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Marshland conversion to cropland in northeast China from 1950 to 2000 reduced the greenhouse effect

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Abstract

It has been well recognized that converting wetlands to cropland results in loss of soil organic carbon (SOC), while less attention was paid to concomitant changes in methane (CH_4) and nitrous oxide (N_2O) emissions. Using datasets from the literature and field measurements, we investigated loss of SOC and emissions of CH_4 and N_2O due to marshland conversion in northeast China. Analysis of the documented crop cultivation area indicated that 2.91 Mha of marshland were converted to cropland over the period 1950–2000. Marshland conversion resulted in SOC loss of ~240 Tg and introduced ~1.4 Tg CH_4 and ~138 Gg N_2O emissions in the cropland, while CH_4 emissions reduced greatly in the marshland, cumulatively ~28 Tg over the 50 years. Taking into account the loss of SOC and emissions of CH_4 and N_2O, the global warming potential (GWP) at a 20-year time horizon was estimated to be ~180 Tg CO_2_eq. yr^{-1} in the 1950s and ~120 Tg CO_2_eq. yr^{-1} in the 1990s, with a ~33% reduction. When calculated at 100-year time horizon, the GWP was ~73 Tg CO_2_eq. yr^{-1} in the 1950s and ~58 Tg CO_2_eq. yr^{-1} in the 1990s, with a ~21% reduction. It was concluded that marshland conversion to cropland in northeast China reduced the greenhouse effect as far as GWP is concerned. This reduction was attributed to a substantial decrease in CH_4 emissions from the marshland. An extended inference is that the declining growth rate of atmospheric CH_4 since the 1980s might be related to global loss of wetlands, but this connection needs to be confirmed.

Keywords: cropland, global warming potential, greenhouse gas, northeast China, soil organic carbon, wetland conversion

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Introduction

Although natural wetlands occupy only 5–8% of the earth's land area (Ramsar Convention Secretariat, 2004; Mitsch & Gosselink, 2007), they store a substantial amount of carbon, with 200–370 Gt C in the top 0–100 cm of soil (Eswaran *et al*., 1993; Batjes, 1996). Further, wetlands are the world's largest methane (CH_4) source, accounting for 20–25% of the total annual emissions (IPCC, 2001; Mitsch & Gosselink, 2007).

Half of the world's wetlands are estimated to have been lost during the 20th century (Moser *et al*., 1996; Revenga *et al*., 2000). A principal cause of wetland loss is draining or filling for agriculture and human settlements. Since the 1950s, tropical and subtropical wetlands have been increasingly degraded or lost through conversion to agricultural use. It is estimated that, by 1985, 56–65% of available wetland had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa, for a total of 26% loss to agriculture worldwide (OECD, 1996). In Europe, conversion to agriculture alone has reduced wetlands by some 60% (World Resources Institute, 2001). In northeast China, net loss of marshlands from conversion to cropland amounted to 1.03 million ha from 1980 to 2000 (Zhang *et al*., 2003); in the Philippines, some 300 000 ha (67%) of the country's mangrove resources were lost from 1920 to 1980 (Zamora, 1984). In the United States, the average annual loss of wetland was estimated to be 185 400 ha for the 1950s–1970s (Frayer *et al*., 1983) and 117 400 ha for the 1970s–1980s (Dahl & Johnson, 1991).

It has been well recognized that wetland conversion results in loss of soil organic carbon (SOC) (e.g., Maltby & Immirzy, 1993; Lal *et al*., 2004; Euliss *et al*., 2006),

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releasing additional CO_2 into the atmosphere. While wetland conversion induces SOC loss, there are concerns over the changes in greenhouse gases (GHGs) of CH_4 and nitrous oxide (N_2O). CH_4 is a very potent GHG, with a global warming potential (GWP) of 72 at 20-year time horizon (IPCC, 2007), and 70% of natural CH_4 is emitted from wetlands (IPCC, 2001). N_2O is an even more potent GHG, with a GWP of 289 (IPCC, 2007), and one-third of its total emissions derives from anthropogenic sources such as fertilizer use (World Meteorological Organization, 2006; IPCC, 2007). Wetland conversion to cropland, on one hand, may reduce CH_4 emission. On the other hand, N_2O emission may be promoted due to cultivation and fertilizer use. To better understand the role of wetland conversion in global warming, a synthetic evaluation of SOC loss and GHG emissions is thus necessary.

The Sanjiang Plain was formerly the largest marshland complex in China. With growing populations, an extensive area of marshland was converted to cropland in this region over the last 50 years (Liu & Ma, 2000; Zhang *et al*., 2003). Efforts have been made to understand the effects of such conversion on soil microbiological properties (Zhang *et al*., 2007a), SOC dynamics (Zhang *et al*., 2007b) and CH_4 emission (Wang *et al*., 2002) in site-specific studies, while less attention has been paid to an overall evaluation of SOC loss and GHG emissions on a regional scale. The objectives of this paper are (1) to estimate loss of SOC and the changes in CH_4 and N_2O emissions due to marshland conversion in the Sanjiang Plain, and (2) to evaluate the consequent changes in GWP over the period 1950–2000.

Materials and methods

Research area

The research area lies in the Sanjiang Plain of northeast China, located between 43°50′N and 48°28′N, latitudinally, and between 129°11′E and 135°05′E, longitudinally, with a total area of 11.59 million ha (He & Zhang, 2001). It covers 23 counties and four administrative farms with a population of 7.8 million. This region is classified with a temperate humid and subhumid continental monsoon climate with a mean annual temperature of $\sim$2.5 °C. Annual precipitation ranges from 350 to 770 mm, $\sim$80% occurring in May to September. Soils are typical of Luvisols, Phaeozems, Cambisols and Histosols.

Wetland plants consist mainly of meadow and marsh vegetation. The beginning of the growing season and senescence of wetland plants occur generally in late May and late September, respectively. Above-ground biomass ranges between 500 and 700 g m^{-2} (Yang *et al*., 2002; Zhang *et al*., 2007; Zhao *et al*., 2008). Irrigated rice or upland crops are planted with one harvest per year after marshland conversion. The majority of upland crops are wheat, maize and soybean. The crop-growing season is generally from May to September. The average grain yields of wheat, maize, soybean and rice over the period 1991–2000 were 2.56, 4.95, 1.81 and 5.56 t ha^{-1}, respectively (Heilongjiang Provencal Bureau of Statistics, 2007).

Data sources

The area of marshland converted to cropland from 1950 to 2000 was obtained from annual statistical reports on a county or an administrative farm scale. The yearly acreage of upland crops and irrigated rice, and the annual rate of synthetic fertilizer N application, were documented in these reports.

To estimate changes in SOC and emissions of CH_4 and N_2O, we made field measurements and compiled data sets from the literature (State Soil Survey Service of China, 1994; Cui 1997; Zhao, 1999; Liu & Ma, 2000; Ding *et al*., 2004; Hao *et al*., 2004; Yang *et al*., 2004, 2006a; Zhang *et al*., 2005, 2007; Chi *et al*., 2006; Yin *et al*., 2006; Wang *et al*., 2006a).

Soil samples were taken from pristine marshland and from cropland that had been cultivated for 1, 3, 5, 9, 13, 15, 17, 22, 25, 27, 33 and 35 years. All cropland fields were plowed to 15–20 cm by machine using a moldboard plow. Three plots (40 m $\times$ 40 m) were arbitrarily established in each field. Twenty cores (0–20 cm depth) were randomly taken, sieved ($<$2 mm) and mixed for each plot. Soil samples in the 20–40 cm depth were taken from the cropland with cultivation of 5, 10 and 15 years in the same manner as that in the 0–20 cm depth. Soil samples were air-dried to determine SOC concentration by a FlashEA 1112 NC Analyzer (Thermo Fisher Scientific Inc., Milan, Italy).

CH_4 flux was measured from June 2002 to September 2005 in two freshwater marsh sites, vegetated with *Calmagrostis angustifolia* and *Carex lasiocarpa*, and one irrigated rice field during the rice growing seasons in May through October, 2002–2005. N_2O flux was measured at the *C. lasiocarpa* site from June 2002 to September 2005. Three replicates were performed. CH_4 and N_2O measurements were made by taking samples of the headspace gas of an open-bottom chamber of known cross-sectional area (50 cm $\times$ 50 cm). Mixing ratios of CH_4 and N_2O were detected by gas chromatography (Agilent 4890, Santa Clara, CA, USA) with flame ionization detector and electron capture detector (Wang & Wang, 2003). The flux was determined from the slope of the mixing ratio change in the four samples taken over a 30-min sampling period. Sample sets which did not yield a linear regression value of $r^2 > 0.90$ were rejected. More details in gas sampling and the determination of

CH_4 and N_2O flux were described elsewhere (Yang *et al*., 2006b; Song *et al*., 2008).

Estimates of SOC loss, CH_4 and N_2O emissions

Annual loss of SOC. SOC density (*SOCD*, $Mg\,C\,ha^{-1}$) was calculated by

$$SOCD = SOC \cdot B \cdot H \times 10^{-1}, \quad (1)$$

where SOC and B are the SOC concentration ($g\,kg^{-1}$) and the bulk density ($g\,cm^{-3}$), respectively. H is the soil thickness (cm). Using Zhang (2006), the soil bulk density was calculated by

$$B = 1.84 - 0.2667\ln(SOC). \quad (2)$$

Changes in SOC were simulated with a two-component model as

$$SOCD_t = SOCD_0[F\exp(-k_1 t) + (1-F)\exp(-k_2 t)], \quad (3)$$

where $SOCD_0$ and $SOCD_t$ are the SOC densities in the pristine marshland and cropland at t years since the onset cultivation, respectively. F is the fractional active-C pool, and (1-F) is the fractional slow-C pool. k_1 and k_2 are the first-order reaction rate (yr^{-1}) for the active-C and slow-C pools, respectively. Data from field measurements and the literature were used to determine the parameters F, k_1 and k_2 by employing a nonlinear iterative algorithm (SPSS, SYSTAT 10 Statistics I. SPPS, Chicago, IL, USA, 2000). Annual loss of SOC was calculated by

$$E_{SOC\_T} = \sum_{i=1}^{T} (SOCD_{T-i} - SOCD_{T-i+1})A_i, \quad (4)$$

where E_{SOC_T} is the annual loss of SOC. A_i is the area of marshland converted to cropland in the ith year. T represents the years since 1950, setting $T = 0$ for the year 1950.

Annual CH_4 and N_2O emissions. Data from the field measurements in this study and from the literature were combined to estimate annual CH_4 and N_2O emissions in the marshland areas. The literature (Cui, 1997; Ding *et al*., 2004; Hao *et al*., 2004; Yang *et al*., 2004, 2006a; Wang *et al*., 2006a; Zhang *et al*., 2007) reported CH_4 and N_2O fluxes during the plant growing season (typically May through October). To obtain annual emissions, these datasets were corrected using the annual measurements in this study:

$$E_c = E_g \times \left(1 + \frac{\bar{E}_n}{\bar{E}_a}\right) \times Q_{10}^{0.1\times(T_i - T_B)}, \quad (5)$$

where E_c is the corrected annual CH_4 or N_2O flux ($kg\,ha^{-1}\,yr^{-1}$). E_g is the CH_4 or N_2O flux during the growing season reported in the literature. $\bar{E}_a$ and $\bar{E}_n$ are the annual mean and the nongrowing season mean flux of CH_4 or N_2O emission measured in this study, respectively. Rice fields in this region are generally drained and no irrigation occurs during the nongrowing season in November through April next year, which restricts CH_4 production. Thus, CH_4 flux during the rice-growing season can be regarded as the annual flux. Recognizing that air temperature in northeast China has increased significantly over the last 50 years (Editorial Committee of China's National Assessment Report on Climate Change, 2007), we used a temperature coefficient Q_{10} to correct the annual CH_4 and N_2O emissions. According to Song *et al*. (2009), more than 90% of the marshland CH_4 and N_2O emissions in this region occurred in the growing season, and the mean values of Q_{10} are 2.39 for CH_4 and 1.92 for N_2O emission, respectively. Thus, we used the mean growing-season temperature (T_i in °C) to correct the effect of global warming on annual emissions for a given year [Eqn (5)]. The average value of growing-season temperature from 2002 to 2005 was used as the baseline (T_B in °C) when the field measurements were performed.

Using Zou *et al*. (2007) and Lu *et al*. (2006), the annual N_2O flux from rice and upland fields was calculated by Eqns (6) and (7):

$$E_{N_2O\_R} = [(0.79 \pm 0.28) + (0.0073 \pm 0.0011)N]\frac{44}{28}, \quad (6)$$

$$E_{N_2O\_U} = [(1.49 \pm 0.73)P + (0.0186 \pm 0.0027)PN]\frac{44}{28}, \quad (7)$$

where $E_{N_2O\_R}$ and $E_{N_2O\_U}$ are the annual N_2O flux ($kg\,ha^{-1}\,yr^{-1}$) from rice and upland fields, respectively. P is annual precipitation (m). N is the annual rate of synthetic fertilizer N application ($kg\,ha^{-1}\,yr^{-1}$). The fraction 44/28 is used to convert mass of N to N_2O.

Annual total of CH_4 emission ($E_{CH_4\_T}$) was estimated by summing up the emissions from the marshland and the rice field [Eqn (8)], and that of N_2O emission ($E_{N_2O\_T}$) was determined by summing up the emissions from the marshland, rice field and upland areas [Eqn (9)]:

$$E_{CH_4\_T} = \bar{E}_{CH_4\_W}A_{W,j} + E_{CH_4\_R}A_{R,j}, \quad (8)$$

$$E_{N_2O\_T} = \bar{E}_{N_2O\_W}A_{W,j} + E_{N_2O\_R}A_{R,j} + E_{N_2O\_U}A_{U,j}, \quad (9)$$

where $E_{CH_4\_R}$ is the annual CH_4 flux from the rice field. Because CH_4 and N_2O emissions from the marshland varied with plant species, we used area-weighted mean CH_4 ($\bar{E}_{CH_4\_W}$) and N_2O ($\bar{E}_{N_2O\_W}$) flux to determine total annual emissions in the marshland. The area of marshland vegetated by different plant species was

obtained from the literature (Cui, 1997). $A_{W,j}$, $A_{R,j}$ and $A_{U,j}$ are the acreages of marshland, rice and upland field in the jth year, respectively.

Estimates of GWP

We calculated an integrated global warming potential (GWP_T) from SOC loss [Eqn (4)] and CH_4 [Eqn (8)] and N_2O emissions [Eqn (9)] by

$$GWP_T = \frac{44}{12} E_{SOC\_T} + RF_{CH_4} E_{CH_4\_T} + RF_{N_2O} E_{N_2O\_T}, \quad (10)$$

where RF_{CH_4} and RF_{N_2O} are the radiative forcing constants of CH_4 and N_2O relative to CO_2. According to the IPCC (2007), the values of RF_{CH_4} and RF_{N_2O} are 72 and 289 at a 20-year time horizon and 25 and 298 at a 100-year time horizon, respectively. The fraction 44/12 is used to convert mass of C to CO_2.

Results

Loss of SOC due to marshland conversion

The total area of marshland in the Sanjiang Plain was $\sim$ 5.3 Mha in the early 1950s (Liu & Ma, 2000). Marshland loss in this region amounted to 2.91 Mha between 1950 and 2000 due to cultivation (Fig. 1). During the first 25 years, cropland increased by 1.24 Mha, at a rate of $\sim 4.73 \times 10^4$ ha yr^{-1}. Extensive conversion occurred from 1976 to 1990, when cropland increased by 1.31 Mha at a rate of $\sim 8.98 \times 10^4$ ha yr^{-1}. In the 1990s, marshland conversion was kept within limits. Cropland increased at a rate of 2.5×10^4 ha yr^{-1}.

Upland cultivation was the dominant new land use when marshland was converted to cropland (Fig. 1), accounting for 94%, 93%, 97%, 91% and 80% of the total cultivated area in the 1950s, 1960s, 1970s, 1980s and 1990s, respectively.

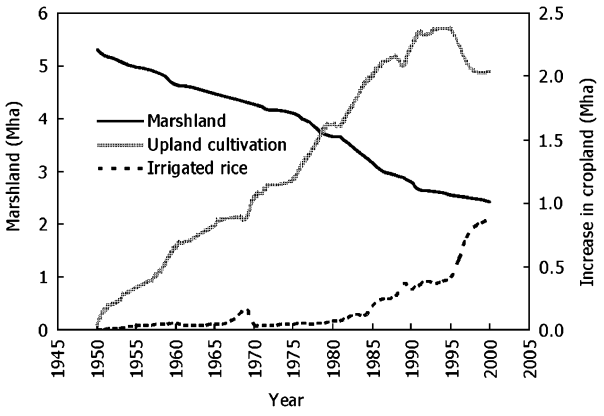

Fig. 1 Conversion of marshland to croplands in northeast China.

Changes in SOC due to marshland conversion can be described well by a two-component model with first-order decay kinetics (Fig. 2). Model fits suggested that the initial fractions of the active-C and slow-C pool are 0.61 ± 0.05 (mean $\pm$ SE) and 0.39 ± 0.05 in the 0–20 cm soil depth (Fig. 2a), and 0.38 ± 0.04 and 0.62 ± 0.04 in the 20–40 cm soil depth (Fig. 2b), respectively. The corresponding first-order decay rates are 0.23 ± 0.054 and 0.002 ± 0.0017 yr^{-1} (Fig. 2a), and 0.18 ± 0.03 and 0.0015 ± 0.0005 yr^{-1} (Fig. 2b), respectively. According to the first-order decay rates, the half-life of the active-C pool is $\sim$ 3 years (0–20 cm) and $\sim$ 4 years (20–40 cm), and that of slow-C pool is 346 years (0–20 cm) and 462 years (20–40 cm). Cultivation for 15 years resulted in $\sim$ 60% (Fig. 2a) and $\sim$ 37% (Fig. 2b) loss of SOC in the soil depths of 0–20 cm and 20–40 cm, respectively. SOC tends to be stable after $\sim$ 20 years since the onset cultivation (Fig. 2).

According to Chen (1996), the area of marshy meadow, humus marsh and peat fen account for 41.2%, 38.8% and 20.0%, respectively, of the total marshland in the Sanjiang Plain. Because the detailed records on the converted acreage from different marshlands are not available, the area-weighted mean $SOCD_0$ was used in Eqn (3) to estimate loss of SOC. SOC densities in these pristine marshlands were estimated based on SOC concentrations from the literature (Table 1). Results indicated that SOC density in the peat fen was much higher than in the marshy meadow and humus marsh (Table 1). Using the average values of SOC density in different marshlands (Table 1), the area-weighted mean $SOCD_0$ and standard error were determined to be 97.94 ± 7.18 Mg ha^{-1} at 0–20 cm depth and 63.64 ± 9.39 Mg ha^{-1} at 20–40 cm depth.

A tremendous SOC loss appeared in the last 25 years (Fig. 3a), with 137–165 Tg SOC lost in the 0–40 cm depth (Fig. 3b). Such a loss is attributed to the extensive marshland conversion to agriculture (Fig. 1). Three apparent peaks of SOC loss occurred in 1979, 1986 and 1991, corresponding to 6.5, 9.0 and 8.1 Tg yr^{-1}, respectively (Fig. 3a). Total SOC loss was estimated to be 238 Tg with a range from 216 to 261 Tg over the 50 years (Fig. 3b). Based on the area of marshland conversion (2.91 Mha) and the area-weighted mean $SOCD_0$, the initial SOC stock (0–40 cm depth) was estimated to range from 422 to 518 Tg in the marshlands. Our estimates suggest that $\sim$ 50% of the SOC disappeared over the 50 years due to marshland conversion. Approximately 70% of this loss occurred in the 0–20 cm depth (Fig. 3a).

CH_4 and N_2O emissions

There was an apparent pattern of seasonal variation in CH_4 flux from the wetland and the rice field

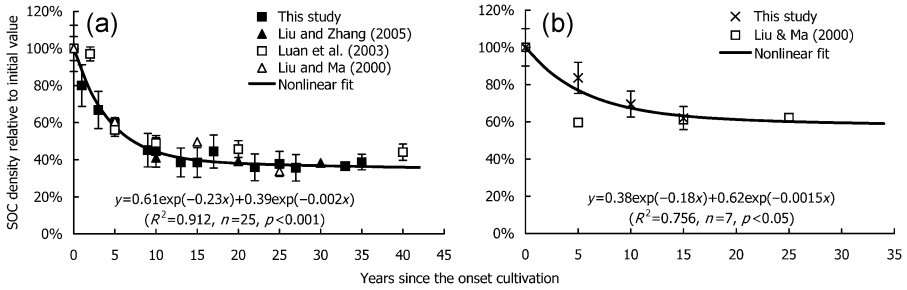

Fig. 2 Nonlinear fit on the observed changes in soil organic carbon density (SOCD): (a) 0–20 cm depth; (b) 20–40 cm depth. The observed SOCD from different data sources was normalized by $SOCD_t/SOCD_0$ to generate a comparable data series. $SOCD_0$ and $SOCD_t$ are the soil organic carbon densities in the pristine marshland and cropland at t years since the onset cultivation, respectively.

Table 1 Soil organic carbon density for different wetland type

	SOC density ($Mg\,ha^{-1}$)*			
Profile (cm)	Marshy meadow	Humus marsh	Peat fen	Reference
0–20	80.8	87.9	197.6	Zhao (1999)
	73.3	88.0	102.0	Zhang *et al*. (2005)
	83.7	96.0	181.0	Zhao (1999), Yin *et al*. (2006)
	59.8	93.9	155.8	Chi *et al*. (2006), Liu & Ma (2000), State Soil Survey Service of China (1994)
Average	74.4	91.5	159.1	
SE	5.3	2.1	20.9	
20–40	39.0	61.7	197.1	Zhao (1999)
	38.0	76.0	126.0	Zhang *et al*. (2005)
	35.1	19.0	159.0	Zhao (1999), Yin *et al*. (2006)
	26.9	27.0	148.5	Chi *et al*. (2006), Liu & Ma (2000) State Soil Survey Service of China (1994)
Average	34.8	45.9	157.7	
SE	2.7	13.7	14.8	

*Estimated by using Eq. (1) from the reported SOC concentration in a given soil layer.
SOC, soil organic carbon.

(Fig. 4a). Higher flux occurred in the growing season. Interannual variation is also obvious. The marshland vegetated with *C. lasiocarpa* showed higher CH_4 emissions in the 2004 and 2005 growing seasons than in 2002 and 2003, while the CH_4 emissions from *C. angustifolia* marshland were higher in 2002 and 2004 than in 2003 and 2005. For the rice field, CH_4 flux was the highest in 2003 of the measurements over the 4 years. It is noteworthy that CH_4 emissions from the wetland were, in general, higher than those from the rice field (Fig. 4a).

Similar to the trend in Fig. 4a, N_2O flux in the *C. lasiocarpa* marshland was higher in the 2004 and 2005 growing seasons than in 2002 and 2003 (Fig. 4b). We observed N_2O uptake during the winter seasons of 2002 and 2003, but uptake did not occur during the 2004 winter season (Fig. 4b).

Seasonal variations of CH_4 and N_2O fluxes (Fig. 4a and b) generally matched variation in air temperature (Fig. 4c) and solar radiation (Fig. 4d). Lower temperature in the winter season was associated with less CH_4 and N_2O emissions. The majority of CH_4 and N_2O emissions occurred in the period from June to early September (Fig. 4a and b) when the higher temperature and solar radiation (Fig. 4c and d) promoted plant growth. The CH_4 and N_2O emissions were thought to be associated with plant growth (Whiting & Chanton, 1993; Rückauf *et al*., 2004).

Tables 2 and 3 summarize CH_4 and N_2O emissions from different data sources. The annual flux from the literature was corrected with Eqn (5). The mean annual CH_4 emissions from marshlands vegetated with *C. angustifolia*, *C. lasiocarpa* and other species were 22.5, 58.4 and $60.9\,g\,m^{-2}\,yr^{-1}$, respectively (Table 2).

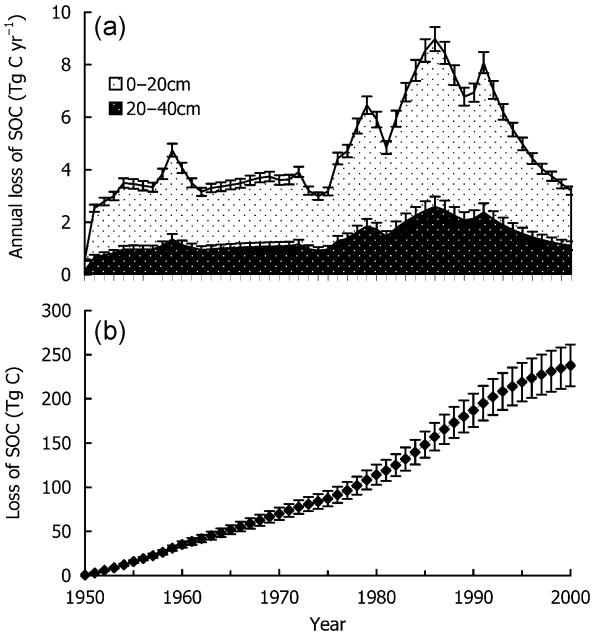

Fig. 3 Estimated soil organic carbon (SOC) loss in northeast China over the period 1950–2000: (a) annual loss; (b) cumulative amount of SOC loss. The vertical bars are standard deviations from eight calculations of $SOCD_0-$SE, $SOCD_0+$SE, $F+$SE, $F-$SE, k_1-SE, k_1+SE, k_2-SE and k_2+SE using Eqn (3). The SOC loss was determined by averaging the results of the eight calculations. See text for the SE values of different parameters.

Marshland conversion to rice fields decreased CH_4 emissions significantly ($P<0.05$), with a reduction of 28–73% (Table 2).

The mean annual N_2O flux from marshland vegetated with *C. angustifolia*, *C. lasiocarpa* and other species was 306.9, 208.6 and 275.1 mg m^{-2} yr^{-1}, respectively (Table 3). Though the annual mean of N_2O emissions from the *C. lasiocarpa* marshland was lower than from other mixed species (Table 3), the difference is not statistically significant ($P>0.15$).

According to Cui (1997), the marshland area vegetated with *C. angustifolia*, *C. lasiocarpa* and other mixed species accounts for 21.6%, 40.1% and 38.3% of the total marshland in the Sanjiang Plain. Based on the average values of annual CH_4 (Table 2) and N_2O (Table 3) fluxes from different plant species, the area-weighted CH_4 [$\bar{E}_{CH_4\_W}$ in Eqn (4)] and N_2O [$\bar{E}_{N_2O\_W}$ in Eqn (5)] emissions in the marshland were estimated to be 516.0 ± 90.7 and 2.55 ± 0.59 kg ha^{-1} yr^{-1}, respectively. The CH_4 emissions from the rice field [$E_{CH_4\_R}$ in Eqn (8)] were 162.3 ± 20.7 kg ha^{-1} yr^{-1} (Table 2).

Marshland conversion reduced CH_4 emissions significantly. Annual CH_4 emissions from the marshland were 2.39 Tg (5.3 Mha) in 1950 and 1.36 Tg yr^{-1} (2.4 Mha) in 2000 (Fig. 5a), respectively. The cumulative CH_4 reduction was estimated to be 27.9 ± 5.0 Tg relative to 1950. Marshland conversion to rice field did not significantly promote CH_4 emission. From 1950 to 1990, the average rate of emissions in the rice field was 12.2 Gg yr^{-1}, while from 1991 to 2000 it was 91.2 Gg yr^{-1} (Fig. 5a) when the rice cultivation was extended (Fig. 1). Cumulative CH_4 emissions from rice cultivation were estimated to be 1.41 ± 0.18 Tg over the 50 years.

N_2O emissions from the marshland were 12.25 Gg yr^{-1} in 1950 and 6.61 Gg yr^{-1} in 2000 (Fig. 5b). The cumulative N_2O reduction was estimated to be 155.8 ± 35.8 Gg relative to 1950. Upland cultivation induced more N_2O emissions than the rice field (Fig. 5b), accounting for 70–95% of total N_2O emissions from the croplands. The cumulative N_2O emissions from croplands were estimated to be 138.0 ± 42.0 Gg, with 121.1 Gg from upland cultivation and 16.9 Gg from rice cultivation over the 50 years.

Changes in GWP

The GWP was calculated for CH_4 ($RF_{CH_4}E_{CH_4\_T}$) and N_2O ($RF_{N_2O}E_{N_2O\_T}$) at 20 and 100-year time horizons. The GWP from CH_4 emissions [Eqn (8)] declined from 172.4 Tg CO_2_eq. yr^{-1} in 1950 to 109.3 Tg CO_2_eq. yr^{-1} in 2000 at the 20-year time horizon (Fig. 6a), and it declined from 59.8 to 38.0 Tg CO_2 _eq. yr^{-1} at the 100-year time horizon (Fig. 6b). The GWP from N_2O emissions [Eqn (9)] was smaller than that from CH_4 emissions by 1 and 2 orders of magnitude when calculated at 100-year (Fig. 6b) and 20-year (Fig. 6a) time horizons, respectively.

Changes in annual integrated global warming potential (GWP_T) at the 20 and 100-year time horizons are given in Fig. 6c and d, respectively. Marshland conversion to croplands reduced GWP_T as a whole. At a 20-year time horizon, the average GWP_T was estimated to be 181.3 Tg CO_2_eq. yr^{-1} in the 1950s and 122.2 Tg CO_2 _eq. yr^{-1} in the 1990s (Table 4), with a $\sim$33% reduction. The average reduction rate was around 1.46 Tg CO_2 _eq. yr^{-1} over the 50 years. When the GWP was calculated at 100-year time horizon, the temporal pattern of GWP_T reduction (Fig. 6d) differed from that with 20-year time horizon (Fig. 6c). The GWP_T declined from the mid-1950s to the mid-1970s, then increased till 1986, and declined sharply thereafter (Fig. 6d). The average GWP_T was 72.8 Tg CO_2_eq. yr^{-1} in the 1950s and 57.5 Tg CO_2_eq. yr^{-1} in the 1990s (Table 4), with a $\sim$21% reduction. The reduction of GWP_T in the 1990s was the most significant among the five decades, $\sim$2.0 Tg CO_2_eq. yr^{-1} with a 20-year time

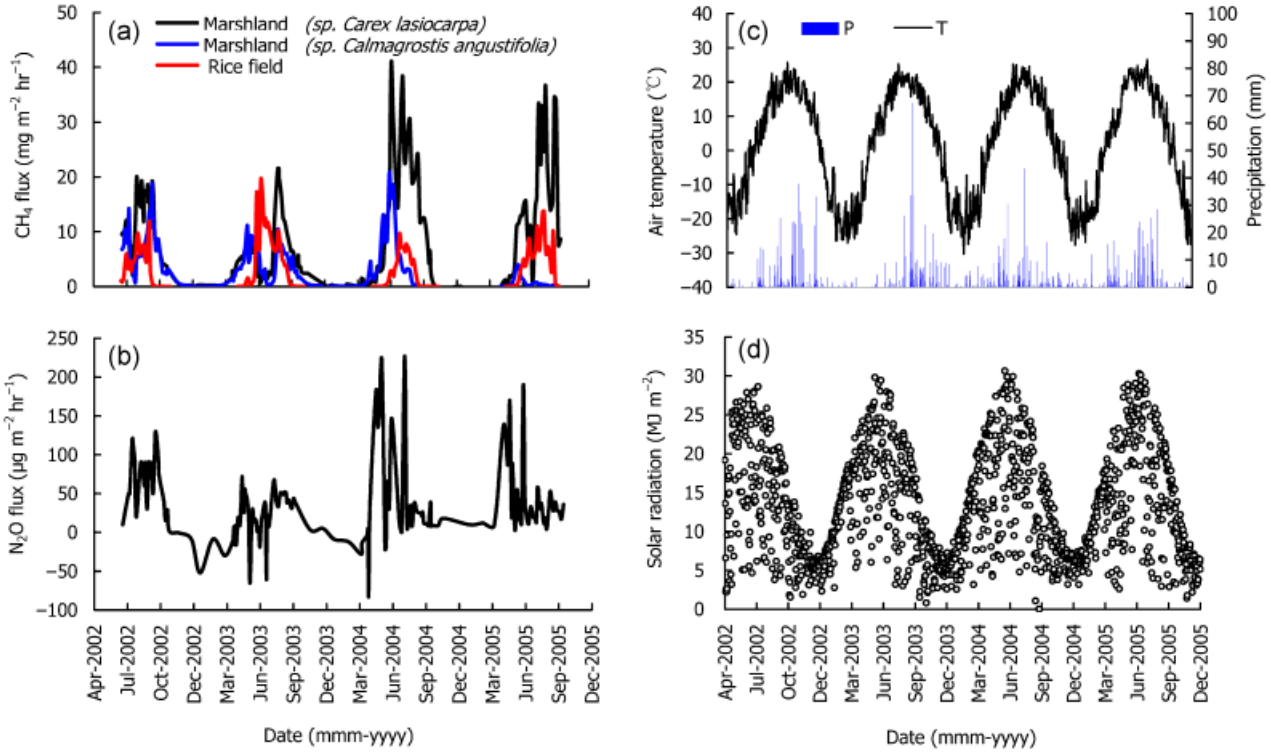

Fig. 4 Seasonal variations in observed greenhouse gas emission and meteorological parameters in northeast China: (a) CH_4 emission from marshland and rice field; (b) N_2O emission from marshland; (c) air temperature T and precipitation P; (d) solar radiation.

horizon and $\sim 1.1\,Tg\,CO_2\_eq.\,yr^{-1}$ with a 100-year time horizon (Table 4).

Discussion

Uncertainties

The present estimates of SOC loss (Fig. 3) and GHG emission (Figs. 5 and 6, Table 4) were made on the basis of literature values (Tables 1–3) and some direct measurements (Figs 2 and 4a, b). Scaling these parameters across the study region may introduce errors into the estimates.

Loss of SOC. Marshland conversion to cropland promoted SOC decomposition (Fig. 3). As a result, additional CO_2 was emitted to the atmosphere. Over the 50 years, the averaged rate was estimated to be $\sim 17.5\,Tg\,CO_2$ per year in the top 0–40 cm of soil. Our estimates, using the nonlinear equation Eqn (3), suggest that the mean loss of SOC in top 0–40 cm soil was 11.2 ± 2.2, 7.4 ± 1.2 and $4.9 \pm 0.7\,t\,C\,ha^{-1}\,yr^{-1}$ over a 10, 25 and 50-year period, respectively, which is consistent with the global range of $1–10\,t\,C\,ha^{-1}\,yr^{-1}$ (Bergkamp & Orlando, 1999). Although the SOC in deep soil layers may be decomposed, the vast majority of the changes in the SOC are believed to occur in the top 30 cm (Smith *et al.*, 2000). Recent research has suggested that in the absence of fresh organic carbon, an essential source of energy for soil microbes, the stability of organic carbon in deep soil layers (60–80 cm depth) is maintained (Fontaine *et al.*, 2007). Fields for cultivation in this region were plowed up to 15–20 cm by machine (Zhang *et al.*, 2007b) and the soils below 20 cm were less disturbed. Crop roots are usually concentrated in the top 0–20 cm depth. The decomposition of SOC below 40 cm may be rather slow, and thus contributing less CO_2 to the atmosphere.

Marshland CH_4 emissions. Of the three GHGs, CH_4 emissions accounted for 60%–90% of our estimated GWP (Table 4). Though we used parameters (Table 2) and area-weighted SE to estimate upper and lower values of CH_4 emissions (Fig. 5a), the spatial and temporal variability in these parameters is not well known due to insufficient observations. First, wide variations in CH_4 emission were observed in wetlands vegetated with different species (Shannon & White, 1994; Öquist & Svensson, 2002). Marshlands vegetated with *C. lasiocarpa* showed higher CH_4 emissions than areas vegetated with *C. angustifolia* (Table 2). Wang *et al.* (2006b) gave the SOC concentration of $174.9\,g\,kg^{-1}$ for

Table 2 CH_4 emission from wetlands vegetated with different plant species

Plant	Period of observation	CH_4 flux ($g\,m^{-2}$)		Source
		Original	Annual*	
Calmagrostis angustifolia	June 2002–May 2003	23.00	23.00	This study
	June 2003–May 2004	21.84	21.84	This study
	June 2004–May 2005	18.62	18.62	This study
	June–September, 2003	4.66	12.29	Yang *et al*. (2006a)
	June–October 2002	31.21	36.89	Hao *et al*. (2004)
	Average		22.53	
	SE		4.04	
Carex lasiocarpa	June 2002–May 2003	44.08	44.08	This study
	June 2003–May 2004	31.34	31.34	This study
	June 2004–May 2005	67.19	67.19	This study
	June–September, 2003	31.62	39.25	Yang *et al*. (2006a)
	May to October, 2001	76.40	78.42	Ding *et al*. (2004)
	May to October, 2002	97.15	99.18	Ding *et al*. (2004)
	June to October 2002	43.70	49.37	Hao *et al*. (2004)
	Average		58.40	
	SE		9.16	
Carex paseudocuraica	June–September, 2003	33.38	39.88	Yang *et al*. (2006a)
Clyceria spiculosa	June–September, 1995	84.68	93.07	Cui (1997)
Carex schmidtii	June–September, 1995	38.62	47.02	Cui (1997)
Mixture with various species	June–September, 1995	55.08	63.47	Cui (1997)
	Average		60.86	
	SE		11.82	
Rice (*Oryza sativa* L.)	June–October, 2002	12.21	14.17	This study
	May–October, 2003	20.35	20.35	This study
	May–October, 2004	11.45	11.45	This study
	May–October, 2005	18.97	18.97	This study
	Average		16.23	
	SE		2.07	

*Corrected by using Eqn (5) for the CH_4 fluxes observed in growing season.
CH_4, methane.

C. lasiocarpa and $75.9\,g\,kg^{-1}$ for *C. angustifolia*. Large variation in CH_4 emissions has also been observed by different researchers at sites with the same dominant plant species (Table 2), suggesting that soil properties may contribute to the variation (Huang *et al*., 2002). Plant community composition and soils are complex in the study area (Zhao, 1999), which makes it difficult to conduct field measurements for all of these factors. These values (Table 2) may only represent CH_4 emissions with the majority of plant species, including *C. angustifolia* and *C. lasiocarpa* (Cui, 1997), although significant variability existed in these values.

Second, an obvious interannual variation in CH_4 flux was observed (Fig. 4a), not related to air temperature (Fig. 4c). Although the influence of temperature on CH_4 emission has been well recognized (Segers, 1998; Whalen, 2005), there remains uncertainty in the temperature calibration of annual CH_4 emissions [Eqn (5)] as the Q_{10} from Song *et al*. (2009) was estimated on the basis of daily measurements. For example, the mean temperature in the 2003 and 2004 growing seasons was relatively consistent, while CH_4 emissions in 2003 were lower than in 2004 (Fig. 4a). When precipitation was cumulated from October through April, we found that precipitation in 2002–2003 was lower (109.7 mm) than in the 2003–2004 nongrowing season (169.0 mm). The higher precipitation in the nongrowing season may bring on deeper standing water early in the growing season, enhancing CH_4 production and emission (Shannon & White, 1994; Ding *et al*., 2002; Song *et al*., 2008). Accordingly, higher CH_4 fluxes appeared early in the growing season of 2004 (Fig. 4a). Precipitation may affect interannual variation in CH_4 emissions, but it does not appear to govern the long-term trend in CH_4 flux over the 50 year study period, because neither annual precipitation nor precipitation in the nongrowing season in the study area shows a significant linear trend over the period 1950–2000 ($P > 0.15$), while these precipitation

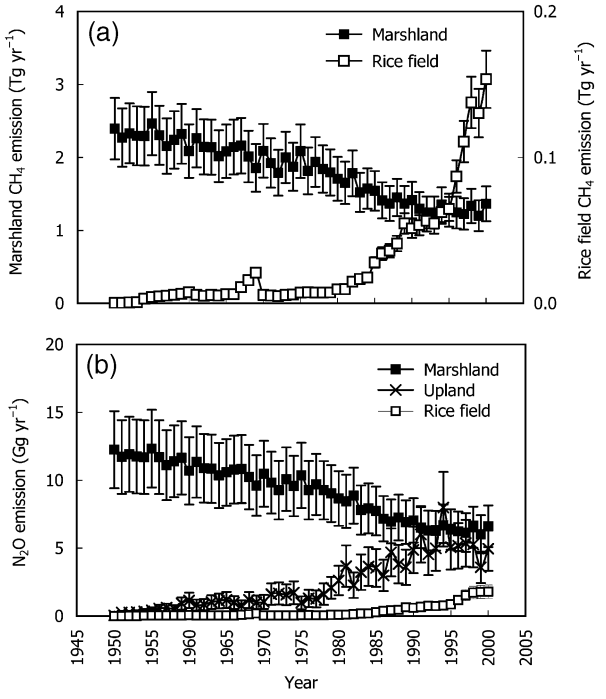

Fig. 5 Estimated greenhouse gas emission attributed to wetland conversion in northeast China: (a) CH_4 emission from marshland and rice field; (b) N_2O emission from marshland and croplands. The vertical bars represent the upper and lower estimates of CH_4 and N_2O emissions, which were computed by annual mean flux [Eqns (8) and (9)] plus and minus SE, respectively. The SE for CH_4 and N_2O emission in marshland is area-weighted, and that for N_2O emission in croplands was determined from the SE of the regression coefficients in Eqns (6) and (7), respectively. See text for the SE values.

values show wide interannual variation, with a coefficient of variance of 19% and 38%, respectively.

Due to large variability, scaling the values of marshland CH_4 emissions (Table 2) across the study region would introduce errors into the estimates (Fig. 5a). For example, when we used the lowest and the highest values of annual CH_4 emissions for *C. angustifolia*, *C. lasiocarpa* and other species (Table 2) to estimate changes in marshland CH_4 emissions, the cumulative CH_4 reduction was estimated to be 17.3 and 47.4 Tg, respectively. Accordingly, the lowest and highest estimates of GWP_T at 20-year time horizon are 113.1 and 283.4 $Tg\,CO_2\_eq.\,yr^{-1}$ in the 1950s, and 78.3 and 173.1 $Tg\,CO_2\_eq.\,yr^{-1}$ in the 1990s, respectively. In this case, uncertainty on the estimates (Table 5) is $\sim 45\%$ at 20-year time horizon. When calculated at 100-year time horizon, the uncertainty is smaller than 40%. To capture the multiple influences of climatic variability, plant community composition and soils on CH_4 emission and thus to improve present estimates, a long-term observation in plots vegetated with different plant species would be required. Alternatively, model simulations such as WMEM (Cao *et al*., 1996) and Wetland-DNDC (Zhang *et al*., 2002) are expected to make more reliable estimates, but these models should be validated and calibrated when they are put into practice.

N_2O emissions. The contribution of N_2O emissions to the GWP was $<7\%$ (Table 5). Lu *et al*. (2006) analyzed 206 measurements of N_2O emissions from upland-crop cultivation worldwide and found that the N_2O emission factor and background emissions were significantly correlated with annual precipitation but not with temperature and soil parameters. The annual amount of N_2O emissions from upland fields was thus estimated by using a precipitation-rectified emission factor [Eqn (7)]. Note that the marshland emitted N_2O similar to cropland where N fertilizer was applied during the 1990s (Table 4), even if the area of marshland and cropland was similar in the same period (Fig. 1). This similarity is due mainly to the lower application rate of N fertilizer. The average rate of synthetic fertilizer N application in the study area was $\sim$70 kg per harvest hectare during the 1990s (Heilongjiang Provencal Bureau of Statistics, 2007), much lower than the national mean of $\sim$155 kg per harvest hectare (National Bureau of Statistics of China, 2008). Lower annual precipitation, with a mean of $\sim$540 mm, also restricted conversion of synthetic fertilizer N to N_2O [Eqn (7)] in the study area.

Area of marshland converted to croplands. The temporal changes in SOC (Fig. 3) and GHG emissions (Fig. 5) develop principally from the area of marshland converted to croplands (Fig. 1). In the same research region, Liu (1997) gave his estimates of the cropland area from marshland conversion in 6 given years (1952, 1959, 1965, 1975, 1983 and 1995). Plotting our estimates against Liu's estimates yields a linear correlation coefficient R^2 of 0.93 ($n = 6$). The conversion of marshland to cropland over the periods 1976–1995 and 1950–1995 was estimated to be 1.54 and 2.78 Mha in this study, respectively, which agrees with Liu's values of 1.62 and 2.88 Mha. Moreover, our estimates suggest a total loss of 1.22 Mha (across 23 counties and four administrative farms) over the period 1980–2000, which is also comparable with the estimate of 1.03 Mha (across 23 counties) by Zhang *et al*. (2003), who used remotely-sensed marsh maps in 1980 and 2000 for their estimate.

Table 3 N_2O emission from wetlands vegetated with different plant species

Plant	Period of observation	N_2O flux ($mg\,m^{-2}$)		Source
		Original	Annual*	
Calmagrostis angustifolia	June–September, 2003	119.9	162.6	Yang *et al*. (2006a)
	May–October, 2002	490.2	523.9	Wang *et al*. (2006a)
	May–October, 2003	114.8	122.7	Wang *et al*. (2006a)
	May–October, 2004	344.4	368.1	Wang *et al*. (2006a)
	May–September, 2004	330.5	373.7	Zhang *et al*. (2007)
	May–September, 2005	257.0	290.6	Zhang *et al*. (2007)
	Average		306.9	
	SE		60.6	
Carex lasiocarpa	June 2002–May 2003	142.0	142.0	This study
	June 2003–May 2004	178.5	178.5	This study
	June 2004–May 2005	294.9	294.9	This study
	June–September, 2003	118.2	160.3	Yang *et al*. (2006a)
	May–October, 2002	234.0	250.1	Wang *et al*. (2006a)
	May–October, 2003	110.4	118.0	Wang *et al*. (2006a)
	May–October, 2004	295.9	316.2	Wang *et al*. (2006a)
	Average		208.6	
	SE		29.5	
Carex paseudocuraica	June–September, 2003	113.7	154.2	Yang *et al*. (2006a)
Mixture with various species	June–September, 2003	33.8	45.9	Yang *et al*. (2004)
Mixture with various species	May–October, 2002	428.4	457.8	Wang *et al*. (2006a)
Mixture with various species	May–October, 2003	194.3	207.7	Wang *et al*. (2006a)
Mixture with various species	May–October, 2004	476.9	509.7	Wang *et al*. (2006a)
	Average		275.1	
	SE		89.5	

*Corrected by using Eqn (5) for the N_2O fluxes observed in growing season.
N_2O, nitrous oxide.

Table 4 Decadal variations in global warming potential attributed to marshland conversion

Decade	Land use	Global warming potential ($Tg\,CO_2\_eq.\,yr^{-1}$)							
		20-year time horizon				100-year time horizon			
		CO_2	CH_4	N_2O	Σ	CO_2	CH_4	N_2O	Σ
1950s	Cropland	11.43	0.23	0.13	181.30	11.43	0.08	0.13	72.82
	Marshland		166.12	3.39			57.68	3.50	
1960s	Cropland	12.97	0.65	0.31	167.56	12.97	0.23	0.32	68.96
	Marshland		150.56	3.07			52.28	3.16	
1970s	Cropland	15.33	0.47	0.45	156.96	15.33	0.16	0.46	66.72
	Marshland		137.91	2.80			47.89	2.88	
1980s	Cropland	26.33	1.89	1.07	142.25	26.33	0.68	1.10	68.87
	Marshland		110.71	2.25			38.44	2.32	
1990s	Cropland	19.22	6.30	1.84	122.21	19.22	2.19	1.90	57.52
	Marshland		92.99	1.86			32.29	1.92	

N_2O, nitrous oxide; CH_4, methane.

Carbon balance in terms of GWP

Wetlands sequester carbon from the atmosphere through photosynthesis by plants and subsequent carbon accumulation in the soil, while they emit about 20–25% of global CH_4 emissions, or about 115–145 $Tg\,CH_4$ per year (Mitsch & Gosselink, 2007). Kasimir-Klemedtsson *et al*. (1997) showed that wetlands in northern Europe accumulate between 0.16–0.25 $t\,C\,ha^{-1}\,yr^{-1}$, but if CH_4 emissions are taken into account these wetlands become a net source of GHGs. Mitra *et al*. (2005) estimated carbon sequestration by wetlands to be 0.2–1.4 $t\,C\,ha^{-1}\,yr^{-1}$ and

Table 5 CO_2 and CH_4 balance attributed to wetland conversion in the United States and northeast China

Decade	Wetland conversion (Mha)	CO_2 (Tg)	CH_4* (Tg)	CH_4* (Tg CO_2_eq)		Balance (Tg CO_2_eq)	
				20-year	100-year	20-year	100-year
USA							
1951–1960	6.3	1272	−7	−503	−175	769	1097
1961–1970	4.2	1523	−17	−1247	−433	277	1090
1971–1980	3.1	1177	−24	−1758	−610	−581	567
1981–1990	2.0	840	−29	−2111	−733	−1271	107
1991–2000	1.7	670	−33	−2378	−826	−1708	−156
Σ	17.2	5482	−111	−7996	−2776	−2514	2706
Northeast China							
1951–1960	0.70	124	−0.8	−60	−21	64	103
1961–1970	0.37	130	−3.2	−233	−81	−103	49
1971–1980	0.60	153	−5.1	−367	−127	−214	26
1981–1990	0.87	263	−8.5	−615	−214	−352	49
1991–2000	0.36	192	−10.2	−737	−256	−545	−64
Σ	2.91	862	−28.0	−2012	−699	−1150	163

*Wetland CH_4 emissions relative to 1950.
CH_4, methane.

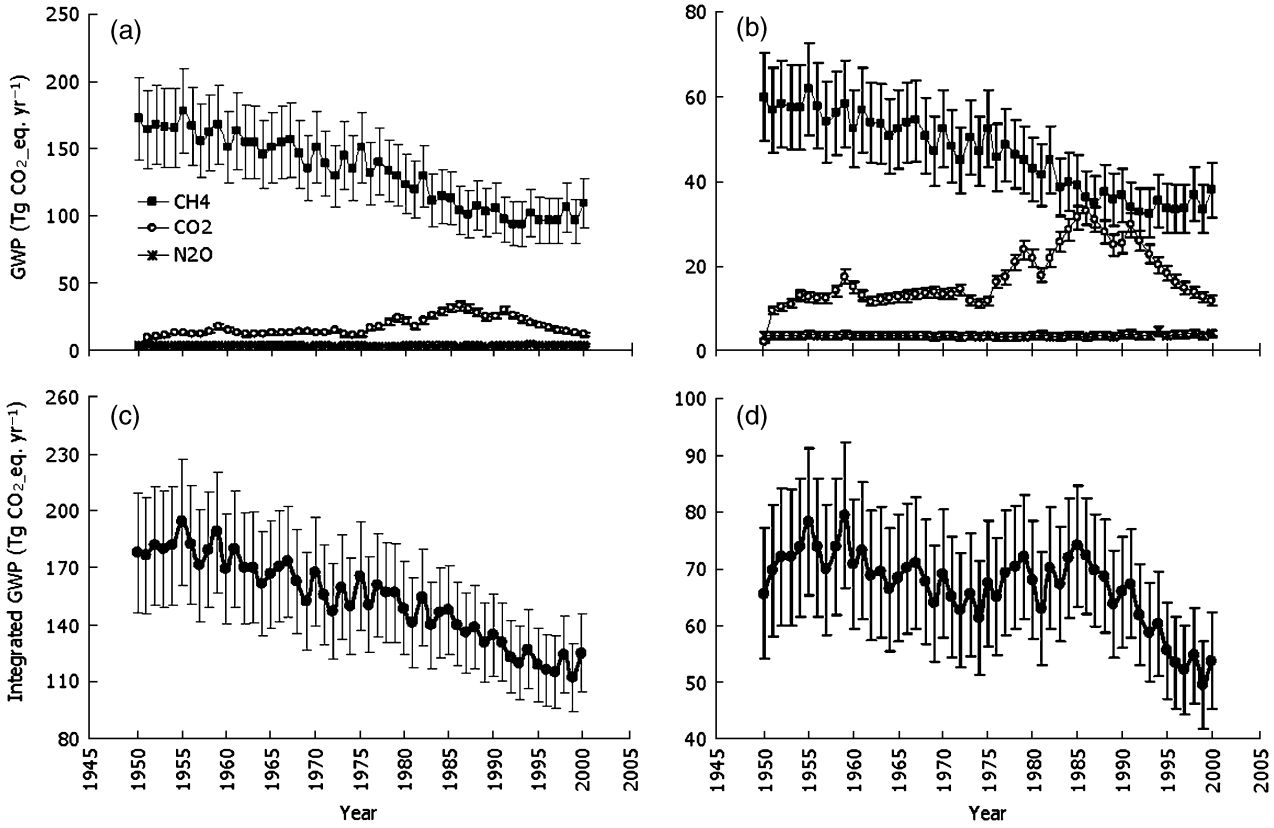

Fig. 6 Estimated global warming potential (GWP) attributed to wetland conversion in northeast China: (a) GWP for different greenhouse gases (GHGs) at 20-year time horizon; (b) GWP for different GHGs at 100-year time horizon; (c) integrated GWP at 20-year time horizon; (d) integrated GWP at 100-year time horizon.

average CH_4 emission rates to be on the order of $200\,kg\,CH_4\,ha^{-1}\,yr^{-1}$. When the GWP of CH_4 is taken into account, Mitra *et al*. (2005) suggested that pristine wetlands should be regarded as a relatively small net source of GHGs due to the counterbalancing of CH_4 emission by carbon sequestration. Recent general overviews indicate that pristine mires contribute to the greenhouse effect at 20 and 100-year time horizons with respect to their CO_2, CH_4 and N_2O balances (Joosten & Clarke, 2002).

By reviewing and synthesizing the published literature and soil databases, Bridgham *et al*. (2006) estimated that North American wetlands are a small to moderate carbon sink of about $49\,Tg\,C\,yr^{-1}$ but emit $9\,Tg\,CH_4$ per year, although large uncertainties existed in these estimates. They drew the conclusion that CH_4 emissions from wetlands (with the exception of estuarine wetlands) may largely offset any positive benefits of carbon sequestration in soils and plants in terms of climate forcing (Bridgham *et al*., 2006). A 6-year field measurement in a northern ombrotrophic bog indicated that the mean NEE-C (NEE, net ecosystem CO_2 exchange) and CH_4-C emissions were -40.2 ± 40.5 and $3.7 \pm 0.5\,g\,m^{-2}\,yr^{-1}$, respectively (Roulet *et al*., 2007), also suggesting that CH_4 emission may offset the CO_2 sequestration in terms of climate forcing.

Although marshland conversion to cropland released a great amount of SOC (Fig. 3), reduction in CH_4 emissions (Fig. 5a) greatly counteracted the GWP of CO_2 emission (Fig. 6). The major cause of wetland loss around the world continues to be conversion to agricultural use (Mitsch & Gosselink, 2007). Wetland drainage for farmers in the United States, for example, progressed at an average rate of 0.49 Mha per year from the early 1900s to 1980 (Mitsch & Gosselink, 2007), and since 1985 little additional drainage has occurred, except in Minnesota and Ohio (Dahl, 2000; Mitsch & Gosselink, 2007). Present study shows CH_4 emission rates of $225–600\,kg\,CH_4\,ha^{-1}\,yr^{-1}$ in the Sanjiang Plain (Table 2), higher than the global mean of $200\,kg\,CH_4\,ha^{-1}\,yr^{-1}$ (Mitra *et al*., 2005). When we used Eqns (3) and (4) to calculate SOC loss and used the global mean rate of $200\,kg\,CH_4\,ha^{-1}\,yr^{-1}$ to calculate CH_4 emissions in the United States over the period 1950–2000, the GWP of CO_2 emissions from soils is also greatly counterbalanced by reduced CH_4 emissions due to wetland conversion (Fig. 7). The amount of SOC loss in the United States was estimated to be $\sim 5.5\,Pg\,CO_2$ over the 50 years, while the cumulative CH_4 reduction amounted to 111 Tg relative to 1950 (Table 5). The GWP of CO_2 emissions derived from SOC loss was fully counterbalanced by CH_4 reduction at 20-year horizon ($\sim 8.0\,Pg\,CO_2$_eq.) and $\sim$50% counterbalanced at 100-year horizon ($\sim 2.8\,Pg\,CO_2$_eq.) over the 50 years

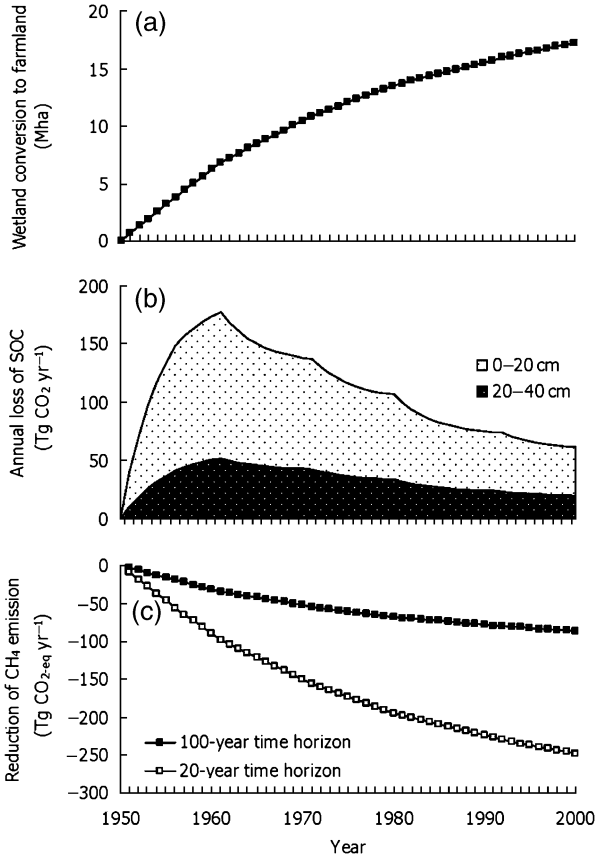

Fig. 7 Estimated soil organic carbon (SOC) loss and CH_4 reduction in the United States over the period 1950–2000: (a) the area of wetland conversion to farmland (sources: Dahl and Johnson, 1991; Dahl, 2000, 2006; Mitsch and Gosselink, 2007); (b) annual loss of SOC; (c) reduction of CH_4 emission from wetlands. Initial SOC density of the wetlands was assumed to be 100 Mg ha^{-1} in the 0–20 cm depth and 65 Mg ha^{-1} in the 20–40 cm depth when the changes in SOC was estimated using Eqn (3). The global mean rate of 200 kg CH_4 ha^{-1} yr^{-1} was used to calculate the CH_4 emission from wetlands.

(Table 5). By contrast, $\sim$80% of the CO_2 GWP in northeast China was counterbalanced by the CH_4 reduction at 100-year horizon (Table 5) because of higher CH_4 emission rates in the pristine marshland (Table 2).

Global perspective on the greenhouse effect due to wetland conversion

From coastal swamps to inland floodplains, since 1900 the world may have lost 50% of the wetlands that used to exist; while much of this occurred in northern countries during the first 50 years of the century, increasing pressure for conversion to alternative land use has been put on tropical and subtropical wetlands since the 1950s (OECD, 1996). According to earlier work by Maltby &

Turner (1983), about 56% of the world wetlands are distributed in tropical and subtropical regions.

Assuming that the world's wetland area (excluding rice paddies) was 700 million ha in the early 2000s (Lehner & Döll, 2004), that 10–25% of world's wetlands loss occurred during the period 1950–2000, and that 60% of this loss was for agricultural use, global wetland area was estimated to be 778 ($700/0.9 \approx 778$) to 933 ($700/0.75 \approx 933$) million ha in the early 1950s, with 47 ($778 \times 0.1 \times 0.6 \approx 47$) to 140 ($933 \times 0.25 \times 0.6 \approx 140$) million ha converted for agricultural use over the period 1950–2000.

Calculations of SOC loss (Table 5) give an average value of approximately 300 $Mg\,CO_2\,ha^{-1}$ over a 50-year period. Extrapolating this value to the area of global wetland conversion for agricultural use, a total amount of 14 ($300 \times 10^{-9} \times 47 \times 10^6 \approx 14$) to 42 ($300 \times 10^{-9} \times 140 \times 10^6 \approx 42$) $Pg\,CO_2$ may have been emitted to the atmosphere over the period 1950–2000, corresponding to 0.28–0.84 $Pg\,CO_2\,yr^{-1}$. Similarly, Bridgham *et al.* (2006) estimated that human disturbance of global peatlands has caused an increased flux to the atmosphere of 0.65–0.98 $Pg\,CO_2\,yr^{-1}$. According to Joosten & Clarke (2002), peatlands represent 50% to 70% of global wetlands. In this case, the annual emission was estimated to range from 0.73 ($0.65 + 0.3 \times 0.28 = 0.73$) to 1.40 ($0.98 + 0.5 \times 0.84 = 1.40$) $Pg\,CO_2$. Note that the net land-to-atmosphere CO_2 flux was $-3.7 \pm 2.2\,Pg\,CO_2\,yr^{-1}$ during the 1990s (IPCC, 2007); the CO_2 emission from wetland conversion may largely counteract the net land-to-atmosphere flux though we have no exact estimates yet.

CH_4 emissions from global natural wetlands were estimated to be 115–145 $Tg\,yr^{-1}$ (Mitra *et al.*, 2005; IPCC, 2007) in the early 2000s. The annual rates would be 128 ($115/0.9 \approx 128$) to 193 ($145/0.75 \approx 193$) $Tg\,yr^{-1}$ in the early 1950s, with the assumption that 10–25% of the world's wetlands loss occurred during the period 1950–2000. In other words, the wetland CH_4 emission in the early 1950s would be 13–48 $Tg\,yr^{-1}$ higher than that in the early 2000s. Results from a bottom-up model inferred a decreasing trend of 0.6 $Tg\,CH_4\,yr^{-1}$ during 1993–2001, in response to a marked decrease in the worldwide flooded area at a rate of $-1.1\%\,yr^{-1}$ for a mean area of $4.2 \times 10^6\,km^2$ (Bousquet *et al.*, 2006). Bridgham *et al.* (2006) estimated that global CH_4 emissions from current natural wetlands are 105 $Tg\,yr^{-1}$, about 55% of original emissions due to loss of area.

The growth rate of atmospheric CH_4 has declined since the 1980s, with virtually no increase from 2004 to 2006 (World Meteorological Organization, 2007), while the trend did not continue. The increased rate of 6 ppb from 2006 to 2007 is the highest annual increase observed since 1998 (World Meteorological Organization, 2008). It is too early to state with certainty that this increase represents the beginning of a new upward trend of CH_4 (World Meteorological Organization, 2008). Increasing CH_4 emissions from anthropogenic sources have been understood (IPCC, 2007), while the cycling of CH_4 is complex and accounting for its atmospheric burden requires an understanding of its many sources and sinks (World Meteorological Organization, 2008). We believe that global wetland loss has reduced the growth rate of atmospheric CH_4. This contribution should be quantified, so as to better understand the global CH_4 budget.

Although we are aware of the possible influence of global wetland conversion on carbon balance and the greenhouse effect, an accurate estimate will be hard without knowing detailed information on wetland change and corresponding GHG fluxes. To better understand the role of global wetland conversion in the greenhouse effect, future research should focus on quantifying historical and spatial changes in wetland area and rates of loss and on determining annual emissions of GHGs (CO_2, CH_4 and N_2O) under various conditions of climates, soils and land cover types.

Conclusions

An estimated 2.91 million ha of marshland was converted to cropland in the Sanjiang Plain of northeast China over the period 1950–2000. Marshland conversion resulted in a loss of ~ 240 Tg SOC, introduced CH_4 and N_2O emissions in the cropland, and reduced CH_4 emissions from the former marshland by a cumulative amount of ~ 28 Tg over the 50 years. Taking the loss of SOC and emissions of CH_4 and N_2O into account, the integrated GWP in the 1990s, compared with the 1950s, was reduced by $\sim 33\%$ at a 20-year time horizon and $\sim 21\%$ at a 100-year time horizon. The changes in GWP are attributed to a significant reduction in CH_4 emissions from the former marshland. We further inferred that the declining growth rate of atmospheric CH_4 since the 1980s might be related to the loss of global wetlands.

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