https://doi.org/10.17221/693/2019-PSE

Effect of long-term differentiated fertilisation regimes on greenhouse gas emissions from a subtropical rice-wheat cropping system

Fa Wang[1], Zhijian Mu[2], Tao Guo[1], Aiying Huang[3], Xiao Lin[1], Xiaojun Shi[1], Jiupai Ni[1]*

[1]College of Resources and Environment, Southwest University, Chongqing, P.R. China
[2]Chongqing Key Laboratory of Agriculture and Environment Research, College of Resources and Environment, Southwest University, Chongqing, P.R. China
[3]College of Agronomy and Biotechnology, Southwest University, Chongqing, P.R. China
**Corresponding author: muzj01@gmail.com*

Citation: Wang F., Mu Z.J., Guo T., Huang A.Y., Lin X., Shi X.J., Ni J.P. (2020): Effect of long-term differentiated fertilisation regimes on greenhouse gas emissions from a subtropical rice-wheat cropping system. Plant Soil Environ., 66: 167–174.

Abstract: A field campaign was conducted using six treatments under the summer rice-winter wheat cultivation system to evaluate the response of soil greenhouse gas (GHG) emissions to long-term differentiated fertilisation regimes. The treatments included control, phosphorus plus potassium, nitrogen only, nitrogen plus phosphorus (NP), nitrogen plus potassium, and NP plus potassium (NPK). Compared to the control, mineral fertilisation increased CH_4 emissions during the rice season by 69% to 175%. Phosphorus amendment also enhanced seasonal CO_2 emissions by 21% to 34% when compared with the treatments without receiving P, while combined use of P and potassium suppressed seasonal N_2O emission to the same level of control. Net CO_2 and N_2O emissions from the dried fallow and wheat seasons and CH_4 emissions from the flooding rice season dominated annual budgets of individual GHGs. All of the soils under different treatments were net sources of global warming and the overall net global warming potential ranged from 9 799 to 14 178 kg CO_2 eq/ha/year with CO_2 emission contributing 52% to 76%, CH_4 contributing 20% to 40% and N_2O occupying the rest. The annual maximum grain yields and minimum GHG intensity was observed at the NPK treatment, suggesting it to be the environmental-friendly optimum fertilisation regime.

Keywords: carbon dioxide; methane; nitrous oxide; fertilisers; global warming effect

Rice is the staple food for nearly half of the world's population. As the most important rice-producing country, China accounts for about 28% of the global rice production and 19% of the world rice-harvested area (FAO 2017). Annual emissions of CH_4 and N_2O from Chinese rice fields are estimated to range from 7.7 to 8.0 Tg and from 88.0 to 98.1 Gg, respectively (Xia et al. 2014). Large uncertainties associated with these estimates result from a complex suite of factors such as soil properties, cropping system, water regime, fertilisers and climate (Zhou et al. 2017, Wu et al. 2019). Nitrogen fertiliser is vital for achieving a sustained rice production to feed the burgeoning population (Datta et al. 2013). Numerous studies have demonstrated a positive relationship between N_2O emission in rice fields and mineral nitrogen (N) input (Wang et al. 2017, Zhou et al. 2017). In contrast, the response of CH_4 emission to N addition is contradictory due to complex effects of N on CH_4 production and oxidation (Cai et al. 2007, Yang et al. 2010). The complementary amendment of phosphorus and potassium to N fertiliser can balance the nutrient requirement of plants and more efficiently deliver added N to crops, thus suppressing N_2O emission (Shang et al. 2011, Mori et al. 2013). Inconsistent impacts of phosphorus (P) addition on CH_4 emission from wetlands, however,

Supported by the Key R&D Program of China, Project No. 2018YFD0800600, and by the National Natural Science Foundation of China, Grant No. 41371211.

https://doi.org/10.17221/693/2019-PSE

were found in different studies, and were seemingly explained by differences in experimental duration and ecosystem type (Song et al. 2012, Medvedeff et al. 2014). Like CH_4, soil respiration and CO_2 emission are also found to respond divergently to chemical fertilisers (Mu et al. 2013).

The summer rice-winter wheat cropping system occupied about 60% of paddy fields in southern China (Xia et al. 2014). Under this system, soils are flooded for about 100 days during the rice season and then are aerobically managed during the fallow and wheat seasons. Such wetting-drying cycles are bound to change soil properties regulating the production and consumption of GHGs and further affect their trade-off relationship. However, previous studies mainly focused on the rice season and attempted to develop mitigation strategies for individual GHG emissions without a full accounting of all contributors to the annual global warming potential (GWP) (Haque et al. 2015). Soil carbon (C) sequestration can offset the global warming effect of CH_4 and N_2O and should thereby be accounted for in the evaluation of the net GWP from rice fields. Rather than direct detection of soil organic C changes over a long time span, the calculation of net ecosystem C budget (NECB) can sensitively reflect seasonal changes in soil C sequestration and storage (Smith et al. 2010). In the present study, a long-term fertilisation experiment was employed to evaluate the effect of mineral fertiliser application on GHG emissions and quantify relative contribution of flooded rice and dried fallow/wheat seasons to the annual GWP in a summer rice-winter wheat cultivation system.

MATERIAL AND METHODS

Field treatments. The study was conducted from May 2014 to April 2015 using six fertilisation treatments initiated in 1991 at the National Monitoring Station for Purple Soil Fertility (29°48'N, 106°24'E) in Beibei, Chongqing Municipality, China. The treatments included unfertilised control (CK); P plus K (PK); N only (N); N plus P (NP); N plus K (NK), and NP plus K (NPK). Urea (46% N), calcium superphosphate (5% P) and potassium sulfate (42% K) were used as the source of N, P and K, respectively. All the treatments were laid out in a randomised block design with each plot measuring 10 m by 12 m. The 60 cm-deep concrete baffles were installed to isolate plots and avoid mixing effects. The plots were continuously subjected to a summer rice-winter wheat rotation. Rice was usually transplanted in middle May and harvested in late August. The water level was always maintained at a depth of 5 cm to 8 cm above soil surface till soil was drained 3 weeks before rice harvest. The field was then left fallow until wheat seeding in early November and harvesting in the next late April. Rice seedlings and wheat seeds were manually transplanted or sown with 20 cm to 30 cm of spacing in the rows and between rows. The rate of N-P-K was 135-26-50 kg/ha for wheat and 150-26-50 kg/ha for rice. All of P and K and 60% of N were applied as basal fertiliser, while 40% of N was applied at the 3 to 4 leaf stage for wheat and 2 to 3 weeks after rice transplanting.

The soil was classified as Typic Purli-Udic Cambisol, and basic properties at the beginning of the current study are shown in Table 1. The climate of the region is continental subtropical monsoon with humid winter and has a 30-year mean annual air temperature of 18.3 °C and annual precipitation of 1 293 mm.

Gas sampling and analysis. In-site fluxes of CH_4 and N_2O were measured at 3 to 5 days interval during the rice season and 7 to 10 days interval during the dried seasons, using the static closed chamber

Table 1. Basic properties of the topsoil (0 cm to 20 cm) under different treatments

Treatment	pH	Total organic carbon	Total nitrogen	Total phosphorus	Total potassium
		(g/kg)			
CK	8.13 ± 0.13	13.91 ± 1.47	1.08 ± 0.12	0.55 ± 0.07	17.90 ± 1.46
PK	7.20 ± 0.03	13.26 ± 0.94	1.34 ± 0.10	0.96 ± 0.18	19.33 ± 0.96
N	7.03 ± 0.10	10.91 ± 1.95	1.19 ± 0.09	0.41 ± 0.07	18.40 ± 1.27
NP	7.28 ± 0.08	14.63 ± 0.88	1.45 ± 0.15	0.79 ± 0.15	18.81 ± 2.02
NK	7.15 ± 0.15	13.94 ± 1.24	1.33 ± 0.12	0.45 ± 0.09	18.96 ± 1.88
NPK	7.25 ± 0.08	12.95 ± 0.76	1.31 ± 0.08	0.77 ± 0.13	18.46 ± 1.65

CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

https://doi.org/10.17221/693/2019-PSE

method (60 cm × 30 cm × 110 cm) as described by Shang et al. (2011). Two bunches of rice or wheat plants were enclosed in the chambers during the gas sampling events. The headspace air samples were collected from 09:00 to 12:00 h by 50 mL-syringes with at 0, 10, 20 and 30 min after chamber deployment. In contrast, soil CO_2 flux from bare plots (1 m × 1 m with 3 replicates) at each treatment was monitored using a small stainless-steel chamber with a size of 20 cm in diameter and 25 cm in height (Mu et al. 2013). Gas samples were immediately transported to the lab for analysing GHG concentrations by gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan). Instantaneous gas fluxes were calculated by a linear regression of gas concentrations in chamber against the sampling time. The cumulative emissions were calculated assuming linear changes in gas fluxes between two successive sampling dates and summing up over each cropping season. The accumulative days were 98, 72 and 179 for the rice, fallow and wheat seasons, respectively. During each gas sampling event, soil temperature at 5 cm was recorded next to each chamber by a digital thermometer (CT-220, Custom, Tokyo, Japan). Soil volumetric water content was measured by a TDR meter (TDR-300, Spectrum Technologies, Illinois, USA).

Calculation and statistical analysis. The net ecosystem carbon budget (NECB) was calculated using the following equation derived from Mu et al. (2013) and Haque et al. (2015):

$$\text{NECB (kg C/ha)} = \text{organic C input from plant residue and fertiliser (kg C/ha)} - R_h \text{ (kg C/ha)} - CH_4 \text{ emission (kg C/ha)}$$

where: R_h – C loss through soil organic matter decomposition as indicated by CO_2 flux measured at bare soils (Haque et al. 2015).

Plant residues remaining in the soils were mainly in the form of roots and parts of straws at rice and wheat harvesting stage since the aboveground biomass was cut at a height of around 20 cm above the ground and removed from the fields. Sparse weeds growing during the fallow period were ploughed in and buried in the soil prior to wheat seeding. The grain, straw, root biomass of rice and wheat to a depth of 30 cm and whole plant of weeds were sampled, dried and weighed, and then analysed for the C content (Vario PyroCube, Elementar, Hanau, Germany). Positive values of NECB indicate the soils as a net sink of atmospheric CO_2, while negative ones indicate the soils as a net source of CO_2.

The net GWP was calculated as the CO_2 equivalent of CH_4 and N_2O emissions minus C loss indicated by NECB, using the 100-year-time scale conversion factors of 28 for CH_4 and 265 for N_2O (IPCC 2014, Wu et al. 2018):

$$\text{Net GWP (kg } CO_2\text{-eq/ha)} = (28 \times CH_4) \text{ (kg } CO_2\text{-eq/ha)} + (265 \times N_2O) \text{ (kg } CO_2\text{-eq/ha)} - (\text{NECB} \times 44/12) \text{ (kg } CO_2\text{/ha)}.$$

The GHG intensity (GHGI) was then calculated as a ratio between net GWP and crop grain yield according to Kim et al. (2019).

All statistical analyses were performed with the SAS 9.4 for Windows (SAS Institute Inc., Cary, USA). The normal distribution of instantaneous gas flux was checked by P-P plot, and effects of fertilisation treatments on seasonal cumulative gas emissions were assessed using the one-way ANOVA, followed by the least significant difference test (*LSD*, $P < 0.05$).

RESULTS AND DISCUSSION

CH_4 fluxes. The CH_4 emission patterns followed the change in soil water regime over the course of the study period (Figure 1). For the rice season, CH_4 fluxes increased from small amount at the date of flooding and transplanting and peaked at the reproductive stage, and then declined gradually to a low rate with water draining at maturing stage (Figure 2). In comparison, CH_4 fluxes maintained at a negligible rate throughout the dried fallow and wheat seasons. All of the treatments acted as the large source of CH_4 during the rice season, but alternated as a minor source or sink of CH_4 during the fallow and wheat seasons. The total CH_4 emissions during the rice season were significantly different among treatments (Table 2). The fertilisation treatments released 69% to 175% higher CH_4 than the control. The combined use of N and P (i.e., NP and NPK treatments) also stimulated CH_4 emission to various extents when compared to separated use of N or P (i.e., N, NK and PK treatments). The stimulatory effect of combined application of fertilisers may result from high soil organic carbon decomposition with increasing microbial biomass and activity and/or more photosynthesised carbon released into soils as exudates due to concurrent N and P addition (Atere et al. 2019, Herbert et al. 2020). Small residual effects of N and P addition appeared to stay during the fallow period. By the wheat season, however, the effect of mineral fertilisation on CH_4 fluxes vanished and no difference was observed among treatments.

https://doi.org/10.17221/693/2019-PSE

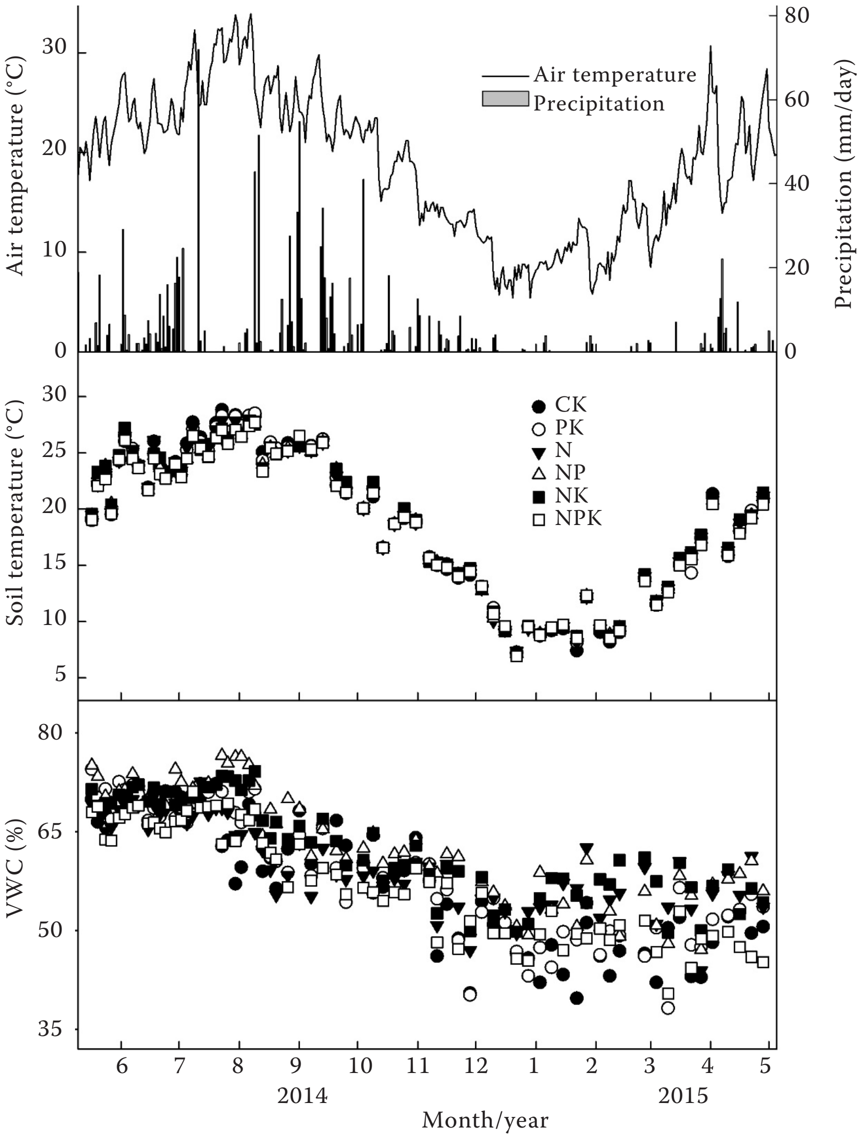

Figure 1. Seasonal variation in weather conditions, soil temperature and volumetric water content (VWC) under different treatments. CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

CO_2 fluxes. Seasonal patterns of CO_2 emission from bare soils mainly followed the seasonal changes in soil temperature (Figures 1 and 2). The mean flux of CO_2 in different seasons was not significantly different under control or NP treatments. For other treatments, mean CO_2 fluxes were generally higher in the fallow period than in the rice and wheat seasons, probably due to the concomitant status of relatively high temperature and moderate soil water content in the fallow period enhancing soil organic carbon (SOM) decomposition and CO_2 release. For the same treatments, however, the wheat season lasted longer and showed a higher rate of cumulative CO_2 emission than the rice and fallow seasons (Table 2). The seasonal CO_2 emissions from P-amended treatments (i.e., PK, NP, NPK) during the rice, fallow and wheat seasons averaged 1 182, 993 and 1 966 kg C/ha, respectively, and were 21% to 34 % higher than those from the non-P-amended treatments.

N_2O fluxes. The N_2O emission patterns during the rice and fallow seasons were characterised by lower flux rates on most sampling dates (Figure 2). By contrast, large temporal variation in N_2O fluxes was observed during the wheat season with one quarter of the flux data from different treatments exceeding 50 μg $N/m^2/h$. Small negative fluxes were much more frequently observed during the rice and fallow seasons than during the wheat season, probably due to the reduction of N_2O to N_2 and low N_2O production in periods of high soil moisture (Ley et al. 2018). The pulses of higher N_2O fluxes were generally observed following fertilisation, which were especially distinct during the wheat season. Compared to separated use of P or K (i.e., NP and NK), the combination of P and K (i.e., PK and NPK) consistently suppressed seasonal N_2O emissions to the same level of unfertilised control (Table 2). The seasonal emission from the N only applied treatment was rela-

https://doi.org/10.17221/693/2019-PSE

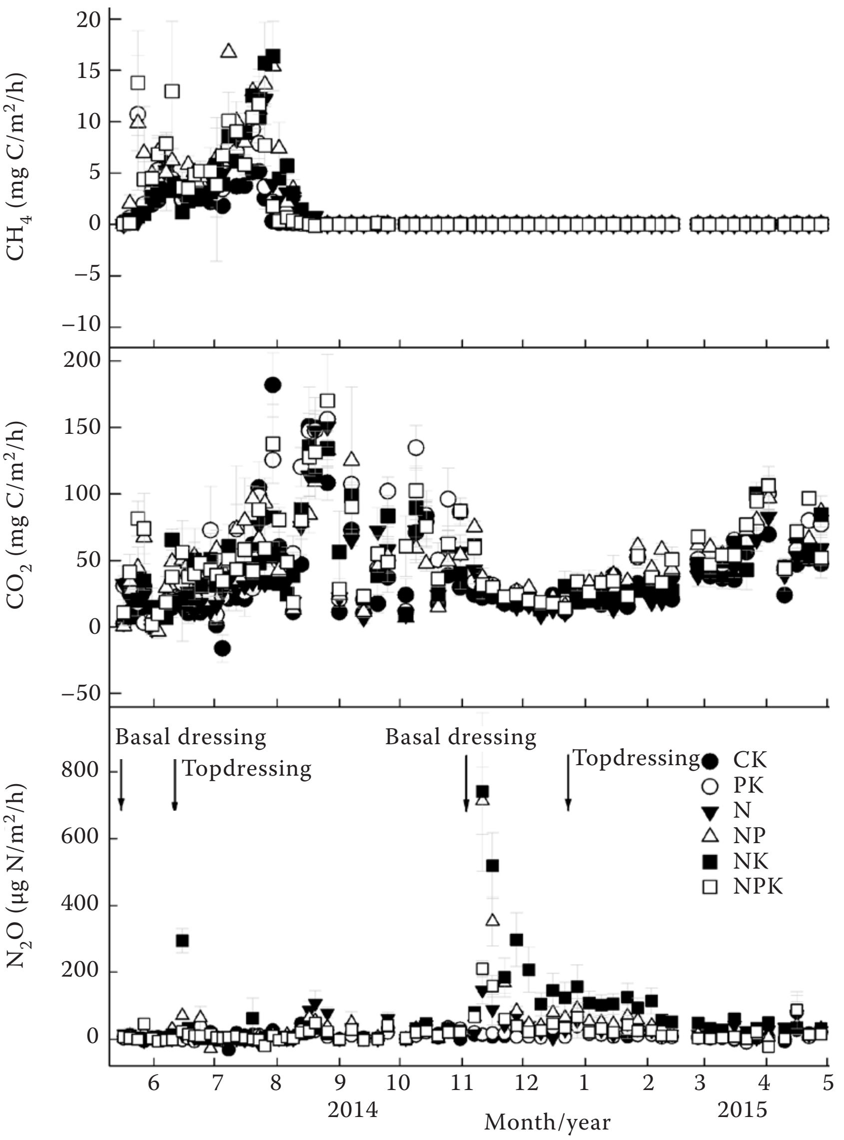

Figure 2. Seasonal variation in fluxes of CH_4, CO_2 and N_2O from soils under different treatments. CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

tively high during the fallow period, but was low and close to those from PK and NPK treatments during the rice and wheat seasons. For the same treatments, N_2O emissions during the wheat season were significantly higher than those during the rice and fallow seasons.

NECB. Compared to the control, fertiliser amendment drastically increased C returns to soils through plant residue during the rice season (Table 3), but it also enhanced soil emission of CO_2 and CH_4. As a result of balance, the amount of soil C gain from residual biomass together with urea was not enough to compensate for the C loss as CO_2 and CH_4, leading NECB to be negative for control and PK treatments (Table 3). For other N-amended treatments during the rice season, however, C input into soils could well offset C loss from soils and NECB ranged from plus 159 to 546 kg C/ha, indicating that those soils acted as a net sink of atmospheric CO_2. In contrast, the soils at all treatments during the dried fallow and wheat seasons showed a net CO_2 emission to the atmosphere with NECB values being negative. The fertilised soils during both seasons showed higher negative values of NECB than the control soils, and tended to release 23% to 91% and 4% to 38% more C to the atmosphere, respectively. In terms of annual values of NECB, the soils at all treatments showed also net sources of CO_2 to the atmosphere with the wheat season contributing 54% to 84% and the fallow season nearly occupied the rest, except for the control for which the rice season covered 20%. The overall net C emission from the soil at the control could be by 32% lower than that at PK, but was by 1% to 20% higher than those at other fertilised treatments. Owing to the sink role or the weak source intensity of rice season, the overall net C emission observed in this study was obviously lower than the values reported

https://doi.org/10.17221/693/2019-PSE

Table 2. Mean in-situ fluxes and cumulative emissions of greenhouse gases (GHGs) from different treatments

Season	CK	PK	N	NP	NK	NPK
Rice						
CH_4 (mg C/m^2/h)	2.17 ± 1.90	3.67 ± 3.10	4.08 ± 3.51	6.05 ± 5.09	4.10 ± 4.95	5.04 ± 4.23
CO_2 (mg C/m^2/h)	41.38 ± 49.85	50.20 ± 41.83	37.05 ± 33.59	51.6 ± 28.03	41.88 ± 30.18	54.89 ± 35.06
N_2O (mg N/m^2/h)	7.89 ± 13.84	5.54 ± 10.79	12.17 ± 25.28	13.19 ± 23.21	19.58 ± 55.72	7.94 ± 14.29
CH_4 (kg C/ha/season)	52 ± 8^{d}	87 ± 7^{c}	96 ± 6^{bc}	152 ± 31^{a}	109 ± 25^{bc}	120 ± 16^{b}
CO_2 (kg C/ha/season)	908 ± 45^{c}	1 126 ± 132^{ab}	798 ± 106^{c}	1178 ± 167^{a}	947 ± 78^{bc}	1 241 ± 39^{a}
N_2O (kg N/ha/season)	0.18 ± 0.07^{bc}	0.13 ± 0.05^{c}	0.23 ± 0.05^{bc}	0.30 ± 0.12^{b}	0.48 ± 0.12^{a}	0.17 ± 0.05^{bc}
Fallow						
CH_4 (mg C/m^2/h)	–0.45 ± 0.79	–1.39 ± 0.62	–0.58 ± 0.65	23.3 ± 4.13	23.01 ± 4.41	7.94 ± 3.16
CO_2 (mg C/m^2/h)	43.08 ± 31.92	76.10 ± 46.74	56.71 ± 39.2	51.93 ± 40.25	61.54 ± 36.91	69.97 ± 40.08
N_2O (mg N/m^2/h)	13.85 ± 14.05	11.17 ± 12.49	25.21 ± 25.4	20.14 ± 17.94	18.69 ± 16.93	15.28 ± 13.83
CH_4 (kg C/ha/season)	–	–0.02 ± 0.04^{b}	0.00 ± 0.11^{b}	0.14 ± 0.11^{a}	0.17 ± 0.42^{a}	0.14 ± 0.13^{a}
CO_2 (kg C/ha/season)	654 ± 114^{d}	1 148 ± 196^{a}	847 ± 199^{bcd}	783 ± 262^{cd}	954 ± 321^{abc}	1 048 ± 185^{ab}
N_2O (kg N/ha/season)	0.23 ± 0.07^{bc}	0.16 ± 0.04^{c}	0.38 ± 0.12^{a}	0.31 ± 0.11^{ab}	0.29 ± 0.15^{ab}	0.24 ± 0.08^{bc}
Wheat						
CH_4 (mg C/m^2/h)	–2.37 ± 0.95	–2.50 ± 0.40	–0.76 ± 1.25	–0.98 ± 0.43	–0.82 ± 0.31	–1.78 ± 0.46
CO_2 (mg C/m^2/h)	31.91 ± 15.94	41.92 ± 21.64	33.57 ± 18.45	47.61 ± 22.66	39.92 ± 24.99	45.75 ± 24.94
N_2O (mg N/m^2/h)	12.54 ± 12.13	12.13 ± 16.58	33.88 ± 30.23	76.87 ± 139.66	126.79 ± 156.59	35.77 ± 47.96
CH_4 (kg C/ha/season)	–0.11 ± 0.07^{a}	–0.10 ± 0.04^{a}	0.00 ± 0.22^{a}	–0.05 ± 0.07^{a}	–0.04 ± 0.04^{a}	–0.07 ± 0.06^{a}
CO_2 (kg C/ha/season)	1 370 ± 217^{d}	1 834 ± 376^{ab}	1 455 ± 255^{cd}	2 034 ± 232^{a}	1 694 ± 86^{bc}	2 029 ± 214^{a}
N_2O (kg N/ha/season)	0.52 ± 0.16^{c}	0.52 ± 0.32^{c}	1.38 ± 0.24^{c}	2.92 ± 0.50^{b}	5.04 ± 2.04^{a}	1.40 ± 0.39^{c}

The cumulative emissions of a gas followed by different superscript letters are significantly different between different treatments during the same seasons at a level of $P < 0.05$. CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

Table 3. Soil gains of organic carbon through urea (kg C/ha) and plant residues (kg C/ha) at harvest stages and net ecosystem carbon budget (NECB, kg C/ha) for different treatments

Season		CK	PK	N	NP	NK	NPK
Rice	straw	265 ± 12	478 ± 6	557 ± 20	657 ± 21	703 ± 17	742 ± 31
	root	295 ± 9	585 ± 22	551 ± 12	757 ± 61	822 ± 70	1 010 ± 41
	urea	0 ± 0	0 ± 0	65 ± 5	65 ± 2	65 ± 3	65 ± 1
	NECB	–400 ± 16	–150 ± 3	279 ± 12	159 ± 4	546 ± 17	456 ± 17
Fallow	straw*	120 ± 5	127 ± 5	118 ± 1	129 ± 7	119 ± 1	134 ± 15
	NECB	–534 ± 16	–1 021 ± 42	–729 ± 27	–654 ± 14	–835 ± 36	–914 ± 56
Wheat	straw	175 ± 7	195 ± 2	158 ± 1	267 ± 12	110 ± 4	443 ± 9
	root	85 ± 2	109 ± 4	81 ± 3	183 ± 5	60 ± 1	344 ± 30
	urea	0 ± 0	0 ± 0	58 ± 2	58 ± 2	58 ± 2	58 ± 2
	NECB	–1 110 ± 42	–1 530 ± 30	–1 158 ± 30	–1 526 ± 62	–1 466 ± 81	–1 184 ± 39
Total	straw	560 ± 27	800 ± 21	833 ± 20	1 053 ± 51	932 ± 26	1 319 ± 82
	root	380 ± 30	694 ± 26	632 ± 34	940 ± 13	882 ± 40	1 354 ± 77
	urea	0 ± 0	0 ± 0	123 ± 4	123 ± 4	123 ± 3	123 ± 3
	NECB	–2 043 ± 79	–2 701 ± 80	–1 608 ± 61	–2 021 ± 64	–1 755 ± 79	–1 642 ± 75

*The collected weed biomass was not further divided into parts of straw and root. CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

https://doi.org/10.17221/693/2019-PSE

Table 4. Crop grain yields, net global warming potential (GWP) and greenhouse gas intensity (GHGI) for different treatments

Season	CK	PK	N	NP	NK	NPK
Rice						
Grain yield (kg/ha)	2 648 ± 70	4 640 ± 173	4 476 ± 205	5 723 ± 120	6 935 ± 245	8 348 ± 546
CH_4 (kg CO_2-eq/ha)	1 925 ± 71	3 261 ± 71	3 585 ± 171	5 285 ± 230	3 621 ± 103	4 483 ± 379
N_2O (kg CO_2-eq/ha)	75 ± 3	54 ± 2	96 ± 3	125 ± 7	200 ± 13	71 ± 1
NECB (kg CO_2-eq/ha)	–1 467 ± 68	–550 ± 24	1 023 ± 44	585 ± 32	2 002 ± 92	1 672 ± 58
Net GWP (kg CO_2-eq/ha)	3 466 ± 135	3 866 ± 129	2 658 ± 109	4 825 ± 276	1 819 ± 146	2 882 ± 207
GHGI (kg CO_2-eq/kg grain)	1.31 ± 0.07	0.83 ± 0.05	0.59 ± 0.01	0.84 ± 0.03	0.26 ± 0.02	0.35 ± 0.02
Fallow						
CH_4 (kg CO_2-eq/ha)	0 ± 0	–1 ± 0	0 ± 0	15 ± 1	15 ± 0	5 ± 0
N_2O (kg CO_2-eq/ha)	96 ± 3	67 ± 4	158 ± 9	129 ± 7	121 ± 8	100 ± 5
NECB (kg CO_2-eq/ha)	–1 958 ± 48	–3 744 ± 86	–2 673 ± 65	–2 400 ± 97	–3 063 ± 183	–3 352 ± 174
Net GWP (kg CO_2-eq/ha)	2 054 ± 87	3 809 ± 102	2 831 ± 88	2 544 ± 174	3 199 ± 126	3 457 ± 68
Wheat						
Grain yield (kg/ha)	948 ± 62	953 ± 30	983 ± 61	2 064 ± 64	766 ± 29	3 738 ± 41
CH_4 (kg CO_2-eq/ha)	–4 ± 0	–4 ± 0	0 ± 0	–2 ± 0	–1 ± 0	–3 ± 0
N_2O (kg CO_2-eq/ha)	217 ± 9	217 ± 8	575 ± 41	1 216 ± 95	2 099 ± 54	583 ± 23
NECB (kg CO_2-eq/ha)	–4 070 ± 120	–5 610 ± 324	–4 246 ± 119	–5 595 ± 180	–5 375 ± 175	–4341 ± 305
Net GWP (kg CO_2-eq/ha)	4 282 ± 176	5 823 ± 171	4 821 ± 388	6 809 ± 279	7 472 ± 309	4 921 ± 350
GHGI (kg CO_2-eq/kg grain)	4.52 ± 0.17	6.11 ± 0.23	4.90 ± 0.29	3.30 ± 0.17	9.76 ± 0.57	1.32 ± 0.11
Total						
Grain yield (kg/ha)	3 596 ± 144	5 593 ± 149	5 459 ± 121	7 787 ± 397	7 701 ± 597	12 086 ± 591
CH_4 (kg CO_2-eq/ha)	1 920 ± 120	3 257 ± 128	3 585 ± 123	5 298 ± 152	3 635 ± 242	4 485 ± 191
N_2O (kg CO_2-eq/ha)	387 ± 23	337 ± 16	829 ± 50	1 470 ± 78	2 419 ± 147	754 ± 12
NECB (kg CO_2-eq/ha)	–7 491 ± 265	–9 904 ± 640	–5 896 ± 281	–7 410 ± 235	–6 436 ± 296	–6 021 ± 386
Net GWP (kg CO_2-eq/ha)	9 799 ± 240	13 498 ± 525	10 310 ± 651	14 178 ± 659	12 491 ± 765	11 260 ± 684
GHGI (kg CO_2-eq/kg grain)	2.72 ± 0.10	2.41 ± 0.12	1.89 ± 0.07	1.82 ± 0.08	1.62 ± 0.13	0.93 ± 0.06

NECB – net ecosystem carbon budget; CK – unfertilised control; PK – phosphorus and potassium; N – nitrogen; NP – nitrogen and phosphorus; NK – nitrogen and potassium; NPK – nitrogen, phosphorus and potassium

for the intensively cultivated upland cropping soils in the same region for which the net C emission varied from 2 703 to 6 203 kg C/ha (Mu et al. 2013).

Net GWP. All the soils under different treatments were net contributors to global warming since the net GWPs were always positive for each of the three seasons (Table 4). The annual net GWPs in different treatments ranged from 9 799 to 14 178 kg CO_2-eq/ha, which were falling into the lower end of the range reported for rice paddies or upland fields under conventional management (Mu et al. 2013, Wu et al. 2018). The dried wheat season contributed 43% to 60% of the annual net GWPs from different treatments. The fallow season further elevated the proportion to 65% to 85%, while the rice season covered the remaining 15% to 35%. The annual net GWPs were not significantly different between control and N treatments. The net GWPs from other treatments, however, increased by 12% to 42% when compared with the control. Annual CH_4 emission from different treatments was exclusively derived from the flooding rice season, and the contribution to annual overall net GWPs ranged from 20% at the control to 40% at the NPK (Table 4). In contrast, the dried wheat season occupied 54% to 84% of annual net CO_2 emission and 56% to 87% of annual N_2O emission. The relative contribution of net CO_2 emission to the overall net GWPs ranged from 52% to 76%, and the contribution of N_2O ranged from 2% to 19% for different treatments. During the rice season, the grain yields of fertilised treatments were 2 to 3 times higher than that of the control with NPK showing the highest results (Table 4). Similarly, NPK performed the best during the wheat season with grain yield being

2 to 5 times higher than those of other treatments. A strong negative relationship existed between seasonal grain yields (i.e., rice or wheat) and seasonal GHGI (R^2 = 0.62 to 0.76). On the annual basis, the lowest GHGI of 0.93 kg CO_2-eq/kg grain yield was observed at the NPK treatment, which was nearly by 43% to 66% lower than those at other treatments.

It can be concluded that net CO_2 and N_2O emissions from the dried seasons and CH_4 emissions from the flooding season dominated the annual budgets of individual GHGs in the summer rice-winter wheat cropping system with CO_2 overwhelmingly contributing to the overall net GWPs. Irrespective of the confounding impact of different combinations of mineral fertilisers on GHGs fluxes and net GWPs, the concomitant application of N, P and K could not only achieve the highest crop yield but also guarantee the lowest GHGI, suggesting it to be the optimum environmentally-friendly fertilisation practice for the summer rice-winter wheat cropping system.

REFERENCES

Atere C.T., Ge T.D., Zhu Z.K., Liu S.L., Huang X.Z., Shibsitova O., Guggenberger G., Wu J.S. (2019): Assimilate allocation by rice and carbon stabilisation in soil: effect of water management and phosphorus fertilisation. Plant and Soil, 445: 153–167.

Cai Z.C., Shan Y.H., Xu H. (2007): Effects of nitrogen fertilization on CH_4 emissions from rice fields. Soil Science and Plant Nutrition, 53: 353–361.

Datta A., Santra S.C., Adhya T.K. (2013): Effect of inorganic fertilizers (N, P, K) on methane emission from tropical rice field of India. Atmospheric Environment, 66: 123–130.

FAO (2017): FAO Statistical Databases. FAO, Rome. Available at: http://faostat.fao.org/

Haque Md.M., Kim S.Y., Ali M.A., Kim P.J. (2015): Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. Plant and Soil, 387: 251–264.

Herbert E.R., Schubauer-Berigan J.P., Craft C.B. (2020): Effects of 10 yr of nitrogen and phosphorus fertilization on carbon and nutrient cycling. Limnology and Oceanography. doi: 10.1002/lno.11411

IPCC (2014): Climate change 2014-synthesis report: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the IPCC. Geneva, Intergovernmental Panel on Climate Change.

Kim G.W., Gutierrez-Suson J., Kim P.J. (2019): Optimum N rate for grain yield coincides with minimum greenhouse gas intensity in flooded rice fields. Field Crops Research, 237: 23–31.

Ley M., Lehmann M.F., Niklaus P.A., Luster J. (2018): Alteration of nitrous oxide emissions from floodplain soils by aggregate size, litter accumulation and plant-soil interactions. Biogeosciences, 15: 7043–7057.

Medvedeff C.A., Inglett K.S., Inglett P.W. (2014): Evaluation of direct and indirect phosphorus limitation of methanogenic pathways in a calcareous subtropical wetland soil. Soil Biology and Biochemistry, 69: 343–345.

Mori T., Ohta S., Ishizuka S., Konda R., Wicaksono A., Heriyanto J., Hardjono A. (2013): Effects of phosphorus addition with and without ammonium, nitrate, or glucose on N_2O and NO emissions from soil sampled under *Acacia mangium* plantation and incubated at 100% of the water-filled pore space. Biology and Fertility of Soils, 49: 13–21.

Mu Z.J., Huang A.Y., Ni J.P., Li J.Q., Liu Y.Y., Shi S., Xie D.T., Hatano R. (2013): Soil greenhouse gas fluxes and net global warming potential from intensively cultivated vegetable fields in southwestern China. Journal of Soil Science and Plant Nutrition, 13: 566–578.

Shang Q.Y., Yang X.X., Gao C.M., Wu P.P., Liu J.J., Xu Y.C., Shen Q.R., Zou J.W., Guo S.W. (2011): Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. Global Change Biology, 17: 2196–2210.

Smith P., Lanigan G., Kutsch W.L., Buchmann N., Eugster W., Aubinet M., Ceschia E., Béziat P., Yeluripati J.B., Osborne B., Moors E.J., Brut A., Wattenbach M., Saunders M., Jones M. (2010): Measurements necessary for assessing the net ecosystem carbon budget of croplands. Agriculture, Ecosystems and Environment, 139: 302–315.

Song C.C., Yang G.S., Liu D.Y., Mao R. (2012): Phosphorus availability as a primary constraint on methane emission from a freshwater wetland. Atmospheric Environment, 59: 202–206.

Wang L., Sheng R., Yang H.C., Wang Q., Zhang W.Z., Hou H.J., Wu J.S., Wei W.X. (2017): Stimulatory effect of exogenous nitrate on soil denitrifiers and denitrifying activities in submerged paddy soil. Geoderma, 286: 64–72.

Wu L., Wu X., Lin S., Wu Y.P., Tang S.R., Zhou M.H., Shaaban M., Zhao J.S., Hu R.G., Kuzyakov Y., Wu J.S. (2018): Carbon budget and greenhouse gas balance during the initial years after rice paddy conversion to vegetable cultivation. Science of The Total Environment, 627: 46–56.

Wu K.K., Gong P., Zhang L.L., Wu Z.J., Xie X.S., Yang H.Z., Li W.T., Song Y.C., Li D.P. (2019): Yield-scaled N_2O and CH_4 emissions as affected by combined application of stabilized nitrogen fertilizer and pig manure in rice fields. Plant, Soil and Environment, 65: 497–502.

Xia L.L., Wang S.W., Yan X.Y. (2014): Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice-wheat cropping system in China. Agriculture, Ecosystems and Environment, 197: 118–127.

Yang X., Shang Q., Wu P., Liu J., Shen Q., Guo S., Xiong Z. (2010): Methane emissions from double rice agriculture under long-term fertilizing systems in Hunan, China. Agriculture, Ecosystems and Environment, 137: 308–316.

Zhou M.H., Zhu B., Wang X.G., Wang Y.Q. (2017): Long-term field measurements of annual methane and nitrous oxide emissions from a Chinese subtropical wheat-rice rotation system. Soil Biology and Biochemistry, 115: 21–34.

Received: December 24, 2019
Accepted: April 6, 2020
Published online: April 20, 2020