranging from 0.010 to 0.024 Pg), Tibetan peatlands accumulated 0.034 Pg C (ranging from 0.017 to 0.067 Pg) and peatlands in southern Hengdu Mountain accumulated 0.013 Pg C (ranging from 0.068 to 0.027 Pg).

Summing up with above-mentioned data, we preliminarily estimated that peatlands covered an area of about 5091 km^2 on the QTP and sequestered 0.543 Pg C (ranging from 0.301 to 0.790 Pg), 88% in Zoige and the rest in other parts of the plateau. The total carbon stock of Qinghai–Tibetan peatlands was much smaller than that of boreal and tropical peatlands (Gorham, 1991; Page et al., 2011; Yu, 2012) and that of alpine grasslands on the same plateau (Wang et al., 2002; Yang et al., 2008). However, on the area basis, the carbon concentration of peatland is larger or comparable to the peatlands in other regions (Gorham, 1991; Page et al., 2011; Yu, 2012) and far larger than that in alpine grasslands (Wang et al., 2002; Yang et al., 2008).

4.3. *The fate of carbon stored in peatlands on the Qinghai–Tibetan Plateau*

Due to sensitivity and fragility of peatlands itself (Li and Zhou, 1998), carbon stored in peatlands is very sensitive to climate change and anthropogenic activities. During the past five decades, the Qinghai–Tibetan Plateau has experienced a universal and significant warming (Yao et al., 1997; Liu and Chen, 2000,; Duan et al., 2006; Li et al., 2010). The temperature has increased by 0.2 °C per decade since 1960, with the warming trend even intensified since 2000 (Yao et al., 2007). Besides, the alpine peatlands have undergone intensive human activities (e.g. overgrazing, draining and mining) due to population pressure (Rattan et al., 2012). Until now, nearly 70% of Zoige peatlands have degraded (Wang et al., 2001; Tian, 2005; Liu and Bai, 2006; Pang et al., 2010; Gao et al., 2010b) and some peatlands have been even destroyed by mining (An et al., 2007). Human activities, together with the ubiquitous warming on the plateau not only shrank the area of intact peatlands (Zhang et al., 2011b), but also caused substantial carbon releasing from peatlands as CO_2 to the atmosphere (Zhu et al., 2012), as DOC and POC to nearby waters, which would contribute greatly to CO_2 emissions from nearby aquatic systems on the plateau (Singer et al., 2012), and decrease emission of CH_4. Moreover, warming-enhanced respiration of subsurface peat buried in meadows or steppes may have transformed peatlands from net CO_2 sinks into net CO_2sources on the plateau (Dorrepaal et al., 2009). Besides, the QTP is also the headwater area for several major Asian rivers, such as the Ganges, Indus, Yangtze, Yellow, Mekong and Salween rivers. Therefore, exported DOC and POC from Qinghai–Tibetan peatlands would influence aquatic carbon dynamics of the downstream region (Mccallister and Del Giorgio, 2012;; Singer et al., 2012). Though, there are few direct data to estimate the value of DOC and POC exported from Qinghai–Tibetan peatlands. E.g. in our previous study, we found that DOC concentrations ranged from 8.84 to 58.11 mg C L^{-1} in the surface water of a peatland lake on the QTP, which was proven mainly originating from surrounding peatlands and causing a very high CO_2 erosion (as high as 489 mg CO_2 m^{-2} h^{-1}) through the lake surface (Zhu et al., 2012).

Substantial carbon releases from peatlands under warming and human disturbance on the plateau will enhance regional warming. Therefore, it is critical to try to reduce the carbon release from peatlands. Fortunately, China began restoring degraded wetlands in the early 1990 (An et al., 2007) and some action has also been taken in the Zoige area (Zhang et al., 2012). Hitherto, 1568 ha of the degraded peatlands in Zoige have been successfully restored by damming (Zhang et al., 2011a) and physical and chemical soil properties, water storage capacity and organic matter content have been improved (Zhang et al., 2012). However, we still cannot estimate and predict the carbon sequestration of restored peatlands in Zoige with very limited data. Therefore, long-term measurements should be focused on the dynamic pattern of carbon cycling and related processes after peatlands restoration to better understand and predict the carbon sequestration potential of alpine peatlands on the Qinghai–Tibetan Plateau in the future.

5. Conclusion

To the best of our knowledge, this is the first study estimating the carbon storage of Zoige peatlands based on detailed fieldwork by measuring peat depth, radiocarbon age and peat and C accumulation rates at 7 sites. Based on the previous study and the supervised classification in this study, we regarded that the intact peatlands covers about three fifths (3179 km^2), and the rest is the degraded peatlands about 1426 km^2, therefore, the total area of Zoige peatlands is 4605 km^2. The current peat C stock was 0.477 Pg (ranging from 0.206 to 0.672 Pg) of Zoige peatlands. We also estimated that peatlands covered an area of about 5091 km^2 on the QTP and sequestered 0.543 Pg C (ranging from 0.301 to 0.790 Pg), 88% in Zoige and the rest in other parts of the plateau.

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