Changes and vertical distribution characteristics of soil organic carbon in different land cover types in Honghe wetland of Sanjiang Plain, China

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Soil organic carbon (SOC) responds rapidly to changes in land cover types, and changes in SOC provide essential guidance for sustainable utilization of land resources and protection of wetlands. The vertical distribution of SOC under different land cover types in Honghe wetland was analysed through soil samples and remote sensing interpretation. Changes in SOC under different land cover types were assessed in 2002 and 2014. The results showed that wetland and meadow were the primary land cover types in Honghe wetland. The reduction in normalized difference vegetation index from 2002 to 2014 was mainly due to wetland and meadow area changes. The SOC contents under different land cover types followed the order: wetland > meadow > forest land > dry field > paddy field in the 0–15 cm soil layer. With increase in soil depth from 0 to 60 cm, SOC contents tended to decrease. According to preliminary estimations, the SOC stocks of wetland, meadow, forest land, paddy field and dry field in the soil profile from 0 to 60 cm were 4.39×10^4, 2.62×10^4, 2.66×10^4, 2.11×10^4 and 1.98×10^4 t/sq. km respectively. The total amount of SOC declined by about 364.8 Gg C in the 0–30 cm soil layer from 2002 to 2014, which resulted in the emission of 1338.82 Gg CO_2 to the atmosphere.

Keywords: Honghe wetland, land cover types, soil organic carbon, vertical distribution characteristics.

SOIL is the largest reservoir of carbon in the terrestrial biosphere[1] and wetland soil stores 45–70% of terrestrial organic carbon[2]. Therefore, wetlands have been recognized as an important component of the global carbon cycle. Despite occupying only 6% of the world's land surface, wetlands contain about 12% of the global carbon pool and are therefore an important carbon sink or source[3]. Soil organic carbon (SOC) content is a key indicator of soil quality and is easily affected by land cover changes and climate. Environmental changes, including changes in water content, temperature, nutrient regimes, and microbial activity caused by human activities, can directly result in changes in SOC content[3]. Numerous studies have shown that SOC can be exported from wetlands by agricultural activity[3–5]. Drainage of soil for agricultural use can lead to increased SOC mineralization[6]. Microbial soil enzymes can also accelerate the process of SOC mineralization[7]. In particular, the conversion from one land cover to another has resulted in clear SOC stock change[8,9]. The change in land cover can lead to an increase in greenhouse gas emissions and result in significant change in CO_2 concentration in the atmosphere[10]. Thus, there is a growing awareness that protecting wetlands and maintaining the soil carbon pool are important in responding to global climate change.

Sanjiang Plain, located in Northeast China, is known for its large area of natural wetlands. In the past few decades, these natural wetlands have substantially diminished because of large-scale agricultural expansion under the national agricultural development policies. With the reclamation of wetlands for agricultural use, natural wetland ecosystems have been destroyed and the soil environment has also been disturbed, which has led to substantial changes in SOC stock. At the regional scale, changes in SOC stock under different land cover types revealed the potential influence of tillage and reclamation.

The aim of this study was to analyse the influence of different land cover types on SOC content in Sanjiang Plain by: (1) determining the changes in land cover types in two different typical years (2002 and 2014) and estimating the SOC stock in surface soil (0–30 cm) in 2014; (2) analysing the vertical distribution characteristics of SOC and determining the influence of each factor (soil moisture content, clay content, soil dissolved organic carbon (DOC), pH) on SOC content; and (3) based on SOC stock changes in 2002 and 2014, calculating the quantity of emitted CO_2 and assessing the impact of SOC stock changes on emitted CO_2, which might help understand the impact of SOC stock changes on the

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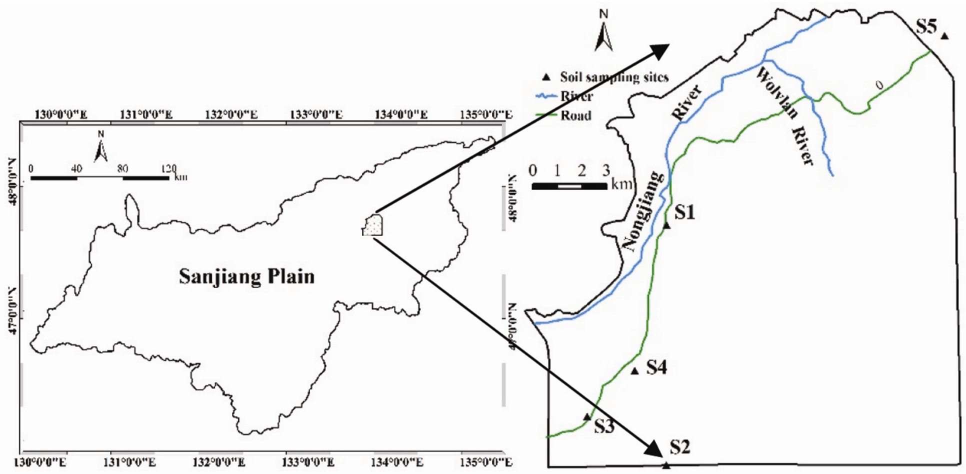

Figure 1. Location of sampling sites within study area in Sanjiang Plain. S1, Wetland; S2, Meadow; S3, Forest land; S4, Dry field; S5, Paddy field.

concentration of greenhouse gases in the atmosphere and the associated climate change. The results of this study could be used as a theoretical foundation for reasonable exploitation and utilization of land resources and protection of wetlands.

Site description

Honghe wetland (Figure 1), a typical marsh wetland in Northeast China, has been listed as a Wetland of International Importance by the Ramsar Convention since 2001. It is located at the junction of Tongjiang city and Fuyuan county in Sanjiang plain, covering an area of 250.9 sq. km. The climate is temperate humid continental monsoon, with a mean annual precipitation of 585 mm, 58.5% of which is concentrated in the period from July to September. The mean annual temperature is 1.9°C with an average frost-free period of more than five months each year and a frozen depth of 160–180 cm (ref. 11). The topography is flat in this area, tending to be relatively higher in the southwest and lower in the northeast. The geomorphic types are mainly terrace and flood land. The zonal soil types mainly include albic soil, peat soil, and meadow soil. Soil parent materials are mainly silty clay loam and silty clay in USDA soil taxonomy. In recent decades, the wetlands have gradually degraded due to excessive excavation of channels and development of farming. The portion of wetland being reclaimed for meadow or even inland forest has increased, which seriously impacts the function of wetland SOC stock.

Materials and methods

Sample collection and testing

Soil samples were collected from five representative land cover types (Figure 1): swamp wetland, meadow, forest land, dry field and paddy field. For each land cover type, three sampling sites were randomly arranged, with a between site interval of >10 m. After removal of the litter layer, the soil was sampled with a 10 cm diameter drill in each layer to the depths of 0–15, 15–30, 30–45 and 45–60 cm. Three soil samples in each layer were collected at each sampling site. Then samples from the same layer of the three sampling sites were mixed into one composite soil sample. Additionally, three parallel soil samples of each layer were collected, leading to a total of 60 samples (3 parallel samples × 4 soil sampling depths × 5 land cover types) being collected in the study area. Each sample was divided into two subsamples that were sealed in polyethylene bags and stored at 4°C. One subsample was used to determine soil moisture content and particle size, while the other was air-dried and passed through a 100-mesh sieve for determining the SOC content, soil DOC and pH. Samples for determining bulk density of each layer were collected with a cutting ring.

Soil moisture content was determined by the oven drying method and particle size with a laser particle size analyser (Bettersize, China); pH was determined with a pH meter in 1 : 5 (soil : deionized water) suspension and SOC content was determined with a total organic carbon analyser (Shimadzu, TOC-VCPH, Japan). Soil DOC was extracted from a mixture of 1 : 25 (soil : deionized water). After the mixture was shaken and centrifuged, the supernatant liquid was filtered through a 0.45 μm carbon-free membrane. Soil DOC was determined in the supernatant with a total organic carbon analyser (Shimadzu, TOC-VCPH, Japan). Soil bulk density was determined by the cutting ring method.

Acquisition of remote sensing data

The differences in the land cover types were obvious in different time periods. To reduce the impact of rainfall on wetland vegetation coverage, years with average rainfall (2002 and 2014) were selected. The remote sensing data of the two years selected covered the same time period as that of the soil sample collection. Data was downloaded from the US Geological Survey, taking into account the interference from cloud cover, resolution and so on. Remote sensing images with a resolution of 30 m in September 2002 and September 2014 were ultimately selected. After pretreatment of remote sensing images, land cover types were classified in the study area.

The changes in vegetation cover in different land cover types were monitored based on the normalized difference vegetation index (NDVI). The calculation of NDVI values was as follows

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}), \quad (1)$$

where NIR is the reflected value of the near infrared band and R the reflected value of the red light band.

Calculation of SOC stock and amount of emitted CO_2

SOC density and SOC stock were calculated by the following formulas[12] respectively.

$$\mathrm{SOC}_d = \mathrm{SOC}_i \times \mathrm{BD}_i \times (1-\delta/100), \quad (2)$$

$$\mathrm{SOC}_s = \sum_{i=1}^{n} \mathrm{SOC}_i \times \mathrm{BD}_i \times H_i \times (1-\delta/100) \times 10^{-1}, \quad (3)$$

where SOC_d is SOC density of the layer i (kg/m^3); SOC_i is SOC content of the layer i (g/kg); BD_i is soil bulk density of the layer i (g/cm^3); SOC_s is SOC stock per unit area (10^3 t/sq. km); H_i is thickness of the layer i (cm); and δ is >2 mm coarse soil fragment (wt.%).

The changes in SOC stock in 2002 and 2014 contributed to CO_2 emission. The amount of CO_2 emission was calculated using the following formula[13,14].

$$\text{Emitted } CO_2 = \text{amount of sequestrated SOC} \times 3.67, \quad (4)$$

where the amount of sequestrated SOC is based on SOC stock in the soil surface (0–30 cm). The factor 3.67 is the molecular weight of CO_2 divided by the atomic weight of carbon.

Regression analysis

Regression analysis[15] was mainly used for analysing the linear relationship between multiple independent and dependent variables. According to the standard path coefficient, which is calculated by IBM-SPSS19.0 (ref. 16), the direct influence of the independent variable on the dependent variable could be estimated. In this study, four related variables affecting SOC contents were selected and the main factor among four factors affecting SOC contents was determined by regression analysis.

Results

Detection of land cover type changes

The changes in land cover types in 2002 and 2014 are shown in Table 1 and Figure 2. Wetland and meadow were the two largest land cover types in Honghe wetland, accounting for more than 85% of the total study area. Forest land and farmland accounted for only a small portion of the study area. The wetland area increased from 2002 to 2014 and reached around 150 sq. km, accounting for 59.37% of Honghe wetland in 2014, whereas the meadow area decreased over this time period. For the main land cover types, the important changes were the decline in meadow area (–23.38%) and the increase in wetland (+22.95%), implying that transformation between wetland and meadow was strong in Honghe wetland. Farmland area accounted for less than 5% of the total area in Honghe wetland. Therefore, the influence of agricultural reclamation activities on wetland evolution was limited in Honghe wetland.

The NDVI value was directly associated with vegetation cover and indirectly with SOC[13]. Higher values of NDVI indicated higher vegetation coverage rate and the SOC content increased with the increase in NDVI value[17]. The maximum NDVI value was 0.766 in 2002 with a mean value of 0.346, while the maximum NDVI value in 2014 was 0.426 with a mean value of 0.184 (Figure 3). NDVI values in 2014 were lower than those in 2002, which indicated the decline in vegetation coverage rate. The reduction in NDVI value from 2002 to 2014 also revealed the decrease in SOC content.

Vertical distribution of SOC content in different land cover types

SOC contents under different land cover types were significantly different (Figure 4). SOC contents of wetland, meadow, forest land, dry field and paddy field in the soil profile from 0 to 60 cm were 99.06–417.70, 43.45–115.49, 39.51–73.34, 15.05–61.97 and 14.98–48.77 g/kg respectively, and showed declining tendency with increase in depth ($P < 0.01$). The coefficient of variation (CV) was used to measure the degree of vertical variation in SOC content. The CVs of SOC contents in paddy field, dry field, forest land, wetland and meadow were 0.41, 0.55, 0.25, 0.54 and 0.38 respectively, which showed moderate variability ($0.1 < \mathrm{CV} < 1.0$)[18]. Within the 0–15 cm soil layer, SOC contents in wetland were 260%,

Table 1. Changes in land cover types of Honghe wetland in 2002 and 2014

	Wetland		Meadow		Forest land		Farmland	
Classification	Area (sq. km)	Proportion (%)	Area (sq. km)	Proportion (%)	Area (sq. km)	Proportion (%)	Area (sq. km)	Proportion (%)
2002	91.4	36.42	132.9	52.93	16.7	6.67	10.0	3.98
2014	149.1	59.37	74.2	29.55	22.2	8.85	5.6	2.23
Change*	+57.7	+22.95	–58.7	–23.38	+5.5	+2.18	–4.4	–1.75

*The values for area and proportion in 2014 minus the ones in 2002 equal the changes in area and proportion, where '+' denotes an increase and '–' denotes a decrease.

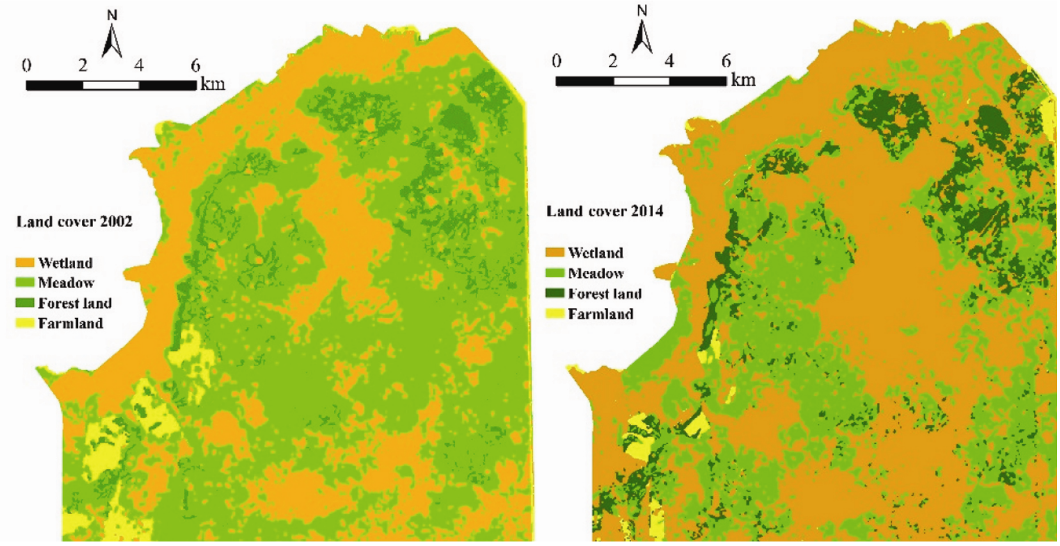

Figure 2. Land cover maps of Honghe wetland in 2002 and 2014.

468%, 572% and 754% higher than in meadow, forest land, dry field and paddy field, respectively, which reflected that the conversion from wetland to paddy field and dry field had dramatically reduced SOC content.

SOC stock in different land cover types

Soil bulk density was one of the most important parameters for calculating SOC density. The average SOC bulk densities of wetland, meadow, forest land, paddy field and dry field in the soil profile from 0 to 60 cm were 0.42, 0.69, 0.90, 1.14 and 1.24 g/cm^3 respectively, and tended to increase gradually with depth ($P < 0.01$) (Figure 5). SOC densities of wetland, meadow, forest land, paddy field and dry field in the soil profile were 64.39–79.17, 39.23–53.12, 42.05–47.67, 22.92–43.89 and 20.01–45.85 kg/m^3 with a mean of 73.01, 43.65, 44.29, 35.20 and 32.92 kg/m^3 respectively, and tended to decrease gradually with depth ($P < 0.01$) (Figure 6).

According to preliminary estimates with eq. (3), SOC stocks of wetland, meadow, forest land, paddy field and dry field in the soil profile from 0 to 60 cm were 4.39 × 10^4, 2.62 × 10^4, 2.66 × 10^4, 2.11 × 10^4 and 1.98 × 10^4 t/sq. km, respectively. In the 0–15 cm soil layer, SOC stocks were in the order: wetland > meadow > forest land > dry field > paddy field, and accounted for between 0.26 and 0.34 of the SOC stock of the whole depth profile (60 cm). This showed that SOC stock within the topsoil (0–15 cm) occupied the largest ratio among total SOC stock in the whole profile. The condition of SOC stock revealed the impact of tillage and reclamation. SOC stocks of wetland were 2.08 and 2.22 times those of paddy field and dry field, respectively. Tillage and reclamation exerted great influence on the decrease in SOC stock, which illustrated that tillage and reclamation changed the distribution structure of SOC.

Regression analysis

In addition to soil bulk density, SOC content was significantly associated with soil moisture content, clay content, soil DOC and pH ($P < 0.01$, $n = 20$) (Table 2). Therefore, soil moisture content, clay content, soil DOC and pH were regarded as the main variable factors influencing SOC content and were used in regression analysis. The dependent variable was treated with Grubbs test[19] to remove high values, and the reduced dataset ($n = 17$) was examined with Shapiro-Wilk test (sig. = 0.123, which is

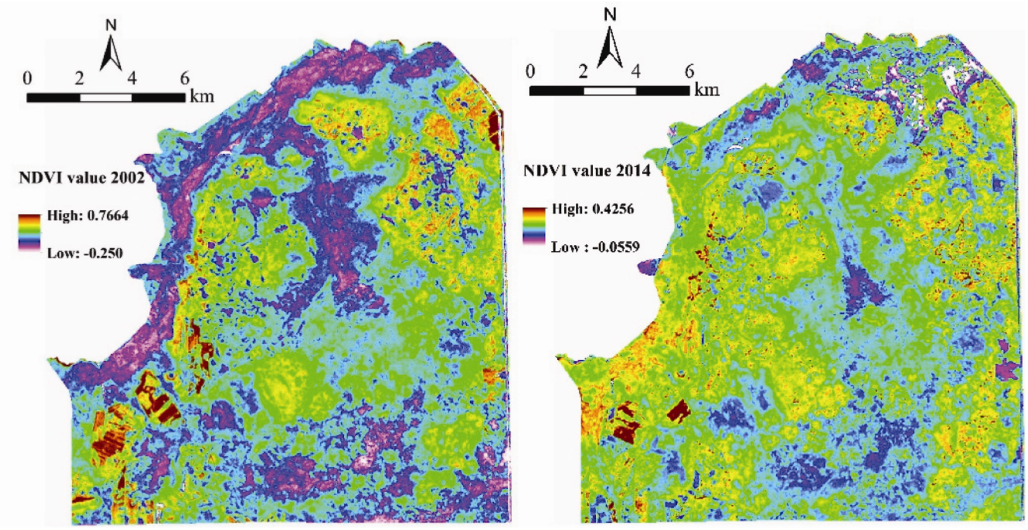

Figure 3. NDVI values in 2002 and 2014.

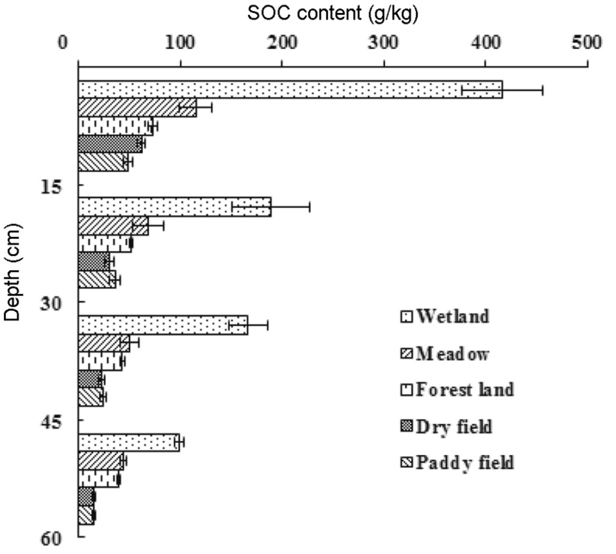

Figure 4. Vertical changes in SOC contents under different land cover types.

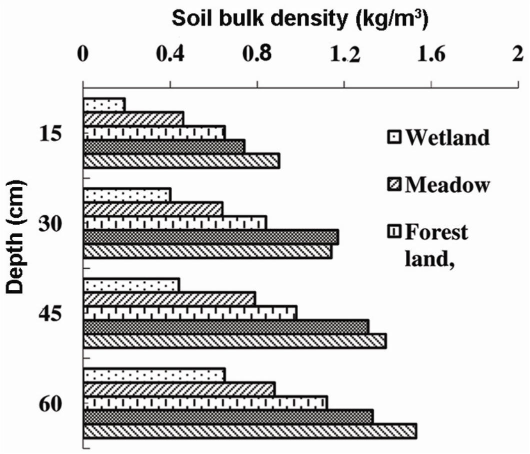

Figure 5. Vertical changes in soil bulk densities in different land cover types.

> 0.05) to ensure that it conformed to a normal distribution. The regression equation was:

$$Y_{\text{SOC content}} = 0.211X_{\text{clay content}} + 0.792X_{\text{moisture content}} + 0.525X_{\text{soil DOC}} - 0.034X_{\text{pH}}.$$

This model was significant ($F = 37.307$, $P = 0.000$), providing confidence in the suitability of regression analysis in this case. The standard path coefficients of clay content, moisture content, soil DOC and pH were 0.211, 0.792, 0.525 and 0.034 respectively. Therefore, the level of influence of each factor on SOC content was in the order: moisture content > soil DOC > clay content > pH.

Discussion

Different factors influencing SOC content

Land cover types: In the study area, SOC contents were in the following order: wetland > meadow > forest land > dry field > paddy field. The conversion of land cover types led to changes in SOC content[8,9] and lower SOC content was associated with more frequent tillage and reclamation[20]. Reduction in SOC occurred upon conversion with tillage and reclamation as a result of reduced inputs of organic matter[21]. The SOC content in forest land resulted from the abundance of fallen leaves covering the soil surface combined with the local temperate humid climate in which humus accelerates SOC accumulation[15].

Moisture content: Soil moisture content is one of the major environmental factors influencing accumulation and conversion of SOC[22,23]. In permanently water logged soil, soil moisture content was high. Perennially water logged environments are conducive to SOC accumulation[12]. Permanent water logging induced anaerobic

Table 2. Pearson's correlation between SOC content and the influential factors[a]

Factors	SOC content	Clay content	Moisture content	Soil DOC	Soil pH
Correlation coefficient	1	–0.827**	0.899**	0.679**	–0.640**

[a]**Correlation is significant at the 0.01 level (2-tailed).

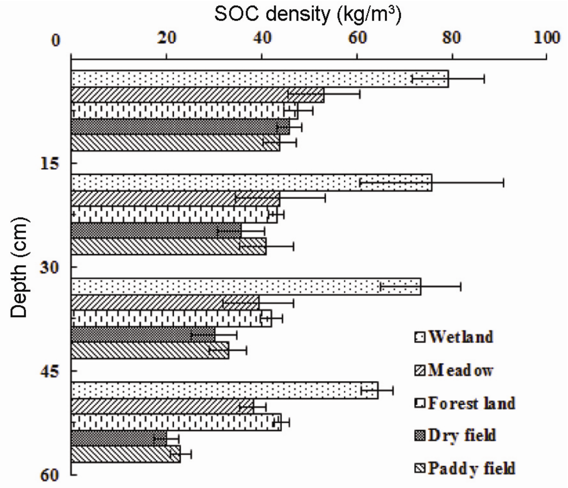

Figure 6. Vertical changes in SOC densities in different land cover types.

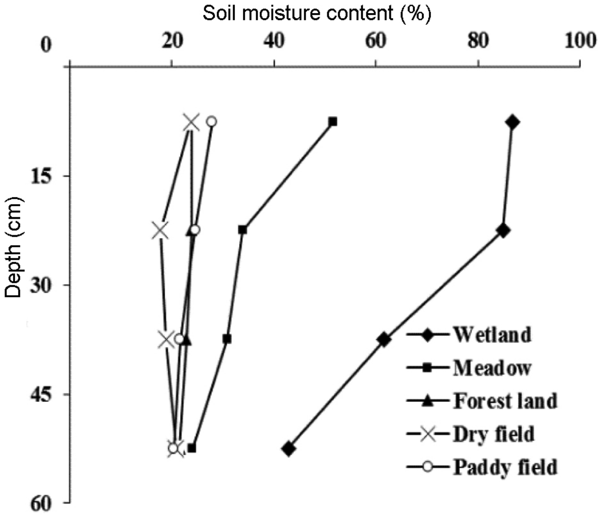

Figure 7. Vertical changes in soil moisture content in different land cover types.

conditions, under which organic carbon in litter decomposed slowly[24]. However, the soil moisture content in meadow was 20–60% (Figure 7) during the sampling period. The aerobic environment aided decomposition of SOC. Moreover, drainage and farmland reclamation of wetland also changed the soil hydrological conditions and reduced soil moisture content. Hence, SOC content tended to decrease gradually. Compared to dry fields, the dry-wet cycle in paddy fields could stimulate soil respiration and promote SOC mineralization[25].

Soil DOC: The dynamic change in soil DOC reflected the stability of SOC[26,27]. Soil DOC was easily used by microbes. Hence, the decomposition of SOC was relatively faster with higher ratios of soil DOC and SOC content[28]. In the study area, the proportion of soil DOC that accounted for total SOC that content was in the order: forest land > paddy field > dry field > meadow > wetland. Hence, the ratios in paddy field and dry field were relatively high, which showed that the SOC in paddy field and dry field was more likely to be used by microbes.

Clay content: Soil clay has a large specific surface area and high charge density, giving it a strong adsorption ability for organic carbon. The highest SOC stock occurred in clay loam soils, while the lowest occurred in sandy clay loam[13]. Soil clay combined with macromolecular organic matter to form steady organic–inorganic compounds with a certain protective effect on SOC[29]. Frequent tillage and reclamation seriously damaged the physical protection of soil aggregates, leading to reduced SOC content. However, SOC content showed negative correlation with clay content in the study area. This indicated that agricultural reclamation damaged soil aggregates, and that salinity and acid ions in soil with a high proportion of clay, had a negative influence on SOC accumulation[30].

pH: In acidic soil, growth of microbial species promoting decomposition of SOC was restricted and microbial activities decreased, which accelerated SOC accumulation[31]. In the study area, the soil was weakly acidic, with pH values in the range 4.59–5.73. Compared to paddy field and dry field (average pH of 5.34), soil pH was lower in meadow and wetland (average pH of 4.87). Reclamation of wetland increased soil pH and enhanced microbial activities, which was more conducive to microbial decomposition of SOC.

Assessment on SOC stock in two typical years

Because of differences in SOC content in different land cover types and changes in land cover area, SOC stocks were different in 2002 and 2014. The data for SOC content in 2002 was from the Chinese Ecosystem Observation and Research Dataset[32]. Because of limitations in soil bulk density dataset, soil bulk density was obtained by the relationship between soil bulk density and SOC content ($\rho = 1.3770 \times e^{-0.0048} \times$ SOC) obtained from the second soil census data in China[33]. Based on SOC stocks in different land cover types in 2002 and 2014, changes in SOC stocks in Honghe wetland between 2002 and 2014 were calculated. The total amount of SOC in the 0–30 cm soil layer in meadow and farmland decreased by 1659.18 and 48.68 Gg C (1 Gg = 10^9 g) respectively, while it increased by 1268.26 and 74.80 Gg C in wetland and forest land respectively (Table 3). The total amount of SOC decreased by about 364.8 Gg C from 2002 to 2014.

Estimation of emitted CO_2

Land cover change has a major impact on wetland SOC stocks. Wetland drainage and subsequent conversion to agriculture resulted in substantially increased decomposition rates of organic matter previously stored under anaerobic conditions, which led to large quantities of carbon being released into the atmosphere[2,34,35]. Therefore, the SOC stock in soil profiles was applied to estimate CO_2 emission that resulted from changes in land cover type[36]. After wetland reclamation, wetland SOC loss in Sanjiang Plain was as high as 80–90% of the original SOC content and the SOC loss was directly released as CO_2 into the atmosphere[37]. Additionally, land cover type changes caused emission of 20% of greenhouse gases globally, leading to reduced carbon stock in potential areas[38].

Based on SOC stock in the 0–30 cm soil layer and changes in the area of land cover types in two typical years, the amount of emitted CO_2 was calculated using eq. (4). According to this preliminary estimate, the amount of emitted CO_2 from the soil surface (0–30 cm) was 1338.82 Gg. In fact, the decrease in wetland area because of tillage and reclamation accompanied by SOC stock degradation encouraged more CO_2 emission. Therefore, the amount of CO_2 emitted to the surrounding atmosphere due to decrease in wetland area can be calculated if the area of wetland reclamation is known.

Conclusion

The SOC content differed remarkably under different land cover types in Honghe wetland of Sanjiang Plain. Differences in SOC stocks under different land cover types in the two typical years changed the amount of CO_2 in atmosphere. In particular, the conversion from wetland to farmland accelerated SOC decomposition, which increased the amount of CO_2 emission. In the long term, large amounts of CO_2 emission increase the greenhouse gas concentration in the surrounding atmosphere. Therefore, to reduce SOC loss and CO_2 emission, excessive drainage of wetlands and farmland reclamation need to be reduced. Reducing the interference of agricultural activities in wetlands and returning farmland to wetland are also effective techniques for the restoration of SOC.

Table 3. SOC Changes in land cover types in Honghe wetland in 2002 and 2014*

SOC (Gg)	Wetland	Meadow	Forest land	Farmland
2002	2190.86	2735.08	227.12	117.00
2014	3459.12	1075.90	301.92	68.32
Change*	+1268.26	–1659.18	+74.80	–48.68

*SOC in 2014 minus that in 2002 equals the change in SOC, where '+' denotes an increase and '–' denotes a decrease.

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