Chin. Geogra. Sci. 2016 Vol. 26 No. 3 pp. 295–303
doi: 10.1007/s11769-016-0809-y

Springer Science Press
www.springerlink.com/content/1002-0063

Distribution and Accumulation of Soil Carbon in Temperate Wetland, Northeast China

LYU Mingzhi[1, 2], SHENG Lianxi[1, 2], ZHANG Zhongsheng[3], ZHANG Li[4]

(1. *Northeast Normal University*, *Changchun* 130024, *China*; 2. *State Environment Protection Key Laboratory of Wetland Ecology and Vegetation Restoration*, *Changchun* 130117, *China*; 3. *Key Laboratory of Wetland Ecology and Environment*, *Institute of Northeast Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 130012, *China*; 4. *Everglades Wetland Research Park*, *Florida Gulf Coast University*, *Naples FL* 34112, *U.S.A.*)

Abstract: Estimating carbon sequestration and nutrient accumulation rates in Northeast China are important to assess wetlands function as carbon sink buffering greenhouse gas increasing in North Asia. The objectives of this study were to estimate accreting rates of carbon and nutrients in typical temperate wetlands. Results indicated that average soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) contents were 37.81%, 1.59% and 0.08% in peatlands, 5.33%, 0.25% and 0.05% in marshes, 2.92%, 0.27% and 0.10% in marshy meadows, respectively. Chronologies reconstructed by ^{210}Pb in the present work were acceptable and reliable, and the average time to yield 0–40 cm depth sediment cores was 150 years. Average carbon sequestration rate ($Carbon_{sq}$), nitrogen and phosphorus accumulation rates were 219.4 g C/(m^2·yr), 9.16 g N/(m^2·yr) and 0.46 g P/(m^2·yr) for peatland; 57.13 g C/(m^2·yr), 5.42 g N/(m^2·yr) and 2.16 g P/(m^2·yr) for marshy meadow; 78.35 g C/(m^2·yr), 8.70 g N/(m^2·yr) and 0.71 g P/(m^2·yr) for marshy; respectively. Positive relations existed between $Carbon_{sq}$ with nitrogen and precipitations, indicating that $Carbon_{sq}$ might be strengthened in future climate scenarios.

Keywords: carbon sequestration; nutrients accumulation; temperate wetlands; Northeast China

Citation: Lyu Mingzhi, Sheng Lianxi, Zhang Zhongsheng, Zhang Li, 2016. Distribution and accumulation of soil carbon in temperate wetland, Northeast China. *Chinese Geographical Science*, 26(3): 295–303. doi: 10.1007/s11769-016-0809-y

1 Introduction

Wetlands provide many ecosystem services, including biodiversity support, flood and storm mitigation, and water quality improvement, particularly through nutrient reduction, which has led some to suggest that wetlands provide more services to human society than does almost any other ecosystem (Costanza *et al*., 1997; Zhang *et al*., 2014). Wetland can be seen as the largest component of the terrestrial biological carbon pool on earth (Adame *et al*., 2015; Bernal and Mitsch, 2012; Chmura *et al*., 2003). It plays a key factor in globe carbon cycles (Craft and Richardson, 1998; Marin-Muniz *et al*., 2014). The Changbai Mountains is the key indicator of climate change in Northeast China, and most of the alpine wetland is the key factor in the fragile alpine ecosystem (Huang *et al*., 2012).

Some research shows that carbon sequestration is only a short-term strategy to mitigating anthropogenic enrichment of atmospheric CO_2 (Lal, 2005). However, because of the huge areas and high productivity, carbon sequestration by temperate wetlands might play important roles in buffering greenhouse gas increasing in atmosphere (Reay *et al*., 2008). Globally, wetlands provide the largest terrestrial carbon stores and a potentially important mechanism for climate change mitigation

Received date: 2015-11-06; accepted date: 2016-03-02
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41471081), Scientific Research Foundation of Graduate School of Northeast Normal University (No. 12SSXT149)
Corresponding author: SHENG Lianxi. E-mail: shenglx@nenu.edu.cn

(Zaehle, 2013). It is estimated that the amount of carbon stored in wetland soils in ~498 Pg, which accounts to more than one third of the total world pool of soil C (Zaehle, 2013). Characterized by high carbon sequestration rates, wetlands trigger carbon circulation on regional scales to great extent (Page *et al*., 2011). However, few are still available on carbon sequestration rates by temperate wetlands in Northeast China, and this draw inconclusive estimation and assessment on wetland function as carbon sink, though Bao *et al*. (2010; 2015) has reported some data about the Changbai Mountains and the Sanjiang Plain.

It is estimated that most wetland areas distributes around the 50°N, which empower wetlands in temperate zones vital roles in reducing atmospheric CO_2 levels. However, agriculture and climate change here have weakened wetlands functions as carbon sink (Bai *et al*., 2007). In the Sanjiang Plain, more than 80% wetland had lost since 1954 (Song *et al*., 2008), and continuous warming accelerate wetland degradation (Song *et al*., 2014). All mentioned above introduce an obscured estimation on carbon stock and sequestration. Based on the current knowledge discussed above, the objectives of the present work are: 1) to estimate carbon sequestration and nutrient accumulation rates in typical peatlands, marsh, marshy meadow and riparian marsh in Northeast China; 2) to discuss the potential factors influencing carbon sequestrations in wetland. Based on these two objectives, we hope to provide scientific basis for assessing the potential carbon storage capacity of wetlands and make predictions about carbon sequestration in the future under global climate change.

2 Materials and Methods

2.1 Site description

Description about the sampling sites in the study area is shown in Table 1. The Jinchuan wetland is a famous site in Jilin Province. It is located in the middle of the Longgang Mountain which is a part of the Changbai Mountains and it is charged by Jinchuan County. The coordinate are 42°16′20″–42°26′57″N and 126°13′55″–126°32′02″E, and elevations ranging between 449.0 m to 1233.3 m above sea level. The Jinchuan wetland is formed based on the volcanic landscape of wetland ecosystems. There is hundreds of river flow through the area, and the maximum river is less 10 m wide and 3 m depth. The Jinchuan wetland district belongs to the North temperate zone continental monsoon climate, with four distinct seasons, spring wind dry, humid and rainy in summer, mild in the autumn cool, the winter are cold. Mean annual temperature of 4.10℃ in the region, 110–120 days of frost-free period, May to September accumulated temperature 2500–2600℃. Annual sunshine hours is 2550 on average, average annual evaporation is 1276.1 mm, average annual precipitation 704.20 mm most is in summer which it takes 61% of annual precipitation. Six community structure are observed in the Jinchuan wetland, birch (*Betula ovalifolia*) and sedge (*Carex schmidtii*); *Carex schmidtii* and typha (*Thelypteris palustris*); *Carex schmidtii* and reed (*Phragmites australis*); *Carex schmidtii*; *Carex tenuiflora*; *Phragmites australis* and *Carex schmidtii*.

The HH-A, HH-B, XK-A and XK-B are all in the Sanjiang Plain, which is 55 m above sea level on average, belongs to the sub-humid warm temperate continental monsoon climate zone, and has a mean annual precipitation of approximately 558 mm, with substantial interannual and seasonal variations (Xiao *et al*., 2015). The Sanjiang Plain inhabits the largest freshwater wetland area in China. Permanently inundated wetlands, seasonally inundated wetlands, and shrub swamps account for 56.9%, 22.6% and 20.5%, respectively, of the

Table 1 Description of sampling sites

Site	Type	Latitude (N)	Longitude (E)	Plant	MAT (℃)	Precipitation (mm)	Hydrology
JC	Peatland	42.27	126.23	*Carex, Phragmites*	4.10	704.20	PL
HH-A	Marsh	47.587	133.501	*Carex lasiocarpa*	3.74	503.43	PL
HH-B	Marshy meadow	47.587	133.501	*D. angustifolia*	3.74	503.43	SL
XK-A	Riparian, marsh	45.381	132.327	*C. pseudocuraica*,	4.33	513.98	PL
XK-B	Riparian, marsh	45.381	132.327	*Glyceria spiculosa*,	4.33	513.98	PL
NW	Marsh	51.085	125.132	*C. lasiocarpa*	–2.35	473.31	PL

Notes: JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng; MAT, mean annual temperature; PL, persistent water-logged; SL, seasonal water-logged.

total wetland area in the Sanjiang Plain. The Da Hinggan Mountains zone, 573 m above sea level, has an average annual temperature of –2.8℃ and average annual precipitation of 746 mm. The low temperature and high amount of precipitation result in low decomposition rate, responsible for widespread permafrost and peatlands here to a great extend. The NW locates in the Da Hinggan Mountains, predominated by Carex and water-logged all the year. It is the representative herb peatlands in Northeast China.

2.2 Soil sampling and preparation

Soil samples were collected in August 2011, 2012 and 2015, from the Jinchuan wetland one for bulk density, carbon content determination and soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) determination the other for radiometric. In this research, 65 samples were taken from three soil cores. Each soil core was collected in 1 m × 1 m quadrat. Every core was measured for the length, divided into 2 cm intervals with 7-cm diameter, and then sealed in plastic bags. Soil core were taken 40 cm depth as average sampling depth. All samples were preserved at 4℃ before analysis. The soil column was then extracted from the coring barrel, subdivided into 2-cm thick segments and dried at 60℃ (to prevent the oxidation of carbon) until a constant weight was obtained. For radiometric, all samples were seal and labeled in the different plastic bags and arrangement by depth sequence from surface to 40 cm depth. For bulk density, carbon content determination and SOC, TN and TP determination all visible roots and litter material were excluded from analysis by sieving the sample with 2-mm mesh. After drying was complete, the 2-cm segments were weighed to determine bulk density.

2.3 Soil carbon and nutrients analysis

Triplicates (50 mg) samples of individual depth segments (2 cm) were analyzed for total organic and inorganic carbon content using a Shimadzu Total Organic Carbon Analyzer (TOC-V series, SSM-5000A, Kyoto, Japan). Total carbon (TC, %) was combustion at 900℃ in analysis chamber. Samples for the determination of inorganic carbon (IC, %) were pre-treated with 10 mol/L H_3PO_4, then combusted at 200℃, using standard procedures for wetland soils. The TOC within each depth segment was calculated as the difference between TC and IC concentrations. Percent TOC was multiplied by 10 to calculate soil carbon concentration in g C/kg, per 2 cm interval of soil.

2.4 Accretion, carbon sequestration and nutrient accumulate rates

Radiometric detector was used to ascertain ^{137}Cs and ^{210}Pb activity (pCi, 10–12 Ci), allowing for estimates of recent soil accretion rates. Ten-gram composite subsamples were analyzed by γ spectrometry for 20 hours, at 661.7 keV and 46.5 keV for ^{137}Cs and ^{210}Pb activity, respectively, using a high efficiency germanium detector (ORTEC High-Purity Germanium (HPGe) Well Detectors, Oak Ridge, USA). Radio cesium (^{137}Cs) is a man-made fallout radionuclide (30.1 years half-life) worldwide distributed as consequence of deposition from atmospheric nuclear weapon tests. The highest ^{137}Cs deposition can be found according to its depositional pattern in 1964. If the ^{137}Cs binds strongly to the sediment and move with it in soil, remaining unaltered and making it a radionuclide widely used as tracer in many studies with many sites, such as wetlands and floodplains (Stark *et al.*, 2006). The activity peak layer in the soil profile was identification by assumed to correspond to the year 1964. Therefore, the sediment accumulated in the wetland since that year can be estimated, and the accretion rate calculated assuming constant sedimentation rate, unless evidence in the profile of the opposite (Beilman *et al.*, 2009; Bernal and Mitsch, 2013; Brenner *et al.*, 2001; Oenema and Delaune, 1988).

In case of ^{137}Cs profile are not conclusive to determine the rate (30.1 years half-life), ^{210}Pb is a radioisotope in the ^{238}U decay series. ^{238}U found naturally in Earth's soil continually decays into gaseous radon-226, which in turn is distributed globally throughout the atmosphere where it is rapidly decays into several other short-lived isotopes. Pb-210 is readily adsorbed to the soil matrix and sediment surface. To account for variable sedimentation throughout time, the Constant Rate of Supply (C.R.S.) model was selected to calculate sediment age.

$$A_{\mathrm{d}} = A_0 \mathrm{e}^{-(\lambda t)} \tag{1}$$

where A_{d} is the excess Pb-210 activity at depth (d), A_0 is the Pb-210 activity at depth zero, λ is the Pb-210 decay constant (0.0311/yr), and t is time (yr).

Carbon sequestration and nutrients accumulate rates (g/(m^2·yr)) was calculated by using following equation:

$$C_{\text{seq}} = BD \times C_{\text{con}} \times A_{\text{d}} \quad (2)$$

where BD is average bulk density (g/cm^3) throughout the dated portion of the soil core profile, C_{con} (g/kg) is the average carbon concentration in the soil sample, and A_{d} is accretion rate supplied by the CRS ^{210}Pb method (cm/yr).

2.5 Statistical analysis

All data were using SPSS Statistical Software version 23.0(X64) for Windows 7 (IBM, Endicott, New York). The normality of carbon sequestration was tested using the Shapiro-Wilk test when necessary at 95% significant level.

3 Results

3.1 Soil bulk density, carbon and nutrient contents

Soil physical and chemical properties varied greatly among wetland types. Bulk density was the lowest in peatlands and the highest in marshy meadows. The average soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) contents were 37.81%, 1.59% and 0.08% in peatlands, 5.33%, 0.25% and 0.05% in marshes, 2.92%, 0.27% and 0.10% in marshy meadows, respectively (Table 2). ANOVA analysis suggested significant different SOC and TN contents from JC site with those from other sites ($P < 0.05$).

We mapped bulk density, SOC and nutrient distribution patterns in vertical directions. It indicated that significant differences exist between peatland and marsh or marshy meadows. From the surface to the bottom layers, bulk density in peatland (JC) and riparian marshes (XK-A, XK-B) changed little, SOC was increasing, and nutrients firstly slightly decreased and then increased, but the TN content in XK-A and XK-B decreased with the depth. In marsh and marshy meadow, soil bulk density were all increasing while carbon and nutrients in most sites were decreasing with depth in spite some special cases. For instance, unexpected peak values for TN and TP in 16–18 layers in HH-A, high TP in 8–10 layers in NW (Fig. 1).

3.2 Chronology of wetland soil accretion

The ^{210}Pb and ^{137}Cs radio activities were used for chronology establishment and verification in vertical directions (Fig. 2, Fig. 3). In all sites, radio activities from ^{210}Pb were all in decreasing in the form of negative exponential curves. By CRS model, we reconstructed chronology for each layers. Profiles formed during 1850–2015 for JC, 1855–2011 for HH-B, 1923–2011 for HH-A, 1807–2012 for XK-A, 1853–2012 for XK-B and 1887–2012 for NW. On average, 150 years were spent to yield 0–40 cm depth sediment cores.

Results indicated that ^{137}Cs showed significant peak values only in JC, HH-A and HH-B while ^{137}Cs activity profiles were chaotic in other sites. For example, ^{137}Cs was still detected in the bottom of XK-A and XK-B. Specially, though very high radio activities from ^{137}Cs were found in 2–4 layers in JC, but it was still monitored in the 38-40 layer. It indicated that ^{137}Cs might undergoing transfer in vertical directions in wetlands where SOC and humic acid were abundant. We compared chronology from ^{137}Cs with that from ^{210}Pb in HH-A and HH-B sites, and found that they matched each other. In HH-A, the layer of 1964 was 22–24 cm depth fingerprinted by ^{137}Cs, which agreed well with that by ^{210}Pb. In HH-B, the layer of 1964 was 14–16 cm, which was corresponding to 1972 fingerprinted by ^{210}Pb. It implied that chronologies reconstructed by ^{210}Pb in the present work were acceptable and reliable.

Table 2 Bulk density, SOC and nutrients contents in wetland soils (mean±SD)

Site	Bulk density (g/cm^3)	SOC (%)	TN (%)	TP (%)	C/N	C/P	N/P
JC	0.24±0.04	37.81±3.71	1.59±0.21	0.08±0.01	24.05±3.33	476±61.0	19.9±2.01
HH-A	0.66±0.33	7.58±3.45	0.60±0.43	0.07±0.03	11.43±4.66	86±34.0	6.94±3.32
HH-B	1.12±0.27	2.92±1.95	0.27±0.16	0.10±0.02	10.25±1.79	267±12.4	2.51±1.14
XK-A	0.58±0.07	5.09±3.23	0.16±0.08	0.03±0.01	30.3±10.90	185±75.0	5.93±2.04
XK-B	0.88±0.15	3.26±1.84	0.05±0.01	0.03±0.01	64.5±28.90	107±73.0	1.59±0.44
NW	0.71±0.29	5.38±2.96	0.17±0.15	0.07±0.05	42.3±26.10	70.6±41.6	1.90±1.30

Notes: JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; C/N, carbon nitrogen ratio; C/P, carbon phosphorus ratio; N/P, nitrogen phosphorus ratio

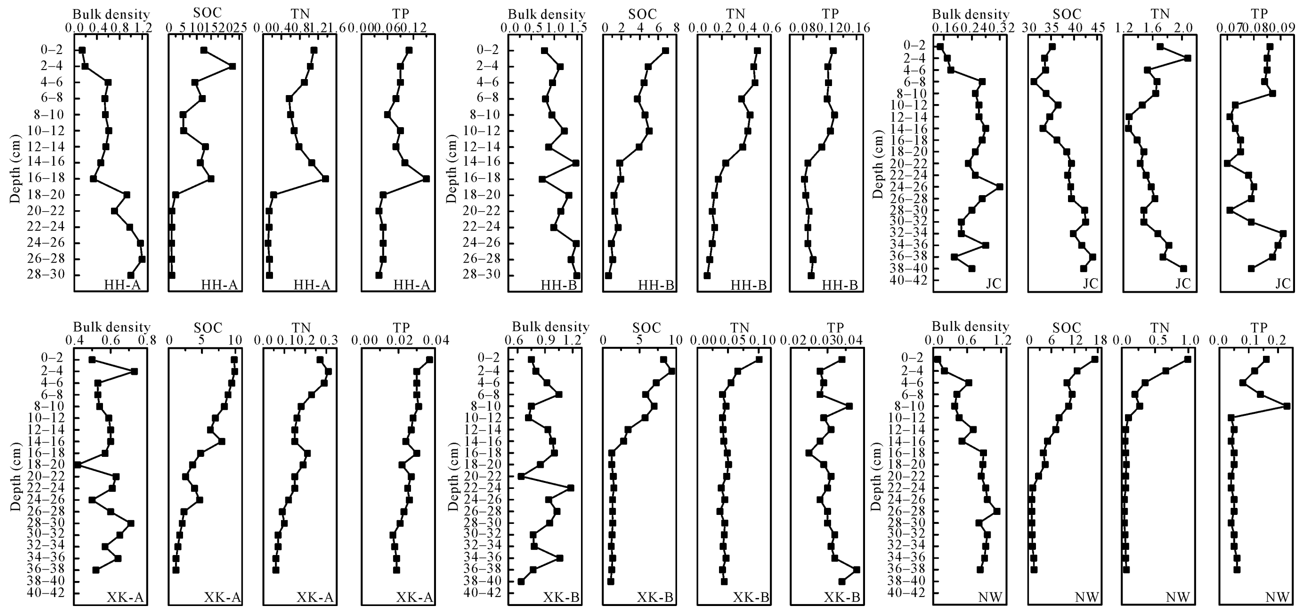

Fig. 1 Distribution patterns of soil bulk density (g/cm^3), SOC (g/kg) and nutrients (g/kg) in vertical direction. JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus

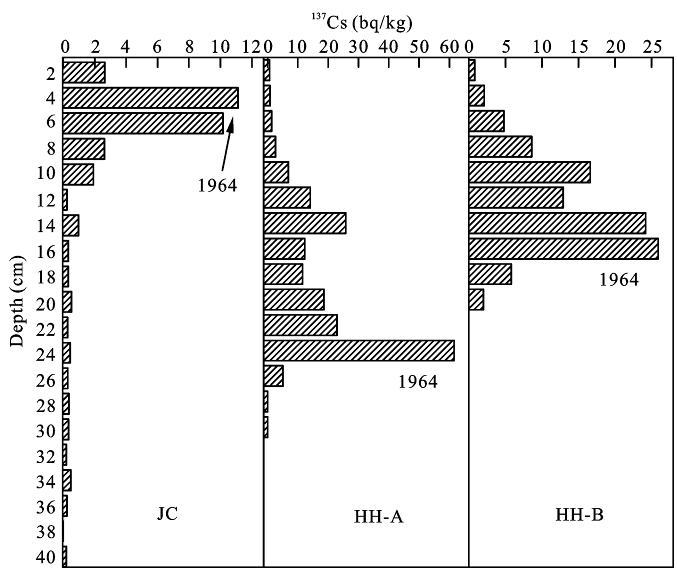

Fig. 2 Radio activities of ^{137}Cs in profiles of Jinchuan (JC), Honghe-A (HH-A) and Honghe-B (HH-B) sites

3.3 Sediment accretion, carbon sequestration and nutrient accumulation rates

The average sediment accretion rates were in the range of 1.85–3.14 mm/yr with an average of 2.53 mm/yr, and the highest was found in HH-A site and the lowest was in XK-A sites. Average carbon sequestration rate (Carbon$_{sq}$), nitrogen and phosphorus accumulation rates were 219.4 g C/(m^2·yr), 9.16 g N/(m^2·yr) and 0.46 g P/(m^2·yr) for peatland; 57.13 g C/(m^2·yr), 5.42 g N/(m^2·yr) and 2.16 g P/(m^2·yr) for marshy meadow; 78.35 g C/(m^2·yr), 8.70 g N/(m^2·yr) and 0.71 g P/(m^2·yr) for marshy; respectively (Fig. 4).

4 Discussion

Wetlands are considered as an effective CO_2 sink due to their high productivity and low decomposition derived from water-logged soil condition and degradation-resistant litters (Choi *et al.*, 2001; Dieleman *et al.*, 2015). Globally, most wetlands emerged in temperate

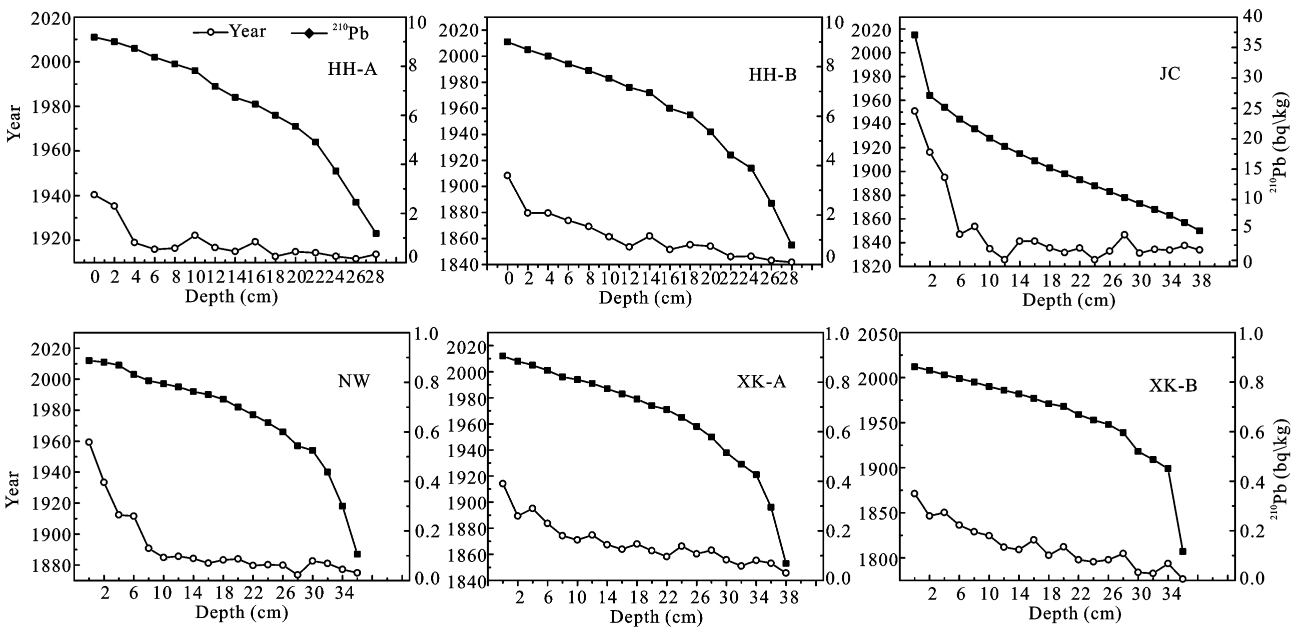

Fig. 3 Radio activities of ^{210}Pb in wetland profiles. JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng

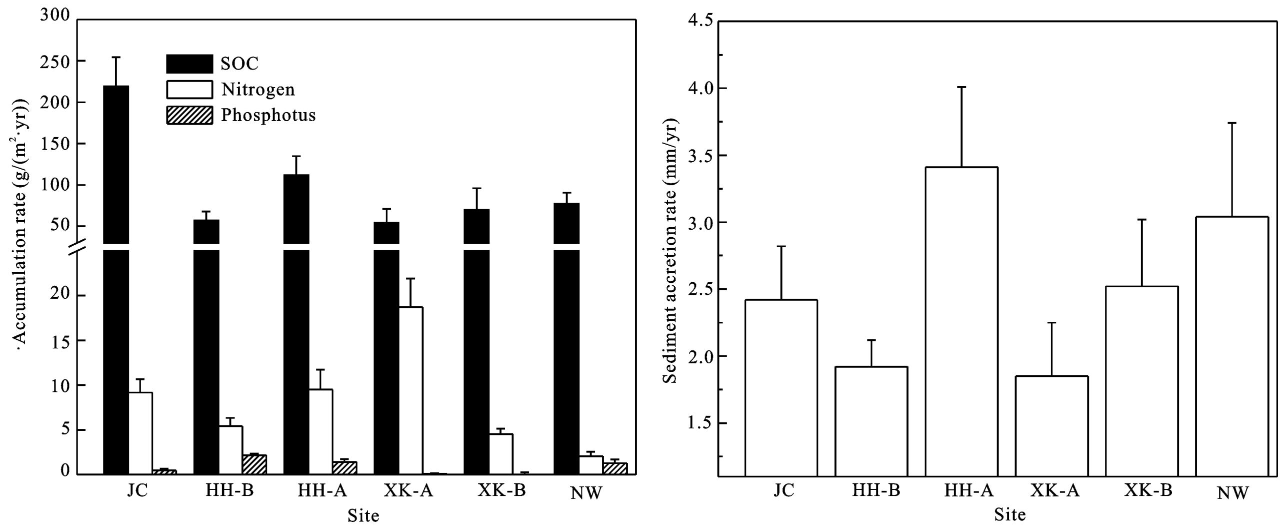

Fig. 4 Soil carbon sequestration, nutrient accumulation and sedimentation accretion in wetlands JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng

zones around 50°N (Kayranli *et al.*, 2010), and it is meaningful to estimate $Carbon_{sq}$ by wetlands under global warming background. The $Carbon_{sq}$ was about 200 g C/(m^2·yr) in the Changbai Mountains peatland, and their results were consistent with that in the present work (Bao *et al.*, 2015). Most of the world's peatlands are located in boreal and subarctic regions, peatlands here accreted at the rate of 0.1–0.8 mm/yr, inducing relative lower $Carbon_{sq}$ (< 100 g C/(m^2·yr)) (Graham *et al.*, 2005), which was much lower than that in the Changbai Mountains and might due to plant cover difference. Sphagnum was in predominant in most boreal peatlands (Bridgham *et al.*, 2006), characterizing with low annual biomass produce while *Carex* and *Phragmites* dominate in the Changbai Mountains with much more biomass. Though lower temperature restricted litter degradation in boreal peatland (Belyea and Malmer, 2004), but it seemed net primary productivity (NPP) might play more important roles in $Carbon_{sq}$ (Cao and Woodward, 1998). Marshes in Northeast China had lower $Carbon_{sq}$ than those from USA and Canada (Table 3). However, most marshes in Table 3 located in estuarine

Table 3 Comparison of $Carbon_{sq}$ (g C/(m^2·yr)) with results from other literatures

Core	Type	Country	$Carbon_{sq}$	Method	Ref.
JC	Peatland	China	219.36	^{210}Pb	This study
HH-B	Marshy meadow	China	57.13	^{210}Pb	This study
HH-A	Prairie Marsh	China	111.68	^{210}Pb	This study
XK-A	Prairie Marsh	China	54.21	^{210}Pb	This study
XK-B	Prairie Marsh	China	69.97	^{210}Pb	This study
NW	Marsh	China	77.55	^{210}Pb	This study
Changbai Mountains	Peatland	China	200	^{210}Pb	(Bao *et al*., 2010)
Da Hinggan Mountains	Peatland	China	203	^{210}Pb	(Bao *et al*., 2010)
Bleak Lake	Peatland	Canada	43	^{210}Pb	(Wieder, 2001)
Oregon Inlect	Marsh	USA	145.5	^{137}Cs	(Craft and Richardson, 1993)
East-2	Marsh	USA	400	^{210}Pb	(Ohlson and Okland, 1998)
Savanna	Marsh	USA	109	^{137}Cs	(Craft and Casey, 2000)
St. Annaland	Marsh	Netherland	139	^{210}Pb	(Callaway *et al*., 1996)

Notes: JC, Jinchuan; HH-A, Honghe-A; HH-B, Honghe-B; XK-A, Xingkai-A; XK-B, Xingkai; NW, Nanweng

in USA. Generally, estuarine at the ecotone of terrestrial and marine ecosystems have more effective biomass than inland marsh because both terrestrial and marine producers contribute to $Carbon_{sq}$ in these sites (Chimner and Ewel, 2005).

$Carbon_{sq}$ varied significantly among wetland types in Northeast China, ranked by peatland > marsh > marshy meadow. Compared with marshy meadow, peatlands and marshes are both water-logged all the year while marshy meadow undergoes seasonal situation submergence. Carbon sequestration is a function of both the biomass produced and the rate of biomass respiration. Litter decomposition was restricted by soil moisture, inducing more soil organic matter formation and stimulating $Carbon_{sq}$ (Kayranli *et al*., 2010). During the past several decades, wetlands in Sanjiang Plain undergone serious degradation, characterizing by transformation from marshes to meadow, and peatland disappearance (Song *et al*., 2008). Based on conclusions from the present work, it was certainly deduced that degradation would weaken wetlands as carbon sink.

Carbon accumulation in wetlands also was restricted by climate change and nutrient supply, especially N and P (Bai *et al*., 2012; Hessen *et al*., 2004).Warming and more precipitation was considered to promote plant growth in consequence with more biomass and litter backward to soil in most zones (Davidson and Janssens, 2006). Adams provided the problem that whether nitrogen input to natural systems could change net primary productivity and consequently affect carbon cycles (Adams, 2003). Correlation analysis suggested significantly positive relationships between soil TN, soil N：P (Fig. 5). Theoretically, nitrogen addition could enhance carbon sink functions because more nitrogen supports higher biomass, but the opposite effect was found in one in situ experiment of marshy meadows (Song *et al*., 2005), showing that increasing N producing more soil respiration, which depleted extra NPP originating from N fertilization effects. However, though nitrogen had questionable and obscure effects on motive carbon sequestration in wetlands(Oren *et al*., 2001), the present work provided evidences, partly, that nitrogen input to temperate wetlands might enhance carbon sequestration at long term time scale, over one hundred years.

5 Conclusions

Estimating carbon sequestration rates is essential to evaluating the carbon sink function of wetlands. Temperate wetlands would play important roles in buffering atmospheric CO_2 increasing. Peatlands and marshes generally had higher $Carbon_{sq}$ and nitrogen accumulation rates than those in marshy meadows, suggesting that wetland degradation would weaken wetland's function acting as carbon sink. Considering the positive relations between $Carbon_{sq}$ with nitrogen and precipitations, $Carbon_{sq}$ might be strengthened in future climate scenarios.

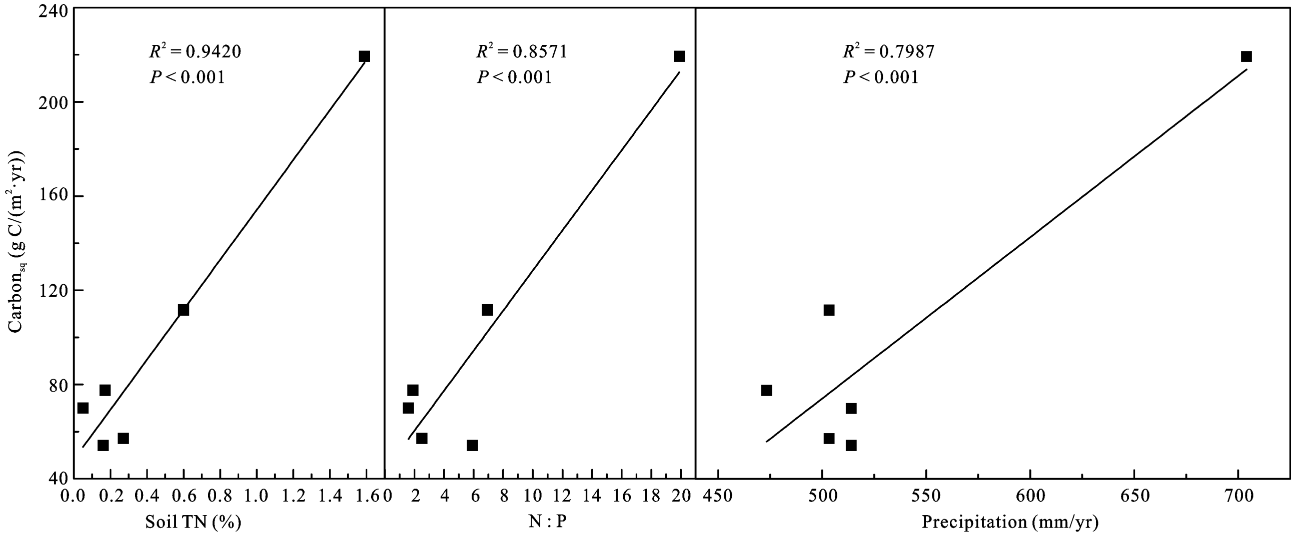

Fig. 5 Correlations between Carbon$_{sq}$ and TN, N ∶ P and precipitation Soil TN, soil total nitrogen

Acknowledgements

We are grateful to Zhang Nannan from Harbin Normal University for the sampling radiometric analyzing.

References

Adame M F, Santini N S, Tovilla C *et al.*, 2015. Carbon stocks and soil sequestration rates of tropical riverine wetlands. *Biogeosciences*, 12(12): 3805–3818. doi: 10.5194/bg-12-3805-2015

Adams M B, 2003. Ecological issues related to N deposition to natural ecosystems: research needs. *Environment International*, 29(2–3): 189–199. doi: 10.1016/S0160-4120(02)00179-4

Bai J, Cui B, Deng W *et al.*, 2007. Soil organic carbon contents of two natural inland saline-alkalined wetlands in northeastern China. *Journal of Soil and Water Conservation*, 62(6): 447–452. doi: 10.1007/s11769-013-0612-y

Bai J H, Wang Q G,, Deng W *et al.*, 2012. Spatial and seasonal distribution of nitrogen in marsh soils of a typical floodplain wetland in Northeast China. *Environmental Monitoring and Assessment*, 184(3): 1253–1263. doi: 10.1007/s10661-011-2037-3

Bao K S, Wang G P, Xing W *et al.*, 2015. Accumulation of organic carbon over the past 200 years in alpine peatlands, Northeast China. *Environmental Earth Sciences*, 73(11): 7489–7503. doi: 10.1007/s12665-014-3922-1

Bao K S, Yu X F, Jia L *et al.*, 2010. Recent carbon accumulation in Changbai Mountain peatlands, Northeast China. *Mountain Research and Development*, 30(1): 33–41. doi: 10.1659/MRD-JOURNAL-D-09-00054.1

Beilman D W, MacDonald G M, Smith L C *et al.*, 2009. Carbon accumulation in peatlands of West Siberia over the last 2000 years. *Global Biogeochemical Cycles*, 23. doi: 10.1029/2007GB003112

Belyea L R, Malmer N, 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. *Global Change Biology*, 10(7): 1043–1052. doi: 10.1111/j.1529-8817.2003.00783.x

Bernal B, Mitsch W J, 2012. Comparing carbon sequestration in temperate freshwater wetland communities. *Global Change Biology*, 18(5): 1636–1647. doi: 10.1111/j.1365-2486.2011.02619.x

Bernal B, Mitsch W J, 2013. Carbon sequestration in freshwater wetlands in Costa Rica and Botswana. *Biogeochemistry*, 115(1–3): 77–93. doi: 10.1007/s10533-012-9819-8

Brenner M, Schelske C L, Keenan L W, 2001. Historical rates of sediment and nutrient accumulation in marshes of the Upper St. Johns River Basin, Florida, USA. *Journal of Paleolimnology*, 26(3): 241–257. doi: 10.1023/A:1017578330641

Bridgham S D, Megonigal J P, Keller J K *et al.*, 2006. The carbon balance of North American wetlands. *Wetlands*, 26(4): 889–916. 10.1672/0277-5212(2006)26[889:Tcbona]2.0.Co;2

Callaway J C, DeLaune R D, Patrick W H, 1996. Chernobyl Cs-137 used to determine sediment accretion rates at selected northern European coastal wetlands. *Limnology and Oceanography*, 41(3): 444–450. doi: 10.4319/lo.1996.41.3.0444

Cao M K, Woodward F I, 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology*, 4(2): 185–198. doi: 10.1046/j.1365-2486.1998.00125.x

Chimner R A, Ewel K C, 2005. A tropical freshwater wetland: II. production, decomposition, and peat formation. *Wetlands Ecology and Management*, 13(6): 671–684. doi: 10.1007/s11273-005-0965-9

Chmura G L, Anisfeld S C, Cahoon D R *et al.*, 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, 17(4). doi: 10.1029/2002GB001917

Choi Y, Wang Y, Hsieh Y P *et al.*, 2001. Vegetation succession and carbon sequestration in a coastal wetland in Northwest Florida: evidence from carbon isotopes. *Global Biogeochemical Cycles*, 15(2): 311–319. doi: 10.1029/2000GB001308

Costanza R, dArge R, deGroot R *et al*., 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387(6630): 253–260. doi: 10.1038/387253a0

Craft C B, Casey W P, 2000. Sediment and nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA. *Wetlands*, 20(2): 323–332. doi: 10.1672/0277-5212(2000)020[0323:SANAIF]2.0.CO;2

Craft C B, Richardson C J, 1993. Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched everglades peatlands. *Ecological Applications*, 3(3): 446–458. doi: 10.2307/1941914

Craft C B, Richardson C J, 1998. Recent and long-term organic soil accretion and nutrient accumulation in the everglades. *Soil Science Society of America Journal*, 62(3): 834–843. doi: 10.2136/sssaj1998.03615995006200030042x

Davidson E A, Janssens I A, 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081): 165–173. doi: 10.1038/nature04514

Dieleman C M, Branfireun B A, Mclaughlin J W *et al*., 2015. Climate change drives a shift in peatland ecosystem plant community: Implications for ecosystem function and stability. *Global Change Biology*, 21(1): 388–395. doi: 10.1111/Gcb.12643

Graham S A, Craft C B, McCormick P V *et al*., 2005. Forms and accumulation of soil P in natural and recently restored peatlands—upper Klamath Lake, Oregon, USA. *Wetlands*, 25(3): 594–606. doi: 10.1672/0277-5212(2005)025[0594:Faaosp]2.0.Co;2

Hessen D O, Agren G I, Anderson T R *et al*., 2004. Carbon, sequestration in ecosystems: the role of stoichiometry. *Ecology*, 85(5): 1179–1192. doi: 10.1890/02-0251

Huang J, Kang S C, Zhang Q G *et al*., 2012. Wet deposition of mercury at a remote site in the Tibetan Plateau: concentrations, speciation, and fluxes. *Atmospheric Environment*, 62: 540–550. doi: 10.1016/j.atmosenv.2012.09.003

Kayranli B, Scholz M, Mustafa A *et al*., 2010. Carbon storage and fluxes within freshwater wetlands: a critical review. *Wetlands*, 30(1): 111–124. doi: 10.1007/s13157-009-0003-4

Lal R, 2005. Forest soils and carbon sequestration. *Forest Ecology and Management*, 220(1–3): 242–258. doi: 10.1016/j.foreco.2005.08.015

Marin-Muniz J L, Hernandez M E, Moreno-Casasola P, 2014. Comparing soil carbon sequestration in coastal freshwater wetlands with various geomorphic features and plant communities in Veracruz, Mexico. *Plant and Soil*, 378(1–2): 189–203. doi: 10.1007/s11104-013-2011-7

Oenema O, Delaune R D, 1988. Accretion rates in salt marshes in the eastern Scheldt, Southwest Netherlands. *Estuarine Coastal and Shelf Science*, 26(4): 379–394. doi: 10.1016/0272-7714(88)90019-4

Ohlson M, Okland R H, 1998. Spatial variation in rates of carbon and nitrogen accumulation in a boreal bog. *Ecology*, 79(8): 2745–2758. doi: 10.2307/176514

Oren R, Ellsworth D S, Johnsen K H *et al*., 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature*, 411(6836): 469–472. doi: 10.1038/35078064

Page S E, Rieley J O, Banks C J, 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, 17(2): 798–818. doi: 10.1111/j.1365-2486.2010.02279.x

Reay D S, Dentener F, Smith *et al*., 2008. Global nitrogen deposition and carbon sinks. *Nature Geoscience*, 1(7): 430–437. doi: 10.1038/ngeo230

Song C, Zhang J, Zhang L, 2005. The variation of carbon stock in freshwater mire after nitrogen input. *Advance in Earth Sciences*, 20: 1249–1255. doi: 1001-8166(2005)11-1249-07

Song Kaishan, Liu Dianwei, Wang Zongming *et al*., 2008. Land use change in Sanjiang Plain and its driving forces analysis since 1954. *Acta Geographica Sinica*, 63(1): 93. (in Chinese)

Song K S, Wang Z M, Du J *et al*., 2014. Wetland degradation: its driving forces and environmental impacts in the Sanjiang Plain, China. *Environmental Management*, 54(2): 255–271. doi: 10.1007/s00267-014-0278-y

Stark K, Wallberg P, Nylen T, 2006. Post-depositional redistribution and gradual accumulation of Cs-137 in a riparian wetland ecosystem in Sweden. *Journal of Environmental Radioactivity*, 87(2): 175–187. doi: 10.1016/j.jenvrad.2005.11.008

Wieder R K, 2001. Past, present, and future peatland carbon balance: an empirical model based on Pb-210-dated cores. *Ecological Applications*, 11(2): 327–342. doi: 10.2307/3060892

Xiao Y, Huang Z, Lu X, 2015. Changes of soil labile organic carbon fractions and their relation to soil microbial characteristics in four typical wetlands of Sanjiang Plain, Northeast China. *Ecological Engineering*, 82: 381–389. doi: 10.1016/j.ecoleng.2015.05.015

Zaehle S, 2013. Terrestrial nitrogen-carbon cycle interactions at the global scale. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 368: 1621. doi: 10.1098/rstb.2013.0125

Zhang Y, Xu H L, Chen H *et al*., 2014. Diversity of wetland plants used traditionally in China: a literature review. *Journal of Ethnobiology and Ethnomedicine*, 10. doi: Artn 7210.1186/1746-4269-10-72