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ORIGINAL ARTICLE

Two approaches for net ecosystem carbon budgets and soil carbon sequestration in a rice–wheat rotation system in China

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Abstract Few studies have comprehensively evaluated the method of estimating the net ecosystem carbon budget (NECB). We compared two approaches for studying the NECB components on the crop seasonal scale as validated by the soil organic carbon (SOC) changes measured over the 5-year period of 2009–2014. The field trial was initiated with four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the local farmer's practices (FP) rate, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase) with no nitrogen (NN) and FP as the controls. Compared with the FP, the four ISSM scenarios of N1, N2, N3 and N4 significantly increased rice yields by 9.5, 19, 33 and 41 %, while increasing the agronomic nitrogen use efficiency (NUE) by 71, 75, 99 and 79 %, respectively. The SOC sequestration potentials were estimated to be −0.15 to 0.35 Mg C ha^{-1} $year^{-1}$ from the net primary production minus heterotrophic respiration approach and −0.32 to 0.67 Mg C ha^{-1} $year^{-1}$ from the gross primary production minus ecosystem respiration approach for the 2010–2011 rice–wheat annual cycle. Similarly, the annual topsoil carbon sequestration rate over 2009–2014 was measured to be −0.22 Mg C ha^{-1} $year^{-1}$ for the NN plot and 0.13–0.42 Mg C ha^{-1} $year^{-1}$ for the five fertilized treatments. Both NECB approaches provided a sound basis for accurate assessment of the SOC changes. Compared to the SOC sequestration rate from the FP, the proposed N3 and N4 scenarios increased the SOC sequestration rates while also improving rice yield and NUE.

Keywords Agronomic nitrogen use efficiency · Integrated soil–crop system management · Net ecosystem carbon budget · SOC sequestration rate · Rice–wheat rotation

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Introduction

Globally society is facing a major climate challenge due to rapidly increasing greenhouse gases (GHGs) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere and their substantial contribution to global climate warming, which may have impacts on climate, sea level, polar ice, biodiversity, agriculture and human life (IPCC 2013).

Sequestration of ecosystem carbon has been giving much attention as a promising option for mitigating climate change on regional (Smith 2004) and global scales (FAO 2001). The agricultural soil carbon pool is the most active one in the global carbon library (Paustian et al. 1998; Pan et al. 2004). It was estimated that 4×10^8–9×10^8 Mg C $year^{-1}$ could be sequestered globally in agricultural soils (Paustian et al. 1998). Paddy fields have a particularly high capacity for soil carbon sequestration (Pan et al. 2004; Zheng et al. 2008; Lu et al. 2009; Shang et al. 2011), which plays important roles in both crop productivity and the global carbon cycle (Huang and Sun 2006; Pan 2008). The total topsoil (0–20 cm) soil organic carbon (SOC) capacity of Chinese paddy soil was estimated to be 1.3×10^9 Mg, and the average density of paddy SOC is higher than that of non-irrigated farmland of 9 Mg C ha^{-1} (Pan et al. 2004; Song et al. 2005).

Measurement of the SOC change is a typical way in which CO_2 exchange is estimated over a sub-decadal or decadal timescale (Robertson et al. 2000; Pan et al. 2004; Shang et al. 2011), but the method is insensitive to seasonal or annual changes (Zheng et al. 2008). The soil carbon sequestration potential can be indirectly determined through soil respiration measurements (Mosier et al. 2006) or modelling (Li et al. 2006; Zhang et al. 2009), but changes of SOC can also be estimated from the net ecosystem carbon budget (NECB) (Robertson et al. 2000; Mosier et al. 2005; Ma et al. 2013). Thereby the NECB can act as a carbon source or sink for a terrestrial ecosystem at annual to decadal timescales, depending upon the balance of the residual of net primary production (NPP) and heterotrophic respiration (Rh), or gross primary production (GPP) and ecosystem respiration (Re), as well as episodic losses and organic matter management (Chapin et al. 2006; Zheng et al. 2008). As such it can be estimated NECB using two approaches: (1) NPP minus Rh and (2) GPP minus Re (Smith et al. 2010). Via the NECB approach, we can assess soil carbon sequestration potential under the current conditions and develop new strategies for mitigating GHGs (Zhang and Wang 2013).

To meet the increasing global demand for food, rice production will increase both in area and intensity. In China during the last decades the increasing use of mineral fertilizers has enhanced crop production substantially (Ju et al. 2009), which has not only resulted in decreased N-utilization efficiency by crops (Vanlauwe et al. 2011), but in many cases also to on-site land degradation (Guo et al. 2010) and enhanced GHGs emissions (Hoben et al. 2011). Therefore, integrated soil–crop system management (ISSM) has been advocated and developed in China to increase rice productivity and agronomic nitrogen use efficiency (NUE).

To this end this study was conducted to (1) comprehensively appraise different approaches on NECB measurements as an alternative method for estimating SOC changes for new field experiments and (2) provide insights into the SOC changes for the different ISSM scenarios with different targets of rice yield and NUE.

Materials and methods

Experimental site

A field experiment was conducted at the Changshu agro-ecological experimental station (31°32′93″N, 120°41′88″E) from June 2009 to June 2014, Chinese Academy of Sciences, Jiangsu Province, China. This region belongs to the Yangtze River Delta, where a flooding rice (*Oryza sativa* L.)–drained wheat (*Triticum aestivum* L.) rotation is the dominant cropping system. The site is characterized by a subtropical humid monsoon climate with an annual mean air temperature of 15.5 °C and a precipitation of 1,038 mm. The soil is classified as an *Anthrosol* (WRB-FAO) developed from lacustrine sediment. The major soil properties at 0–20 cm were as follows: bulk density, 1.11 g cm^{-3}; pH, 7.35; organic matter content, 35.0 g kg^{-1}; total N, 2.1 g kg^{-1}. The daily mean air temperatures and precipitation during the 2010–2011 rice–wheat cropping seasons were acquired from the Changshu station (Fig. 1).

Field trial treatments and management of the experiment

A completely randomized design was employed with six treatments and four replicates, including the control treatment NN and conventional fertilization FP of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, and four ISSM practices at different nitrogen (N) application rates relative to the FP rate, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase), for improving rice yield and NUE. The agronomic NUE in this study was calculated as the difference in grain yield between the fertilizer

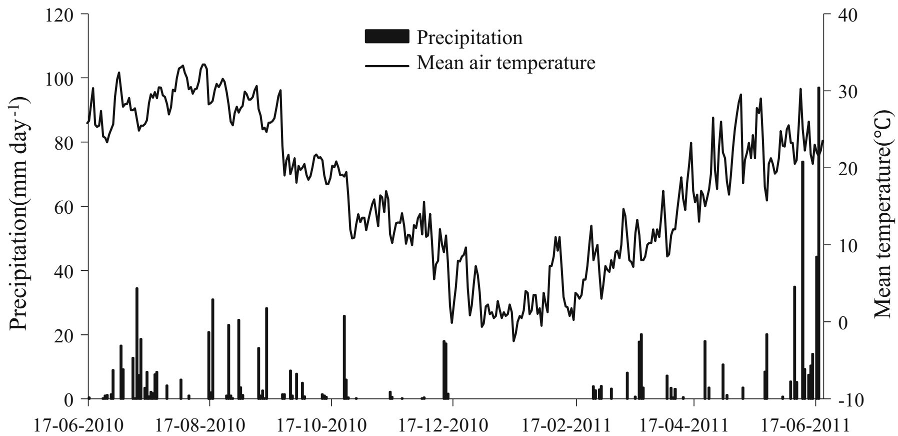

Fig. 1 Daily mean air temperature and precipitation during the rice–wheat rotation in 2010–2011 in Changshu, China

treatment and the NN plots and was divided by the N fertilizer rate. Each plot was 6 m × 7 m in size with independent drainage/irrigation systems. Detailed N fertilization and field management practices of the six different treatments are provided in Table 1 (Ma et al. 2013).

Topsoil organic carbon sequestration measurement

Soil samples were collected in 2009 and 2014 from all experimental plots at the ploughing depth of 0–20 cm after the wheat harvest to measure topsoil SOC content. Each sample of approximately 1 kg was a composite of five sub-samples randomly taken within a plot. Visible plant detritus and any fragments were removed after air-drying at room temperature and ground to pass a 2 mm sieve; a portion was subsequently ground in a porcelain mortar to pass a 0.154 mm sieve for SOC measurement. Total SOC was analyzed by wet digestion with H_2SO_4–$K_2Cr_2O_7$ (Lu 2000).

The soil organic carbon sequestration rates (SOCSR) were calculated as follows:

$$\mathrm{SOCSR}\ (\mathrm{Mg\ C\ ha^{-1}year^{-1}}) = (\mathrm{SOC_t} - \mathrm{SOC_0})/\mathrm{T} \times \gamma \times (1 - \delta_{2\ \mathrm{mm}}/100) \times 20 \times 10^{-1} \quad (1)$$

In Eq. (1), SOC_t and SOC_0 are the SOC contents measured in the soils sampled after wheat was harvested in 2014 and 2009, respectively. T refers to the period of the experiment year. γ and $\delta_{2\ mm}$ are the average bulk density and the gravel content (>2 mm) of the topsoil (0–20 cm), respectively whereby it is well known that the sand fractions of paddy soils in China are typically negligible (Li 1992). The number 20 refers to topsoil thickness in centimeters.

Chamber measurement of methane fluxes, total ecosystem respiration and heterotrophic respiration

We used the 2010–2011 rice–wheat rotation cycle to gain insight into the NECB components. Thus, the CH_4, Re and Rh fluxes were measured in each plot of the field experiment from 17 June 2010 to 17 June 2011. CH_4 and Re emissions were determined simultaneously and using the static-opaque chamber method described by Ma et al. (2013). Re includes the respiration of the plants and the soil microorganisms. The cross-sectional area of the chambers was 0.25 m^2 with a height of 0.5 or 1.1 m adapted to crop growth. Gas samples were collected from 9:00 to 11:00 am using an airtight syringe with a 20-ml volume at intervals of 10 min (0, 10, 20 and 30 min after chamber closure). The fluxes were measured once a week and more frequently after fertilizer application or a change in soil moisture.

The Rh was simultaneously measured with CH_4 and Re using a separate cylindrical chamber. The chamber covered a field area of 0.04 m^2 and was placed on a fixed PVC frame on each plot. The chamber was 0.25 m high and wrapped with a layer of aluminum foil to minimize air temperature changes inside the chamber during sampling.

Table 1 The establishment of different treatments for the annual rice–wheat rotations during the 2010–2011 cycle

Scenario	NN[a]	FP	ISSM-N1	ISSM-N2	ISSM-N3	ISSM-N4
Rice-growing season						
Chemical fertilizer application rate (N:P:K:Si:Zn, kg ha^{-1})	0:39:100:0:0	300:39:100:0:0	225:39:100:0:0	270:39:100:0:0	300:47:119:52:6	375:55:149:52:6
Split N application ratio		6:2:0:2	5:1:2:2	5:1:2:2	5:1:2:2	5:1:2:2
Rapeseed cake manure (Mg ha^{-1})	0	0	0	0	2.25	2.25
Water regime	F–D–F–M[b]	F–D–F–M	F–D–F–M	F–D–F–M	F–D–F–M	F–D–F–M
Planting density (cm)	20 × 20	20 × 20	20 × 15	20 × 15	20 × 15	20 × 20
Wheat-growing season						
Chemical fertilizer application rate (N:P:K, kg ha^{-1})	0:39:149	180:39:149	135:39:149	162:39:149	180:47:179	225:55:224
Split N application ratio		6:1:3	6:1:3	6:1:3	6:1:3	6:1:3
Seed sowing density (kg ha^{-1})	180	180	180	180	180	180

[a] *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

[b] *F–D–F–M* flooding–midseason drainage–re-flooding–moist irrigation

Gas samples were analyzed for CH_4 and CO_2 concentrations using a gas chromatograph (Agilent 7890A, Shanghai, China) equipped with a hydrogen flame ionization detector (FID) and a SS-2 m × 2 mm Porapak Q (80/100 mesh) column. The oven temperature remained at 50 °C, and the detector was kept at 300 °C. The carrier gas was purified N_2 with a flow rate of 35 ml min^{-1}.

Emissions of CH_4, Re and Rh are presented as the mean values of four replicate measurements. The seasonal amounts of these gases were interpolated from the emissions between every two adjacent measurement intervals. The cumulative CH_4, Re and Rh fluxes for each treatment and mean values of the rotation cycle are shown in Table 2.

Calculation of net ecosystem carbon budget and estimation of net ecosystem carbon budget derived soil organic carbon sequestration rates

In croplands, NECB is the term applied to the total rate of organic carbon accumulation in (or loss from) ecosystems (Ciais et al. 2010). Based on studies by Smith et al. (2010) and Ma et al. (2013), we summarized the components for the NECB of seasonal or annual croplands using intermittent chamber measurements (Eq. (2)):

$$\text{NECB} = \text{NEP} - \text{Harvest} - CH_4 + \text{Manure} \quad (2)$$

Here, NEP (net ecosystem production) is obtained by two approaches (Ciais et al. 2010; Smith et al. 2010) and listed in Eqs. (3) and (4).

$$\text{NEP} = \text{NPP} - \text{Rh} \quad (3)$$

On the other hand, the sum of heterotrophic respiration (Rh) and autotrophic respiration (Ra) represents the total ecosystem respiration (Re). By definition, GPP = NPP + Ra and the sum of the belowground fraction of Ra and Rh is termed soil respiration. Accordingly, NEP can be similarly determined by the difference between GPP and Re:

$$\text{NEP} = \text{GPP} - \text{Re} \quad (4)$$

Gross primary production (GPP) is inferred from NPP (net primary production) using the NPP/GPP ratio (Luyssaert et al. 2007). The NPP/GPP ratio of 0.58 is deduced from the resulting MODIS GPP and NPP products (Zhang et al. 2009). Rh and Re are

Table 2 Seasonal methane (CH_4) emissions, ecosystem respiration (Re), heterotrophic respiration (Rh), rice and wheat grain yields during the rice- and wheat-growing seasons during the 2010–2011 rotation

Treatment	Rice season				Wheat season			
	CH_4 (kg C ha^{-1})	Re[b] (kg C ha^{-1})	Rh (kg C ha^{-1})	Yield (Mg ha^{-1})	CH_4 (kg C ha^{-1})	Re (kg C ha^{-1})	Rh (kg C ha^{-1})	Yield (Mg ha^{-1})
NN[a]	159.69b[c]	6175e	1521abc	5.91e	5.32a	3731b	1596a	1.86d
FP	246.65ab	8254d	1739a	8.86d	14.66a	7224a	2274c	5.74abc
ISSM-N1	198.50b	8161 cd	1790a	9.70c	9.24a	7782a	2500c	5.13c
ISSM-N2	208.17b	9168bc	1419bc	10.54b	6.32a	6911a	3232b	5.86ab
ISSM-N3	364.79a	9592b	1319c	11.78a	5.51a	6916a	3531b	5.48bc
ISSM-N4	255.50ab	11024a	1603ab	12.50a	−4.30a	8119a	3989a	6.18a

[a] *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

[b] Re, ecosystem respiration, Rh, heterotrophic respiration

[c] Different lower case letters within the same column for each item indicate significant difference at $P < 0.05$ by the Tukey's multiple range test

measured simultaneously using the static, opaque chamber method.

In croplands, NPP is estimated by Eq. (5) (Smith et al. 2010):

$$NPP = NPP_{grain} + NPP_{straw} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposit} \quad (5)$$

Grain and straw biomass NPP was converted using the dry biomass weighed at harvest. Other components were estimated using allometric relationships according to Huang et al. (2007), in which the aboveground/root ratio was fixed at 1.0/0.1 for rice and 0.9/0.1 for wheat (Huang et al. 2007). Litter was estimated to account for 5 % of the aboveground and root dry biomass (Kimura et al. 2004), and rhizodeposits account for 15 % (Mandal et al. 2008) and 18 % (Gregory 2006) of the total biomass for rice and wheat, respectively.

Harvest data include straw removed and grain measured directly at harvest and converted to carbon by crop-specific carbon contents of 0.42 and 0.49 for rice and wheat straw, respectively, and 0.38 and 0.39 for rice and wheat grain, respectively (Huang et al. 2007). During this study all harvested biomass was removed from the field.

Manure was applied as rapeseed cake (5 % N of dry weight) for the treatment N3 (FP rate) and N4 (25 % increase) (Table 1).

The apparent average conversion rate of organic carbon gain to SOC was reported to be 213 g kg^{-1} in paddy soil (Xie et al. 2010). Thus, the SOC change was estimated from the NECB using a coefficient of 0.213 for paddy soils in this study.

$$SOCSR = 0.213 \times NECB \quad (6)$$

Statistical analysis

All data were subjected to one-way analysis of variance using JMP, ver. 7.0 (SAS Institute, USA, 2007). Tukey's multiple range tests were used to determine whether significant differences occurred between the treatments at a significance level of $P < 0.05$. A paired *t* test was used to examine differences among the three calculation methods of SOC sequestration rate. The statistical analyses were carried out using version 18.0 of the SPSS software package for Windows (SPSS, Chicago, IL, USA).

Results

Methane emissions during the rice–wheat rotation

The temporal variations of CH_4 fluxes during the 2010–2011 rice–wheat rotation are shown in Fig. 2a.

During the rice-growing season, similar temporal trends with varying amplitudes of CH_4 fluxes were observed for each treatment. The net CH_4 fluxes increased after transplantation and peaked at 38.7 mg C m^{-2} h^{-1} for the N3 (FP rate) treatment and decreased strongly during the midseason drainage to control ineffective tillers. After reflooding, the CH_4 fluxes increased again to a low emission peak and then gradually decreased to a negligible amount toward harvest (Fig. 2a).

CH_4 emission from the rice-growing season was significantly higher than that from the wheat-growing season and was thus negligible during the wheat-growing season (Fig. 2a). During the rice-growing season, all plots served as net sources of atmospheric CH_4, but the CH_4 fluxes of the wheat-growing season may be negative.

The highest cumulative CH_4 emission rates were recorded in the N3 (FP rate) plot (364.8 kg C ha^{-1}). Except for the N3 treatment, differences between cultivation practice patterns were not significant for cumulative CH_4 emission rates during the rice-growing season (Table 2, $P < 0.05$). Yet, compared with the NN plots, the FP, N2 (10 % reduction) and N1 (25 % reduction) plots with inorganic fertilizer application increased 54.5, 30.4 and 24.3 % CH_4 emission rates, respectively averaged over the rice-growing seasons. CH_4 emission rates were further enhanced by 128.4 % in N3 plots and by 60.0 % in N4 (25 % increase) plots due to the combined application of inorganic and organic fertilizers.

Ecosystem respiration fluxes during the rice–wheat rotation

Re fluxes remained positive during the cycle of rice–wheat rotation (Fig. 2b), reflecting the seasonal trends of plant growth and temperature. The rice-seasonal or annual cumulative Re emissions differed among the cultivation practice patterns (Tables 2, 3, $P < 0.05$).

During the rice-growing season, the Re peaked at approximately one month after rice transplanting which reflects the high microbial activity during this period.

The average Re fluxes and the cumulative Re emissions from the rice–wheat rotation ranged from 126.2 ± 3.3 to 243.9 ± 4.2 mg C m^{-2} h^{-1} and 9,903 ± 260 kg C ha^{-1} to 19,143 ± 329 kg C ha^{-1} for all treatments (Table 3; Fig. 2b). The cumulative Re emissions of the N3 (FP rate) treatment was higher than those from the remaining five treatments.

Fig. 2 Seasonal variations of **a** methane (CH_4), **b** ecosystem ▶ respiration, and **c** heterotrophic respiration during the cycle of rice–wheat rotation in 2010–2011 in Changshu, China. The *solid arrows* represent fertilization and *dotted line arrow* denotes the transplanting or seeding date for rice and wheat, respectively. *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

Heterotrophic respiration fluxes during the rice–wheat rotation

During the 2010–2011 annual rotation, Rh fluxes gently fluctuated in the rice-growing season and rapidly increased during the late wheat-growing season (Fig. 2c). Rh emissions varied from 1.1 to 285.5 mg C m^{-2} h^{-1}. Rh flux was highest at 285.5 mg C m^{-2} h^{-1} in N4 (25 % increase) and all treatments showed similar Rh flux patterns (Fig. 2c).

Crop production and agronomic nitrogen use efficiency

Grain yields of rice and wheat strongly reflected treatment differences (Table 2).

Grain yields ranged from 5.91 to 12.50 Mg ha^{-1} for rice and 1.86 to 6.18 Mg ha^{-1} for wheat and the agronomic NUE of the fertilized plots ranged from 9.84 to 19.56 kg grain kg^{-1} N for rice and 21.56 to 24.69 kg grain kg^{-1} N for wheat (Fig. 3).

Compared with FP, rice-grain yields increased by 41.1 % for N4 (25 % increase), 33.0 % for N3 (FP rate), 19.0 % for N2 (10 % reduction) and 9.5 % for N1 (25 % reduction) plots. At the same time, the agronomic NUE significantly increased by 99, 79, 75 and 71 % for the N3, N4, N2 and N1 plots, respectively, compared to the FP plot (Fig. 3a). Because no ISSM strategy was developed for the wheat crop, the wheat-grain yields and agronomic NUE did not increase.

The net ecosystem carbon budget measured by two approaches

The NEP values ranged from 5.15 to 15.20 Mg C ha^{-1} $year^{-1}$ and from 4.35 to 16.71 Mg C ha^{-1} $year^{-1}$ for the two methods, respectively (Table 3).

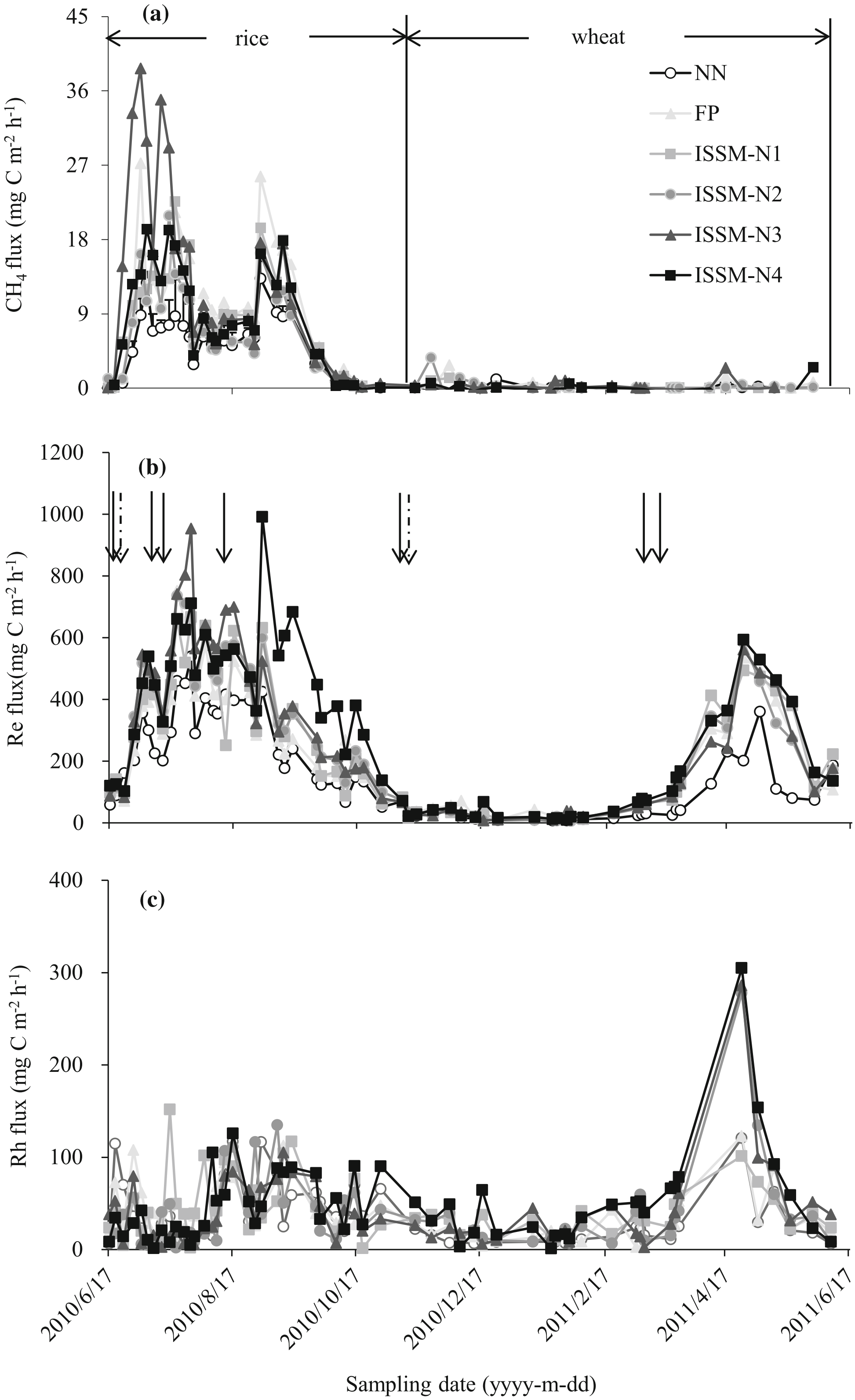
(a)
rice
wheat
NN
FP
ISSM-N1
ISSM-N2
ISSM-N3
ISSM-N4
CH4 flux (mg C m-2 h-1)
(b)
Re flux(mg C m-2 h-1)
(c)
Rh flux (mg C m-2 h-1)
2010/6/17
2010/8/17
2010/10/17
2010/12/17
2011/2/17
2011/4/17
2011/6/17
Sampling date (yyyy-m-dd)

Table 3 Net ecosystem carbon budget (NECB) and its main components for the annual cycle of rice–wheat rotation in 2010–2011 ($Mg\ C\ ha^{-1}\ year^{-1}$)

Code	NPP[c]	Rh	GPP	Re	Harvest	CH_4	NEP_1	NEP_2	$NECB_1^b$	$NECB_2$
NN[a]	8.26d[b]	3.12d	14.25d	9.90c	5.69d	0.16b	5.15d	4.35d	−0.70c	−1.50d
FP	15.78c	4.01c	27.20c	15.48b	10.73c	0.26ab	11.76c	11.72c	0.78ab	0.74bc
ISSM-N1	15.89c	4.29bc	27.39c	15.94c	10.84c	0.20b	11.60c	11.45c	0.56b	0.41cd
ISSM-N2	17.79b	4.65bc	30.67b	16.08b	12.13b	0.22b	13.14b	14.59ab	0.79ab	2.25abc
ISSM-N3	17.94b	4.85b	30.93b	16.51b	12.26b	0.37a	13.09b	14.42b	1.35ab	2.69ab
ISSM-N4	20.80a	5.59a	35.85a	19.14a	14.21a	0.28ab	15.20a	16.71a	1.64a	3.15a

[a] *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 $kg\ N\ ha^{-1}$ for the rice crop and 180 $kg\ N\ ha^{-1}$ for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

[b] Different lower case letters within the same column for each item indicate significant difference at $P < 0.05$ by the Tukey's multiple range test

[c] NECB = NEP – Harvest − CH_4 + M, *NECB* net ecosystem carbon budget, *NEP* net ecosystem production. $NEP_1 = NPP - Rh$, $NEP_2 = GPP - Re$, *NPP* net primary production, *Rh* heterotrophic respiration, *GPP* gross primary production, *Re* ecosystem respiration. NPP/GPP = 0.58

[d] $NPP = NPP_{grain} + NPP_{shoot} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposit}$

Over the cycle of rice–wheat rotation in 2010–2011, all treatments, except for the control, led to carbon gains of 0.56–1.64 $Mg\ C\ ha^{-1}\ year^{-1}$ with an average of 1.02 $Mg\ C\ ha^{-1}\ year^{-1}$ and 0.41–3.15 $Mg\ C\ ha^{-1}\ year^{-1}$ with an average of 1.85 $Mg\ C\ ha^{-1}\ year^{-1}$ for both approaches (Table 3).

Soil organic carbon measurements and soil organic carbon changes based on the net ecosystem carbon budget approaches

From 2009 to 2014 topsoil (0–20 cm) SOC increased from 22.43, 21.59, 21.81, 23.39 and 23.56 $g\ C\ kg^{-1}$ in 2009 to 23.14, 21.89, 22.25, 24.24 and 24.51 $g\ C\ kg^{-1}$ in 2014 for FP and ISSMs plots, respectively.

Compared with the unfertilized control, mineral fertilizer application significantly increased topsoil SOC (Table 4). Over the 5-year period of 2009–2014, topsoil SOC content of all the fertilizer treatments increased from 22.43, 21.59, 21.81, 23.39 and 23.56 $g\ C\ kg^{-1}$ in 2009 to 23.14, 21.89, 22.25, 24.24 and 224.51 $g\ C\ kg^{-1}$ in 2014 for the FP and four ISSM scenarios, respectively. Annual SOC sequestration rates varied from −0.22 to 0.42 $Mg\ C\ ha^{-1}\ year^{-1}$, −0.15 to 0.35 $Mg\ C\ ha^{-1}\ year^{-1}$, −0.32 to 0.67 $Mg\ C\ ha^{-1}\ year^{-1}$ for the field measurement and the two estimation approaches, respectively, for all treatments (Table 4). The NPP minus Rh approach (0.12–0.35 $Mg\ C\ ha^{-1}\ year^{-1}$) underestimated the SOC sequestration rate, while the GPP minus Re approach (0.09–0.67 $Mg\ C\ ha^{-1}\ year^{-1}$) overestimated the SOC sequestration rate slightly. However, a paired *t* test showed that no significant difference was detected between the two calculation approaches in SOC sequestration rate (Table 5).

Discussion

Effects of different approaches on the net ecosystem carbon budget estimation and soil organic carbon changes for different integrated soil–crop system management scenarios

Consistent with previous reports, the rice–wheat systems have experienced increases in topsoil organic carbon in fertilizer plots over the last decade (Table 4). Annual SOC increase rates averaged 0.13–0.42 $Mg\ C\ ha^{-1}\ year^{-1}$ excluding the untreated control. No significant differences between field measurement and the two estimation approaches were found in the SOC sequestration rates for any of the treatments (Table 5, $P > 0.05$). Compared with the measured values of the SOC sequestration rate, the NPP minus Rh approach (−0.15 to 0.35 $Mg\ C\ ha^{-1}\ year^{-1}$) underestimated the SOC sequestration rate whereas the GPP minus Re approach (−0.32 to 0.67 $Mg\ C\ ha^{-1}\ year^{-1}$) slightly overestimated it (Table 4).

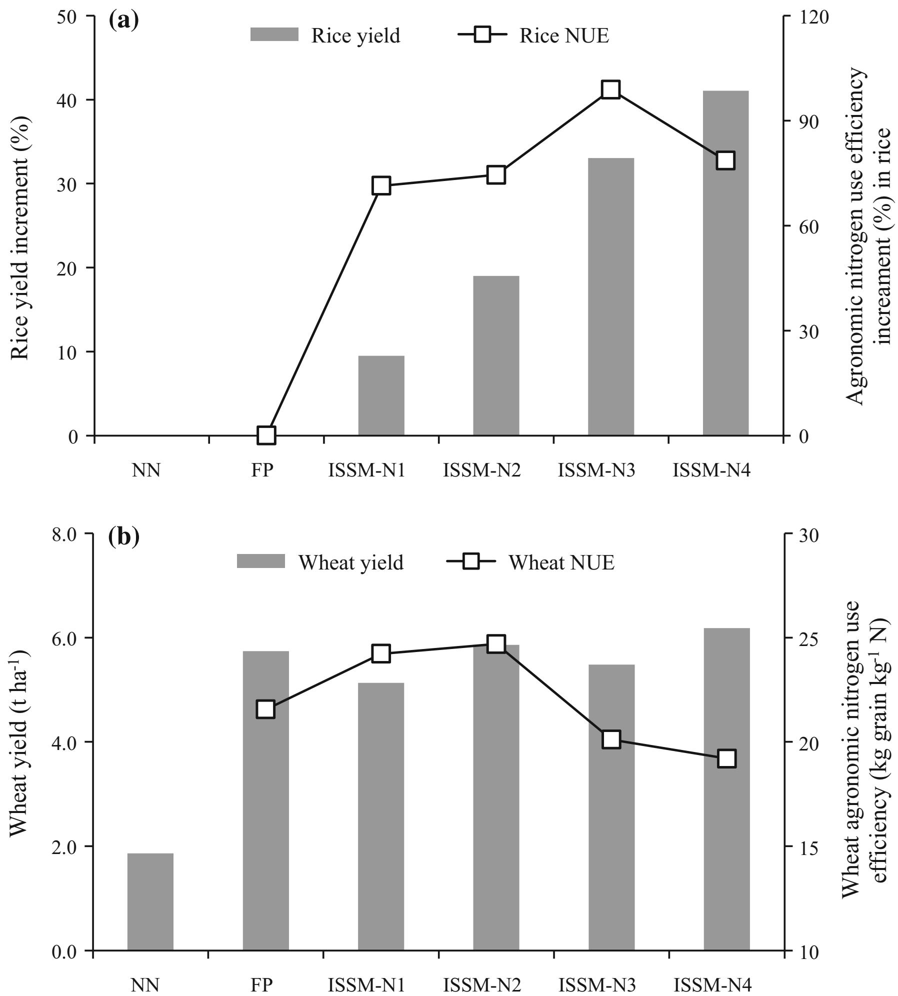

Fig. 3 **a** Rice grain yield and agronomic nitrogen use efficiency (NUE) increments and **b** wheat grain yield and agronomic NUE during the rice–wheat growing season in 2010–2011 in Changshu, China. *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

In an earlier survey data summary, Liao et al. (2009) reported an annual provincial mean SOC sequestration rate in Jiangsu of 0.16 ± 0.09 Mg C ha^{-1} from 1982 to 2004, where the dominant ecosystem was annual upland rice crop rotation. The estimated range for the topsoil mean SOC was 0.28–0.47 Mg C ha^{-1} $year^{-1}$ for all upland and paddy soils in eastern China (Sun et al. 2009) while annual SOC sequestration rates of 0.13–2.20 Mg C ha^{-1} $year^{-1}$ were estimated by Pan et al. (2004) for paddy soils in China. Thus, our estimation of SOC changes are well within the range of estimates of the regional or national mean SOC sequestration rates of paddy soils (Pan et al. 2004; Huang and Sun 2006; Xie et al. 2007; Liao et al. 2009; Sun et al. 2009).

Overall NECBs were significantly affected by management practices (Table 3, $P < 0.05$), but there were no obvious differences between the FP and the four ISSM scenarios. Following the approach of Smith et al. (2010), we estimated the net carbon budget of the rice–wheat rotation ecosystem through different channels. In this system, resulting from the two estimation approaches, all of the cultivation patterns were characterized by carbon accumulation in addition to the NN pattern. The NN pattern had slight carbon consumption, mainly due to the low crop yield and biomass with no chemical fertilizer or organic fertilizer applied (Table 2). Huang et al. (2010) found that long-term imbalance fertilization will reduce soil fertility, making crop yields and fertilizer use efficiency reduced.

Table 4 Changes in soil organic carbon (SOC) and estimated sequestration rate of SOC for different measurements

Code	SOC[b] (g C kg^{-1})		Average SOC sequestration rate(Mg C ha^{-1} $year^{-1}$)		
	2009	2014	$SOCSR_m^c$	$SOCSR_1^d$	$SOCSR_2$
NN[a]	21.52a	21.03c	−0.22c	−0.15c	−0.32d
FP	22.43a	23.14ab	0.32ab	0.17ab	0.16bc
ISSM-N1	21.59a	21.89bc	0.13b	0.12b	0.09cd
ISSM-N2	21.81a	22.25bc	0.19ab	0.17ab	0.48abc
ISSM-N3	23.39a	24.24a	0.38a	0.29ab	0.57ab
ISSM-N4	23.56a	24.51a	0.42a	0.35a	0.67a

[a] *NN* no N application, *FP* farmer's practice; The four integrated soil–crop system management (ISSM) practices at different nitrogen application rates relative to the FP rate of 300 kg N ha^{-1} for the rice crop and 180 kg N ha^{-1} for the wheat crop, namely, N1 (25 % reduction), N2 (10 % reduction), N3 (FP rate) and N4 (25 % increase)

[b] *SOC* soil organic carbon, *SOCSR* soil organic carbon sequestration rates

[c] $SOCSR_m$, measured values of SOC sequestration rate

[d] $SOCSR_1$, $SOCSR_2$, NECB derived SOC change equal to 0.213 × NECB (Xie et al. 2010)

Table 5 Correlation coefficients and *t* test comparisons among different values of soil organic carbon (SOC) sequestration rate for fertilizer treatments

Analyte	n[b]	Items	Ratio	Correlation coefficients	*t* Statistic for paired difference test	sig. (2-tailed)
SOCSR[a]	6	M/S_1^c	1.29	0.976	1.454	0.206
	6	M/S_2	0.74	0.888	−0.903	0.408
	6	S_1/S_2	0.58	0.951	−1.347	0.236

[a] *SOCSR* soil organic carbon sequestration rates

[b] *n* number of samples

[c] *M* measurement method, S_1, S_2 estimation methods

The adapted approaches in this study are applicable to trials requiring multiple field plots of a short-plant ecosystem on crop seasonal time scale. Thus, these approaches may provide a methodological alternative to estimate NECBs and SOC changes of fragmented terrains at high temporal and spatial resolutions.

Effects of different integrated soil–crop system management scenarios on the main components of net ecosystem carbon budget including biomass, ecosystem respiration, heterotrophic respiration or methane

In the cycle of rice–wheat rotation, the crop yields and other biomass were significantly affected by the management practices (Table 3, $P < 0.05$). The N4 (25 % increase), N3 (FP rate), N2 (10 % reduction) and N1 (25 % reduction) practices increased rice yields by 41.1, 33.0, 19.0 and 9.5 % compared to the FP practice. Grain yield was the dominant component of the NECB. The ISSM practices aiming for a higher grain yield also gained a higher NECB (Table 3), which supports the assumptions by Burney et al. (2010) and Smith et al. (2010). Wheat production was not significantly improved because the optimized ISSMs were designed and developed for the rice crop, not for the wheat crop.

Different cultivation patterns significantly affect the annual emissions of Re and Rh (Table 3, $P < 0.05$). Observations were obtained in 2010–2011, and the cumulative Re and Rh emission rate were recorded with the highest flux of 19.14 and 5.59 Mg C ha^{-1} $year^{-1}$ for the N4 plot and the lowest flux of 9.90 and 3.12 Mg C ha^{-1} $year^{-1}$ for the NN plot, respectively. In this study, higher respiration was mainly because of the higher biomass, which showed relatively good agreement with the results of Phillips and Podrebarac (2009). Many scholars confirmed that inorganic fertilizers can improve crop yields, biomass and SOC content, thereby increasing the amount of ecosystem respiration (Al-Kaisi and Yin 2005; Manna et al. 2007; Purakayastha et al. 2008; Gong et al. 2009; Ma et al. 2011). In the rice-growing season, emissions of Rh were lower, which may be due to the state of the soil in the flooded rice fields leading to heterotrophic respiration of CO_2 not being emitted into the atmosphere. The maximum Rh during the late wheat-growing season coincided with maximum Re, mainly due to suitable temperature and moisture conditions to stimulate microbial activity, which coincided the previous report that air temperature was found to regulate the CO_2 emissions from the non-waterlogged period over the entire rice–wheat rotation season (Zou et al. 2004).

For the whole cycle of rice–wheat annual rotation, seasonal changes of CH_4 emissions were mainly controlled by water management, which is consistent with the extremely anaerobic conditions that CH_4 generation requires (Conrad 2007). The water regime is known as one of the most important practices that affect CH_4 emissions in rice production. In contrast with continuous flooding, midseason drainage incurred a drop in CH_4 fluxes during the rice-growing season (Zou et al. 2005). Different levels of nitrogen fertilizer and organic fertilizer amendment did not affect the CH_4 emission mode. In the upland period, due to the lack of anaerobic conditions, CH_4 emissions did not occur. No obvious difference in the annual cumulative CH_4 emissions was found among all the treatments (Table 3, $P < 0.05$). There was no correlation between the CH_4 emissions and N rate (Table 3). Previous reports on the influence of synthetic fertilizer on the CH_4 emission rates from rice fields are inconsistent. Some studies suggested that the CH_4 emissions decreased with the application of inorganic fertilizer (Krüger and Frenzel 2003), but others suggested an increase or no change (Cai et al. 2007). In this study, compared to the FP treatment, the annual cumulative CH_4 emissions increased without a significant difference in the N3 and N4 plots, which is likely due to the organic material incorporation increasing the CH_4 emissions from the rice paddies (Tables 1, 2), and this is supported by previous reports (Adhya et al. 2000; Zou et al. 2005; Naser et al. 2007; Ma et al. 2009). Additionally, the seasonal CH_4 emission was enhanced by inorganic fertilizer, which could be explained by the fact that the rice plants served as a pathway for the CH_4 emissions and an additional substrate for methanogens (Yan et al. 2005; Linquist et al. 2012).

Conclusions

The two NECB approaches derived SOC changes agreed well with the field measured SOC changes. Thus, these two estimation approaches provide a methodological alternative to estimate SOC changes for a short-plant ecosystem on a crop-seasonal or annual time scale. Slightly carbon loss occurred during the rice–wheat rotation (−0.15, −0.32 and −0.22 Mg C ha^{-1} $year^{-1}$) for the no nitrogen application plot, but obvious carbon gains occurred (0.12–0.35, 0.09–0.67 and 0.13–0.42 Mg C ha^{-1} $year^{-1}$) for the local farmer's practices and integrated soil–crop system management scenarios from the two estimation approaches and field measurement, respectively. Compared to the SOC sequestration rate from the local farmer's practices, the integrated soil–crop system management scenarios with the same or 25 % more nitrogen increased the SOC sequestration rates to some extent, indicating that the proposed integrated soil–crop system management scenarios can simultaneously achieve improved food production and NUE with equivalent soil carbon gains.

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