Carbon Accumulation in Temperate Wetlands of Sanjiang Plain, Northeast China

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Wetland ecosystems contain large C stocks and are considered to play an important role in global C cycling, thus having potential implications for global climate change. The Sanjiang Plain wetland is the largest freshwater marsh in China and a principle element of the Wetlands of International Importance with three Ramsar wetland sites (Xingkai Lake, Sanjiang, and Honghe) since 2002. Nevertheless, little is known about organic C storage, and no data combining both long- and short-term C accumulation rates have been reported for this region. We used 10 cores collected from previous investigations to determine radiocarbon age and long-term (apparent) rate of C accumulation (LORCA) based on dry bulk density and organic C content; we used five recent cores representing the three main wetland types in Sanjiang Plain to estimate the recent (apparent) rate of C accumulation (RERCA) inferred from ^{210}Pb dating. The LORCA ranged from 5 to 61 g C m^{-2} yr^{-1} with an average of 22 ± 5 g C m^{-2} yr^{-1} (±SE), and the RERCA ranged from 170 to 384 g C m^{-2} yr^{-1} with a mean of 264 ± 45 g C m^{-2} yr^{-1} (±SE). The average C flux was 0.05 Tg C yr^{-1} for herbaceous peatland, 0.02 Tg C yr^{-1} for humus marsh, and 0.03 Tg C yr^{-1} for marshy meadow and the total soil C pool in Sanjiang Plain wetlands was estimated to be 0.36 Pg C. Our results are in good agreement with other published relevant data and may be useful for predicting global climate change. The Sanjiang Plain wetlands deserve more attention in wetland protection and restoration of the wetland ecosystem and wise use of wetlands for agricultural development.

Abbreviations: AMS, accelerator mass spectrometry; BP, before present; LORCA, long-term (apparent) rate of carbon accumulation; RERCA, recent (apparent) rate of carbon accumulation.

It has become increasingly important to quantify C pools and fluxes in terrestrial ecosystems due to the role of C in global climate change. Wetlands are among the most important ecosystems on Earth and store nearly one-third of global soil C pools, despite the fact that they cover only 6 to 8% of the land and freshwater surface (Clymo, 1984; Gorham, 1991; Mitsch and Gosselink, 2007). Natural wetlands, especially peatlands, generally accumulate C as a result of a greater rate of inputs (organic matter produced in situ and ex situ) than outputs (decomposition under waterlogged conditions, erosion due to high precipitation, and soil disturbance) (Bernal and Mitsch, 2008; Kayranli et al., 2010). There is concern that climate changes, such as warmer temperatures or decreased precipitation, may accelerate decomposition rates in wetlands, and thus the projected global climate change may have an impact on C cycling and accumulation in peat (Charman et al., 1994; Intergovernmental Panel on Climate Change, 2007). Therefore, it is necessary to increase our knowledge about the rate of C accumulation and its changes with time when estimating the C dynamics in wetlands.

There have been several detailed calculations of LORCA and RERCA in boreal peatlands (Tolonen and Turunen, 1996). The LORCA and RERCA are analogous but across different time scales and can be estimated for a given peatland from the bulk density, C content, and the age of strata obtained from peat cores. The LORCA is based on the age of the basal peat, while RERCA is based on the age of a horizon near the surface in a core. The age of basal peat is normally estimated via ^{14}C

Soil Sci. Soc. Am. J. 75:2386–2397
Posted online 27 Sept. 2011
doi:10.2136/sssaj2011.0157
Received 28 Apr. 2011.
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dating with a half-life of 5568 ± 30 yr and effective dating range up to approximately 50,000 yr, while the age of near-surface layers is commonly estimated via ^{210}Pb dating with a half-life of 22.3 yr and effective dating range up to 200 yr (Turetsky et al., 2004). Determination of both LORCA and RERCA in wetlands is crucial in understanding the global C cycle and ascertaining the role of wetlands in increasing atmospheric CO_2 at different time scales and subsequent global warming (Vitt et al., 2000; MacDonald et al., 2006; Beilman et al., 2009).

Wetlands are found in all climatic zones ranging from tropics to the subarctic and arctic. Much research on C accumulation has been performed in boreal and subarctic peatlands (Gorham, 1991; Botch et al., 1995; Tolonen and Turunen, 1996; Turunen et al., 2001, 2004; Borren et al., 2004; Loisel and Garneau, 2010) and in subtropical and tropical wetlands (Craft and Richardson, 1998; Aucour et al., 1999; Page et al., 2004; Bernal and Mitsch, 2008; Chimner and Karberg, 2008). In contrast, relatively few studies have been done on wetlands in more temperate parts of the world. Brinson and Malvárez (2002) reviewed and examined the status of global temperate freshwater wetlands including North America, South America, northern Europe, the northern Mediterranean, temperate Russia, Mongolia, Northeast China, Korea and Japan, and southern Australia and New Zealand. These temperate wetlands occupy a very crucial position in estimating global C pools (Armentano and Menges, 1986), and they are distributed in the more densely populated regions and subjected to anthropogenic influences, such as widespread drainage of organic soils in wetlands for agriculture. Therefore, it is necessary to estimate the C accumulation in these endangered wetlands before degradation accompanying development occurs and to raise public recognition about wetland conservation and restoration from the perspective of a C sink.

The objective of this study was to estimate both long- and short-term C accumulation rates, namely LORCA and RERCA, in three main types of wetlands (herbaceous peatland, humus marsh, and marshy meadow) in the Sanjiang Plain temperate wetlands, Northeast China. The rates of sediment accretion were measured by ^{14}C and ^{210}Pb radiometric techniques. The Sanjiang Plain wetlands are rich in biodiversity and natural resources, but their ecological functions have gradually become fragile because of the rapid acceleration of human disturbance. These estimates, therefore, will contribute to the development of methods and policies to safeguard the Sanjiang Plain wetlands and maintain or restore their capability in C sequestration and their role in global C dynamics.

MATERIALS AND METHODS

Site Description

The Sanjiang Plain region (43°50′–48°28′ N, 129°12′–135°6′ E) lies in China's extreme northeastern corner. It includes an extensive low plain formed by three major rivers, Heilong, Songhua, and Wusuli, on the northwest side of Wanda Mountain and an alluvial plain as a result of the Wusuli River and its branches and Xingkai Lake on the south side of Wanda Mountain, with a total area of 11.6 × 10^6 ha (Fig. 1). This region has a temperate humid and subhumid continental monsoon climate, with mean annual temperatures ranging from 1.9 to 3.9°C and precipitation from 500 to 650 mm, occurring mainly in May to September. This region is a large Cenozoic subsidence area and belongs to a typical inland faulted basin from the view of geotectonic stages (Niu et al., 1990). Geographically, it is mainly the first terrace and floodplain, with some low hills dotting the plain. The land mass in the Sanjiang Plain region has evolved since the onset of the Quaternary, and today the flat landscape is covered continuously by clay layers with depths of 3 to 17 m (Richardson and Ho, 2003). Most of the rivers in this region have riparian wetlands supporting meadow and marsh vegetation. The soils are typical of Luvisols, Phaeozems, Cambisols, and Histosols (Bu et al., 2008).

The wetlands in the Sanjiang Plain region are widespread, with a total area of 0.9 × 10^6 ha in 2005 (Song et al., 2008). Generally, freshwater sedge (*Carex* spp.) marshes are the major form of Sanjiang Plain wetland. More than 60% of the wetland soils are gley wetlands, which occur in the floodplains adjacent to the rivers and are largely devoid of peat. The remaining area is peatlands in this region that have been limited to ancient riverbeds and waterlogged depressions (Richardson and Ho, 2003). The Sanjiang Plain wetlands mainly consist of herbaceous peatland (20%), humus marsh (43%), and marshy meadow (37%) (Zhang et al., 2008). Several representative wetland sites of each type of wetland were chosen to represent the whole Sanjiang Plain region, and their area, mean depth of peat, and major plant species are described in detail (Table 1). Four of the recent and short sediment cores were used to represent the general condition of wetland patches with humus marsh or marshy meadow characteristics around our sampling site.

In this region, wetlands have been experienced unprecedented degradation. In 1949, the wetlands area was approximately 5.3 × 10^6 ha, occupying 49% of the total Sanjiang Plain region, which was formerly the largest freshwater marshland complex in China (Richardson and Ho, 2003). With increasing population during the last 50 yr, large-scale reclamations have led to up to 2.91 ×10^6 ha of natural marshland being converted to cropland (Huang et al., 2010a; Fig. 2). Meanwhile, the area of farmland has greatly increased, from 0.08 × 10^6 ha in 1949 to 5.57 ×10^6 ha in 2005, and the Sanjiang Plain is currently one of the most productive agricultural regions in China (Huang et al., 2010b). To protect this important wetland region, three wetland reserves, the Honghe National Nature Reserve (Ramsar Site 1149), the Sanjiang National Nature Reserve (Ramsar Site 1152), and the Xingkai Lake National Nature Reserve (Ramsar Site 1155), were established and were listed in 2002 as wetlands of international importance by the Ramsar Convention on Wetlands (2002).

Sediment Cores

This study used cores of organic deposits obtained from 15 sites across the Sanjiang Plain region (Fig. 1) ranging in depth from 32 to 257 cm. The specific names of the sampling sites and their locations are described in detail in Table 1. Ten cores (NXL, YMC, XBC, DBC, SHC, FBC, BBR, QTC, CFC, and UWR) were sampled by drilling a hole or digging up a block during the peat resource survey in Sanjiang Plain during 1983 to 1985 (Niu, unpublished data, 1986) and archived for investigation of peat formation and study of paleoclimatic and paleoenvironmental changes (Ye et al., 1983; Xia, 1988; Xia and Wang, 2000; Zhang et al., 2004a,b). Five cores (HNR, SNR, ABR, THF, and QFC) were

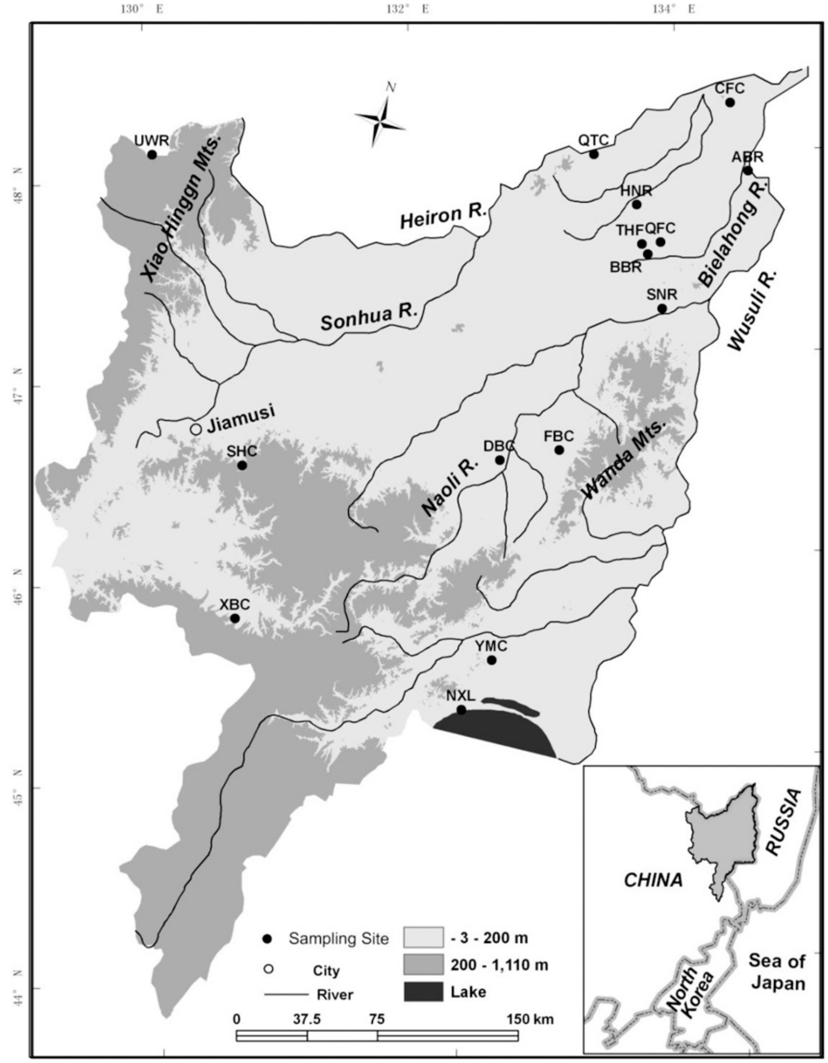

Fig. 1. The Sanjiang Plain of Northeast China and location of sampling sites (map by M. Hou and K. Bao).

taken to a depth of about 30 cm using a manual soil probe (2.64 cm in diameter) with an open side for easy removal of the peat samples (Jia et al., 1995) in October 2007. The cores were sectioned in the field at 1- or 2-cm intervals for dry bulk density and radiometric measurements and at 5-cm intervals for organic C concentrations. All samples were stored in polyethylene bags until the laboratory analysis. The geographic coordinates of the sampling sites were determined with a portable global positioning system (Garmin GPS 12XL, Garmin International, Olathe, KS), and the depth of each core was measured by a standard meter ruler (Table 2). The sites in this study are distributed widely across the Sanjiang Plain region to span the main wetland categories in this region.

Data Collection

The ^{14}C data are summarized from previous studies for the 10 previously collected cores (Table 2), and the organic C content was estimated by multiplying the organic matter content by 0.50 (Ye et al., 1983; Niu, unpublished data, 1986; Xia, 1988; Xia and Wang, 2000; Zhang et al., 2004a,b). The dry bulk densities of the XBC, SHC, FBC, BBR, QTC, CFC, and UWR cores were given in Niu (unpublished data, 1986), and the values used for the NXL, YMC, and DBC cores are the average dry bulk density of peat profiles in the top 50 to 75 cm in the Sanjiang Plain (Zhang et al., 2008).

For the remaining five cores, five peat samples from the basal level were selected and submitted to the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, in Xi'an for accelerator mass spectrometry (AMS) ^{14}C dating. The AMS ^{14}C data were calibrated using the computer program CALIB 4.3 (Stuiver et al., 1998). The soils for organic C analysis were loosely disaggregated to facilitate air drying at 20°C and, when dry, were ground with an agate mill to pass through a 0.18-mm mesh sieve. Their organic C concentrations were determined using potassium dichromate oxidation. The dry bulk density was calculated from dry stable weight and the known volume by weighing a volumetric subsample of each slice after drying at 105°C for 12 h. All sample aliquots (approximate 5 g) of these five cores, after picking out the coarse plant residues and drying at 105°C for 12 h, were sent to the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, in Nanjing for ^{210}Pb dating using a low-background γ-ray spectrometer with a high pure Ge semiconductor (ORTEC, Oak Ridge, TN). The total ^{210}Pb radioactivity was measured via γ emissions at 46.5 keV, and the ^{226}Ra was determined with the 295 keV as well as 352 keV γ-rays emitted by its daughter nuclide ^{214}Pb after 3 wk of storage in sealed containers to allow radioactive equilibrium (Bao et al., 2010a). The supported ^{210}Pb activity in each sample was assumed to be in equilibrium with the in situ ^{226}Ra,

Table 1. Detailed information about the wetlands of the sampling area in temperate wetlands of Sanjiang Plain, northeast China.

Wetland sampling site	Core	Area	Mean depth	Predominant vegetation
		ha	m	
Herbaceous peatland				
North bank of Xingkai Lake	NXL	40†	1.50†	*Carex pseudocuraica* F. Schmidt, *Glyceria acutiflora* Torr., *Ottelia alismoides* (L.) Pers.†
Yangmu village in Mishan County	YMC	50‡	1.00‡	*Deyeuxia angustifolia* Vickery, *Salix bracgyboda*‡
Xingshu village in Boli County	XBC	300‡	0.66‡	*Carex lasiocarpa* Ehrh., *G. acutiflora*, *Equisetum fluviatile* L.‡
Dongsheng village in Baoqin County	DBC	1880‡	0.62‡	*D. angustifolia*, *C. lasiocarpa*‡
Shengjiadian village in Huachuan County	SHC	106‡	1.15‡	*Carex* spp., *D. angustifolia*‡
Farmland (no. 853) in Baoqin County	FBC	560‡	0.86‡	*Phragmites australis* (Cav.) Trin. ex Steud., *C. lasiocarpa*, *Iris tectorum* Maxim.‡
Beidawan of Bielahong River	BBR	11,575‡	0.98‡	*C. lasiocarpa*, *Carex appendiculata* (Trautv. et Mey) Kuk., *P. australis*‡
Qindeli Farmland in Tongjiang County	QTC	11,200‡	1.90‡	*Carex meyeriana* Kunth, *C. pseudocuraica*, *Typha orientalis* Presl.‡
Chuangye village in Fuyuan County	CFC	9000‡	0.75‡	*Carex* spp., *D. angustifolia*, *Betula platyphyla* Sukaczev‡
Upstream of Wulaga River	UWR	235‡	0.45‡	*C. meyeriana*, *C. lasiocarpa*, *Vaccinium uliginosum* L., *Sphagnum* sp.‡
Honghe Nature Reserve	HNR	30§¶	0.60§	*D. angustifolia*, *C. lasiocarpa*, *C. pseudocuraica*§
Humus marsh				
Second bridge of Naoli River	SNR	25§¶	0.90§	*Carex* spp, *D. angustifolia*§
Ancient riverbed of Bielahong River	ABR	20§¶	0.90§	*Carex* spp., *D. angustifolia*§
Marshy meadow				
Third experimental area of Honghe Farmland	THF	20§	0.50§	*D. angustifolia*, *C. lasiocarpa*§
Qianfeng Farmland in Fuyuan County	QFC	15§	0.50§	*D. angustifolia*, *Carex* spp.§

† Zhang et al. (2004b).

‡ Niu (unpublished data, 1986) and Zhao (1999).

§ Wang et al. (2006).

¶ The area of wetland patches at the sampling site.

Fig. 2. Wetland loss is a major environmental problem in Sanjiang Plain, Northeast China, in recent years because of dramatic agricultural development: (A) a hilly valley peatland in Shenjiadian village in Sanjiang Plain converted to upland field and surface plants (scrub and birch forest) have been destroyed; (B) a natural marsh near Qianfeng Farmland in Sanjiang Plain has been drained to convert to paddy land.

and thus unsupported ^{210}Pb activities were determined from the difference between the total ^{210}Pb and the supported ^{210}Pb activity. Standard sources and sediment samples of known activity provided by the China Institute of Atomic Energy were used to calibrate the absolute efficiencies of the detectors. Counting times of ^{210}Pb ranged from 50,000 to 86,000 s, and the measurement precision was ±10% at the 95% level of confidence. The constant rate of supply (CRS) model was used to reconstruct recent peat chronologies because it is believed to constitute the best model for peatlands (Appleby and Oldfield, 1978; Turetsky et al., 2004).

Long-Term and Recent Rates of Carbon Accumulation

The LORCA and the RERCA were calculated for each peat profile using the known depth, dry bulk density, organic C content, and age according to the following equation: RCA (g C $\mathrm{m^{-2}\,yr^{-1}}$) $= Z\,(\mathrm{cm})/T\,(\mathrm{yr}) \times D\,(\mathrm{g\,cm^{-3}}) \times C\,(\%) \times 100$, where RCA refers LORCA or RERCA and 100 is the unit transferring coefficient; for LORCA, Z is the total depth of the sediment core, T is the basal ^{14}C age, D is the mean dry bulk density of the total core, and C is the mean organic C content of the total core; for RERCA, Z is the dated depth, T is the corresponding ^{210}Pb age, D is the corresponding dry bulk density, and C is the mean organic C content of the corresponding section (Tolonen and Turunen, 1996; Bao et al., 2010b).

Table 2. Locations and depths of peat and summary of ^{14}C data for the 15 sampling cores from the temperate wetlands of Sanjiang Plain, northeast China.

Core	Location	Sampling depth	Dated depth	Material dated	^{14}C age	Reference
		cm	cm		yr BP	
NXL	45°19´36˝ N, 132°9´4˝E	150	79–80	peat	1205 ±139	Zhang et al. (2004b)
			118–120	peat	1486 ± 140	
			150	organic/mineral sediment	1857	
YMC	45°34´00˝ N, 132°23´0˝ E	150	76–80	peat	860 ± 180	Xia and Wang (2000)
			100–104	peat	1048 ± 247	
			126–130	peat	1900 ± 205	
			139–145	peat	3400 ± 342	
XBC	45°49´30˝ N, 130°34´20˝ E	60	30–40	peat	modern C	Niu (unpublished data, 1986)
			55–60	peat	3991 ± 82	
DBC	46°33´30˝ N, 132°31´0˝ E	157	25–27	peat	405 ± 130	Zhang et al. (2004a)
			50–52	peat	620 ± 94	
			65–67	peat	1333 ± 177	
			80–82	peat	2158 ± 207	
			105–107	peat	2968 ± 227	
			120–122	peat	3678 ± 412	
			135–137	peat	4027 ± 308	
			150–152	organic/mineral sediment	4417 ± 307	
SHC	46°35´10˝ N, 130°39´20˝ E	200	100–110	peat	1267 ± 76	Niu (unpublished data, 1986)
			195–200	clay mineral	2541 ± 80	
FBC	46°35´30˝ N, 132°57´0˝ E	120	118–120	peat	1585 ± 90	Ye et al. (1983)
BBR	47°32´20˝ N, 133°41´0˝ E	180	50–55	peat	820 ± 70	Niu (unpublished data, 1986)
			110–120	peat	3075 ± 70	
			170–180	organic/mineral sediment	4615 ± 75	
QTC	48°3´15˝ N, 133°20´10˝ E	257	65–67	peat	1285 ± 75	Xia (1988)
			110–113	peat	4965 ± 90	
			150–153	peat	7645 ± 105	
			220–223	peat	9525 ± 125	
			253–257	clay mineral	10,585 ± 515	
CFC	48°15´50˝ N, 134°22´30˝ E	170	95–100	peat	3625 ± 80	Xia (1988)
			145–150	peat	9300 ± 100	
			160–170	organic/mineral sediment	10,295 ± 305	
UWR	48°23´50˝ N, 130°3´10˝ E	65	53–63	peat	1318 ± 65	Niu (unpublished data, 1986)
HNR	47°47´22˝ N, 133°37´43˝ E	54	52–54	peat	2897 ± 143	this study
SNR	47°15´49˝ N, 133°45´42˝ E	32	31–32	organic/mineral sediment	3912 ± 193	this study
ABR	47°55´4˝ N, 134°28´6˝ E	35	34–35	organic/mineral sediment	5910 ± 170	this study
THF	47°35´28˝ N, 133°38´49˝ E	32	31–32	organic/mineral sediment	3428 ± 167	this study
QFC	47°35´41˝ N, 133°47´1˝ E	35	34–35	organic/mineral sediment	2990 ± 190	this study

RESULTS

Dry Bulk Density and Organic Carbon Content

The mean dry bulk density and organic C content of the sediments are given in Fig. 3. The dry bulk density of the sediment in our cores varied between 0.15 g cm^{-3} (BBR) and 0.78 g cm^{-3} (THF), with a mean of 0.34 ± 0.05 g cm^{-3} (±SE), and there is an obvious decreasing trend in the mean dry bulk density in relation to the wetland category: marshy meadow > humus marsh > herbaceous peatland. The mean organic C concentration of the Sanjiang Plain wetlands is 29.49 ± 1.87% for herbaceous peatland, 12.48 ± 3.30% for humus marsh, and 7.47 ± 5.14% for marshy meadow.

Chronology of Peat Deposits

The results of both conventional ^{14}C and AMS ^{14}C are shown in Table 2 and used to calculate the LORCA. Peat formation in the Sanjiang Plain wetland started as early as approximately 10,000 ^{14}C yr before present (BP), for example the QTC and CFC peat cores. The mean time of peat development in this region was about 4000 ^{14}C yr BP. The time of peat deposit evolution for the whole region is not homogeneous, however, and the history of the peatland at some sites is not very long, for example, about 1318 ^{14}C yr BP for the UWR core and a modern ^{14}C age at 30 to 40 cm for the XBC core.

Radioisotope results for ^{210}Pb were plotted and are given in Fig. 4. In all sampled sites, the unsupported ^{210}Pb activity gradually declined with increasing depth and became constant at depths ranging from 25 cm (SNR) to 48 cm (HNR), which is consistent with the equilibrium depth of the total ^{210}Pb and the supported ^{210}Pb. The continuous dating records were reconstructed on the basis of the CRS model, and the age–depth relationships for these

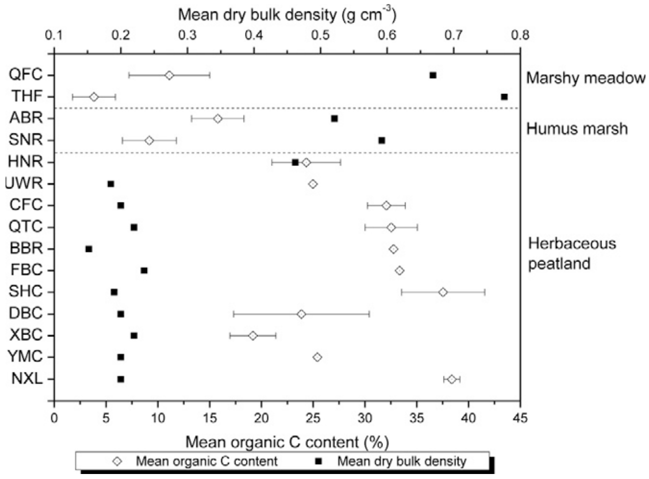

Fig. 3. Mean organic C content and mean dry bulk density of sediments in temperate wetlands of Sanjiang Plain, Northeast China. The data on organic C content of the NXL, YMC, XBC, DBC, SHC, FBC, BBR, QTC, CFC and UWR cores were calculated by multiplying the organic matter content (Niu, unpublished data, 1986) by 0.50. The data on dry bulk density of the XBC, SHC, FBC, BBR, QTC, CFC, and UWR cores are from Niu (unpublished data, 1986), and the values for the NXL, YMC, and DBC cores are expressed as the average dry bulk density of peat profiles in the top 50 to 75 cm in the Sanjiang Plain (Zhang et al., 2008).

five cores are plotted in Fig. 5. These peat cores are dated back to about 200 yr from the time of core collection.

Long-Term and Recent Rates of Carbon Accumulation

The LORCA values since peatland initiation in the Sanjiang Plain wetland were estimated from the mean organic C content and the basal age inferred from ^{14}C (Fig. 6). The highest average value was 61 ± 2 g C m^{-2} yr^{-1} (±SE) for the NXL core, and the smallest average was 5 ± 3 g C m^{-2} yr^{-1} for the SNR core. Based on these data, the LORCA of the three types of wetlands in the Sanjiang Plain region was estimated to be 8.5 ± 3.2 g C m^{-2} yr^{-1} for marshy meadow, 4.7 ± 0.3 g C m^{-2} yr^{-1} for humus marsh, and 28.2 ± 6.1 g C m^{-2} yr^{-1} for herbaceous peatland. The area-weighted LORCA of the Sanjiang Plain wetlands was estimated to be 5 to 61 g C m^{-2} yr^{-1}, with a mean of 22 ± 5 g C m^{-2} yr^{-1}.

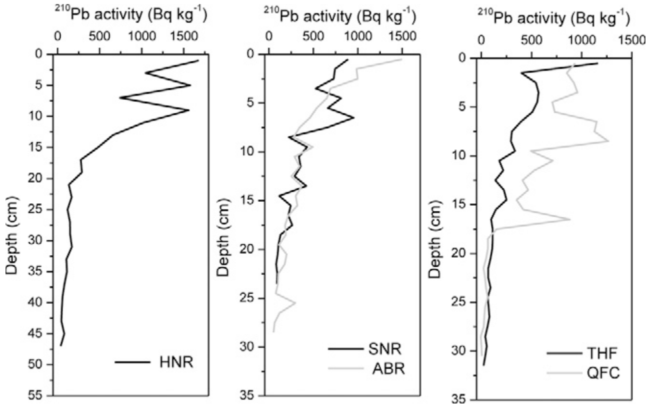

Fig. 4. Radioisotope results for ^{210}Pb content plotted as activity vs. depth for five cores from the temperate wetlands of the Sanjiang Plain, Northeast China.

The use of ^{210}Pb dating allowed the RERCA (g C m^{-2} yr^{-1}) to be determined. The values for each profile are summarized in Table 3. The highest average was 384 ± 93 g C m^{-2} yr^{-1} for the ABR core, and the smallest average was 170 ± 63 g C m^{-2} yr^{-1} for the QFC core. Given the five cores representing the three main wetland types in the Sanjiang Plain, the RERCA of the Sanjiang Plain wetland was estimated to be 170 to 384 g C m^{-2} yr^{-1} with a mean of 264 ± 45 g C m^{-2} yr^{-1}.

Estimation of Carbon Pool

For the three types of wetlands, the soil C density, annual C budget, and the total C pool were estimated (Table 4). According to the mean LORCA value and the mean time of peat initiation for each wetland type, the soil C accumulation during the last 4000 yr was determined to be 113 kg C m^{-2} in the herbaceous peatland, 19 kg C m^{-2} in humus marshes, and 25 kg C m^{-2} in marshy meadows of the Sanjiang Plain wetlands. Based on the mean LORCA and the area proportion of each type of wetland, the organic C flux was calculated to be 0.05 Tg C yr^{-1} in the herbaceous peatland, 0.02 Tg C yr^{-1} in humus marshes, and 0.03 Tg C yr^{-1} in marshy meadows of the Sanjiang Plain wetlands. By multiplying the C density with the area of each type of wetland, the C stock subtotals were estimated to be 0.21 Pg C for herbaceous peatland, 0.07 Pg C for humus marsh, and 0.08 Pg C for marshy meadow, and thus the total C stock of the Sanjiang Plain wetlands was 0.36 Pg C.

DISCUSSION

Sediment Characteristics

An organic soil (a Histosol) is generally characterized by high organic matter (organic C content >20%) and lower bulk density (0.2–0.3 g cm^{-3}) in the upper 1 m of the profile, whereas a mineral soil (e.g., a Spodosol) is generally characterized by low organic matter (organic C content <20%) and relatively high bulk density (1.0–2.0 g cm^{-3}) (Mitsch and Gosselink, 2007). Thus, the results of the dry bulk density (Fig. 3) indicate that the soil of the Sanjiang Plain wetlands is mainly an organic soil, and herbaceous peatlands represent a high organic C content relative to the other two wetland types in the Sanjiang

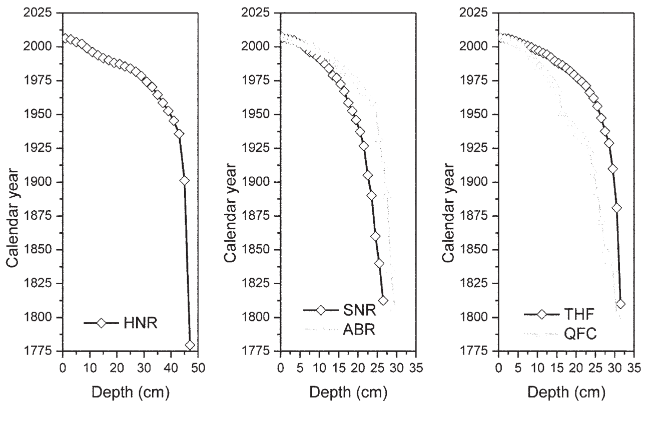

Fig. 5. Calendar year derived from ^{210}Pb content vs. depth for five cores from the temperate wetlands of the Sanjiang Plain, Northeast China.

Plain, suggesting that these two sediment characteristics are good indicators of sediment composition.

The dating results of the sediments show some differences in peat deposit chronology among these sites (Table 2). This is probably the result of the restraint of regional geomorphology and the variation in sediment thickness because peatlands often developed first on negative landforms such as the ancient channel fed with groundwater, the middle and upper reaches of some marsh rivers, and deep depressions (Niu et al., 1990). For example, the QTC and CFC peat cores were considered to be the standard section of recording peat formation and paleoclimatic change during the Holocene in this region due to their long history of development and intact information about paleogeographic environmental changes (i.e., spores and pollen, residual plant material, clay minerals) (Xia, 1988; Yang, 1990).

The latitudinal distribution of the basal ^{14}C age and the mean sediment rate inferred from the total depth of the cores and the basal ^{14}C age is shown in Fig. 7. It can be seen that the peatlands in the northern Sanjiang Plain (e.g., 48° N) have an older history than the peatlands in the south (e.g., 45° N), which illustrates the importance of climate in determining peat deposits. As for the sediment rate, there is an obvious difference among the wetland types rather than along the latitude. The sediment rate of the herbaceous peatlands ranges from 0.15 to 0.81 mm yr^{-1} (average of 0.44 mm yr^{-1}), while for humus marshes and marshy meadows, the sediment rate is 0.06 to 0.12 mm yr^{-1}, with an average of 0.08 mm yr^{-1}, which suggests that the peat-accumulating process is becoming weaker. It could be supposed that the pristine peatlands would gradually degrade into marshy meadows.

Comparisons of Carbon Accumulation Rates with Other Studies

Using peat C characteristics from 15 radiocarbon-dated and five ^{210}Pb-dated peat cores, we quantified both LORCA and RERCA. In comparison with the other very few reported studies of temperate freshwater wetlands (Table 5), we found the mean (22 ± 5 g C m^{-2} yr^{-1}) and range (61 g C m^{-2} yr^{-1}) of LORCA from our study to be quite consistent with the values for the conterminous U.S. peatlands (Armentano and Menges, 1986; Bridgham et al., 2006). In addition, the many LORCA studies for boreal and subarctic peatlands and tropical wetlands allow comparison of our results with those from different biomes (Table 5). Although these LORCA data, including both the published ones and our results, are almost on the same order of magnitude, differences in the ranges of accumulation rates can be still observed. We expect that these contrasts may be explained by differences in the specific local situations in combination with climate change and the different calculation methods used by the researchers.

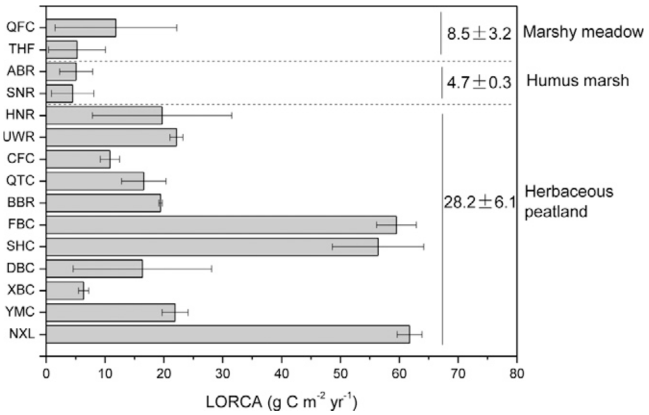

Fig. 6. The long-term (apparent) rate of C accumulation (LORCA) in 15 cores from the temperate wetlands of the Sanjiang Plain, Northeast China.

Relevant studies on short-term C accumulation worldwide are available to ensure comparisons of the RERCA values estimated by various dating methods (Table 6). Our results are very consistent with these values on a century time scale, and these comparisons suggest that our results are useful for a complete picture of the global C cycle. The uncertainty around this estimate is still large due to the limited number of sediment cores, so further high-resolution sampling of wetland soil cores is needed.

As shown in Table 4, the C density (kg C m^{-2}) and the C flux (Tg C yr^{-1}) were compared with previous relevant studies in the Sanjiang Plain wetland, other countries' wetlands, as well as global peatlands. The C density we found is within the range of the organic C pool, 30 to 108 kg C m^{-2}, calculated as the average of the total global peatland area, about 5 × 10^{6} km^{2} (Gorham, 1991), and the total C pools, 150 to 540 Pg (Turunen et al., 2002; Otieno et al., 2009). It is also comparable to the mean C accumulation of 42 to 88 kg C m^{-2} in peatlands south of 60° N in West Siberia during the last 2000 yr (Beilman et al., 2009). Compared with the study in Finland, the annual C flux we found in the Sanjiang Plain wetlands is also quite consistent with the corresponding values reported by Turunen et al. (2002).

Zhang et al. (2008) reported a mean C pool of 83 kg C m^{-2} for herbaceous peatland, 27 kg C m^{-2} for humus marsh, and 17 kg C m^{-2} for marshy meadow determined by the C density method in the Sanjiang Plain wetlands. Our results are on the same order of magnitude as these values; however, we represented a larger spatial range compared with the sampling sites of Zhang et al. (2008). In addition, Zhang et al. (2008) seems to have underestimated the C accumulation because their calculated C densities for the herbaceous peatland and marshy meadow were smaller than our results although they used the combination of depth of the organic horizon and 1-m illuvial horizon. There still exists an uncertainty to some extent in the estimation of C accumulation for the humus marsh and marshy meadow because of the limited number of sampled cores in our study. Putting these two studies together, the C density of herbaceous peatland we reported plus the C densities of humus marsh and marshy meadow in Zhang et al. (2008) can allow an accurate assessment of the C accumulation in the Sanjiang Plain wetlands.

Relationship between Long-Term and Recent Rates of Carbon Accumulation

The LORCA and RERCA are analogous and can be estimated for a given peatland from peat columns of known (dry) bulk density, C content, and age. Differences exist in age determination.

Table 3. Near-surface peat ^{210}Pb ages and the recent apparent rate of C accumulation (RERCA) at five sites in temperate wetlands of Sanjiang Plain, northeast China.

Wetland type	Core	Depth	Organic C content†	Depth	Dry bulk density	^{210}Pb age	RERCA
		cm	%	cm	g cm^{-3}	yr BP	g C m^{-2} yr^{-1}
Herbaceous peatland	HNR	0–5	28.52	4–6	0.099	3.49	606.46
		5–10	29.48	8–10	0.103	8.03	420.53
		10–15	34.59	14–16	0.131	15.37	419.29
		15–20	29.18	18–20	0.204	18.76	391.56
		20–25	22.96	24–26	0.344	22.98	412.94
		25–30	16.09	28–30	0.366	28.38	327.36
		30–35	9.51	34–36	0.834	42.43	222.82
		35–48	9.51‡	46–48	1.310	227.42	92.66
Mean ± SE							361 ± 53
Humus marsh	SNR	0–5	13.88	4–5	0.245	3.69	457.82
		5–10	15.89	9–10	0.281	14.45	323.57
		10–15	14.82	14–15	0.395	29.97	226.49
		15–20	5.73	19–20	0.831	61.07	72.51
		20–25	2.82	24–25	0.983	194.54	19.89
Mean ± SE							220 ± 80
	ABR	0–5	16.83	4–5	0.252	3.90	608.35
		5–10	24.79	9–10	0.258	9.98	636.77
		10–15	22.78	14–15	0.263	19.39	461.48
		15–20	18.03	19–20	0.517	31.81	340.57
		20–25	11.08	24–25	0.846	51.66	197.59
		25–30	9.41	29–30	0.789	200.91	61.50
Mean ± SE							384 ± 93
Marshy meadow	THF	0–5	13.20	4–5	0.279	2.81	756.68
		5–10	6.25	9–10	0.374	9.07	251.82
		10–15	0.77	14–15	0.513	17.39	27.93
		15–20	1.49	19–20	0.912	27.78	57.18
		20–25	0.72	24–25	1.467	44.87	27.35
		25–32	0.59	31–32	0.888	196.94	7.44
Mean ± SE							188 ± 119
	QFC	0–5	13.53	4–5	0.259	4.40	407.02
		5–10	23.16	9–10	0.075	18.09	250.92
		10–15	26.54	14–15	0.234	34.79	239.37
		15–20	7.97	19–20	0.992	67.25	76.36
		20–25	2.03	24–25	1.158	99.37	24.06
		25–30	2.29	29–30	1.372	170.82	22.51
Mean ± SE							170 ± 63

† Peat samples for organic C content measurement were sectioned at 5-cm intervals for the upper 30- or 35-cm layers of each core.

‡ Organic C content below 35 cm was not determined and an alternative to the 35- to 48-cm section was to use the corresponding data of the 30- to 35-cm section.

The former dates the basal peat and the latter is based on the given dated horizon in a surface core (Tolonen and Turunen, 1996). To investigate the relationship between LORCA and RERCA, the five short cores of recent age were dated by AMS ^{14}C and ^{210}Pb techniques, and comparisons of both calculated C accumulation rates are illustrated in Fig. 8. The ^{14}C dating was measured to the base of each core and the age was up to a magnitude of 1000s yr; the ^{210}Pb dating was measured to the lower layers very close to the bottom of each core and the age was just a magnitude of 100s yr (Tables 2 and 3; Fig. 8). In addition to the difference in age, the RERCA of each core was 20 to 75 times greater than the corresponding LORCA value. This is consistent with the well-known fact that the recent C accumulation is usually much higher than long-term C accumulation; however, almost the same deep cores produced a wide difference in the two types of chronologies and two C accumulation rates. This may be primarily due to the uncertainties in the dating methods. Two possible scenarios exist to explain this: the ^{14}C analysis offered an older age for the short modern cores or the ^{210}Pb dates underestimated the age in the uppermost sections of the cores because of the possible post-depositional mobility of ^{210}Pb. Under the former scenario, the LORCA was underestimated because of the old date; under the latter scenario, the RERCA was overestimated. Therefore, more work should now follow on high-precision dating for modern peats.

Based on the five RERCA profiles, an increasing trend of C accumulation from the bottom to the surface was observed (Table 3). This is consistent with the temporal variation of organic C content. Recent C accumulation results do not justify the actual net rate of

Table 4. Storage of organic C estimated in the three types of wetlands in the Sanjiang Plain region and comparison of the C density and the C flux with previous reports.

Location	Area	Mean depth	Mean age	C density	C flux	C stock	Reference
	10^6 ha	cm	yr	kg C m^{-2}	Tg C yr^{-1}	Pg C	
Sanjiang Plain, China	0.90†					0.36	this study
Herbaceous peatland	0.18‡	140	4000	113	0.05	0.21	
Humus marsh	0.39‡	34	4000	19	0.02	0.07	
Marshy meadow	0.33‡	34	3000	25	0.03	0.08	
Sanjiang Plain, China							Zhang et al. (2008)
Herbaceous peatland		200§		83			
Humus marsh		139§		27			
Marshy meadow		120§		17			
Raised-bog region, Finland							Turunen et al. (2002)
Bog	0.43	143	3200		0.12		
Fen	0.18	141	5000		0.03		
West Siberia peatland, Russia		29–231	2000	42–88			Beilman et al. (2009)
Global peatlands	500			30–108		150–540	Gorham (1991), Otieno et al. (2009)

† Total area of Sanjiang Plain wetland in 2005 (Song et al., 2008).

‡ Calculated based on proportion: herbaceous peatland (20%), humus marsh (43%), and marshy meadow (37%) (Zhang et al., 2008).

§ Total depth of the thickness of the organic horizon plus 1 m of the underlying mineral soil; the corresponding organic C accumulation is the total organic C storage in the organic horizon plus 1 m illuvial horizon combined.

C accumulation (ARCA), however, because of the continuous C loss throughout the peat columns via decay and leaching throughout the peatlands' development history (Clymo, 1984; Tolonen and Turunen, 1996). The true site of peat accumulation is the lower thicker layer (catotelm) rather than the upper oxidative layer (acrotelm), where it takes in CO_2 through photosynthesis, converts it to plant material, and finally passes it on to the catotelm so that about 5 to 10% of the biomass produced annually forms peat (Clymo, 1984; Gorham, 1991; Warner et al., 1993). Therefore, the RERCA values we calculated cannot suggest the variation in C accumulation on the Sanjiang Plain wetlands, and more and deeper cores are needed to supply enough data to estimate the ARCA by modeling approaches like Clymo-type peat accumulation (Clymo, 1984) or other models (e.g., Frolking et al., 2010; Yu, 2011).

Sustainable Use of Wetlands in Sanjiang Plain

It can be concluded that the average LORCA is 22 ± 5 g C m^{-2} yr^{-1} and the total C stock is 0.36 Pg C in the Sanjiang Plain wetlands. The RERCA temporal variations show an accelerating trend in sediment accumulation in this area, although there are some uncertainties in the estimations of RERCA because of the limited number of representative cores. These natural wetlands are critically important to global climate change as a result of their role in modulating atmospheric concentrations of CO_2 and CH_4. Song et al. (2009) examined the CH_4 exchange between the pristine marsh ecosystem and the atmosphere from 2002 to 2005 and found that the mean annual budget of CH_4 was 39.40 ± 6.99 g C m^{-2} yr^{-1} for the undrained wetland in the Sanjiang Plain region. If the average LORCA (22 ± 5 g C m^{-2} yr^{-1}) estimated in this study is considered to correspond to the present-day rate of C accumulation, then the Sanjiang Plain wetlands may be regarded as a net C source of approximately 18 g C m^{-2} yr^{-1} to the atmosphere. This may provide evidence for the view that marshland conversion to cropland could reduce the greenhouse effect (Huang et al., 2010a).

It should be pointed out, however, that wetland loss is one of the biggest environmental problems in the Sanjiang Plain in recent years because of agricultural development (Zhang et al., 2010). With intensive marsh reclamation under the policy driver of intensifying crop yields, abundant hilly valley peatlands have been converted to upland fields and a large number of ditch systems have been built to discharge standing water in natural marshes so as to transform them to paddy land (Fig. 2). Degradation of wetlands and disturbance of their anaerobic environment lead to a higher rate of decomposition of the large amount of C stored in them and thus an increasing loss of C reserves due to the release of greenhouse gases to the atmosphere (Song et al., 2009) as well as flow of dissolved organic C to the hydrosphere (Song et al., 2011).

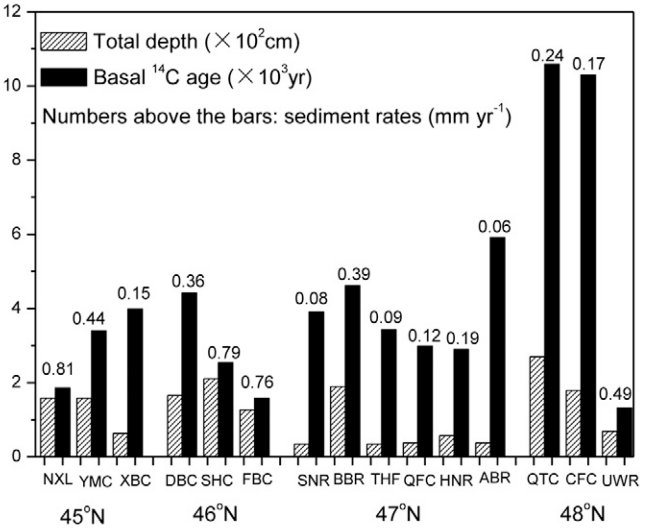

Fig. 7. Latitudinal distribution of the total depth and the basal ^{14}C age for each sediment core from the temperate wetlands of the Sanjiang Plain, Northeast China.

Table 5. Comparison of the long-term apparent rate of C accumulation (LORCA) in wetlands using ^{14}C, accelerator mass spectrometry (AMS) ^{14}C, and pollen dating methods.

Region	LORCA	Dating method	Source
	g C m^{-2} yr^{-1}		
Temperate wetlands			
Wetlands of Sanjiang Plain, China	5–61 (22 ± 5†)	^{14}C, AMS ^{14}C	this study
Northern conterminous U.S. peatlands	48‡	^{14}C	Armentano and Menges (1986)
Conterminous U.S. peatlands	71‡	^{14}C, pollen	Bridgham et al. (2006)
Boreal and subarctic peatlands			
Finnish peatlands	2.8–88.6	^{14}C, pollen	Tolonen and Turunen (1996)
Peatlands of western Canada	19.4	^{14}C	Vitt et al. (2000)
Boreal peat bogs in eastern Canada	4.9–67.5	AMS ^{14}C	Loisel and Garneau (2010)
Southern taiga of western Siberia	17.9–73.4	^{14}C	Borren et al. (2004)
Peatlands of western Siberia	3.6–44.1	AMS ^{14}C	Beilman et al. (2009)
Tropical wetlands			
Burundi peat bog, East Africa	20–200	^{14}C	Aucour et al. (1999)
Kalimantan peat bog, Indonesia	56.2	^{14}C	Page et al. (2004)
Andes Mountains peatlands, Ecuador	46	AMS ^{14}C	Chimner and Karberg (2008)

† Mean ± SE.

‡ Estimates from data including the dating collected from the published literature.

Table 6. Comparison of the recent apparent rate of C accumulation (RERCA) in wetlands using ^{210}Pb, ^{137}Cs, and pine dating methods.

Region	RERCA	Dating method	Source
		g C m^{-2} yr^{-1}	
Wetlands of Sanjiang Plain, China	170–384, 264 ± 45†	^{210}Pb	this study
U.S. Everglades	94–161	^{137}Cs	Craft and Richardson (1993)
Finnish peatlands	11.8–290.3	pine	Tolonen and Turunen (1996)
Peatlands of eastern Canada	40–117	^{210}Pb	Turunen et al. (2004)
U.S. river-dominated tidal marshes	40–124	^{137}Cs	Loomis and Craft (2010)
Changbai Mountain peatlands, China	124.2–292.8	^{210}Pb	Bao et al. (2010b)

† Mean ± SE.

In addition to the changes in C storage, the ecosystem services including the wetland biodiversity, wildlife habitat, the functions of water reserves and flood storage, among others, have been degrading significantly. Unfortunately, the increased threats and pressures on wetlands associated with an increasing population and rapidly developing economy will exist for a long time. The lack of a national long-term strategic plan for wetland conservation and restoration in the Sanjiang Plain wetlands may result in more significant losses in C sequestration function and other ecosystem services. Therefore, it is imperative for the Chinese government to undertake a series of prudent actions now to actively implement the sustainable use of wetlands in the Sanjiang Plain region.

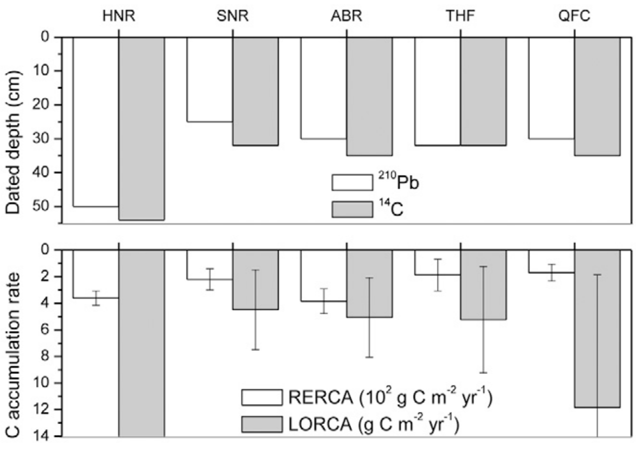

Fig. 8. Comparisons of the depth dated by ^{210}Pb and ^{14}C and the C accumulation rates calculated from ^{210}Pb (recent rate of C accumulation, RERCA) and ^{14}C (long-term rate of C accumulation, LORCA) for five cores from the temperate wetlands of the Sanjiang Plain, Northeast China.

ACKNOWLEDGMENTS

We thank Yuxia Zhang, Haiyang Zhao, and Bokun Lou for laboratory assistance and Bingwen Chen, Conglin Li, Chaoying Wang, Lei Chen, and Ruishan Wang in Changchun Institute of Geography, Chinese Academy of Sciences, for their contributions to the previous ^{14}C measurements. Kunshan Bao is grateful to Ming Hou for useful help in study region mapping and wetlands issue discussions. Research support was provided by the Knowledge Innovation Program of Chinese Academy of Sciences (no. KZCX2-EW-319), the National Basic Research Program of China (no. 2012CB956103), and the National Natural Science Foundation of China (no. 40830535).

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