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Regulating effects of climate, net primary productivity, and nitrogen on carbon sequestration rates in temperate wetlands, Northeast China

Zhongsheng Zhang[a,*], Christopher B. Craft[b], Zhenshan Xue[a], Shoungzheng Tong[a], Xianguo Lu[a]

[a] Institute of Northeast Geography and Agroecology, Chinese Academy of Science, 130012 Changchun, Jilin Province, People's Republic of China
[b] School of Public and Environmental Affairs, Indiana University, 1315 E. 10th St., Bloomington, IN 47404, USA

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ABSTRACT

Temperate wetlands in the Northern Hemisphere have high long-term carbon sequestration rates, and play critical roles in mitigating regional and global atmospheric CO_2 increases at the century timescale. We measured soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) from 11 typical freshwater wetlands (Heilongjiang Province) and one saline wetland (Jilin Province) in Northeast China, and estimated carbon sequestration rates using ^{210}Pb and ^{137}Cs dating technology. Effects of climate, net primary productivity, and nutrient availability on carbon sequestration rates (R_{carbon}) were also evaluated. Chronological results showed that surface soil within the 0–40 cm depth formed during the past 70–205 years. Soil accretion rates ranged from 2.20 to 5.83 mm yr^{-1}, with an average of 3.84 ± 1.25 mm yr^{-1} (mean ± SD). R_{carbon} ranged from 61.60 to 318.5 gC m^{-2} yr^{-1} and was significantly different among wetland types. Average R_{carbon} was 202.7 gC m^{-2} yr^{-1} in the freshwater wetlands and 61.6 gC m^{-2} yr^{-1} in the saline marsh. About 1.04×10^8 tons of carbon was estimated to be captured by temperate wetland soils annually in Heilongjiang Province (in the scope of 45.381–51.085°N, 125.132–132.324°E). Correlation analysis showed little impact of net primary productivity (NPP) and soil nutrient contents on R_{carbon}, whereas climate, specifically the combined dynamics of temperature and precipitation, was the predominant factor affecting R_{carbon}. The negative relationship observed between R_{carbon} and annual mean temperature (T) indicates that warming in Northeast China could reduce R_{carbon}. Significant positive relationships were observed between annual precipitation (P), the hydrothermal coefficient (defined as P/AT, where AT was accumulative temperature ≥10 °C), and R_{carbon}, indicating that a cold, humid climate would enhance R_{carbon}. Current climate change in Northeast China, characterized by warming and drought, may form positive feedbacks with R_{carbon} in temperate wetlands and accelerate carbon loss from wetland soils.

1. Introduction

Wetlands are natural ecosystems characterized by waterlogged soils and/or the presence of standing water during at least part of the year, unique soil conditions that differ from adjacent uplands, and the presence of vegetation adapted to wet conditions (Erwin, 2009). Because of oxygen-poor soil conditions due to water saturation, incomplete decomposition is pervasive in wetlands, especially in moss peatlands, where soil is low-nutrient and litters are abundant in degradation-resistant compounds such as tannins and polyphenols in litters (Blodau et al., 2004; Bridgham et al., 2006). Wetlands usually act as carbon sinks. Though they occupy only about 2%–6% of the earth's land surface, they contain a large portion (approximately one third) of the carbon stored in the terrestrial soil reservoir (Kayranli et al., 2010; Whiting and Chanton, 2001). Wetlands can have massive carbon stores and high sequestration ability per unit area, stemming from the combination of high net primary productivity (NPP) and low decomposition rates. Due to these characteristics, wetlands function as long-term sinks for atmospheric carbon dioxide (CO_2) (Hopkinson et al., 2012). Boreal and subarctic peatlands are estimated to store approximately 30% of the global soil C, equivalent to approximately 455 billion metric tons (Belyea and Malmer, 2004; Gorham, 1991), which is vital to buffering global or local atmospheric CO_2 increases.

Globally, wetland formation strongly depends on topography and climate, and they are widespread on flat or low-lying land

* Corresponding author at: Key Laboratory of Wetland Ecology and Environment, Institute of Northeast Geography and Agroecology, Chinese Academy of Science, 130012 Changchun, Jilin Province, People's Republic of China.
E-mail address: zzslycn@163.com (Z. Zhang).

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with cool and moist climates such as the temperate zones of the Northern Hemisphere (Turunen et al., 2004). Matthews and Fung (1987) estimated that the total global wetland area was 5.3 million km^2, half of which (2.6 million km^2) was at latitudes north of 50°N (Matthews and Fung, 1987). According to the latest wetland resources survey performed by China's Forestry Administration, the Northeast region, predominantly temperate and monsoonal, represents 14% of the total wetland area in China (http://www.shidi.org/zt/2014xwfbh/,in Chinese). Northeast China has low-lying depressions and floodplains, low temperatures, numerous rivers, and moderate precipitation, which yield widespread and various wetlands, including bogs, fens, moors, marshes, and swamps.

Carbon sequestration by wetlands is important for buffering atmospheric greenhouse gas emissions in temperate zones. Previous studies have focused on tundra in arctic or subarctic regions (Belyea and Malmer, 2004; Gorham, 1991), tropical and subtropical tidal marshes (Bernal and Mitsch, 2013), estuarine wetlands (Callaway et al., 2012), and boreal and temperate mires and peatlands. However, estimation of carbon sequestration by wetlands in Northeast China, which is crucial to carbon cycling in North Asia, is poorly elucidated (An et al., 2007; Song et al., 2009). Though Bao et al. (2011) recently found that carbon sequestration rates in peatlands of Northeast China ranged from 170 to 384 gC m^{-2} yr^{-1} (mean, 264 ± 45 gC m^{-2} yr^{-1}) (Bao et al., 2011), mires and marshy meadows were not involved in the study and potential factors affecting carbon sequestration processes were not discussed. Carbon sequestration processes in wetlands, essentially governed by the net effect of carbon input and output, are regulated by multiple factors such as climate, vegetation, nutrients, and soil moisture (Lal, 2003; Whiting and Chanton, 2001). These factors generally affect wetland carbon cycling, but their interaction mechanisms are still not well understood.

Climate change is believed to affect the movement and extinctions of various species, change the composition of communities, and alter the functions of ecosystems (Dieleman et al., 2015). For instance, on-going warming is thought to induce expansion and promote NPP of shrubs, resulting in more carbon deposited in soil as recalcitrant leaf litter across cold biomes, which would form a negative feedback with global warming (Cornelissen et al., 2007). As decomposition depends strongly on temperature and concomitantly is susceptible to warming, soil respiration also increases in response to rising soil temperature, which accelerates organic matter mineralization and enhances carbon loss from the soil pool (Rustad et al., 2001). Kirschbaum predicted that soil respiration was more sensitive to temperature in cooler climates and that a 1 °C increase in average temperature could reduce soil C pools by 10% in areas with average annual temperatures of 5 °C (Kirschbaum, 1995). In addition, a recent global experiment suggested that climate warming might reduce carbon sequestration in streams by causing a shift from macroinvertebrate-mediated decomposition to microbial decomposition, increasing CO_2 production and decreasing production of more recalcitrant carbon compounds (Boyero et al., 2011). These studies underscore the fact that carbon sequestration processes will depend on carbon cycling dynamics, which are regulated by NPP, soil respiration, microbial activities, and other direct and indirect factors.

The effects of climate change on carbon cycling in wetlands become more complicated when the effects of warming, precipitation changes, and variation in nutrient availability are combined. In wetlands, hydrological regimes often govern nutrient cycling (Hefting et al., 2004). Subtle changes in hydrologic variation could provoke substantial fluctuations in wetland soil C pools (Chmura et al., 2003), as a higher water level is associated with increased organic matter burial in wetland soils (Blodau et al., 2004). However, more work is needed to reveal the impacts of multiple environmental factors on carbon sequestration.

Based on the current knowledge discussed above, the objectives of the present work are: (1) to estimate carbon sequestration by typical temperate wetlands in Northeast China using ^{210}Pb and ^{137}Cs dating technology; and (2) to discuss the impacts of potential factors (climate, NPP, nutrients) on carbon sequestration in wetlands. Based on these two aims, we hope to provide a scientific estimation of potential carbon storage capacities by wetlands and to make predictions about carbon sequestration under future global climate change scenarios.

2. Materials and methods

2.1. Study areas

Northeast China has various wetland types, including marsh, moor, bog, fen, and swamp. According to a survey by China's Forestry Administration, Heilongjiang, Jilin, and Liaoning Provinces have 753.6 km^2 of wetland area. In the present work, 12 typical marshes and marshy meadows were selected for soil sample collection, of which 11 sites are in Heilongjiang Province and one site (the MM site) is in Jilin Province. Most sites belong to the Sanjiang Plain and the Daxingan Mountain zones (Fig. 1, Table 1).

The MM site, one of the Ramsar Wetlands of International Importance, is a typical inland saline wetland, with a total area of 1440 km^2. The main soil types include alkali, sandy, alluvial soil and chernozem. Vegetation is dominated by *Carex*, *Phragmites*, *Typha*, *Suaeda,* and *Calamagrostis angustifolia*.

The Sanjiang Plain is 55 m above sea level on average. It belongs to the sub-humid warm temperate continental monsoon climate zone, and it has a mean annual precipitation of approximately 558 mm, with substantial interannual and seasonal variation. 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 total wetland area in the Sanjiang Plain. The Daxingan Mountain zone, 573 m above sea level, has an annual average temperature of −2.8 °C and average annual precipitation of 746 mm. The low temperatures and high amount of precipitation result in low decomposition rates and are responsible for widespread permafrost and peatlands in the study area.

The geographic coordinates of all sites were recorded using a portable global positioning system (Garmin GPS 12 XL, Garmin International, Olathe, KS). Details of these 12 sample sites are shown in Table 1.

2.2. Sampling method

In August 2011 and 2012, we collected soil cores with three replicates at every site to a depth of 40 cm. Soil cores were sliced into 2-cm increments in the field, sealed in polyethylene bags, and brought back to the laboratory. Increments were air-dried at 60 °C, weighed for bulk density, ground and sieved through a 2 mm nylon mesh, and analyzed for organic C, total nitrogen, and total phosphorus. Bulk density was calculated from the dry weight per unit volume for each depth increment after validation for moisture contents of an air-dried subsample that was dried at 105 °C (Loomis and Craft, 2010).

2.3. Chemical analysis

Soil organic matter (SOM) was measured by the $K_2Cr_2O_7$—H_2SO_4 oxidation method, and soil organic carbon (SOC) was estimated using a conversion factor of 1.724. Total soil nitrogen (TN) was measured using the Kjeldahl digestion procedure with a Kjeltec Auto Analyzer (Behr LaborTechnik, Germany). Total soil phosphorus (TP) was digested using H_2SO_4—$HClO_4$ and measured with a