Carbon benefits completely offset by nitrogen fertilization induced greenhouse gas emissions in Chinese main cropping systems

Bing Gao[1,2], Lilai, Xu[1,2], Wei, Huang[1,2], Xiaotang Ju[3]*, Shenghui Cui[1,2]*

[1] Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, PR China
[2] Xiamen Key Lab of Urban Metabolism, Xiamen 361021, PR China
*Corresponding author: Shenghui Cui
Institute of Urban Environment, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen 361021, P.R. China.
Phone: +86-592-6190957; Fax: +86-592-6190977.
E-mail: shcui@iue.ac.cn
[3] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
*Corresponding author: Xiaotang Ju and Shenghui Cui
College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China.
Phone: +86-10-62732006; Fax: +86-10-62731016.
E-mail: juxt@cau.edu.cn

Abstract

Cropland soil is recognized as a potential major contributor to mitigation global warming by using soil as a carbon sink to sequester carbon dioxide in recent years. Large amount of studies have reported that the soil organic carbon (SOC) content in Chinese cropland soil was increased. While the climate benefits of carbon sequestration in agricultural soils was offset by the N_2O emissions from greater use of fertilizer and CO_2-eq releases during the manufacture and distribution of the large amounts of applied fertilizer. In this study, we calculate the net GWP of the Chinese main cropping systems by reviewing the studies on soil GHG emissions, CO_2-eq emissions and SOC change, to see the integrate effect of cropping systems on GHG emissions. The results showed that the Chinese main cropping systems were large source of CO_2-eq, fall in a range of 2209 ± 2557 kg CO_2-eq ha^{-1} yr^{-1} for MNE to 23581 ± 16925 kg CO_2-eq ha^{-1} yr^{-1} for GV, following the rank of MNE < MNW < WM < SR < RR < RW < OV < DR < GV. N_2O emissions, CO_2-eq emissions from the manufacture and distribution of N fertilizer, power used for irrigation were the top three sources of CO_2-eq, they totally contribute to 86.6–93.6% of the TPCE in five dry croplands cropping systems. But four rice-based cropping systems, CH_4 emissions become one of the large contributors of TPCE except the top three sources of CO_2-eq in dry land cropping systems.

Keywords: intensive agriculture, cropping systems, soil organic carbon, GHG emissions, net GWP.

Introduction

Increasing emphasis has been put on promote soil C sequestration as an effective measure to mitigate the increase of atmospheric CO_2 concentrations (McCarl et al., 2007), and cropland soil is recognized as a potential major contributor to mitigation (Smith et al., 2008; Pan et al., 2010). Recent studies indicated that the soil organic carbon (SOC) content in Chinese cropland soil was increased. It means that the atmospheric CO_2 were shifted into SOC pools in Chinese agricultural soils, and it could play an important role in mitigating the rapidly increasing CO_2 emissions in China (Pan et al., 2010).

However, along with CO_2, methane (CH_4) and nitrous oxide (N_2O) emission from cropland soil are two critical GHG because of their high potent impact on global warming (Robertson et al., 2000; Reay et al., 2012; IPCC, 2014). In addition, manufacture and distribution of fertilizers and pesticides, irrigation and farm operations all required fossil fuel which combustion produces GHG emissions (Robertson and Grace, 2004; Snyder et al., 2009; Grassini and Cassman, 2012). The net exchange of these GHG as the form of CO_2-eq between cropland soils and atmosphere composes the net global warming potential (GWP) of the crop system (Robertson et al., 2000; Adviento-Borbe et al., 2007; Grassini and Cassman, 2012), which provides a measure of the cumulative radiative forcing of various GHG relative to CO_2 (Robertson and Grace, 2004).

Large numbers of studies were carried out widely over China, for research soil GHG emissions and (or) calculated the GWP in different cropping systems, in recent two decades. However, we found these studies are incomparable because the different calculation components and parameters for calculating the hidden CO_2 emissions in the calculation of GWP. This shortcoming limits our overall evaluation of GWP in the Chinese main crop systems and thus impairs effective decision regarding mitigation. The objectives of the present work were: (i) to analyze the changes in SOC in the Chinese main cropping systems under conventional farming practices; (ii) to estimate the net GWP of the Chinese main crop systems; (iii) to explicit the main controlling factors on net GWP in different crop systems, and give some effective management tactics for reducing net GWP of the main crop systems over China.

Materials and Method

Description of the Chinese main crop systems

Rice, wheat and maize are three main food crops in China. According to Chinese crop region, diversities of rice, wheat and maize cropping systems exist depending on the broadly change climatic regimes and regional climatic conditions in China. e.g. (i) the winter wheat and summer maize double-cropping system (WM) on the North and Southwest of China; (ii) the rice and winter wheat annual rotation system (RW) in the Central and East of China; (iii) the double rice cropping systems (DR) in the Central and South of China; (iv) the rice and rapeseed annual rotation system (RR) in the Central and Southwest China; (v) Single rice per year (SR) in the Central and Northeast China; (vi) single spring maize per year in the Northeast (MNE) and Northwest of China (MNW). The above cropping systems add up to 70% of the national crop sowing area and 96% of food production in 2010 (China Agriculture Yearbook, 2011). In addition, vegetables production including greenhouse vegetables (GV) and open field vegetables (OV), rapidly developed in the last three decades and it accounts for about 13% of the national crop sowing area in 2014 (NBSC, 2015).

Data sources

The data used for estimating net GWP of the main cropping systems including soil GHG emissions (N_2O and CH_4), the ‘hidden’ CO_2 from the manufacture and transportation of the chemical fertilizer (N, P_2O_5 and K_2O), power used for irrigation, fuel combustion in farm operations and the application of pesticides, and the changes in SOC (Robertson et al., 2000; Mosier et al., 2006; Grassini and Cassman, 2012). They were published in literatures, dissertations, books or research reports from 2000 to 2016. We collected the above data according to different crop systems and their distribution area except SR, GV and OV systems, due to their distribution and data sizes. The principle of literature collection and the methods for calculating the changes in SOC were omitted at here. The spatial distribution of the collected SOC change is shown in Fig. 1.

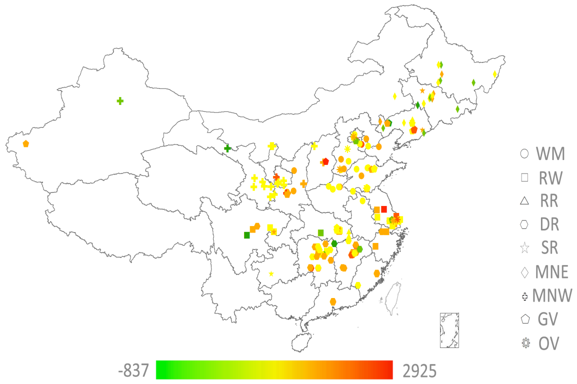

Fig. 1. Spatial distribution of the collected SOC change in the Chinese main cropping systems

Calculation of CO_2-eq from different sources or sinks

CO_2-eq emissions from N_2O and CH_4 emissions was estimated by multiplying their anniversary emission fluxes (kg N_2O or CH_4 ha^{-1} yr^{-1}) in different cropping systems with the GWP horizon factors of 298 and 25 in a 100-yr time scale, respectively (Forster et al., 2007). CO_2 emissions from the applied fertilizers were estimated by the application rate (kg $N/P_2O_5/K_2O$ ha^{-1} yr^{-1}) multiplying with the cost of CO_2 during the manufacture and distribution of them in China, 8.30 kg CO_2 kg^{-1} N (Zhang et al., 2013), 1.50 kg CO_2kg^{-1} P_2O_5 and 0.98 kg CO_2 kg^{-1} K_2O (Huang et al., 2011). The methods for calculate the CO2-eq from power for irrigation, pesticide application and fuel were omitted at here.

Annual topsoil (0-20 cm) organic carbon sequestration rate (δSOC, kg C ha^{-1} yr^{-1}) was estimated on the basis of topsoil SOC content increase rate (dSOC/dt, g C kg^{-1} yr^{-1}).

Net GWP estimates

To understand a complete accounting of the climatic impact of the Chinese main cropping systems in different regions, we calculated the combined GWP (net GWP) by the following equation (Mosier et al., 2006; Grassini and Cassman, 2012):

$$\text{Net GWP (kg } CO_2\text{-eq ha}^{-1}\text{ yr}^{-1}) = 298 \times N_2O + 25 \times CH_4 + 8.3 \times \text{N rate} + 1.50 \times P_2O_5 \text{ rate} + 0.98 \times K_2O \text{ rate} + 1.30 \times \text{electricity rate} + 3.93 \times \text{fuel rate} + 18.0 \times \text{pesticide} - \delta SOC/12 \times 44 \quad (1)$$

where 12 and 44 are the molecular weights of C in CO_2 and of CO_2.

Results

Overall variation of SOC in Chinese main cropping systems

The SOC of 9 cropping systems showed varying degrees of increase (Fig. 2), fall in a range of 16 ± 475 (MNE) to 948 ± 0 (SR, standard deviation is 0 because only 1 data for this system under method I), and 269 ± 353 (MNW) to 485 ± 254 (SR) kg C ha^{-1} yr^{-1} under method I and II, respectively. Under method III, the change of SOC in the entire Chinese croplands was 200 ± 138 kg C ha^{-1} yr^{-1}. By comparison the changes of SOC calculated by different methods, the standard deviation of method I larger than that of methods II and III except MNW and OV, caused by the SOC content is rather changeable when the monitoring duration < 5 years.

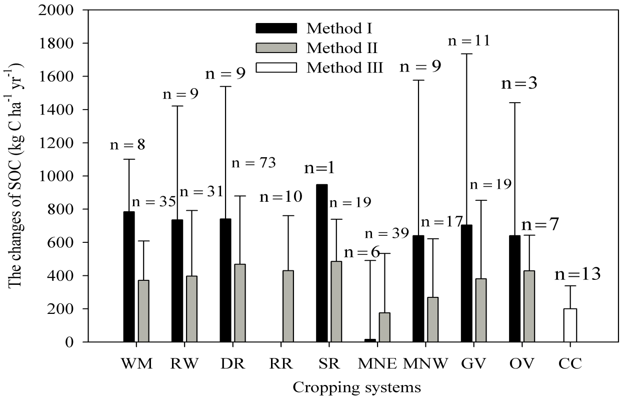

Fig. 2 The change of SOC in Chinese main cropping systems under different methods

Net GWP and its controlling factors in the main crop systems

The changes of SOC contents from method II were used for calculated the net GWP of the Chinese main cropping systems. 9 cropping systems showed net emissions of GHG from soils to atmosphere (Table 1), fall in a range of 2209 ± 2557 kg CO_2-eq ha^{-1} yr^{-1} for MNE to 23581 ± 16925 kg CO_2-eq ha^{-1} yr^{-1} for GV, following the rank of MNE < MNW < WM < SR < RR < RW < OV < DR < GV. In five dry croplands (WM, MNE, MNW, GV, OV), the application of fertilizer N, power for irrigation and N_2O emissions are the top three emission sources of CO_2-eq, they account for 34.6–60.6%, 14.4–27.0% (except MNE, no irrigation for maize) and 18.9–37.2% of the total positive CO_2-eq emissions (TPCE) from N_2O and CH_4 emissions, fertilizer input, power for irrigation, fuel in farm operations and pesticides applications, respectively. They totally contribute to 86.6–93.6% of the TPCE in five dry croplands cropping systems. But four rice-based cropping systems (RW, DR, RR, SR), CH_4 emissions become one of the large contributors (31.7–63.1%) of TPCE except CO_2-eq from N_2O emissions (4.2–19.4%), fertilizer N (11.9–23.6%) and irrigation (16.0–32.8%), these four emission sources explained 93.6–95.3% of the TPCE in RW, DR, RR and SR. CH_4 emissions in WM, MNE, MNW, GV, OV only contribute a small amount of net GWP, < 1%. CO_2-eq from the application of P_2O_5 and K_2O, fuel in farm operations, and pesticide application explained 1.5–3.7%, 2.1–8.5%, 0.8–1.8% of the TPCE in 9 cropping systems.

Table 1. Net GWP (kg CO_2-eq ha^{-1} yr^{-1}) of the Chinese main cropping systems under farmers' practices

Crop system	N_2O	CH_4	Fertilizer inputs		Irrigation	Fuel	Pesticides	SOC change	Net GWP*
			N	P_2O_5+K_2O					
WM	1666±779	-54±30	4094±1006	319±181	2218±675	425±147	134±48	-1360±873	7442±3739
RW	3044±1991	5417±3767	3740±817	452±167	2638±1386	371±150	172±80	-1456±1448	14378±9806
DR	797±625	11972±6780	2264±794	314±156	3040±1407	403±212	181±110	-1720±1507	17251±11591
RR	2601±1195	4259±2244	2750±1017	382±188	2962±793	292±279	188±18	-1578±1140	11856±6874
SR	899±779	4105±3296	1248±626	155±126	3299±2387	280±181	80±44	-1778±931	8288±8370
MNE	741±373	-17±15	1730±584	107±102	0±0	242±161	51±9	-645±1313	2209±2557
MNW	1480±1832	-84±77	2638±751	155±76	1414±1747	275±85	78±41	-986±1294	4970±5903
GV	7560±4376	-63±35	8640±4293	842±592	6740±5164	516±508	745±226	-1397±1731	23581±16925
OV	6364±4294	61±163	7169±4023	370±506	2455±1901	458	213±83	-1573±788	15517±11758

[*] Net GWP calculated by equation 1.

Discussion

SOC change is the net balance of soil carbon decomposition and new carbon input, and it also means the exchange of CO_2 between soil and atmosphere. Many scientists have proposed to sequestrate more atmospheric CO_2 into stable soil organic carbon pools by increasing SOC, to mitigate global climate change (Robertson et al., 2000; Lal, 2004; Robertson and Grace, 2004). In the past three decades, the top SOC (0-20 cm) content significantly increased in most of the agricultural soils over China except Chernozems in the Northeast China, the mean increase rate of SOC was maintained at 0.22% per year from the period of 1979-1982 to 2007-2008 (Yan et al., 2011), about 680 kg C ha^{-1} yr^{-1}. Total top SOC increased by 0.64 Pg C (1 Pg = 10^{15} g), with the mean rate at 0.30 Tg per year from 1985 to 2006, the mean annual stock increase may offset roughly 20% of the total CO_2 emissions of China for 1994 (Pan et al., 2010). In this study, we found the changes in SOC fall in a range of 16 ± 475 (MNE) to 948 ± 0, and 269 ± 353 (MNW) to 485 ± 254 (SR) kg C ha^{-1} yr^{-1} under method I and II, respectively. The total SOC increase with a rate of 0.29 Tg C per year in 9 cropping systems.

While the climate benefits of carbon sequestration in agricultural soils was offset by the N_2O emissions from greater use of fertilizer and CO_2-eq releases during the manufacture and distribution of the large amounts of applied fertilizer (Schlesinger, 2010). In addition, large amounts of CO_2-eq generated from power for irrigation, fuel in farm operations and pesticides application during the process of crop production (Mosier et al., 2006; Adviento-Borbe et al., 2007; Grassini and Cassman, 2012). Therefore, almost all crop systems showed positive net GWP when consider all sources and sinks of CO_2-eq from GHG emissions, SOC change and agricultural inputs and managements (Table 1).

There are many opportunities can be adopted for reducing net GWP by increasing SOC sink in low initial SOC content regions, reducing excessive N fertilizer inputs and irrigation rate, decreasing N_2O and CH4 emissions. We should pay more attention on reducing net GWP from open field vegetables and double rice cropping systems, and the largest challenge for the latter was decreasing emissions of CH4 after straw and manure application.

Conclusion

We found that the SOC increased in the Chinese main cropping systems under farmers' practice. It means the croplands soil of China sequestrated atmosphere CO_2 into soil C pool and plays a cooling effect. However, this effect was completely offset by the soil GHG emissions and the hidden CO_2 emissions from the manufacture and distribution of fertilizers, power for irrigation and fuel in farm operations and the application of pesticides. N_2O emissions, CO_2-eq emissions from the manufacture and distribution of N fertilizer, power used for irrigation were the top three sources of CO_2-eq, they totally contribute to 86.6–93.6% of the TPCE in five dry croplands cropping systems. But four rice-based cropping systems (RW, DR, RR, SR), CH_4 emissions become one of the large contributors of TPCE except the top three sources of CO_2-eq in dry land cropping systems. Thereby, reduce N_2O, CO_2-eq emissions from fertilizer N input and power for irrigation by optimizing N and water management and increase SOC contents by conservation tillage should be considered for mitigate GHG emissions in Chinese dry land cropping systems, and decrease CH_4 emissions should be considered more in rice-based cropping systems. CH_4 emissions in WM, MNE, MNW, GV, OV can be omitted in the calculation of net GWP because it only contribute a small amount of net GWP.

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