Comparison of carbon footprint and net ecosystem carbon budget under organic materials retention combined with reduced mineral fertilizer

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Research

Keywords: Astragalus sinicus L., rice straw, reduced mineral fertilizer, carbon footprint, greenhouse gas emission, net ecosystem carbon budget

Posted Date: August 28th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-51084/v1

Version of Record: A version of this preprint was published on March 1st, 2021. See the published version at https://doi.org/10.1186/s13021-021-00170-x.

Abstract

Background: Excessive application of chemical fertilizer has resulted in lower nitrogen uptake and utilization of crops, decreasing soil fertility, increasing greenhouse gas emissions and worse environment pollution and organic fertilizer materials retention is regard as the key to solve these problems. Whether the retention of *Astragalus sinicus* L. (Chinese milk vetch) and rice straw would induce lower greenhouse gas emissions and higher carbon sink remains unclear. The objective of this study is to conduct an assessment of carbon budget under *Astragalus sinicus* L. and rice straw retention combined with reduced mineral fertilizer based on the two years field experiment in a paddy field in southern China. Four treatments were designed: control CK (winter follow, 120 kg ha^{-1} N fertilizer for each rice season) and three treatments with *Astragalus sinicus* L. and rice straw retention named RA, RB and RC (reduced N fertilizer 15%, 27.5% and 40% in turn during each rice season).

Results: Treatments RA, RB and RC increased GHG emissions by 9.30%~101.25%, among which CH_4 accounted for more than 60%; Carbon input of crops from Treatments RA, RB and RC increased by 2.25%~12.10% compared with control CK over the two years. Though treatments RA, RB and RC enhanced CO_2 emission, however, treatment RB decreased carbon footprint and became C sink.

Conclusions: The results of this study reveal that treatment RB is better in reducing chemical fertilizer amount, increasing crop yield and C balance, which is more conductive to sustainable development of agriculture.

Background

Carbon (C) footprint refers to the total carbon dioxide (CO_2) emissions generated directly or indirectly by an activity or product throughout its life cycle and expressed in CO_2 equivalent (CO_2-eq)[1]. Greenhouse gas (GHG) emissions come from agriculture accounts for 20%~30% in the globe[2]. The C footprint in agriculture can systematically evaluate the indirect C emissions (diesel, electricity, fertilizer, pesticide and agricultural film) from agricultural inputs and the total amount of direct C emissions[3]. The C budget and balance includes C input (mostly coming form crop C sequestration and C output (direct and indirect GHG emissions) in agriculture ecosystem.

Rice is one of the important crops in the world while paddy field is also an important agriculture GHG emission source[4]. Rice planting area in China occupies approximately 19% in the world [5]. With the increase of population in the future, the demand for rice will inevitably increase, which will consume more energy, chemical fertilizers and pesticides, contributing directly and indirectly to GHG emissions from farmland. The global CO_2 released by soil (680 pg) is 1.31 times of that released by fuel combustion (520 pg) every year [4]. Methane (CH_4) and nitrous oxide (N_2O) emission from paddy fields in China accounts for 17.9% and 80% of the total emissions and their concentrations are also increasing at the speed of 0.03 and 0.75 ppb/a in recent years [6,7,8].

Meanwhile, farmland ecosystem is an also important system for C sequestration and GHG reduction. Increasing studies indicate that straw retention can sequestrate C and reduce GHG emission through directly inputting soil organic carbon (SOC) and C storage [9,10]. China is abundant with crop straw resources, with an average annual production of 7.6 to 8.2 million tons [11], accounting for about 25% in the world [12]and the rice straw in the south of China accounts for about 50% ~ 60% [13].

Winter green manure and double-rice rotation is the traditional planting patterns in the South of China. *Astragalus sinicus* L. and rice straw contain a lot of nutrients and their reasonable application can not only replace part of chemical fertilizer, solving the adverse problems caused by excessive application of chemical fertilizer [14], but also can avoid the resources waste and environmental pollution resulted from straw burning [15] as well as increase SOC [16,17]. However, increased CH_4 emission in paddy field after straw retention may offset GHG emission reduction effect of soil C sequestration [18,19], which can not be ignored as an important GHG leakage. To clarify whether the reduced mineral fertilizer under *Astragalus sinicus* L. and rice straw retention can lower GHG emissions and enhance C sink, it is necessary to conduct an analysis to reveal whether there are trade-offs between these two indicators by using C footprint and net ecosystem carbon budget (NECB).

At present, most studies mainly focus on the effect of different tillage system and different rotation patterns on C footprint [20,21,22] or use the available data to calculate C footprint [23,24], However, little is known on comprehensive effects of reduced mineral fertilizer under organic materials retention on footprint and NECB. To provide theoretical basis for C sequestration and emission reduction of paddy field and sustainable development of agriculture, we conducted the two-year field experiment to test the following hypotheses: (1) whether straw retention can increase crops C input? (2) whether C input can offset the increased GHG emissions after straw retention ?

Materials And Methods

Experiment site characteristics

The field experiment was conducted at Yujiang County, Yingtan City from 2017 to 2019. This place belongs to subtropical monsoon humid climate with mean annual temperature and precipitation of 17.6°C and 1741 mm, respectively. Most of the soils are silt-deposited soils and a few are red loam soils. Before the experiment, the organic matter content and total nitrogen (N) content in surface soil (0-15 cm) were 34.7 g kg^{-1} and 1.9 g kg^{-1}.

Experiment design and management

Four treatments with triplicates were designed (Table 1): CK (winter fallow, without organic materials retention and 120 kg ha^{-1} N fertilizer was applied for each rice season), and three treatments with *Astragalus sinicus* L. and rice straw retention combined with reduced mineral fertilizer named RA (-15% N fertilizer for each rice season), RB (-27.5% N fertilizer for each rice season), and RC (-40% N fertilizer for each rice season). Each plot area is 25 m^2 (5m×5m), around which there are protection lines to prevent water and fertilizer cross-contamination.

According to conventional dosages, pure phosphorus and potassium was 20 kg ha^{-1} and 60 kg ha^{-1} respectively. 60%, 30% and 10% N fertilizer (N 46%) was used as basic, tiller and panicle fertilizer respectively. Phosphate fertilizer ($P_2O_5$12%) was used as basic fertilizer and applied once. 70% and 30% potassium fertilizer (K_2O 60%) was applied as tiller and panicle fertilizer. The N and P basic fertilizers were applied 1 day before rice transplanting, the tiller fertilizer was applied 5-7 days after rice transplanting and the panicle fertilizer was applied when the main stem was 1-2 cm long.

Experiment materials

The species of *Astragalus sinicus* L. was Yujiang Daye. Seeds of 37.5 kg ha^{-1} were sewn on 3 October in 2017 and 7 October in 2018, and they were weighted, mixed, calculated the average value (retention amount of Astragalus sinicus L. was the same for each plot except control CK) and plowed into the field at the blooming stage in the middle of April of next year. The early rice was "Yueru No. 6", which was transplanted on 26 April 2018 and 25 April 2019 and harvested on 12 July 2018 and 11 July 2019; the late rice was "Huarun No. 2" that was transplanted on 18 July 2018 and 15 July 2019 and harvested on 2 November 2018 and 16 November 2019. After the early rice harvest, the straw was cut into 3-5 cm sections with a guillotine, and then plowed into the field. After the late rice harvest, the straw was left and covered with the field. The residue height of rice was 2-3 cm.

Measurement of items and methods

Collection and measurement of GHG

GHG were collected by using static chamber with the size of 50 cm×50 cm×50 cm. When the rice plant exceeded 50 cm, the other chamber with the same size and two-way opening was added. There is one fixed sampling base with a groove of 5 cm depth filled with water when measuring at per plot. Samples were collected once per 7-8 days and 15 days from 8:00 to 11:00 during rice [25] and *Astragalus sinicus* L. growth period, respectively. A 50 ml syringe was used to extract the gas at 0, 10, 20 and 30 min and the syringe was pulsed back and forth 5-10 times to evenly mix the gas. After the gas was extracted and stored in vacuum bags, gas samples were quickly taken back and analyzed by using Agilent 7890A gas chromatography.

Calculation of GHG

The gas emission flux is calculated according the equation: $F=\rho\times h\times dc/dt\times 273/(273+T)$

Where F is the gas emission flux, ρ is the gas density under standard conditions (kg/m^3), h is the net height (m) of sampling box, dc/dt is the change rate of gas concentration in the sampling tank per unit time, T is the average temperature (°C) in the sampling tank during sampling process, and 273 is the constant of the gas equation.

The cumulative emissions of CH_4 and N_2O from paddy fields were calculated as follows:

$$Tn=\sum_{i=1}^{n} F_i * D_i$$

Where Tn is cumulative annual emission, Fi is the average daily emission flux of CH_4 and N_2O between two sampling periods; Di is the number of days between two sampling intervals.

C footprint calculation

According to PAS 2050[26], C footprint of agricultural production is calculated as the sum of all direct and indirect GHG emissions during one crop production in a certain cropping system (kg CO_2-eq ha^{-1}) based on life cycle assessment. Therefore, in this study, C footprint of Astragalus sinicus L. and rice production includes indirect and direct GHG emissions from the initial agricultural materials inputs (fertilizers, pesticides, machinery, electric irrigation) to the end products (Astragalus sinicus L. and rice). GHG emissions from agricultural materials inputs are estimated using the following formula:

$$CE_{input} = \sum(A_i \times \delta_i)$$

In the formula, CF_{input} refers to the total GHG emissions (kg CO_2 -eq /ha^{-1}) of agricultural input, *i* refers to a certain agricultural input, Ai is the intensity or quantity of the *i*th individual agricultural input (pesticide /fertilizer, kg·ha^{-1}; electricity, kwh·ha^{-1}; Diesel, L·ha^{-1}), and δ_i is the coefficient factors of the *i*th individual agricultural input. The GHG emission factors of agricultural inputs are shown in Table 2.

$$CF =(CE_{input} + EN_2O + ECH_4)/Y$$

In the formula, CF refers to C footprint, and ECH_4 and EN_2O refers to CH_4 and N_2O cumulative emissions are converted to CO_2-eq from soils during Astragalus sinicus L. and rice growth season. Y refers to the amount of Astragalus sinicus L. stalk and rice yield kg·ha^{-1}.

Total C input and NECB

Total C input based on C sequestration in biomass was estimated using the following equation [27]:

$$E_{input}=B_{total} (B_{grain} +B_{straw} + B_{root} + B_{litter} +B_{rhizodeposites}) \times f_c \times (44/12)$$

Crop yield and straw were weighed on site, root biomass, litter and rhizodeposites are calculated according to Salam et al[28] and Huang et al[29], fc is the C percentage in grain (40% for rice) [30].

NECB=E_{input}-E_{output} (CO_2 equivalent of CH_4 and N_2O cumulative emission plus CO_2 emissions from plant respiration and soil microbial respiration).

Data analysis

The test data were analyzed and processed by Microsoft Excel 2010 and SPASS 17.0 software, and the mapping was done by origin 9.0 software, Single factor ANOVA test is used in the data statistical model and LSD method was used to test the difference significance

Results And Discussion

GHG emissions

The GHG emissions from all the treatments includes indirect emission of agricultural inputs (Table 2) and direct CH_4 and N_2O emission (Table 3), among which the former accounts for more than 17% and the latter occupies more than 60%. The GHG emissions from all the treatments ranged from 9731 to 19584 kg $CO_{2\text{-eq}}$ ha^{-1} and treatments RA, RB and RC with organic materials retention combined with different reduced mineral fertilizer increased by 9.30%~101.25% compared with that of control CK over the two years. The difference of GHG emissions between treatments RA, RC and control CK was significant (P<0.05), while the difference between control CK and treatment RB was insignificant (Table 3). This phenomenon maybe caused by the fact that GHG emissions are affected by many factors, such as temperature, precipitation, field management measures, C/N ratio of organic materials, turnover depth and decomposition rate of straw, SOC, some physical and chemical characteristics and some factors vary from year to year. From Table 5 we can see that straw retention as well as fertilizer and year had significant effect or interactive effect on GHG emissions.

C footprint components of all the treatments

The C emission per unit area of all the treatments was 9731 to 19584 kg $CO_{2\text{-eq}}$ ha^{-1} and the C footprint per unit production was 0.52~1.01 kg $CO_{2\text{-eq}}/kg^{-1}$. The C footprint of all the treatments are mainly from C output of soil CH_4, N fertilizer and electricity consumption for irrigation (Table 2), accounting for 60.25%~81.88%, 6.64%~15.73% and 5.35%~10.77%, respectively (Fig. 2). Compared with C footprint of control CK, treatments RA and RC increased by 60.32% and 34.92%, while treatment RB decreased by 17.46%, which maybe attributed to the less N fertilizer application amount, lower C output of CH_4 and N_2O as well as higher yield of treatments RB (table 3). Our result was consistent with previous studies which reported soil CH_4 was dominate source of C footprint in paddy field [31,32]. Compared with control CK, treatments RA, RB and RC enhanced CH_4 emission mainly resulting from the following reasons: (1) The continuous flood irrigation provided a favorable anaerobic environment for the growth and reproduction of methanogenic bacteria[33,34,35]; (2) Mulching and retention of rice straw and *Astragalus sinicus* L. can maintain soil moisture, provide organic matter for soil and reduce soil redox potential, thus making CH_4 emission increase [36,37]; (3) Organic materials retention supplied methanogenic bacteria with adequate substrates[38,39,40], while the decomposition of straw consumed oxygen, enhanced soil anaerobic environment and inhibited the activity of methane oxidizing bacteria, thus promoting CH_4 emission[41]; (4) The application of mineral fertilizer and the decomposition of organic materials accelerated the rice and its root growth, thus making the secretion and abscission of rice root increase and providing a substrate for related microorganisms, resulting in the rapid increase of CH_4 emission[42]. Fertilizer and site years had significant interactive effect on C footprint (Table 5).

NECB

The NECB can be used to assess the short-term net C budget balance via C input and output in an aggro-ecosystem[43]. For *Astragalus sinicus* L. and double rice cropping system with retention of *Astragalus sinicus* L. and rice straw combined with different amount of reduced mineral fertilizer, C input of crops varied from 31.98 Mg CO_2-eq ha^{-1} to 35.85 Mg CO_2-eq ha^{-1} and C output ranged from 26.59 Mg CO_2-eq ha^{-1} to 40.79 Mg CO_2-eq ha^{-1}. Control CK and treatment RB became C sink compared with treatments RA and RC, because control CK was winter fallow and its C output was the least and treatments RB had the most crop biomass and C input (Table 4). Straw retention had significant effect on crop biomass and C input. The effect of Year as well as fertilizer*year on NECB was significant (Table 5).

CO_2 emission contributed to the largest proportion for C output. CO_2 emission was significantly affected by straw retention (Table 5). CO_2 emission from treatments RA, RB and RC was higher than that of control CK (Table 4), which might result from the accumulation of soil total organic carbon, microbial biomass carbon, soluble organic carbon caused by *Astragalus sinicus* L. and straw retention and the abundance of bacteria participating in C cycle, and promoted soil CO_2 emission[44,45,46]. The application of mineral fertilizer and the decomposition of straw increased soil organic matter, which also promoted the growth and reproduction of soil microorganisms and enhanced soil respiration[47,48]. With the growth of *Astragalus sinicus* L. and rice plants, crop root secretion and abscission increased, the micro biological activity and rice respiration strengthened, thus increasing CO_2 emission[49,50]as well as straw carbon decomposition also stimulated the mineralization of soil organic carbon to produce CO_2 [51](Li et al. 2016).

Conclusion

The GHG emissions of treatments RA, RB and RC increased by 9.30%~101.25% over the two years compared with that of control CK mainly resulting from increased soil CH_4 emission, which occupied more than 60%. Meanwhile the treatments RA, RB and RC increased the yield (*Astragalus sinicus* L. straw, rice straw and yield) by 28.08%~34.99% compared with that of control CK. Treatment RB decreased C footprint mainly attributed to reduced N fertilizer and higher yield compare with control CK. Treatment RB became C sink, because increased C input outweighing the increased C output. These results suggest that treatment RB is better in reducing chemical fertilizer amount, increasing crop yield and C balance, which is more conductive to sustainable development of agriculture.

Abbreviations

C: Carbon; **N:** Nitrogen; **CO_2:** Carbon dioxide; **GHG:** Greenhouse gas; **CH_4:** Methane; **N_2O:** Nitrous oxide; **SOC:** Soil organic carbon; **NECB:** Net ecosystem carbon budget

Declarations

Acknowledgement: We would like to thank Yang Wenting, Yang Binjuan and Zhou Quan for their help in our research group.

Authors' contributions

L Y conducted the field experiment and wrote the manuscript, T H Y and Z C analyzed the data, P S reviewed and edited the manuscript and H G Q applied for financial support for the project.

Funding

This research was financially supported by the National Natural Science Foundation of China, grant number: 41661070, and the National Key R&D Program, grant numbers: 2016YFD0300208.

Data sharing and and Data Accessibility

The data that supports the findings of this study are available in the supplementary material of this article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

None declared.

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Tables

Table 1 Field experimental design

treatments	Chinese milk vetch retention amount （kg ha^{-1}）	Rice straw retention amount （kg ha^{-1}）	N application of each rice season（kg ha^{-1}）
CK	0	0	120
RA	full	6000	-15%
RB	full	6000	-27.5%
RC	full	6000	-40%

Table 2 GHG emission factors and application rate of agricultural inputs

T	Gas emission source	Emission coefficient	Agricultural materials			
			Unit	Application rate		
				Chinese milk vetch	Early rice	Late rice
CK	N fertilizer	6.38	Kg/ha^{-1}	0	120	120
RA	N fertilizer	6.38	Kg/ha^{-1}	0	102	102
RB	N fertilizer	6.38	Kg/ha^{-1}	15	87	87
RC	N fertilizer	6.38	Kg/ha^{-1}	30	72	72
Same for all the treatments	P fertilizer	0.44	Kg/ha^{-1}	0	20	20
Same for all the treatments	K fertilizer	0.61	Kg/ha^{-1}	0	60	60
Same for all the treatments	Diesel for machinery	2.63	Kg/ha^{-1}	41	70	70
Same for all the treatments	Pesticide	14.0	Kg/ha^{-1}	7	13	13
Same for all the treatments	Electricity for irrigation	1.12	Kg/ha^{-1}	0	468	468

Note: T represents treatment; the data were obtained from the average value of agricultural input in this study.

Table 3 average annual GHG emissions and C footprint during crop growth seasons over the two years (kg $CO_{2\text{-eq}}$ ha^{-1})

T	Indirect input						Direct input		Average GHG emissions	Yield (kg.ha^{-1})	Carbon footprint (kg CO_2-eq /kg^{-1})
	N	P	K	Diesel	Electricity	Pesticides	CH_4	N_2O			
CK	1531	18	73	476	1048	462	5863c	260	9731c	15209b	0.63c
RA	1301	18	73	476	1048	462	16037a	169	19584a	19479a	1.01a
RB	1206	18	73	476	1048	462	7164c	189	10636c	20530a	0.52c
RC	1110	18	73	476	1048	462	13577b	261	17025b	20124a	0.85b

Note: T represents *treatment*; Y represents Chinese milk vetch straw and rice biomass (rice straw and yield).

Table 4 Assessment of C budget and balance in different treatments（Mg CO_2 ha^{-1}）

Items	CK		RA		RB		RC	
	C Input	C Output	C Input	C Output	C Input	C Output	C Input	C Output
	31.98						32.70	
›ut of Chinese milk vetch and rice			35.37		35.85			
						10.64		
GHG (direct and indirect)		9.73		19.58				17.03
CO_2 Cumulative emissions		16.86		21.21		21.64		19.78
Total	31.98	26.59	35.37	40.79	35.85	32.29	32.70	36.80
NECB	5.39		-5.42		3.56		-4.1	

Table 5 Interactions of straw retention, fertilizer and year on mean GHG, CO_2, C input, C footprint, crop biomass and NECB during the crop growing season. F-values are provided for interactions.

	GHG	CO_2	C input	C footprint	Crop biomass	NECB
Straw retention [a]						
-SR	9731.44	16860.67	31981.66	0.6450	15208.83	5.39
+SR	15748.89**	20879.21	34641.17*	0.7922	20044.44***	-1.99
Year [b]						
2018	14235.30	26169.29	32901.9658	0.7808	18278.67	-7.50
2019	14253.75	13579.86 ***	35050.6183	0.7300	19392.42	7.22***
F-values						
Fertilizer *Year	51.458 ***	49.338***	0.924	6.271**	1.000	6.689**

There were significant interactions (Fertilizer×Yield) for the six variables. * ($0.01 < P \leq 0.05$), ** ($0.001 < P \leq 0.01$), or *** ($P \leq 0.001$) are used to represent significant effects among the treatments. [a,b] Values were averaged across different treatments, crop, and years.

-SR represents straw (*Astragalus sinicus* L. and rice) retention

+SR represents no straw (*Astragalus sinicus* L. and rice) retention

Figures

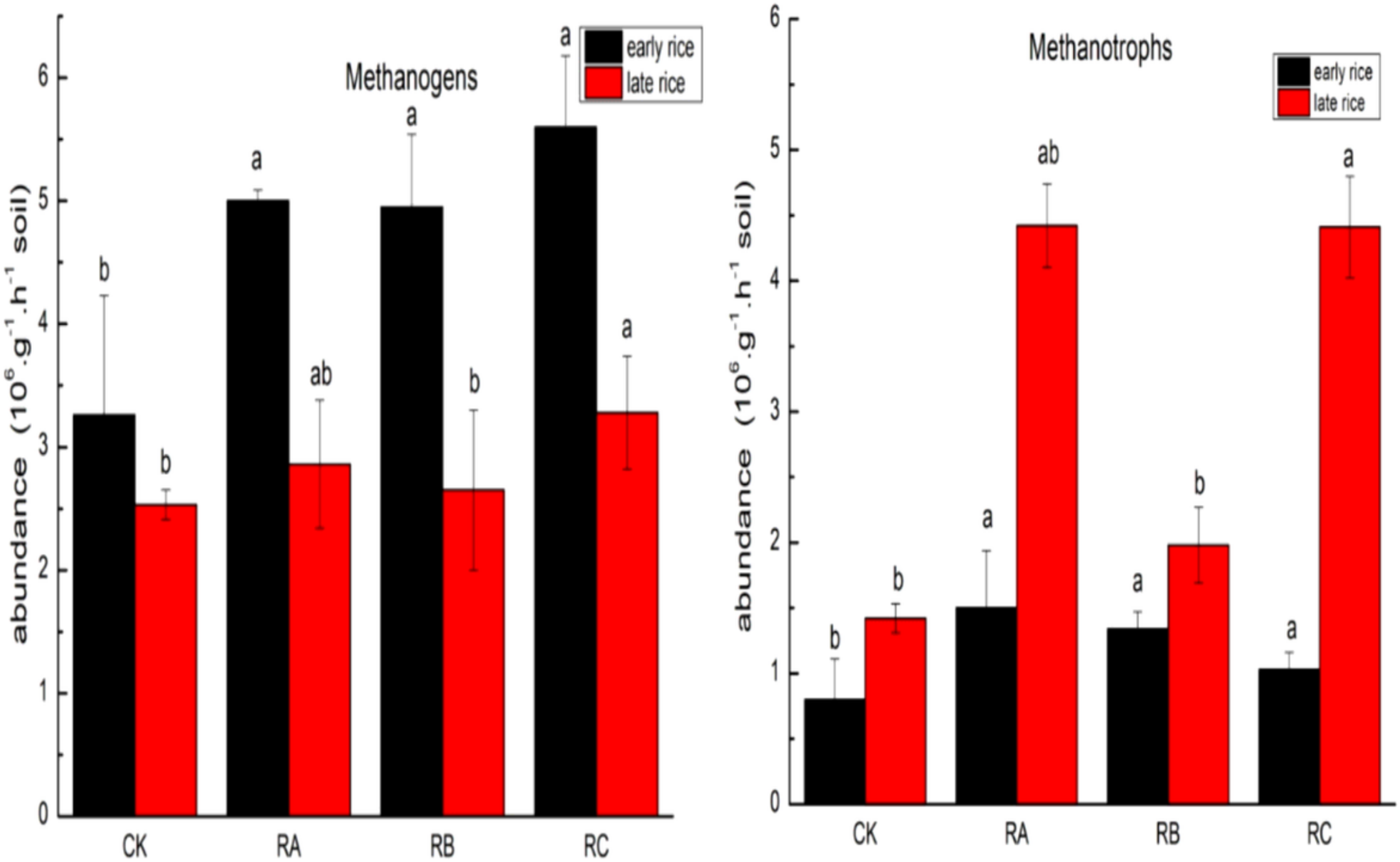

Figure 1

Abundances of methanogens and methanotrophs during the 2018 rice season in response to incorporation of Chinese milk vetch and rice straw combined with reduced chemical fertilizer. Different lowercase letters in the same column indicate significant differences among the treatments at P≤0.05.

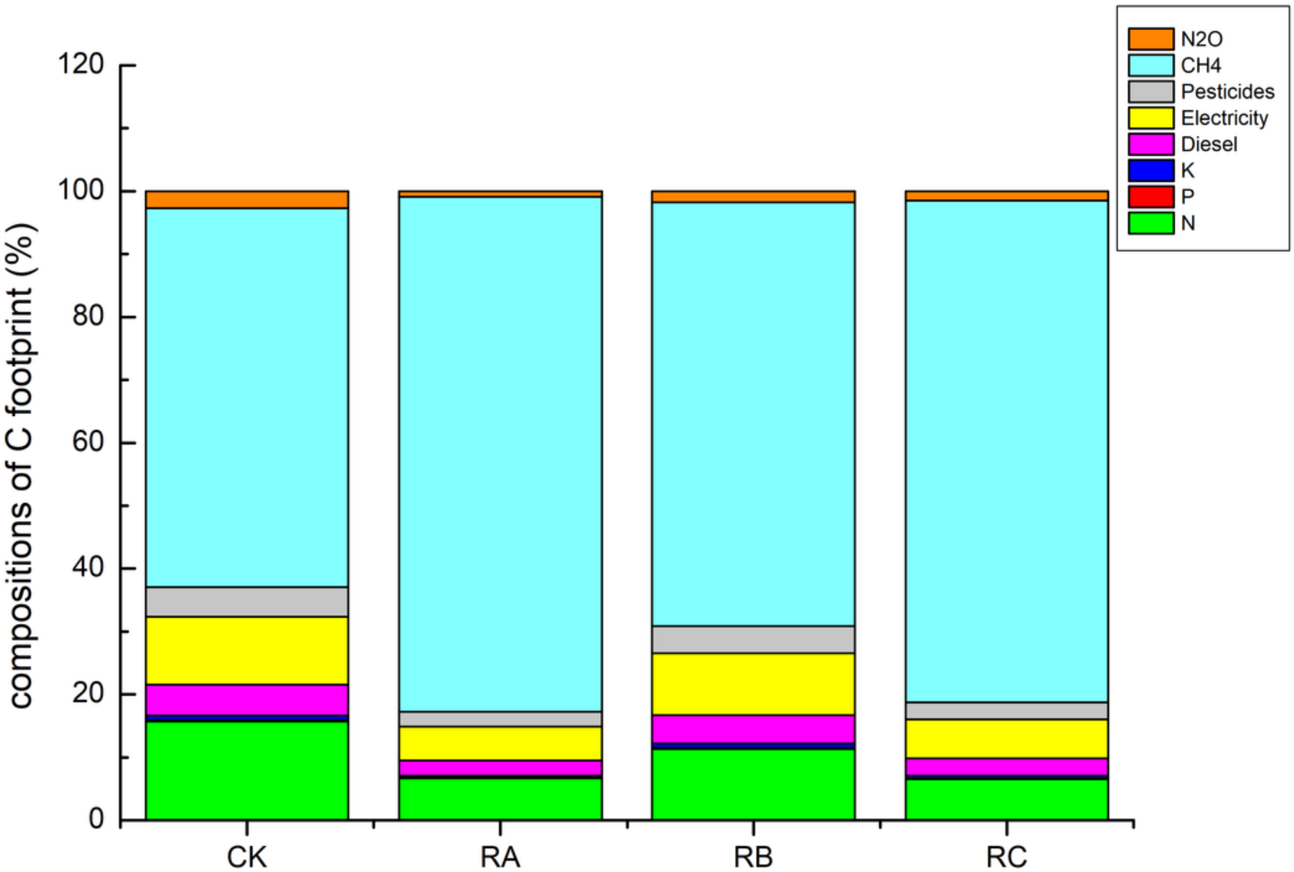

Figure 2

average annual compositions of C footprint during crop growth season over the two years

Supplementary Files

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- supplementarymaterials.xlsx