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Do Fallow Season Cover Crops Increase N_2O or CH_4 Emission from Paddy Soils in the Mono-Rice Cropping System?

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Abstract: Cover crop management during the fallow season may play a relevant role in improving crop productivity and soil quality, by increasing nitrogen (N) and soil organic carbon (SOC) accumulation, but has the possibility of increasing greenhouse gas (GHG) emissions from the soil. A year-long consistency experiment was conducted to examine the effects of various winter covering crops on annual nitrous oxide (N_2O) together with methane (CH_4) emissions in the mono-rice planting system, including direct emissions in the cover crop period and the effects of incorporating these crops on gaseous emissions during the forthcoming rice (*Oryza Sativa* L.) growing period, to improve the development of winter fallow paddy field with covering crops and to assess rice cultivation patterns. The experiment included three treatments: Chinese milk vetch-rice (*Astragalus sinicus* L.) with cover crop residue returned (T1), ryegrass (*Lolium multiflorum* L.)-rice with cover crop residue returned (T2), and rice with winter fallow (CK). Compared with CK, the two winter cover crop treatments significantly increased rice yield, soil organic carbon (SOC) and total nitrogen (TN) by 6.9–14.5%, 0.8–2.1% and 3.4–5.4%, respectively. In all cases, the fluxes of CH_4 and N_2O could increase with the incorporation of N fertilizer application and cover crop residues. Short-term peaks of these two gas fluxes were monitored after all crop residues were incorporated in the soil preparation period, the early vegetative growth period and the midseason drainage period. The winter cover crop residue application greatly enhanced CH_4 and N_2O cumulative emissions compared with CK (by 193.6–226.5% and 37.5–43.7%, respectively) during rice growing season and intercropping period. Meanwhile, the mean values of global warming potentials (GWPs) from paddy fields with different cropping crops were T2 > T1 > CK. Considering the advantages of crop productivity together with environmental safety and soil quality, Chinese milk vetch-rice with cover crop residue returned would be the most practicable and sustainable cultivation pattern for the mono-rice cropping systems.

Keywords: winter cover crop; CH_4; N_2O; paddy soil

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Citation: Li, J.; Wang, S.; Shi, Y.; Zhang, L.; Wu, Z. Do Fallow Season Cover Crops Increase N_2O or CH_4 Emission from Paddy Soils in the Mono-Rice Cropping System? *Agronomy* **2021**, *11*, 199. https://doi.org/10.3390/agronomy11020199

Academic Editor: Augustine K. Obour
Received: 24 December 2020
Accepted: 19 January 2021
Published: 21 January 2021

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1. Introduction

It is assumed that agricultural soils are a major source of greenhouse gas (GHG) leading to Earth's climate change, particularly nitrous oxide (N_2O) and methane (CH_4)—the most important long-lived GHGs [1]. The global warming potentials (GWPs) of N_2O and CH_4 are 298 and 25 times higher than that of carbon dioxide (CO_2). Moreover, both gases are reactive chemicals, CH_4 influences the atmospheric chemistry and oxidation capacity, and the increased N_2O in the atmosphere affects ozone depletion in the stratosphere [2]. Rice is one of the most prominent cereal crops and plays an essential role in maintaining global food security [3]. However, rice fields account for 5–19% and 60% of global agricultural CH_4 and N_2O emissions, respectively [4]. In paddy fields, CH_4 and N_2O emissions mostly rely on crop/soil management practices, such as fertilization, irrigation, soil cultivation and organic farming. Thus, these changes in agricultural practices would also provide mitigation options [5]. CH_4 is produced by the decomposition of organic materials in

anoxic flooded paddy soils via methanogenesis. In addition, N_2O is generated through nitrification/denitrification processes [6,7], and denitrification is a more effective N_2O production process [8,9]. Therefore, effective measures to reduce greenhouse gases in paddy fields are urgent scientific and societal challenges [10,11].

The preservation and maintenance of soil quality is the key to securing the high yield and stable harvest of rice grains. Replacing bare fallow with cover crops (CCs) is considered one of the most effective solutions for increasing organic substances, avoiding erosion, improving soil physiochemical features, reducing soil nitrogen leaching, suppressing weeds and reducing disease incidence [12,13]. However, because of the water and N requirements of winter cover crops, the alterations in soil moisture as well as C and N pools can exist during the cover crop period in paddy fields, thereby affecting the GHG emission process [14,15]. Moreover, it has been indicated that recycling cover crop residues would be beneficial for improving the soil conditions, reducing the application of N fertilizers, and supporting sustainable rice production [16]. Therefore, winter cover crop recycling in rice cultivation systems has the possibility of improving rice production and reducing adverse influences on the environment. The incorporation of different cover crop residues with variable characteristics would also have different effects on the net GHG budget for growing systems. To date, extensive research has been performed to assess the influence of winter cover crop return on soil nutrients and physiochemical properties, greenhouse gas emissions and rice grain production [17,18]. However, there is limited research that simultaneously compares the influences of various winter cover crops during the intercropping period and the influence of returned cover crops for forthcoming rice growth on annual GHG emissions in the mono-rice cropping systems.

Thus, field experiments were conducted (a) to quantify the annual N_2O and CH_4 emissions from winter cover crops in the cover crop period and rice growth period, (b) to evaluate the impacts of different cover crops on the GWP and (c) to determine the most feasible and sustainable management practices that can reduce GHG emissions and increase crop productivity. The findings of this paper can provide sound information for winter cover crop development in the mono-rice cultivation system.

2. Materials and Methods

2.1. Experimental Sites

Field experiments were conducted at Jingzhou Experimental Station in Hubei Province, China (29°98′ N, 111°66′ E). The annual rainfall is 1980 mm, and the average annual temperature is 17.5 °C. The soil is classified as fluvo-aquic soil, and the texture is silty loam. The experimental soils (0–20 cm) displayed the following characteristics: pH 7.2 (soil:water, 1:2.5); soil organic carbon (SOC), 29.89 g/kg; available P (Olsen extractable), 6.37 mg/kg; total N, 2.03 g/kg; total K, 2.81 g/kg; and soil bulk density, 1.19 g/cm^3.

2.2. Experimental Design and Field Management

The treatment plots selected for this study included Chinese milk vetch (*Astragalus sinicus* L.)-rice (*Oryza. Sativa* L.) with cover crop residue returned (T1), ryegrass (*Lolium multiflorum* L.)-rice with cover crop residue returned (T2), and rice for winter fallow (CK). All treatments were applied according to a randomized block design and were repeated three times. The plot area was 25 m^2 (5 × 5 m). The ridges of the blocks were wrapped with plastic mulch to ensure independent nutrient and water management. After harvesting the cover crops, parts of the crop residues were incorporated into the soils using a moldboard. The Chinese milk vetch, ryegrass and rice residue applied were 14,200, 14,200 and 7500 kg/ha, respectively. Before incorporation, the Chinese milk vetch, ryegrass and rice residue were weighed and cut into 2 to 3 cm pieces. The basal chemical fertilizers were urea, diammonium phosphate, and potassium sulfate, equivalent to approximately 160 kg/ha, 45 kg/ha P_2O_5, and 75 kg ha^{-1} K_2O per year, respectively. N fertilizer was used in three applications: 50% as the basic fertilizer before transplanting, 25% at the tillering stage, and the remaining 25% in the panicle period. One-month-old seedlings (cv. Huaan

3) were transplanted at a hill spacing of 20 × 16.7 cm, and two plants were planted on each hill. The seeds of Chinese milk vetch and ryegrass were broadcast in late September each year, and the sown rates were 30 and 21 kg/ha, respectively. Detailed schedules of the field operations throughout the whole study are demonstrated in Figure 1 [19]. The daily precipitation and air temperature are presented in Figure 2.

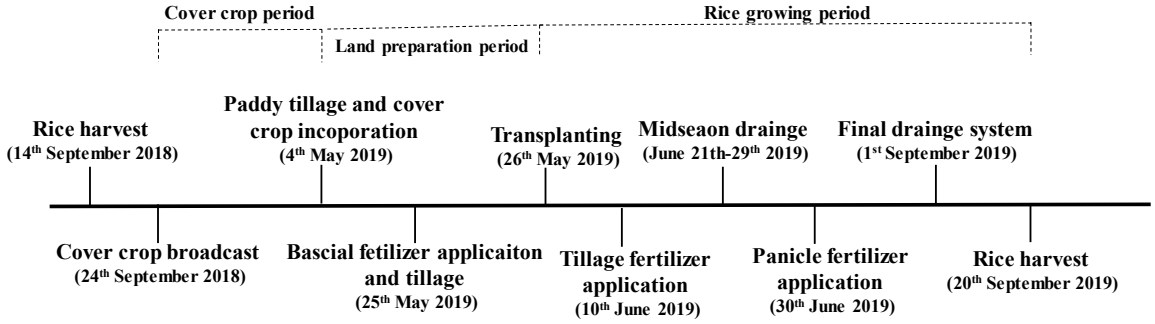

Figure 1. Field operations during the experimental period.

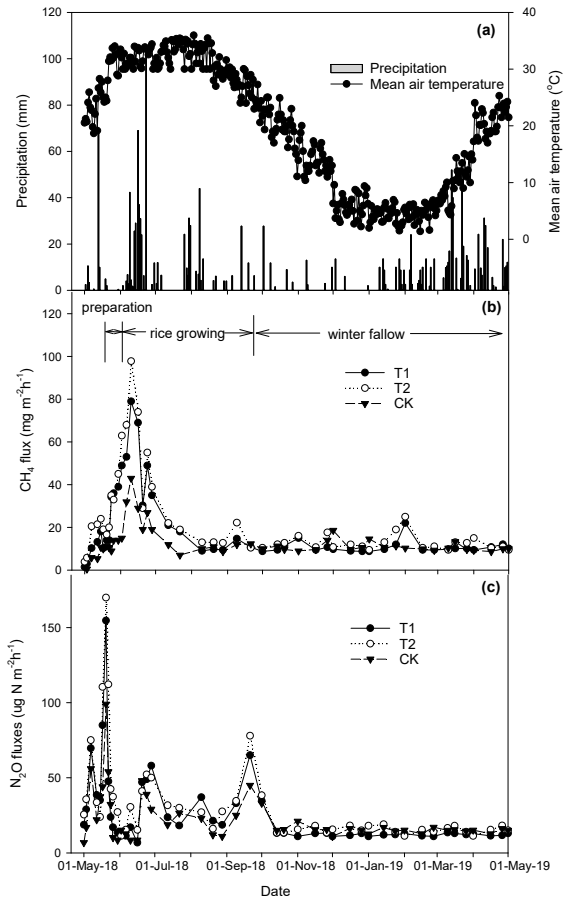

Figure 2. Average daily air temperature and precipitation (**a**), CH_4 flux (**b**) and N_2O flux (**c**) during the year 2018–2019 under different management practices. CK: Rice with winter fallow; T1: Chinese milk vetch-rice with cover crop residue returned; T2: Ryegrass-rice with cover crop residue returned.

2.3. Gas Sampling and Auxiliary Measurements

CH_4 and N_2O emissions were measured using the static chamber method (Li et al. 2018). The chamber (diameter 30 cm, height 50 cm) was made of a 5 mm PVC board and PVC base (diameter 30 cm, height 10 cm). The small fan was equipped on the chamber top to ensure that air in the chamber could be mixed evenly. The chamber base with a groove

in the collar was inserted 5 cm into the soil to allow rice plants to grow inside the base. Gas sampling occurred 2–3 times per week during the land preparation and rice growing period and once per week during the cover crop period. The gas samples were collected using a 50 mL syringe and were transferred to a 100 mL gasbag at 0, 30 and 60 min for analysis. The temperature inside the chamber was recorded by the thermocouple 20 cm from the body top. Measurement of gas samples was carried out using a gas chromatograph (Agilent 7890B; Delaware, USA).

The emission fluxes of N_2O and CH_4 were calculated as follows [20]:

$$F = \rho \times h \times dc/dt \times 273/(273 + T), \quad (1)$$

where F is the N_2O flux ($\mu g/m^2/h$) or the CH_4 flux ($mg/m^2/h$); ρ indicates the standard state density (N_2O 1.964 kg/m^3 and CH_4 0.714 kg/m^3); h represents the chamber height above the soil (m); dc/dt is the slope of the gas concentration curve; 273 is the gas constant; and T is the mean air temperature during gas sampling (°C).

The total emissions of N_2O (kg N_2O/ha) and CH_4 (kg CH_4/ha) over the measurement period were obtained by integrating the average of two adjacent measurement fluxes (Vitale et al. 2018). GWPs (kg CO_2-eq ha^{-1} $year^{-1}$) were determined according to a previously described equation [21] as follows:

$$GWP = 25 \times CH_4 + 298 \times N_2O \quad (2)$$

2.4. Soil Sampling and Measurement

After harvesting rice, the soil was sampled at the upper layer (0–20 cm). Soil pH in the 1:2.5 (v/v) soil:water suspension was measured. SOC was determined by wet digestion with H_2SO_4-$K_2Cr_2O_7$. Total N was measured by semimicro Kjeldahl digestion with $CuSO_4$, K_2SO_4 and Se. The available P was extracted with $NaHCO_3$ (0.5 M) and determined using the molybdate colorimetric method. The available K was extracted with 1 M NH_4OAc solution (1:10 v/v) and measured using a flame photometer (FP640).

2.5. Statistical Analysis

Statistical tests were performed using the SPSS software ver. 16.0 (SPSS Inc., Chicago, IL, USA). All data were tested by one-way variance analysis and Duncan's test. The mean ± standard error (SE) and the least significant difference (LSD) at a significance level of 0.05 were calculated to compare treatment means.

3. Results

3.1. CH_4 and N_2O Emissions

In the period of land preparation, CH_4 emissions increased slightly under all the treatments, and a small peak was observed at approximately seven days after land preparation. Afterward, in the rice growing period, the flux of CH_4 reached a peak at two weeks after rice transplanting and then declined rapidly and returned to background levels. Moreover, the CH_4 flux showed a small peak in all the treatments during the mid-season aeration stage. The CH_4 flux remained relatively low and stabilized during the fallow period in winter. Throughout most of the growing season, the daily CH_4 emissions between the T1 and T2 treatments had the same patterns, and both were higher than those in the fertilizer-only plots, following the sequence of T2 > T1 > CK (Figure 2). The total emissions of CH_4 from paddy soils in the land preparation, rice growing and cover crop periods were 112.8, 331.3, and 368.5 kg CH_4-C/ha, respectively. Among the fertilized treatments, the annual cumulative CH_4 emissions followed the order T2 > T1 > CK (Table 1).

Table 1. Cumulative CH_4 and N_2O emissions in the three treatment groups during land preparation, rice growing and winter fallow periods.

Treatment	CH_4 Emission (kg CH_4-C/ha)				N_2O Emission (kg N_2O-N/ha)			
	Land Preparation	Rice Growing	Winter Fallow	Total	Land Preparation	Rice Growing	Winter Fallow	Total
CK	13.20 ± 0.01^{c}	85.32 ± 0.10^{c}	14.32 ± 0.06^{b}	112.84 ± 0.09^{c}	0.21 ± 0.01^{c}	0.61 ± 0.01^{c}	0.30 ± 0.01^{c}	1.12 ± 0.02^{c}
T1	54.06 ± 0.03^{a}	245.14 ± 0.16^{b}	32.10 ± 0.03^{a}	331.30 ± 0.11^{b}	0.34 ± 0.01^{a}	0.67 ± 0.01^{b}	0.53 ± 0.01^{b}	1.54 ± 0.01^{b}
T2	32.93 ± 0.03^{b}	301.25 ± 0.23^{a}	34.32 ± 0.02^{a}	368.50 ± 0.10^{a}	0.29 ± 0.02^{b}	0.73 ± 0.02^{a}	0.59 ± 0.01^{a}	1.61 ± 0.02^{a}

All data (n = 3) are expressed as mean ± SE. The values with different superscript letters are significantly different ($p < 0.05$). CK, rice with winter fallow; T1, rice-ryegrass cropping system; T2, rice-Chinese milk vetch cropping system.

The patterns of N_2O flux in paddy soil were similar to those of CH_4 flux, prominent during the tillage and rice growing periods but negligible in the winter fallow season (Figure 1). Four N_2O emission peaks were detected during soil preparation, fertilization, mid-season drainage and last drainage (rice harvest period). During the rice growing season, N_2O flux reached a peak on day one after fertilization and then declined gradually (Figure 1). Most emissions occurred in the first seven days after being fertilized, and emissions were relatively low in the late rice-growing season. As seen in Table 1, the annual total N_2O emission followed the sequence of T2 (1.61 kg N_2O/ha) > T1 (1.54 kg N_2O/ha) > CK (1.12 kg N_2O/ha) for the rice-fallow cropping system. The N_2O emissions from the rice growing period accounted for 43.5–54.4% of the annual total emissions, followed by the land preparation period and the cover crop period, accounting for 18.1–22.1% and 26.7–36.6% of the total annual emissions, respectively.

3.2. Rice Yield, Soil Properties and GWPs of CH_4 and N_2O

The rice grain production in the T1 and T2 treatments was increased by 6.9% and 14.5% compared with that in the CK (Table 2). Compared with CK, the addition of cover crops increased the SOC and total N content by 0.8–2.1% and 3.4–5.4%, with the highest SOC and total N occurring in T1. On the basis of GWPs, the contribution of CH_4 from paddy fields to global warming is greater compared to that of N_2O. According to the global warming potential, it accounted for 89.4–95.0% of the total GWP during the annual cycle (Table 2 and Figure 1). The GWPs of CH_4 and N_2O from the mono-rice cultivation system showed the trend T2 (9693 kg CO_2/ha) > T1 (8742 kg CO_2/ha) > CK (3155 kg CO_2/ha). The per yield GWPs of T2 and T1 were also remarkably higher than those of CK treatment ($p < 0.05$).

Table 2. Mean grain yield, annual CH_4 and N_2O emissions, estimated global warming potential (GWP) and greenhouse gas intensity (GHGI) under different treatment.

Treatment	Grain Yield (t/ha)	SOC (g kg^{-1})	Total N (g kg^{-1})	GWP of CH_4 (kg CO_2-eq/ha/y)	GWP of N_2O (kg CO_2-eq/ha/y)	GWPs of CH_4 and N_2O (kg CO_2-eq/ha/y)	GHGI (kg kg/y)
CK	7.93 ± 0.06^{c}	29.87 ± 0.11^{b}	2.01 ± 0.01^{b}	2821 ± 241^{c}	334 ± 10^{c}	3155 ± 236^{c}	0.39 ± 0.01^{c}
T1	9.08 ± 0.11^{a}	30.50 ± 0.09^{a}	2.12 ± 0.02^{a}	8283 ± 212^{b}	459 ± 9^{b}	8742 ± 235^{b}	0.96 ± 0.02^{b}
T2	8.48 ± 0.10^{b}	30.11 ± 0.06^{ab}	2.08 ± 0.03^{ab}	9213 ± 209^{a}	480 ± 4^{a}	9693 ± 214^{a}	1.14 ± 0.02^{a}

All data (n = 3) are expressed as mean ± SE. The values with different superscript letters are significantly different ($p < 0.05$). CK, rice with winter fallow; T1, rice-ryegrass cropping system; T2, rice-Chinese milk vetch cropping system.

4. Discussion

4.1. CH_4 and N_2O Emissions from Paddy Soils

It has been demonstrated that farming systems, crop residues, fertilization, fertilizer types and efficient irrigation in rice fields are the main driving forces of CH_4 and N_2O emissions [22,23]. In the present study, compared with CK, the addition of cover crops enhanced the CH_4 fluxes (T1 and T2) seven to 14 days after land preparation and the early rice-growing period (Figure 2), which was consistent with previous research [24,25]. The high emission of CH_4 following land preparation may be relevant to the increase in available organic matter, while the existence of intense reducing conditions in the

rhizosphere caused by flooding may be attributable to the high emission of CH_4 in the early rice-growing period [26]. During the same period, however, because of the lack of organic substances, less CH_4 production occurred in the NPK-only plots. In the rice growing period, CH_4 emissions rose gradually with organic substance decomposition and peaked at the tillering stage. However, the CH_4 flux of T1 and T2 was maintained at much low levels after rice harvest in the winter cover crop growing period. This is likely related to the improvement of soil aeration in this period, the restricted methanogen activities, and the reduced physiological activities of rice plants, thus prohibiting the transport and emission of CH_4 [27].

The annual total CH_4 emission varied from 112.84 to 368.50 kg CH_4-C/ha in our study (Table 1), which is consistent with prior works conducted on rice planting systems [28,29]. In the present study, the annual total CH_4 emissions were greatly enhanced due to the addition of winter cover crops. Pandey et al. (2012) also showed that although straw return helped to improve soil fertility, it increased the emission of CH_4 simultaneously [30]. The reasons for the increased CH_4 emissions from paddy fields after application of organic materials would probably be attributed to the supply of available C and N sources for microbial activities and methanogenic substrates for accelerating soil oxygen consumption and decreasing soil redox potential (Eh), which increased CH_4 emissions from paddy fields after incorporating winter cover crop residue into soil [24,26,31]. As a support, the application of cover crops favored SOC and total N accumulation by the increased N and C availability in this study (Table 2). The differences among the treatments suggested that CH_4 emissions in rice fields were influenced by various winter cover crops. The highest total CH_4 emissions were found in the T2 treatment, which might be associated with the different residue decomposition rates during the rice growth season.

It has been suggested that N_2O production and emission in rice fields depend on temperature, oxygen, soil moisture, soil organic matter, and pH [32,33]. In our research, the N_2O emission flux peaked at the early land preparation period, mid-season drainage and last drainage prior to rice harvesting (Figure 2). In the soil preparation period, alternate drying–wetting cycles of soil could promote the emission of N_2O. In addition, the incorporation of winter cover crops during the soil preparation stage may also trigger microbial activity, and the rapid decomposition of organic substances provides a more available N source, thus leading to more N_2O emissions [34]. Higher emissions of N_2O were observed during mid-season and last drainage, due to N fertilization after panicle initiation, high temperature and anoxic environment (Figure 2). In this work, the emissions of N_2O from both T2 and T1 treatments were higher than those from the CK. Petersen et al. (2011) also found that there was a large positive interaction between N_2O emissions and chemical nitrogen fertilizer or green manure during the rice growing seasons [35]. This was probably attributed to (1) the increased level of soil N after fertilization and (2) the incorporation of residue providing microorganisms with more substrates for the soil nitrification/denitrification process [36]. The absence of N fertilization in the winter cover crop growth period could explain the low N_2O flux determined in the two cover crop treatments (Figure 2).

In our study, the annual total N_2O emission varied from 1.12 to 1.16 kg N_2O-N/ha (Table 1). It has been reported that 60% of published studies indicated that the cultivation of cover crops could increase N_2O emissions, while 40% demonstrated that the cultivation of cover crops could reduce N_2O emissions [37]. The differences in the studies can be explained by different cover crop performances, soil properties, cultivation systems, cover crop incorporation methods and N_2O sampling timings. The total N_2O emissions from T1 and T2 increased by 37.5% and 43.7%, respectively, and those from T2 were higher than those from T1, which might be associated with the different rates of straw decomposition. Further research is needed to study the microprocesses related to N_2O emissions in the soil after winter cover crop incorporation.

4.2. GWPs of CH_4 and N_2O

The GWPs in the two cover crop treatments were much higher than those in the fertilizer-only group ($p < 0.05$), which was in good agreement with the study of Zhu and co-workers (2012) [38]. Although the global warming impact of N_2O was 12 times larger than that of CH_4, the cumulative emission of CH_4 was approximately 370 times higher than that of N_2O (Table 2), leading to the majority of GWPs are made up of CH_4. This is probably related to the fact that CH_4 emission is a contributing factor for GWP in paddy fields [28], which accounts for >90% of the GWP in this study (Table 2). The cultivation of cover crops may offer more N and available C, increase the abundance of methanogens, and directly or indirectly offer more dissolve organic C, which is an important factor for CH_4 production [39], thus leading to higher GWPs and per yield GWPs for T2 and T1 than the CK treatment.

5. Conclusions

Our results indicated that the paddy soil with cover crop residues was the main source of atmospheric CH_4. Compared with CK, the CH_4 emissions of T1 and T2 increased in the rice growing period and cover crop period. The GWPs of CH_4 in the T1 and CK plots were markedly decreased compared to those in T2 ($p < 0.05$). The N_2O emissions were susceptible to external influences and varied significantly in the rice growing season. Although the total emissions of T2 and T1 were greater than that of CK, the GWPs of N_2O were noticeably lower than those of CH_4. Thus, N_2O emission represents a weak source of GHGs in paddy soils. Notably, the GWPs (on the basis of N_2O and CH_4) of T1 and CK treatments were lower compared to those of T2 treatment. Higher grain yield was recorded in the T2 and T1 treatments than in the plots treated with NPK alone. Therefore, considering the total experimental period (fallow + rice crop), T1 is the most promising way to enhance rice production, SOC and total N accumulation and stabilize GHG emission, indicating that Chinese milk vetch-rice with a cover crop residue returned cropping pattern is probably the most viable and sustainable choice for mono-rice cropped regions.

Author Contributions: Conceptualization, J.L.; methodology, J.L.; software, J.L.; validation, L.Z., Z.W. and Y.S.; formal analysis, J.L. and S.W.; investigation, S.W.; resources, J.L.; data curation, J.L.; writing—original draft preparation, J.L.; writing—review and editing, J.L.; visualization, J.L.; supervision, Z.W. and Y.S.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Natural Science Foundation of China (Nos. 41807107). The National Key Research and Development Program of China (Nos. 2017YFD0200708, 2018YFD0200200).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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