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

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Research

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Abstract

**Background:** Excessive application of chemical fertilizer has resulted in lower nitrogen uptake and utilization efficiency of crops, decreasing soil fertility, increasing greenhouse gas emissions, and worse environment pollution. Organic material retention is regarded as the key to solve these problems. 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-year field experiment in a paddy field in the south of China. The experiment was randomized complete block design including four treatments with triplicates: 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 by 15%, 27.5%, and 40% in each rice season).

**Results:** Treatments RA, RB, and RC increased greenhouse gases emissions by 9.30%~101.25%, among which CH₄ 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 CO₂ emissions, however, treatment RB decreased carbon footprint and became carbon sink.

**Conclusions:** The results of this study reveal that treatment RB (*Astragalus sinicus* L. and rice straw retention with reduced N fertilizer by 27.5%) is better in reducing chemical fertilizer amount, increasing crop yield and carbon input, which is more conducive to sustainable development of agriculture.

**Background**

Carbon (C) footprint refers to the total carbon dioxide (CO₂) emissions generated directly or indirectly by an activity or product throughout its life cycle and expressed in CO₂ equivalent (CO₂-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 from 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 emissions 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. CO₂ is considered to be the major greenhouse gas because of the highest concentration in the atmosphere and the longest duration of its existence. CO₂ contributes 60% to global warming[6]. According to the fifth report of IPCC, the atmospheric concentrations of CO₂ had reached 391*10⁶ (V/V) by 2011, which were 40% higher than that before the Industrial Revolution[7]. The global CO₂ released by soil (680 pg) is 1.31 times of that released by fuel combustion (520 pg) every year [4]. Methane (CH₄) and nitrous oxide (N₂O) emissions 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 [8,9,10].

Meanwhile, farmland ecosystem is also an important system for C sequestration and GHG reduction. Increasing studies indicate that straw retention can sequestrate C and reduce GHG emissions through directly inputting soil organic carbon (SOC) and increasing C storage [11,12]. China is abundant with crop straw resources, with an average annual production of 7.6 to 8.2 million tons [13], accounting for about 25% in the world [14] and the rice straw in the south of China accounts for about 50% ~ 60% [15].

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[16], but also avoid the waste of resources and environmental pollution resulted from straw burning [17] as well as increase SOC content[11,12]. However, increased CH₄ emissions in paddy field after straw retention may offset GHG emissions 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 systems and different rotation patterns on C footprint ([20], [21],[22]) or use the available data to calculate C footprint or use remote sensing and numeric modeling to investigate the water-carbon interactions or simulate C sequestration([23],[24],[25],[26],[27]). However, little is known on comprehensive effects of reduced mineral fertilizer under organic material retention on C footprint and NECB. To provide theoretical basis for C sequestration and emissions reduction of paddy field and sustainable development of agriculture, we conducted the two-year field experiment to test the following hypotheses: (1) whether organic material retention combined with reduced mineral fertilizer can increase crop C input? (2) whether C input can offset the increased GHG emissions? (3) Whether fertilizer and year had interactive effect on C footprint and NECB?

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 pH, organic matter content, total nitrogen (N) content, total phosphorus, and total potassium in surface soil (0-15 cm) were 5.12, 34.7 g kg\(^{-1}\), 1.9 g kg\(^{-1}\), 0.66 mg kg\(^{-1}\), and 15.33 mg kg\(^{-1}\).

Experiment design and management

The experiment adopted split plot design. The main zone includes two kinds of rice straw retention amount (0 and 6000 kg ha\(^{-1}\)). The secondary zone includes reduced chemical fertilizer at 3 different rates compared with control CK. They combine in pairs, and there are four treatments with triplicates (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.

The 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. Phosphorus fertilizer (P\(_2\)O\(_5\) 12%) was used as basic fertilizer and applied once. 70% and 30% potassium fertilizer (K\(_2\)O 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 sown 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 ([28]) 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 emissions flux is calculated according the equation:

\[ F = \rho \times h \times \frac{dc}{dt} \times 273 \times \frac{273 + T}{T} \]  

(1)

Where \( F \) is the gas emissions flux, \( \rho \) is the gas density under standard conditions (kg m\(^{-3}\)), \( h \) is the net height (m) of sampling box, \( \frac{dc}{dt} \) 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\(_2\)O from paddy fields were calculated as follows:

\[ T_n = \sum_{i=1}^{n} F_i \times D_i \]  

(2)

Where \( T_n \) is cumulative annual emissions, \( F_i \) is the average daily emissions flux of CH\(_4\) and N\(_2\)O between two sampling periods; \( D_i \) is the number of days between two sampling intervals.

**C footprint calculation**

According to PAS 2050[29], 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 and expressed in CO\(_2\) equivalent (CO\(_2\)-eq). Therefore, in this study, C footprint of *Astragalus sinicus* L. and rice production includes indirect and direct GHG emissions, of which the former are from agricultural inputs (fertilizers, pesticides, machinery, electric irrigation) while the later are from CH\(_4\) and N\(_2\)O emission in the paddy field. GHG emissions from agricultural inputs are estimated using the following formula:

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

(3)

In the formula, \( CE_{input} \) refers to the total GHG emissions (kg CO\(_2\)-eq ha\(^{-1}\)) from agricultural inputs, \( i \) refers to a certain agricultural input, \( A_i \) 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 \( \delta_i \) is the coefficient factors of the \( i \)th individual agricultural input. The GHG emissions factors from agricultural inputs are shown in Table 2.

\[ CF = (CE_{input} + EN_2O + ECH_4) / Y \]  

(4)

In the formula, \( CF \) refers to C footprint, and \( ECH_4 \) and \( EN_2O \) refers to CH\(_4\) and N\(_2\)O 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. 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 [30]: \( E_{input} = B_{total} \ (B_{grain} + B_{straw} + B_{root} + B_{litter} + B_{rhizodeposites}) \times f_c \times (44/12) \)  

(5)

Crop yield and straw were weighed on site, root biomass, litter and rhizodeposites are calculated according to Salam et al[31] and Huang et al[32]. \( f_c \) is the C percentage in grain (40% for rice) [33].

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

(6)


**Data analysis**

A statistical analysis was performed using Microsoft Excel 2010 and SPASS 17.0 software. Origin 9.0 software was used to create a diagram. A mixed linear model was used to analyze the effects of fertilizer and year on mean GHG, CO$_2$, C input, C footprint, crop biomass and NECB during the crop growing season. Mean values for each variable were compared by a one-way ANOVA, followed by a Duncan’s post hoc test ($P < 0.05$).

**Results And Discussion**

**GHG emissions**

The GHG emissions from all the treatments includes indirect emissions from agricultural inputs (Table 2) and direct CH$_4$ and N$_2$O emissions (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$_2$-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), which maybe caused by the different turnover depth and decomposition rate of *Astragalus sinicus* L. and rice straw in each plot. The study result of Zhu et al. [34] indicated that different depth of straw retention (0 ~ 10cm, 10 ~ 20cm, 20 ~ 30cm, 30 ~ 40cm) had different effects on GHG emissions. This might because that the different depth of straw retention made the straw lie in different soil layers with different natural conditions and microbial diversity, which affected straw decomposition rate [35],[36] and SOC content [37], thus affecting GHG emissions. From Table 5 we can see that straw retention had significant effect on GHG, C input, and crop biomass. Year had significant impact on CO$_2$ and NECB. Moreover fertilizer and year had significant effect or interactive effect on GHG emissions, CO$_2$, C footprint, and NECB.

**C footprint components of all the treatments**

The C emissions per unit area of all the treatments was 9731 to 19584 kg CO$_2$ eq ha$^{-1}$ and the C footprint per unit production was 0.52~1.01 kg CO$_2$ 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$_2$O 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 [38],[39]. Compared with control CK, treatments RA, RB and RC enhanced CH$_4$ emissions mainly resulting from the following reasons: (1) The continuous flood irrigation provided a favorable anaerobic environment for the growth and reproduction of methanogens and methanotrophs (Fig.1) [40],[41],[42]; (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 leading to the CH$_4$ emissions increase [43],[44]; (3) Organic materials retention supplied methanogenic bacteria with adequate substrates [1,45],[46] while the decomposition of straw consumed oxygen, enhanced soil anaerobic environment and inhibited the activity of methane oxidizing bacteria, thus promoting CH$_4$ emissions [47]; (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$_4$ emissions [48].

Fertilizer and site years had significant interactive effect on C footprint (Table 5). Fertilizer (mineral fertilizer combined with organic materials) had different effect on GHG emissions when the rainfall and temperature were different over the two years, therefore, there exists an interactive effect between fertilizer and year. Different temperature and rainfall can affect the evaporation and loss rate of N fertilizer, thereby affecting N$_2$O emissions, because there was a linear relationship between N$_2$O emissions and N fertilizer [49],[50]. Meanwhile temperature, rainfall and crop straw retention also affect soil moisture and aeration condition, thus affecting GHG emissions. CH$_4$ is produced in an anaerobic environment [51]. Nitrification is sufficient when the soil contains sufficient oxygen, while denitrification mainly occurs in poor oxygen environments in soils [52],[53]. Moreover, rainfall can improve
the temperature of soil water, enhance microbial activity, increase organic matter/N mineralization rate, and promote the rapid release of large amounts of C and N in soil in a short period, thus promoting GHG emissions[[54],[55],[56]].

**NECB**

The NECB can be used to assess the short-term net C budget balance via C input and output in an aggro-ecosystem[[57]]. For control CK and the treatments 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\textsubscript{2} -eq ha\textsuperscript{-1} to 35.85 Mg CO\textsubscript{2} -eq ha\textsuperscript{-1} and C output ranged from 26.59 Mg CO\textsubscript{2} -eq ha\textsuperscript{-1} to 40.79 Mg CO\textsubscript{2} -eq ha\textsuperscript{-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\textsubscript{2} emissions contributed to the largest proportion for C output. CO\textsubscript{2} emissions was significantly affected by straw retention (Table 5). CO\textsubscript{2} emissions 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. Moreover, the application of mineral fertilizer and the decomposition of straw also promoted the growth and reproduction of soil microorganisms, thus enhancing soil respiration and promoting soil CO\textsubscript{2} emissions[[58],[59],[60],[61],[62]]. With the growth of *Astragalus sinicus* L. and rice plants, crop root secretion and abscission increased, which strengthened the microbial activity and rice respiration, thus increasing CO\textsubscript{2} emissions[[63],[64]]. Moreover, straw C decomposition also stimulated the mineralization of SOC to produce CO\textsubscript{2}[[65]].

**Conclusion**

The GHG emissions of treatments RA, RB and RC with organic material retention combined with reduced mineral fertilizer at the rate of 15%, 27.5%, and 40% respectively increased by 9.30%~101.25% over the two years compared with that of control CK, mainly resulting from increased soil CH\textsubscript{4} emissions, which occupied more than 60%. Meanwhile the treatments RA, RB and RC increased the yield (including *Astragalus sinicus* L., and rice biomass) 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 (*Astragalus sinicus* L. and rice straw retention with reduced N fertilizer by 27.5%) became C sink, because increased C input outweighed the increased C output. These results suggest that treatment RB is better in reducing chemical fertilizer amount, increasing crop yield and C input, which is more conductive to sustainable development of agriculture.

**Abbreviations**

C: Carbon; N: Nitrogen; CO\textsubscript{2}: Carbon dioxide; GHG: Greenhouse gas; CH\textsubscript{4}: Methane; N\textsubscript{2}O: Nitrous oxide; SOC: Soil organic carbon; NECB: Net ecosystem carbon budget

**Declarations**

**Data sharing and Data Accessibility**

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

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**Ethics approval and consent to participate**

Not applicable.
Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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.

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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 Agricultural inputs (Ai), and related coefficient factors (\(\delta_i\)) and application rate

| Treatments | GHG emission source from agricultural inputs | Emission coefficient | Agricultural inputs | 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: the data were obtained from the average value of agricultural input in this study. N represents Nitrogen fertilizer; P represents Phosphate fertilizer; K represents Potash fertilizer; GHG represents Greenhouse gas.

Table 3 average annual GHG emissions and C footprint during crop growth seasons over the two years (kg CO$_2$ eq ha$^{-1}$)

| T   | Indirect emission | Direct emission | Average GHG emissions | Yield (kg.ha$^{-1}$) | Carbon footprint (kg CO$_2$-eq/kg$^{-1}$) |
|-----|------------------|----------------|-----------------------|----------------------|----------------------------------------|
|     |                  |                |                       |                      |                                        |
| N   | P    | K    | Diesel | Electricity | Pesticides | CH$_4$ | N$_2$O |                |                      |                                        |
| 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; GHG represents Greenhouse gas; C represents Carbon; Yield represents Chinese milk vetch straw and rice biomass. The different lowercase letters indicate significant differences among treatments at $P < 0.05$.

Table 4 Assessment of C budget and balance in different treatments (Mg CO$_2$ ha$^{-1}$)

| Items                                      | CK           | RA           | RB           | RC           |
|--------------------------------------------|--------------|--------------|--------------|--------------|
| C input of Chinese milk vetch and rice     | 31.98        | 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        | 35.37        | 40.79        | 35.85        |
| NECB                                       | 5.39         | -5.42        | 3.56         | -4.1         |

Note: GHG represents Greenhouse gas; CO$_2$ represents Carbon dioxide; C represents Carbon; NECB represents Net ecosystem carbon budget.
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             |         |         |         |             |              |       |
| +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** |

Note: There were significant interactions (Fertilizer×Year) 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.

GHG represents Greenhouse gas; CO$_2$ represents Carbon dioxide; C represents Carbon; NECB represents Net ecosystem carbon budget.

-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 $P \leq 0.05$. 
Figure 2

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

Supplementary Files

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- FigureS1.png
- supplementarymaterials.xlsx