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Tillage, residue and nitrogen management effects on methane and nitrous oxide emission from rice–wheat system of Indian Northwest Indo-Gangetic Plains

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ABSTRACT

Zero-tillage, residue management and precision nutrient management techniques are being promoted in the rice–wheat (RW) production system of Indo-Gangetic Plains (IGPs) to enhance climate change adaptation and increase food production. These management practices may also influence greenhouse gas emissions through their effects on various soil processes such as oxidation-reduction and nitrification–denitrification. We measured soil fluxes of CH_4 and N_2O in RW system under three tillage and residue management systems layered with four nitrogen (N) management treatments. The tillage and residue management systems comprised: conventional tillage (CT), zero-tillage without residue retention (ZT − R) and ZT with full residue retention (ZT + R) for both the crops. The four N management treatments for rice were: (a) basmati cultivar with recommended dose of nitrogen (RDN) applied in three splits, (b) basmati cultivar with 80% RDN as basal dose followed by Green Seeker (GS) guided N application, (c) hybrid cultivar with RDN applied in three splits and (d) hybrid with 80% RDN as basal dose followed by GS guided N application. The four N management treatments for wheat comprised combinations of RDN with and without relay green gram (GG), and 80% of RDN as basal dose followed by GS guided N application with and without relay GG. We employed the static chamber method to collect gas samples from the experimental plots which were subsequently analysed using gas chromatograph. Significant CH_4 emissions were detected only in the CT rice system during the initial phase of continuous flooding, irrespective of N management strategies. N fertilization management affected the pattern of N_2O emission with higher emission rates during crop establishment phase under 80% RDN as basal followed by GS guided N application than conventional RDN. In case of wheat, 80% RDN as basal followed by GS guided N application also induced higher cumulative N_2O emissions than applying RDN at three regular splits. In rice, ZT-based RW system emitted more N_2O than CT-based system. Overall ZT-based RW system reduced CH_4 emission but this benefit is counterbalanced by higher N_2O production compared to CT-based RW system.

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1. Introduction

The Indo-Gangetic Plain (IGP) of South Asia is home to nearly one billion people. In Indian IGP, Rice (*Oryza sativa* L.)–Wheat (*Triticum aestivum* L.) (RW) is the dominant cropping system, occupying about 10.3 million ha and accounts for 23% and 40% of India's rice and wheat area, respectively (Gathala et al. 2013). Rice is grown during the summer season (June to October) and wheat during the winter season (November to April), leaving the land fallow for about 60–65 days after wheat harvest until rice planting. However, sustainability of conventional RW system has recently been questioned due to the high labour, water and energy requirements (Jat et al. 2009; Kumar et al. 2013) which are gradually becoming scarce and expensive.

In RW system, the soil and water requirements of the two crops are drastically different. Rice seedlings are generally transplanted in puddled and submerged soils, while wheat is planted in a well-pulverized, aerobic soil to attain potential yield. These cycles of aerobic and anaerobic conditions in the soil considerably influence CH_4 and N_2O emissions in RW system.

Nitrous oxide from soil is emitted during the processes of nitrification and denitrification under alternate wetting and drying cycles in RW system. Biochemical decomposition of organic matter in anaerobic environments, known as methanogenesis, is responsible for CH_4 emission. In the rice fields, anaerobic conditions occur due to continuous flooding and are considered to be one of the most important source of atmospheric CH_4 (Neue et al. 1997). In India, CH_4 emission from rice constitute 21% of total agricultural emission (INCCA 2010). Further, farmers apply large amounts of nitrogenous fertilizer in RW system of IGP (Sapkota et al. 2014), portion of which is lost through soil N_2O emission. These emissions together with large amount of emission associated with production and transportation of fertilizer (about 100 million tons CO_2-eq year^{-1}) (Jat et al. 2015) makes RW system one of the major contributor of agricultural greenhouse gas (GHG) emission in India.

Conservation agriculture (CA) based technologies involving minimum soil tillage, retention of crop residues on soil surface and appropriate crop rotation are being advocated as alternatives to conventional RW systems for improving productivity and enhancing resource use efficiency (Ladha et al. 2009; Saharawat et al. 2011; Gathala et al. 2013). The CA technologies are also reported to reduce GHG emission mainly due to reduced use of the inputs and also by modifying soil environment (Sapkota et al. 2014; Aryal et al. 2015). Tillage and crop establishment, residue and water management, and timing and method of N application practices are known to affect emissions of GHGs from soil. For example, decreasing number of irrigations and duration of flooding in rice field will periodically elevate soil redox potential (Eh) thereby reducing CH_4 emission; at the same time saving irrigation water and increasing yield (Li 2011). However, this process may induce N_2O emission. The potential benefits of CA-based practices on productivity, profitability and soil quality have been widely studied but their effects on GHG emissions from soil are rarely studied and the results are inconsistent. For example, conventional tillage (CT) has been reported to either increase (Ussiri et al. 2009), have no effect (Jantalia et al. 2008; Dendooven et al. 2012) or decrease (Steinbach & Alvarez 2006) emission of N_2O compared to zero tillage (ZT) systems. To address current gaps in knowledge on the GHG mitigation potential of CA-based practices, field experiment was established in 2011 to quantify the effect of tillage, residue and N management techniques on CH_4 and N_2O emissions in RW cropping system. The data presented here comes from two cycles of RW rotation i.e. 2011–12 and 2012–13.

Table 1. Basic soil properties of the study site (0–15 cm depth).

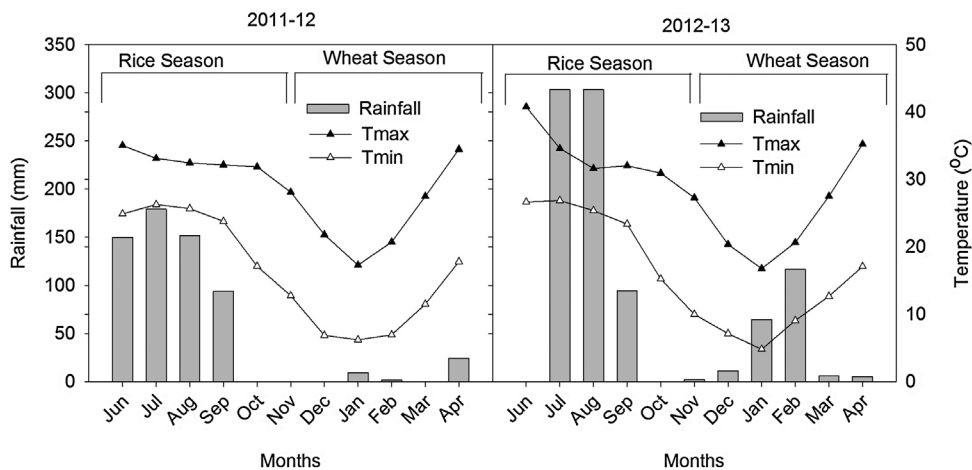| Soil properties	Value
pH	7.6
Electrical conductivity (ds m^{-1})	0.34
Soil organic carbon (%)	0.71
Available nitrogen (kg ha^{-1})	95
Available phosphorous (kg ha^{-1})	16
Available potassium (kg ha^{-1})	281

Figure 1. Monthly minimum temperature (mean), maximum temperature (mean) and rainfall (total) of the experimental site during 2011–2012 and 2012–2013 RW season.

2. Material and methods

2.1. Experimental site

The experiment was conducted at village Taraori (29°48′35″ N and 76°55′16″ E) in Karnal district of Haryana, India. Although the experiment was designed, executed and managed by researchers, farmers were actively participated in technology testing and the research site was taken as strategic learning platform. The field was under continuous RW rotation for more than fifteen years. The soil of the experimental site is sandy clay loam with medium organic matter content. Soil properties of the experimental field at the beginning of experiment are presented in Table 1. The climate of the area is semi-arid, with average annual rainfall of 700 mm, 75–80% of which is received during June–September (Figure 1). The lowest temperature is observed during January (daily minimum ranges from 0–4 °C) and the highest temperature is observed during June (daily maximum ranges from 40–44 °C). Monthly rainfall distribution along with minimum and maximum temperature during two experimental years is presented in Figure 1.

2.2. Experimental design and treatment

Three main-plot factors and four sub-plot factors were factorially combined in a split-plot design with three replications. Three main-plot factors included in this study involved

Table 2. Description of three tillage and residue management methods (main plot factors) included in the study. CT = conventional tillage, ZT − R, ZT without residue retention, ZT + R, ZT with retention of previous crop residues.

Main plot factor	Tillage and crop establishment		Residue management
	Rice	Wheat	Both crops
CT	3 passes of dry tillage with harrow, 2 passes of cultivator in ponded water followed by 1 planking. Rice seedlings are manually transplanted in random geometry	2 passes of harrow, 1 pass of cultivator followed by 1 planking. Wheat seeds are broadcasted in random geometry	All removed
ZT − R	No preparatory tillage. Dry rice seeds are directly seeded on flat soil in row geometry using no-till seed-cum-fertilizer drill.	No preparatory tillage. Wheat seeds are directly seeded on flat soil in row geometry using no-till seed-cum-fertilizer drill	All removed
ZT + R	Same as in ZT except that seeding was done with 'happy turbo seeder' a no-till drill that can handle previous crop residue	Same as in ZT except that seeding was done with 'happy turbo seeder' a no-till drill that can handle previous crop residue	All retained

combination of tillage and residue management methods for both rice and wheat, details of which are given in Table 2. Sub-plot treatments in rice included combination of two rice varieties (Basmati and Hybrid) and two N management strategies as below:

(1) Basmati (var. Pusa-1121) with recommended dose of nitrogen-RDN (Basmati + RDN)
(2) Hybrid (Arize 6129) with RDN (Hybrid + RDN)
(3) Basmati (Pusa-1121) with 80% of RDN as basal supplemented with Green Seeker (GS) guided application (Basmati + 80%RDN + GS)
(4) Hybrid (Arize 6129) with 80% of RDN as basal supplemented with GS guided application (Hybrid + RDN + GS).

Sub-plot treatments in succeeding wheat included combination of green gram (GG) (*Vigna Radiata* L.) and N management strategies as:

(1) RDN
(2) RDN with relay GG at last irrigation of wheat (RDN + GG)
(3) 80% of RDN as basal supplemented with GS guided application (80%RDN + GS)
(4) 80% of RDN as basal supplemented with GS guided application followed by relay GG at last irrigation of wheat (80%RDN + GS + GG).

2.3. Crop management

In CT system, rice seedlings were raised using a seed rate of 12 kg ha^{-1} and 25 days old seedlings were transplanted manually in random geometry with about 30 seedlings m^{-2}. In this system, wheat seeds (150 kg seed ha^{-1}, var DPW 621–50) were broadcasted after land preparation and incorporated into the soil with the last tillage operation (Table 2). In the zero-tillage system without residue retention (ZT − R), both rice and wheat were seeded without any preparatory tillage at a row spacing of 20 cm using ZT seed-cum fertilizer drill

having inclined-rotary-plate seed metering systems. The metering plate has a variable grove size and number and therefore same driller can be used for direct seeding of different crops by simply changing the inclined plates (Kapil et al. 2012). In zero-tillage system with residue retention (ZT + R), both rice and wheat crops were seeded at 20 cm row spacing using "turbo happy seeder" which is capable of direct drilling of seed and fertilizer on the surface with previous crop residues (Sidhu et al. 2015) . In both the ZT systems (ZT − R and ZT + R), seed rate was 25 and 100 kg ha^{-1} for rice and wheat, respectively. Crops were fertilized according to the nutrient prescription of Chaudhary Charan Sigh Haryana Agricultural University, Hisar, Haryana (India). The RDN rates are 90 kg, 120 kg and 150 kg ha^{-1} for basmati rice, hybrid rice and wheat, respectively. Both rice and wheat received uniform application of 60 kg P_2O_5 and 50 kg K_2O ha^{-1}. In addition, 25 kg ha^{-1} of $ZnSO_4$ as a source of Zn and 20 kg ha^{-1} of bentonite sulphur as a source of sulphur were applied to both basmati and hybrid rice as basal application on all the plots.

In the plots with RDN, the total amount P and K and 33% of N was applied as basal dose at the time of seeding/transplanting and the remaining two-third of N was applied in two equal splits at 20–25 and 40–45 days after seeding/transplanting in rice and wheat. In the plots with 80% RDN + GS, total amount P and K along with 80% of RDN was applied as basal dose at the time of seeding/transplanting and the remaining N was applied as guided by the GS optical sensor using a standard calibration curve (Bijay-Singh et al. 2011).

During the rice cycle, CT plots were kept continuously flooded (5 cm standing water) for the initial one month and the subsequent irrigations were scheduled at the appearance of hairline cracks on the soil surface i.e. around −40 to −50 kPa matric potential (Gathala et al. 2011a). In ZT plots, first irrigation was applied immediately after seeding. The second irrigation was given one week after seeding and subsequent irrigations were applied as described under CT system.

Irrespective of the tillage and residue management, wheat received a total of 4 irrigations (6–7 cm each) at 20–25, 45–50, 75–80 and 95–100 days after sowing. In ZT plots (ZT − R and ZT + R), weeds prior to seeding of rice and wheat were killed by pre-plant application of glyphosate (1.25 g a.i. ha^{-1}) but no herbicides were applied in CT plots before seeding. To control the grassy weeds in rice, CT plots were sprayed with butoachlor (@1300 g a.i. ha^{-1}) 2 days after transplanting whereas ZT plots with and without residue retention were sprayed with Topstar (112 g a.i. ha^{-1}) 2 days after sowing followed by spray application of Nominee gold (Bispayriback sodium, 50 ml a.i. ha^{-1}) at 25 days after sowing. Post emergence weeds in wheat were controlled by spray application of Total (metsulfuran methyl 75% + Sulfosulfuran, 1250 ml a.i ha^{-1}).

2.4. Determination of biomass yield and carbon input

In order to estimate the carbon input to the soil, total biomass yield of rice and wheat was measured at harvest. Biomass yield was determined by manually harvesting the crop from 1×5 m^{-2} randomly selected 3 quadrates within each plot for both rice and wheat. The aboveground dry biomass returned to the soil was calculated as a fraction of straw yield returned to the field. Based on our experience, we assumed 5% of aboveground biomass was returned to the field even in the treatments where aboveground residues were removed. In the plots with residue retention, straw yield was considered as the total aboveground biomass returned into the soil. Root biomass was calculated based on the published values

of shoot: root ratio; 5.66 for rice (Salam et al. 1997) and 7.4 for wheat (Bolinder et al. 2007). The carbon input was estimated considering a concentration of 0.45 kg C kg^{-1} dry matter biomass (Johnson et al. 2006).

2.5. GHG flux measurement and calculation

The GHG (CH_4 and N_2O) flux from the soil was measured using static chamber method. The concentration of specific gas in the sample were analysed on gas chromatograph. The details of gas sampling method, sampling protocol and analysis are described below.

2.5.1. Collection of gas sample

Gas samples were collected using two-part static chambers. The base of the chamber (43 cm i.d.) made up of the galvanised steel was semi-permanently installed in the plots keeping two rows of plants inside the chamber. It consisted of a circular channel to hold the upper part of the chamber. At the time of sampling, the upper part of the chamber was placed over the base of the chamber giving a total headspace volume of 105.41 L. The circular channel was filled with water and vents were sealed with adhesive to make the assembly airtight. The chamber was equipped with a battery-powered fan to facilitate mixing of the gas in chamber headspace. Gas sampling commenced just before seeding in each crop. Thereafter, gas samples were collected once a week and for seven consecutive days after fertilizer N application. Gas samples were collected through a septum fitted on the chamber using a 50 ml polypropylene disposable syringe with three-way leur lock. The gas (50 ml) in the syringe was injected into the pre-evacuated and labelled 30 ml vials, which ensured higher pressure inside the vial to avoid contamination from ambient air. At each sampling, gas samples were collected at an interval of 0, 10, 20 and 30 min. Sampling was performed during time of the day when soil surface temperature is believed to be equal to the daily average i.e. between 10:00 and 13:00 h.

2.5.2. GHG analysis

Collected air samples were analysed for GHG (CH_4 and N_2O) using a Gas Chromatograph (GC) equipped with flame ionization detector (FID) and electron capture detector (ECD). To address the issue of GC drift, GC was calibrated periodically using standards of CH_4, N_2O and CO_2 of known concentration from Linde Engineering India Pvt. Ltd.

2.5.3. Data analysis and interpretation

Gas concentration at each sampling period was converted into mole of gas by using ideal gas law taking chamber temperature into account. The mole unit of gas was then converted into weight of gas considering the molecular weight of a particular gas. Linear regression was performed considering sampling time as independent variable and gas concentration as dependent variable to calculate the rate of gas emission per unit of time to come up with the flux per unit area per day. The fluxes in between two sampling dates were estimated by linear interpolation. To determine the global warming potential from soil emission, N_2O
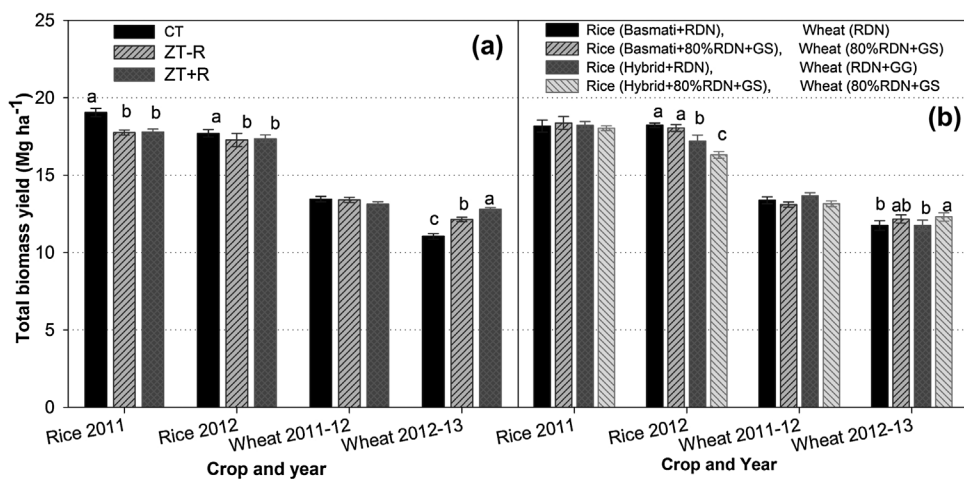
Figure 2. Total aboveground biomass yield of rice and wheat during two years of experimentation as affected by (a) tillage & residue management and (b) variety & N management (in rice) and N management and green gram (in wheat). Within main-plot and sub-plot factors and within crop-year, bars bearing different lowercase letters are significantly different from each other based on LSD test ($p = 0.05$).

and CH_4 were converted into CO_2 equivalents using 100 year time horizon factors of 310 for N_2O and 21 for CH_4 (IPCC 2007).

3. Results and discussion

3.1. Biomass yield

Interaction effects of main-plot and sub-plot treatments were not significant for total biomass yield in both the years. Therefore, simple effects are reported and discussed. In rice, tillage and residue management significantly affected total aboveground biomass yield of rice in both 2011 and 2012 (Figure 2(a)). In both the years, total biomass yield (grain + straw) of rice was significantly higher in CT than in ZT − R and ZT + R. The biomass yield of rice under ZT system was similar with and without residue retention in both the years. Higher rice biomass yield under CT system as compared to ZT system can be attributed to better weed control (visual observation, data not collected), reduction in percolation loss of water and nutrients, quick establishment of seedlings and improved nutrient availability as reported by other researchers from the region (Gathala et al. 2011a; Jat et al. 2014). In RW system, yield benefit of ZT in rice is manifested only after 3–4 years whereas that in wheat can be obtained right from the first year (Jat et al. 2014). Reduced biomass yield in rice with the conversion of CT system to ZT system in initial years of study has also been reported by other researchers in this region (Jat et al. 2009, 2014; Kumar & Ladha 2011). On the other hand, effect of sub-plot treatments (combinations of variety and N management) was significant only in 2012. In this year, total biomass yield was significantly higher in the case of Basmati rice as compared to hybrid rice under both N management strategies. In general, the hybrid yielded more grain than basmati whereas basmati yielded more straw than hybrid. N management did not significantly affect biomass yield of rice.
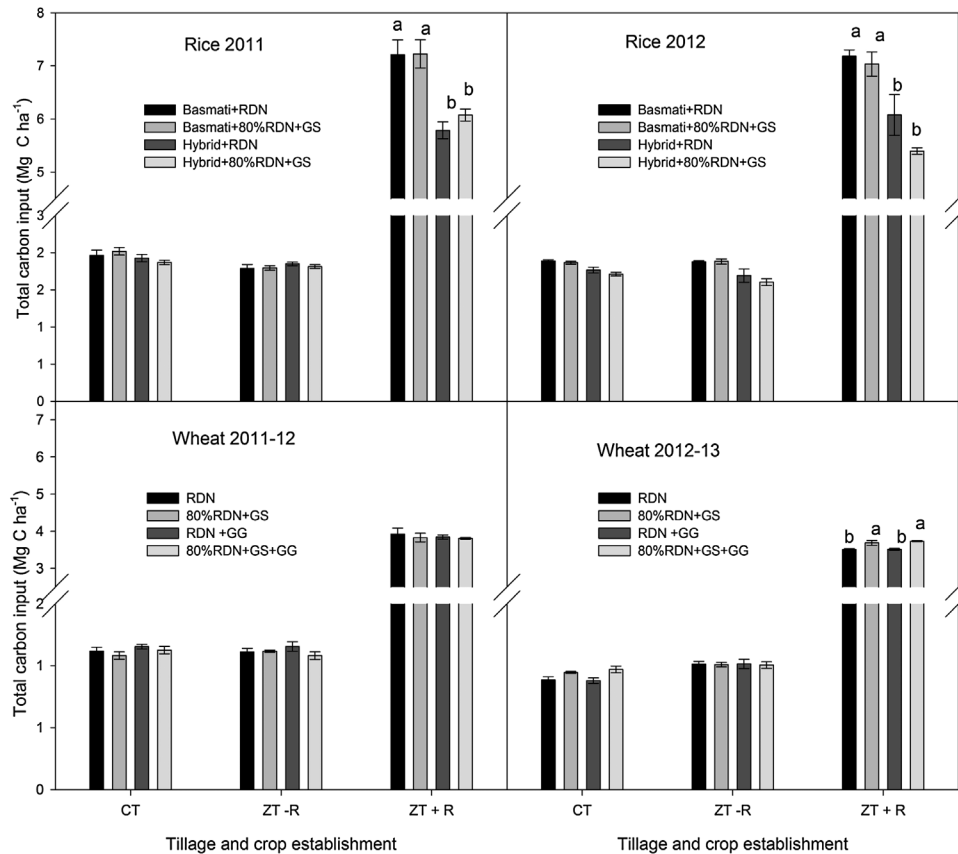
Figure 3. Total C input from rice and wheat during two years of experimentation as affected by tillage & residue management and variety & N management. Within a crop and year, means followed by different lowercase letters are significantly different from each other based on LSD test ($p = 0.05$).

In the case of wheat, total biomass yields were similar under different tillage and residue management as well as N management treatments in the first year. In the second year, tillage & residue management as well as N management had significant effects on total biomass production (Figure 2(a) and (b)). Tillage by N management interaction was not significant for grain, straw as well as total biomass yield in both the years. In second year, wheat biomass yield was significantly higher in ZT + R followed by ZT − R; CT recorded the lowest biomass yield (Figure 2(a)). Our findings are in agreement with the results of other researchers in IGP region (Jat et al. 2009; Gathala et al. 2011a) who reported higher wheat yield after direct seeded rice than after puddled transplanted rice. Higher wheat yield after direct seeded rice compared to that after puddled transplanted rice in our study was probably due to better root system and early establishment of wheat as a result of improved soil physical properties. Puddling is known to create compact layer at 15–25 cm depth and to disrupt soil aggregates which consequently results into poor root development and growth of subsequent wheat (Jat et al. 2009; Gathala et al. 2011b, 2011a).

Interaction effects of main plot (tillage and residue management) and sub-plot (combination of variety and N management) treatments were significant for total amount of C input
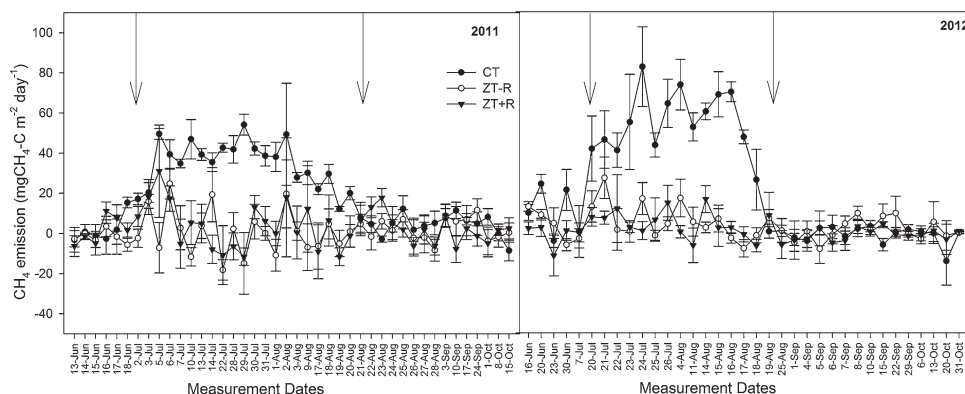
Figure 4. Daily CH4 emission during 2011 and 2012 rice growing season as affected by tillage and residue management. The mean values are averaged over four sub-plot factors (combination of variety and N management) and three replications ($n = 12$). The vertical bars show the standard errors of the mean.

from rice in RW system in both years. In both the years, the effect of sub-plot treatments on total C input from rice was not significant under CT and ZT − R systems where residues were taken off the field. But the sub-plot treatment effect was significant under ZT + R system where residues were retained in the field. In this system, the treatments with basmati rice had higher C input than the treatments with hybrid rice in both the years (Figure 3, upper panels), N management had no significant effect on total C input from rice. This is mainly because higher residue (straw) yields of Basmati as compared to hybrid. In ZT + R total residues of both rice and wheat were retained in the field (Table 2).

Main-plot by sub-plot interaction effect on total C input from wheat was significant only in second year. However, for the uniformity of presentation main-plot by sub-plot effects are presented for both the years (Figure 3, lower panels). In ZT + R, applying 80% RDN as basal followed by GS guided N application (with and without GG) provided significantly higher C input from wheat than three splits of RDN (Figure 3, lower right panel). This differential effect of N management on biomass C input under different tillage and residue management was mainly due to the differences in the magnitude of biomass returning into the systems. In the CT and ZT system without residue retention, about 5% of total biomass yield was returned into the system whereas in ZT + R 100% of the total residue was retuned into the system.

3.2. CH$_4$ emission

During rice season, CH$_4$ emission was detected only in CT plots but not in ZT plots irrespective of residue management. The trend of CH$_4$ emission was similar in Basmati and Hybrid and under both N management strategies. Therefore, daily emissions averaged over main plot factor (tillage and residue management) are presented. In CT plots, CH$_4$ emission started immediately after transplanting in both the years and continued for about a month, after which no CH$_4$ emission was observed. Elevated CH$_4$ emission was observed after 5th July in 2011(transplanted on 4th July) and after 20th July in 2012 (transplanted on 18th July) (Figure 4). CH$_4$ emission in our study was influenced by water management in rice field. In CT plots, continuous standing water was maintained for about a month after transplanting during which soil reduction occurs. In both the years, soil redox potential during this

continuous flooding period in CT plots was below −150 mV. Thereafter irrigation in CT plots was scheduled based on appearance of hairline (very small) cracks on the soil surface. No CH_4 emission was observed when irrigation was scheduled based on appearance of hairline cracks on the soil surface. In ZT plots (with and without residue retention), standing water could be observed only on the day of irrigation but the field would remain moist until next irrigation. Therefore, no CH_4 emissions were detected in these plots during the whole rice growing period. We speculate that despite increased availability of carbon in ZT + R plots, non-emission of CH_4 was because soil redox potential (Eh) remained above the critical level needed for methanogenesis. In ZT − R and ZT − R plots, soil redox potential were negative from 10 days after sowing until about 60 days after sowing but were never dropped below −100 mV. Methane is usually produced when the soil Eh is sufficiently low, typically less than −100 mV (Masscheleyn et al. 1993). Unlike flooded rice in East Asia and China, rice fields in NW India are flooded continuously only during the initial one month after transplanting and thereafter alternate wetting and drying cycles are followed which do not allow development of moisture conditions for methanogenesis. The fluctuation of CH_4 emission from small positive to small negative fluxes in ZT − R and ZT + R during whole rice growing period and in CT during later stage of crop growth could be due to intermittent aerobic conditions favouring the growth of methanotrophs resulting into uptake of CH_4. Negative fluxes of methane during later stages of rice growth has been also reported by Bhatia et al. (2011) and Pathak et al. (2003) from silty clay loam soil of New Delhi, India. In both the years, total seasonal CH_4 emission was much higher in CT based system than ZT based system, irrespective of residue retention (Table 2). CH_4 emission was not detected during the wheat growing season.

3.3. N_2O emission

Seasonal trends of N_2O emission from rice and wheat cropping seasons were similar in all plots irrespective of tillage and residue management as well as N management strategies in both the years of study (Figures 5 and 6). Fertilizer N application clearly induced N_2O emission from soil. N_2O emission from all the plots after fertilizer N application could be due to the marked increase in nitrate content in the soil which was prone to denitrification losses as has been observed by Malla et al. (2005). The fertilizer-induced peak of N_2O emission was higher when fertilizer application was coincided with sufficient moisture causing anaerobic microsites in the field. In rice season, N_2O flux occurred immediately after application of basal fertilizer in 2011 but not in 2012 under ZT − R and ZT + R systems. This was probably induced by favourable soil moisture condition from sufficient rainfall in the month of June in 2011 (Figure 1). No rainfall was received in June 2012 due to which dry soil condition might have arrested the process of denitrification in ZT systems during initial period of rice establishment. In both the years, N_2O emission in CT plots occurred only after cessation of CH_4 emission (Figure 5) when the plots were dried for the first time after continuous flooding. Increased daily emission rate during the peak time was normally higher in ZT + R system in 2012 (Figure 5) probably because of higher carbon availability from crop residues for denitrifying bacteria which was not the case in the first year. Application of 80% RDN as basal induced slightly higher N_2O emission at the beginning of the season than three-split application of RDN but not much difference was observed among N fertilizer application strategies thereafter. Higher N_2O emission at the beginning of the crop season due to application of 80% RDN as basal was more obvious in case of wheat than in rice. Therefore, N_2O
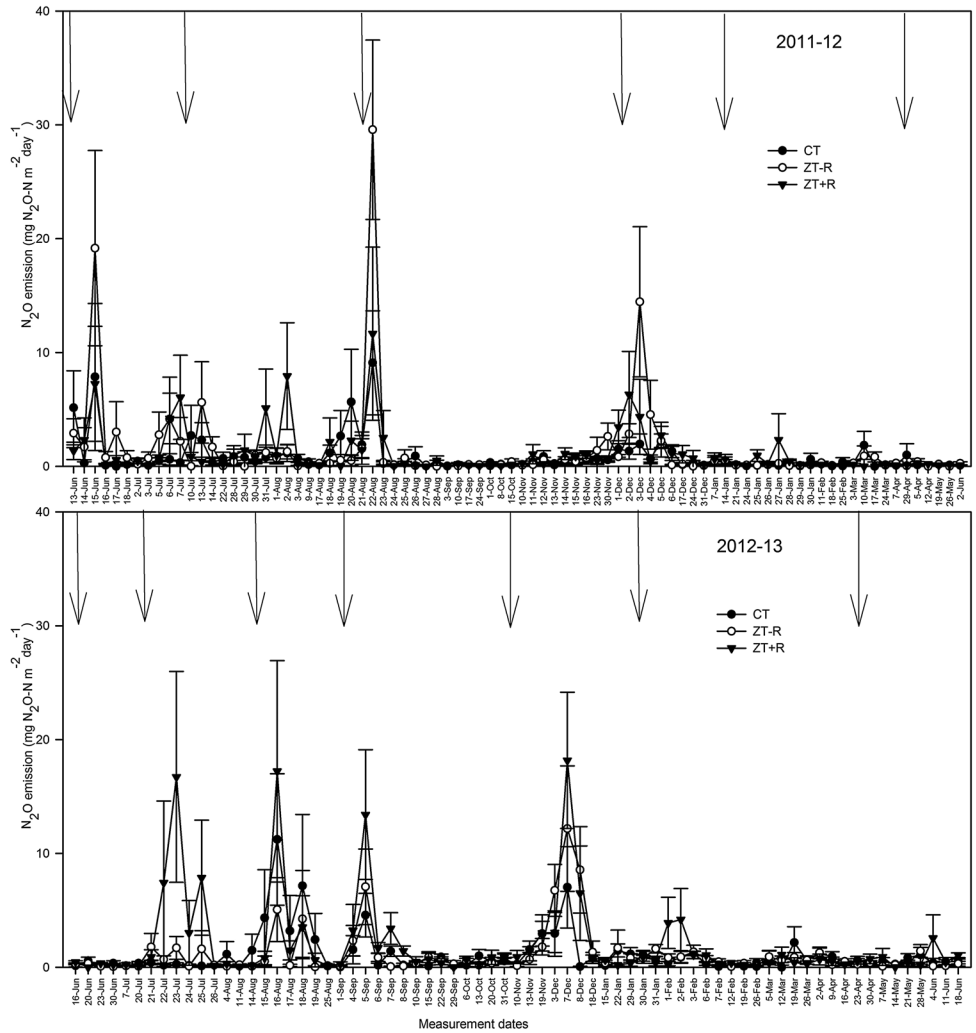
Figure 5. Seasonal trend of N_2O emission during 2011–12 (upper panel) and 2012–13 (lower panel) RW cropping season under different tillage and residue management methods. N_2O emission rate per day in each main-plot factor is averaged over four sub-plot factors (combination of variety and N management in rice and that of green-gram and N management in wheat) and three replications ($n = 12$). The vertical bars show the standard error of the mean. Down arrows indicate the date of fertilizer application.

emission trend induced by N management strategies are presented only for wheat season (Figure 6). Inclusion of GG in the system had no apparent effect on N_2O emission. The biomass growth of GG was not satisfactory in both the years and due to this the influence of GG on soil N dynamics was not significant.

Interactions of main-plot and sub-plot factors were not significant for cumulative CH_4 and N_2O and in both the crops in both years. Therefore, only simple effects are presented and discussed. In 2011, the seasonal cumulative N_2O emission during rice season was higher in ZT-based systems (with and without residue retention) as compared to CT-based systems (Table 3). However, higher N_2O emission under ZT system as compared to CT system was
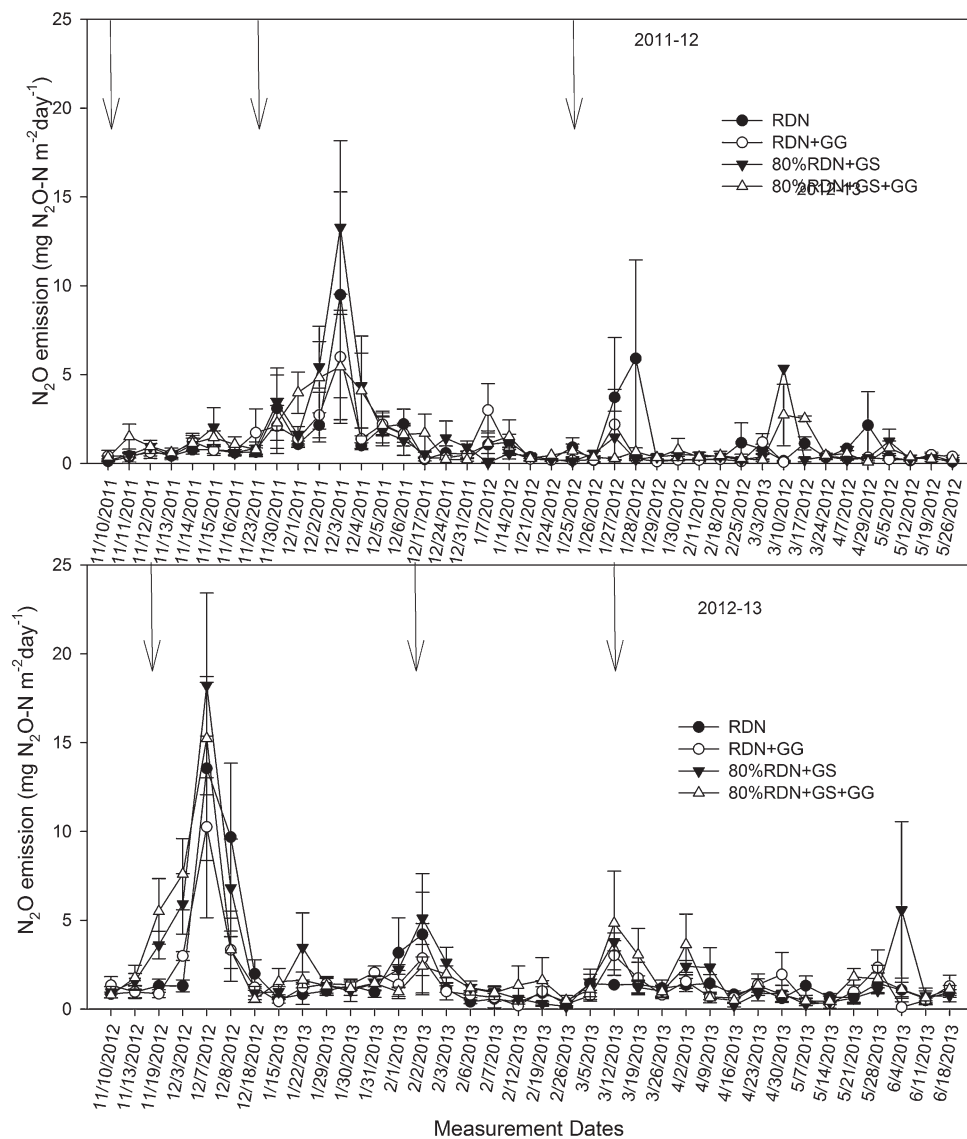
Figure 6. Daily N$_2$O emission rate in 2011–12 (upper panel) and 2012–13 (lower panel) wheat growing season as affected four N management strategies. Means of each N management strategy is averaged over three main-plot factors and three replications ($n = 9$). The vertical bars show the standard error of the mean. Arrows indicate the time of fertilizer application.

not observed in 2012 rice season. Although application of 80% RDN as basal dose induced high emission rate during initial period of rice establishment, it did not increase the total seasonal N$_2$O emission as compared with three-split application of RDN in both the years.

In wheat, effect of tillage and residue management on seasonal cumulative N$_2$O emission was not significant in both the years but the effect of N management was significant in second year. In this year, basal application of 80% RDN followed by GS guided N application induced significantly higher total N$_2$O emission than three-split application of RDN

Table 3. Seasonal cumulative flux of N_2O and CH_4 from RW production and system level global warming potential in 2011–12 and 2012–13. Within same gas, crop and year, means in the same column bearing different lowercase letters are significantly different from each other based on LSD test (p = 0.05).

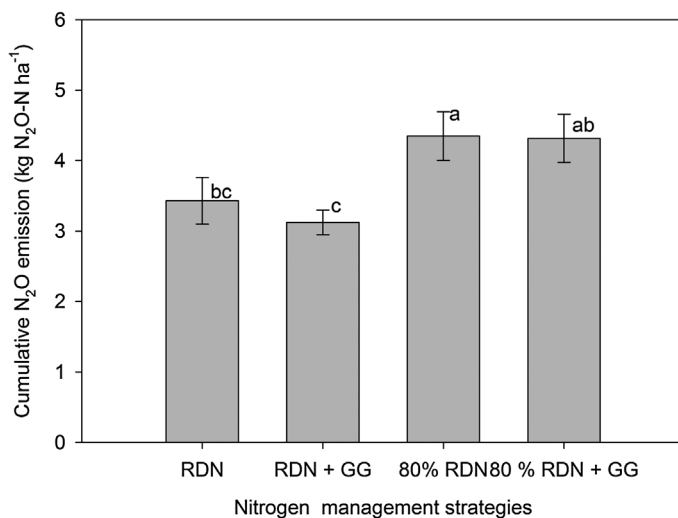| Tillage and residue management	N_2O emission (kg N ha^{-1})		CH_4 emission (kg C ha^{-1})	Total GWP from emission (kg CO_2-eq ha^{-1})
	Rice	Wheat	Rice	RW system
2011–12				
CT	2.33b	1.77	20.95a	2581
ZT	3.07a	1.74	1.10b	2368
ZT+R	2.98ab	1.68	1.55b	2316
2012–13				
CT	1.83	3.42	27.68a	3327
ZT	2.05	4.07	0.56b	2995
ZT+R	2.65	3.92	3.97b	3312

Figure 7. Effect of N management strategies on cumulative N_2O emission during wheat season in 2012–13. The means are average of three main-plot factors and three replication (*n* = 9). The vertical bars show the standard error of the mean. Bars bearing different lowercase letters are significantly different from each other based on LSD test (*p* = 0.05).

irrespective of GG integration (Figure 7). Presence of more NO_3 in the soil than crop demand in the initial stage of establishment due to application of 80% RDN at the time of planting might have induced nitrification as well as denitrification led N_2O emission in these treatments. In general, cumulative N_2O emission from wheat season was much higher in 2012–13 probably because of higher soil moisture status favourable for denitrification throughout the growing season due to higher seasonal rainfall in this year than in 2011–12 (Figure 1). On an average, 1.9% of applied N in rice was emitted as N_2O under CT system which further increased to 2.5% in ZT systems. The percentage of applied N emitted as N_2O was slightly lower in wheat; 1.7% in CT system and 1.9% in ZT systems. As in the case of CH_4, C input from preceding crop residue did not have significant influence on total seasonal N_2O emission in the succeeding crop.

4. Conclusions

We studied the effect of tillage, residue and N management on GHG (CH_4 and N_2O) emissions from a two-year RW system. Rates of CH_4 and N_2O emission differed significantly between CT and NT systems but the rates were similar for residue retention and removal treatments. CH_4 emission was detected only in CT rice production system, mainly during the initial phase of continuous flooding. The NT system, both with and without residue retention, induced higher cumulative emissions of N_2O than CT system. Applying 80% RDN as basal followed by GS guided N management strategy induced higher rate as well as cumulative emission of N_2O compared to three-split application of RDN. Total loss of applied N as N_2O ranged between 1.7–2.5%, which was much higher than IPCC emission factor of 1%. Inclusion of green-gram showed no apparent effect on seasonal emissions of N_2O and CH_4. Retention of crop residues under ZT + R system had no effect on GHG emission from the succeeding crop. Total GWP due to GHG emission was not significantly different among the studied treatment. From this study, we conclude that the positive effect of ZT-based RW system in reducing CH_4 emission could be forfeited by the higher N_2O emission.

Disclosure statement

No potential conflict of interest was reported by the authors.

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