Environ Sci Pollut Res (2017) 24:4603–4612
DOI 10.1007/s11356-016-8189-5

RESEARCH ARTICLE

Global warming potential and greenhouse gas emission under different soil nutrient management practices in soybean–wheat system of central India

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Received: 7 March 2016 / Accepted: 29 November 2016 / Published online: 12 December 2016

Abstract Soil nutrient management is a key component contributing to the greenhouse gas (GHG) flux and mitigation potential of agricultural production systems. However, the effect of soil nutrient management practices on GHG flux and global warming potential (GWP) is less understood in agricultural soils of India. The present study was conducted to compare three nutrient management systems practiced for nine consecutive years in a soybean–wheat cropping system in the Vertisols of India, in terms of GHG flux and GWP. The treatments were composed of 100% organic (ONM), 100% inorganic (NPK), and integrated nutrient management (INM) with 50% organic + 50% inorganic inputs. The gas samples for GHGs (CO_2, CH_4, and N_2O) were collected by static chamber method at about 15-day interval during 2012–13 growing season. The change in soil organic carbon (SOC) content was estimated in terms of the changes in SOC stock in the 0–15 cm soil over the 9-year period covering 2004 to 2013. There was a net uptake of CH_4 in all the treatments in both soybean and wheat crop seasons. The cumulative N_2O and CO_2 emissions were in the order of INM > ONM > NPK with significant difference between treatments ($p < 0.05$) in both the crop seasons. The annual GWP, expressed in terms of CH_4 and N_2O emission, also followed the same trend and was estimated to be 1126, 1002, and 896 kg CO_2 eq ha^{-1} year^{-1} under INM, ONM, and NPK treatments, respectively. However, the change in SOC stock was significantly higher under ONM (1250 kg ha^{-1} year^{-1}) followed by INM (417 kg ha^{-1} year^{-1}) and least under NPK (198 kg ha^{-1} year^{-1}) treatment. The wheat equivalent yield was similar under ONM and INM treatments and was significantly lower under NPK treatment. Thus, the GWP per unit grain yield was lower under ONM followed by NPK and INM treatments and varied from 250, 261, and 307 kg CO_2 eq Mg^{-1} grain yield under ONM, NPK, and INM treatments, respectively.

Keywords Climate change mitigation · GWP per unit yield · Organic farming · Trace gas emission

Introduction

In the backdrop of climate change threats, there is an enormous global challenge to feed 9–10 billion people by 2050 with limiting land resources (Smith et al. 2013). The solution to these challenges can be met partly by suitable land management options having potential complementarities between their adaptation benefits and the greenhouse gas (GHG) mitigation advantages (Smith et al. 2013; Ogle et al. 2014). In other words, the land management practices should provide adaptation-led mitigation benefits to combat the climate change threats for sustainable food production. Agricultural land use is a potent contributor to GHG mitigation as it occupies about 40–50% of the Earth's land surface and accounts for 10–12% of the total anthropogenic GHG emissions (Smith et al. 2007). Methane (CH_4) and nitrous oxide (N_2O) are key GHGs, having higher global warming potential (GWP) than CO_2. Despite being a source of GHGs, the mitigation potential from agriculture has been estimated to be 5.5–6.0 Pg CO_2 eq year^{-1} by the year 2030 (Smith et al. 2008). The behavior of agricultural land use as a net source or sink is primarily decided by the management practices such as tillage, fertilizer

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management, irrigation, crop rotation, and crop residue management (Mosier et al. 2006; Lenka and Lal 2013; Zhao et al. 2015).

Soil nutrient management is one of the key components of management in all agricultural production systems. The nutrient management methods, particularly N management, can affect the GHG emission from these production systems (Six et al. 2004; Hu et al. 2013; Ma et al. 2013). Globally, the three major soil nutrient management practices in agricultural soils are either organic-based, chemical fertilizer-based, or integrated nutrient management (INM) methods involving both organic inputs and chemical fertilizers. The soil productivity, soil quality, and environmental benefits of nutrient management through organics and INM methods over only mineral fertilization practices are well documented (Aldanondo-Ochoa and Almansa-Sáez 2009; Gracia and de Magistris 2008). From a review of 130 studies, it could not be conclusively proven that GWP per unit product favors organic farming (Lynch et al. 2011). However, with the concerns of climate change, global warming potential of agricultural practices including agronomic, nutrient, and water management methods needs to be well understood (Six et al. 2004; Smith et al. 2013; Ogle et al. 2014).

Increasing numbers of studies have suggested analyzing GHG emissions from crop management practices in terms of per unit yield, rather than per unit land area for easier trade-off decisions so as to enhance crop production with reduced GHG emissions (Linquist et al. 2012; Zheng et al. 2014). For instance, organic farms tend to have greater soil organic matter content and less nitrogen losses (nitrogen leaching, nitrous oxide emissions, and ammonia emissions) per unit of field area (Tuomisto et al. 2012). On the contrary, when translated in terms of per product, the N_2O emission was higher in organic than mineral fertilized fields (Tuomisto et al. 2012). Higher GHG flux (CH_4 and N_2O emission) has also been reported when manure or crop residues are added under varied soil types (Stevens and Laughlin 2001; Khalil et al. 2002; Bhattacharyya et al. 2012).

Comprehensive GHG accounting studies have mostly focused on wet land rice-based systems (among crops) (Shang et al. 2011; Bhattacharyya et al. 2012; Ma et al. 2013) and on tillage practices (among management practices) (Mosier et al. 2006; Dendooven et al. 2012). However, well-aerated agricultural soils (non-rice-based cropping systems) and management practices other than tillage have received little attention. While rice paddy-based systems are reported to be net emitters of GHG (Shang et al. 2011; Ma et al. 2013), minimum or no-tillage methods have a sink potential (Robertson et al. 2000; Six et al. 2004; Mosier et al. 2006). Despite nutrient management being a critical factor, very little information is available as to what extent these practices contribute to the GWP in Indian soils and cropping systems. Indian works in this line of research have been limited to comparing the GHG flux in rice-based cropping systems only (Bhatia et al. 2005; Bhatia et al. 2012; Bhattacharyya et al. 2012). Information on the GHG emission and global warming potential from non-rice-based cropping systems with different nutrient management practices is limited. Therefore, the present study was undertaken to evaluate three predominant nutrient management practices (fully organic, integrated nutrient management, and fully chemical) in terms of the GHG emission and global warming potential in a predominant cropping system (soybean–wheat) spread across 4.5 million hectare (Behera et al. 2007) in central India.

Materials and methods

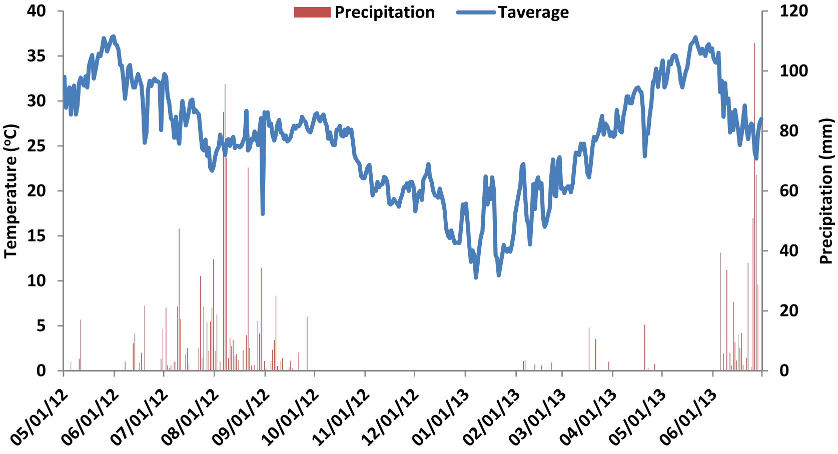
Experimental site

The study was conducted in a 9-year-old on-going experiment of the Network Project on Organic Farming of the Indian Council of Agricultural Research, with soybean (*Glycine max* L.)–wheat (*Triticum durum* L.) cropping system. The experiment was initiated in July 2004 at the research farm of the Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India. The study location is situated at 23°18′ N latitude, 77°24′ E longitude and 485 m above mean sea level. The region has hot sub-humid climate with 920 mm of mean annual rainfall and 1400 mm of mean annual potential evapotranspiration. The maximum temperature reaches its peak in May, with average monthly maximum of 37.1 °C (May), and minimum temperature is lowest during January (10.4 °C) (Fig. 1). Soil of the experimental area is a non-calcareous Vertisol (Isohyperthermic Typic Haplustert) and predominantly clay in texture (52% clay), neutral to alkaline in reaction (pH = 7.85), low in soluble salt content (electrical conductivity of 0.50 dS m^{-1}) with Ca as the dominant exchangeable cation in the Ap horizon. The average initial soil organic carbon (SOC) content as estimated by Walkley and Black method was found to be 0.53 and 0.37% at the 0–15 and 15–30 cm soil depths, respectively. The cation exchange capacity of surface soil was 44.5 c mol (p^+) kg^{-1}. The NH_4^+ and NO_3^--N content of surface soil were 5.25 and 5.60 ppm, respectively (Page et al. 1982). The available soil nitrogen content as determined by alkaline permanganate distillation method of Subbiah and Asija (1956), Olsen's P, and 1 N ammonium acetate extractable K content (Page et al. 1982) were 254.2, 12.77, and 530.2 kg ha^{-1}, respectively.

Experimental details

The study was conducted in a 9-year-old on-going experiment involving three nutrient management methods, viz. 100% organic (ONM), 100% inorganic (NPK), and 50% inorganic + 50% organic (integrated nutrient management (INM)) with seven replicated chambers in each nutrient management plot

Fig. 1 Daily average air temperature and precipitation during the study period (May 2012 to June 2013)



in a randomized block design. Soybean was grown in *kharif* (July to October) as rainfed and wheat in *rabi* (November to April) with a pre-sowing irrigation of 5.0 cm followed by two irrigations depending on prevailing weather conditions, in all the years. In organic (ONM) treatment, nutrients were applied as cattle dung manure for soybean crop (3.5 ton ha^{-1}) and cattle dung manure (3.0 ton ha^{-1}) + vermicompost (2.5 ton ha^{-1}) + poultry manure (1.6 ton ha^{-1}) in the wheat crop. Manures were applied on nitrogen (N) equivalent basis of each crop requirement. For the INM treatment, 50% of the organic manure dose of the ONM treatment was applied along with the rest added through inorganic fertilizers. In the NPK treatment, nutrients were applied as basal through urea, single super phosphate, and muriate of potash. All the organic amendments were applied 2 weeks before sowing of soybean and wheat crops. Conventional tillage (two passes of cultivator) was practiced uniformly for all the three nutrient management treatments before sowing of each crop. The isolation distance between the main plots was 3.0 m, and *Sesbania spp.* was grown as barrier crop/trap crop during *kharif*. Leaf eating caterpillars and griddle beetle were the major pests observed on the soybean crop in *kharif* season. Sesbania crop, which was grown as a border crop, also acted as a trap crop. Further, Neem oil (Azadirachtin @ 0.03%) was sprayed at 30 and 45 days after sowing (DAS). In the durum wheat, no major insect infestation was observed. No major disease was observed in both the crops. The details of crop cultivars and the fertilizer dose used in the experiment are presented in Table 1.

Greenhouse gas sampling and measurements

The static chamber technique was adopted for sampling methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) (Hutchinson and Livingston 1993) using vented polyacrylic chambers of 71 cm × 46 cm × 15 cm (length × width × height) dimension placed between crop rows. The chambers were equipped with sampling port. The chamber base was embedded 5 cm below the soil surface for the entire duration of the study except during farm operations (tillage, soybean planting, and harvest). The gas in the chamber was drawn off using a syringe, and immediately transferred into a 20-ml vacuum glass container. Gas samples were collected synchronously at 0, 30, and 60 min after sealing the chamber into the frame base. Sampling was done during noon to 2:00 pm on the sampling days from seven replicated chambers in the treatment plots.

The first gas sampling was made 1–2 days after basal fertilization and consecutively at frequent intervals throughout the growing seasons of soybean and wheat, and also during the fallow period. A gas chromatograph meter (CIC Varoda, India) fitted with a stainless steel column (Porapack N; length 2 m outer diameter: 1/8 in and Chromosorb 101; length 4 m outer diameter 1/8 in) and thermal conductivity detector (TCD), a flame ionization detector (FID), and an electron capture detector was used for measuring CO_2, CH_4, and N_2O, respectively. The gas emission flux was calculated from the difference in gas concentration according to the Eq. 1.

Table 1 Details of crop cultivar and agronomic management adopted in the study

Crop	Cultivar	Duration (Days)	Date of Sowing	Date of harvest	Spacing (cm)	Recommended dose of chemical fertilizers (kg ha^{-1})		
						N	P_2O_5	K_2O
Soybean *(Glycine max L.)*	JS-335	110	03/07/12	09/10/12	45 × 5	30	26.2	16.6
Durum wheat *(Triticum durum L.)*	HI-8498	130	06/11/12	14/03/13	22.5 × 5	80	17.5	33.2

$$F = \Delta C \frac{v}{At} \rho \quad (1)$$

where F is the gas emission flux (mg m^{-2} h^{-1}), ρ is the gas density at the standard temperature and pressure, ΔC is the change in concentration of gas (ppm in CO_2 and CH_4, ppb in N_2O) inside the chamber, and t is the time conversion factor. The negative fluxes of GHG indicate the uptake of a given gas by soil, and positive fluxes indicate the net emissions from soil. The weather data on daily rainfall and daily average temperature used for this study were recorded at the weather station at the Central Institute of Agricultural Engineering farm, which is about 1 km from the experimental area.

Estimation of yields of soybean and wheat

Soybean and wheat yields were determined from the total plot area by harvesting all the plants excluding the plants bordering the plot. The grains were separated from the panicle/pod, dried, and weighed. Grain moisture was determined immediately after weighing, and subsamples were dried in an oven at 65 °C for 48 h. The grain yields of the two crops (soybean and wheat) were converted to wheat grain equivalent yield by taking into consideration the minimum support price of Government of India for the 2012–2013 crop season.

Soil sampling and analysis

At the initiation of the nutrient management experiment, soil physical (texture, bulk density) and chemical properties (electrical conductivity, pH, organic carbon content, ammonium, and nitrate nitrogen) of the field were determined for 0–15 cm soil depth, following the standard procedures (Page et al. 1982). After 9 years of the nutrient management experiment, soil samples from the experimental plots were collected using a core sampler at wheat harvest in 2013. The entire volume of soil was weighed and mixed thoroughly, and a subsample was taken to determine dry weight. The fresh soil was air-dried for 7 days, sieved through a 0.5 mm sieve, mixed, and stored in sealed plastic jars for analyses. Soil samples were analyzed for soil organic carbon following Walkley and Black (1934) method. The rate of change of SOC storage (ΔSOC) was determined by using Eq. 2.

$$\Delta \text{Soil Organic Carbon} \left(\frac{\frac{kg}{ha}}{yr} \right) = \frac{\text{Final SOC storage} - \text{Initial SOC storage}}{\text{Number of intervening years}} \quad (2)$$

where

SOC = Soil organic carbon

$$\text{SOC storage}\left(kg/ha\right) = \text{SOC}(\%) \times \text{bulk density}\left(\text{Mg}\,\text{m}^{-3}\right) \times \text{depth}(\text{cm}) \times 1000$$

Global warming potential and greenhouse gas intensity

The global warming potential (GWP) of the management treatments was computed by taking into account the respective GWP coefficients of CH_4 and N_2O using the following equation (Watson et al. 1996):

$$GWP_{CO2equivalent} = (CH_4 \times 28) + (N_2O \times 265)$$

Based on a 100-year time frame, the GWP coefficients for CH_4 and N_2O are 28 and 265, respectively, when the GWP value for CO_2 is taken as 1 (IPCC 2014). The GHG emission per unit crop yield was expressed in terms of kg CO_2eq kg^{-1} grain yield and computed from the ratio of GWP and the crop grain yield.

Statistical analysis of data

The daily fluxes of CO_2, CH_4, and N_2O for each sampling date were analyzed using the GLM procedure available in SAS 9.2 for Windows (SAS Institute Inc. Cary NC USA) to detect the effects of soil nutrient management. The analysis of variance was conducted as applicable for a randomized block design. Means were separated using the least square significance test. Unless indicated otherwise, differences were considered only when significant at $p < 0.05$.

Results and discussion

Changes in top soil SOC content and available N

After 9 years of soil nutrient management, treatments showed significant difference with respect to SOC content, available N, and change in SOC stock (ΔSOC $year^{-1}$) in the 0–15 cm soil depth (Table 2). As expected, long-term organic manure application (ONM) significantly ($p < 0.05$) increased top soil SOC compared to other treatments. The SOC content varied from 0.62 to 1.13%. The rate of change of SOC stock in the top soil was in the order of ONM (1250 kg ha^{-1} $year^{-1}$) > INM (417 kg ha^{-1} $year^{-1}$) > NPK (198 kg ha^{-1} $year^{-1}$). Soil available N also followed similar trend. As expected, addition of organic manures helped a higher SOC build-up rate and improved nutrient status in the soil under ONM and INM treatments.

Some studies indicate linear increase in SOC levels due to the application of organic manure in combination with inorganic fertilizer (Böhme et al. 2005; Li et al. 2010). Results

Table 2 Effect of nutrient management treatments on soil organic carbon (SOC) content, available N, SOC sequestration rate in the 0–15 cm soil depth, and seasonal emissions of carbon dioxide, methane, and nitrous oxide

Treatment	SOC (%)*†	Available N (kg ha^{-1})	ΔSoil carbon (kg ha^{-1} yr.$^{-1}$)	Seasonal flux (kg ha^{-1})					
				Soybean#			Wheat##		
				CO_2^{-} C	CH_4–C**	N_2O–N	CO_2–C	CH_4–C	N_2O–N
ONM	1.13a	283a	1250a	1303b	−0.071c*	1.20b	4158b	−0.092a	1.22b
NPK	0.62b	229c	198c	923c	−0.043a	1.02c	2957c	−0.167c	1.15b
INM	0.71b	241b	417b	1467a	−0.067b	1.36a	4486a	−0.116b	1.36a

ONM 100% organic, *NPK* 100% inorganic, *INM* 50% organic + 50% inorganic

*In a column, values followed by the same letter are not significantly different at $p < 0.05$ by Duncan's multiple range test

**Negative sign indicates CH_4 oxidation by methanotrophs

Soybean includes the fallow period after soybean harvest and before wheat sowing

Wheat includes the fallow period after wheat harvest and before soybean sowing

†0–15 cm soil depth

from the present study are consistent with previous observations which documented that SOC was considerably greater in soils receiving organic manure (Simon and Czako 2014) and FYM + mineral N (Lenka et al. 2013) than plots receiving only NPK fertilizers.

Soil CO_2 flux

During the soybean crop, the soil CO_2–C flux was significantly higher (Table 2) in INM treatment as compared to ONM and NPK treatments. The seasonal CO_2 flux varied from 1467 under INM to 1303 and 923 kg CO_2–C ha^{-1} under ONM and NPK, respectively (Table 2). Temporal variation in the CO_2 flux was also observed with the highest flux in the initial period which gradually reduced with crop growth season (Fig. 2a). A dip during mid-August was due to continuous rainfall and increased soil moisture (Fig. 3a) during that period. At the first sampling date, i.e., 3 days after sowing (DAS) of soybean, the flux was in the range of 52.4 to 95.4 mg CO_2-C m^{-2} h^{-1}, with the lowest value under NPK treatment and ONM and INM being at par (Fig. 2a). Highest peak at the first sampling was due to the fact that soil was freshly disturbed during sowing of the crop and thus leading to higher efflux of C. The CO_2 flux is a function of not only temperature, but also of soil moisture content, the level of soil disturbance and the soil C content (Lenka and Lal 2013; Wang et al. 2015). In the present study, the flux values under ONM and INM treatments were at par, though both were higher than the NPK treatment in the first month of the crop period. However, afterwards, there was a clear trend of CO_2 flux in the order of INM > ONM > NPK. Higher flux under INM than ONM might be due to better microbial activity in the former because of added N in form of chemical fertilizers. Though the soil organic carbon (SOC) content was higher under ONM, a lower flux was in the line of expectation due to the fact that adequate N supply is required for microbial activity to continue emission at a rate equal to that in the INM. As compared to chemical treatment, higher CO_2–C fluxes in the INM and ONM treatments were due to higher availability of organic C resulting in increased soil respiration (Scott et al. 2000; Iqbal et al. 2009).

Higher CO_2–C flux was observed in the wheat crop season (including fallow after the crop). However, the pattern of difference between the nutrient management treatments was similar to that in the soybean crop (Table 2). The seasonal CO_2 flux in the wheat season varied from 4486 under INM to 4158 and 2957 kg CO_2–C ha^{-1} under ONM and NPK, respectively

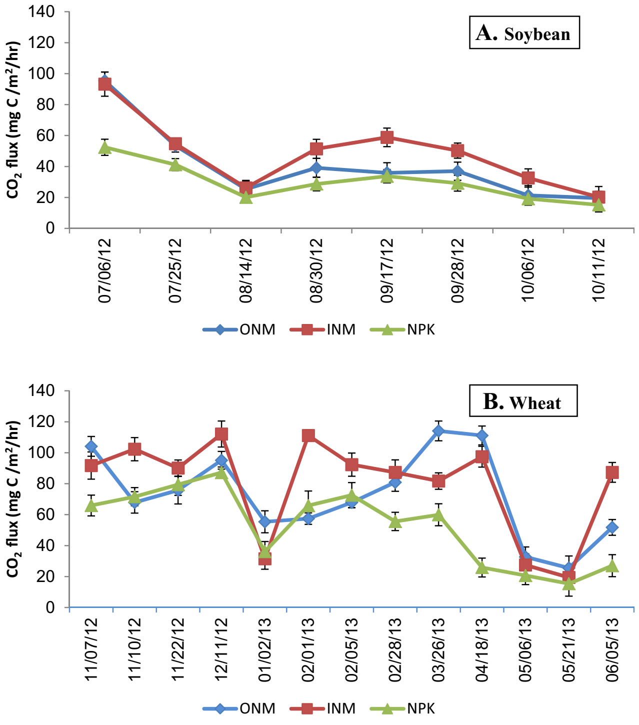


Fig. 2 Effect of 9 years of nutrient mangement on CO_2 emission in **a** soybean and **b** wheat during 2012–2013 crop season. *Error bars* indicate standard error of mean

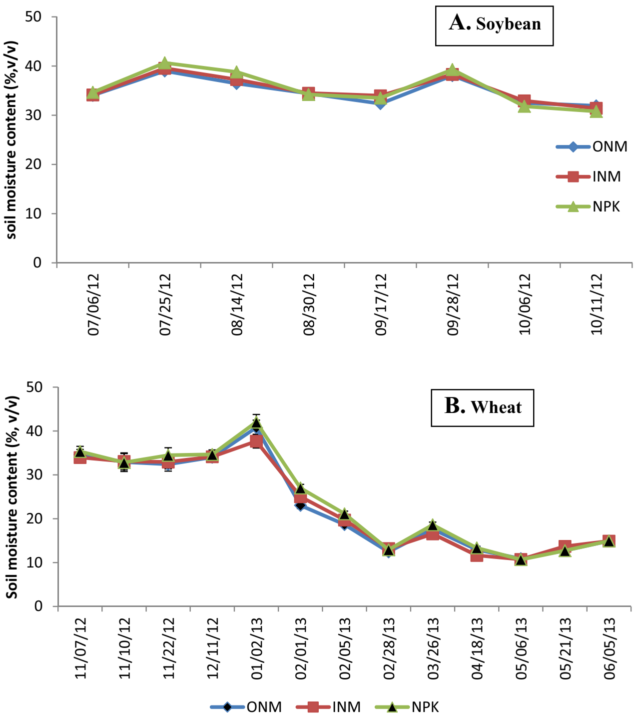


Fig. 3 Soil moisture distribution in the 0–15 cm soil depth in **a** soybean and **b** wheat during 2012–2013 crop season. *Error bars* indicate standard error of mean

(Table 2). In general, lowest emission was observed in the NPK treatment in all sampling days, and the trend was in the order of INM > ONM > NPK (Fig. 2b). The flux during the wheat growth period was higher and varied from 81.7–112.1 mg C m^{-2} h^{-1} under INM, 55.4–114.1 mg C m^{-2} h^{-1} under ONM, and 25.8–87.2 mg C m^{-2} h^{-1} under NPK, respectively (Fig. 2b). The seasonal variability in the CO_2 flux was mainly due to variation in soil moisture and average temperature condition (Lenka and Lal 2013; Mancineli et al. 2015). Some mid-way dips observed in the flux rate were uniformly observed in all the treatments which coincided with dip in temperature (Figs. 1 and 2b). Few studies are available with regard to the GHG flux under soybean–wheat cropping system in Indian condition. However, the CO_2 emission as observed in the study is in the range of flux reported by Bhatia et al. (2005) and Bhatia et al. (2012) under Delhi climate. However, the CO_2 flux values were higher in the wheat season in the present study because our data includes the emission during the fallow period covering the summer months, where a high CO_2 emission is expected due to higher temperature. Lower CO_2 flux under fully inorganic treatment as compared to fully organic and INM treatments was also reported by Bhatia et al. (2005) in wheat crop under continuous rice-wheat cropping system in the Indo-Gangetic Plains. Treatments with an optimum availability of C and N substrate are likely to show higher CO_2 flux due to better mineralization and higher soil respiration (Pathak and Rao 1998; Iqbal et al. 2009). In Indian flooded rice soils, Bhattacharyya et al. (2012) reported significantly higher CO_2–C flux under rice straw + green manure treatment, followed by rice straw + urea and the least under urea treatment.

Methane (CH_4) flux

The seasonal cumulative values over the soybean season were significantly lower under ONM and highest under NPK treatment (Table 2). In general, there was net uptake of CH_4 during both the crop seasons. In case of soybean, net uptake of CH_4 was observed except three sampling dates with net CH_4 efflux (Fig. 4a). The period showing CH_4 efflux corresponded to the period of high soil wetness due to continuous rainfall received during mid-August to mid-September (Figs.1 and 3a). Both CH_4 uptake and efflux were higher under ONM and lowest under NPK treatment. The seasonal cumulative values over the soybean season were in the range of −0.071 to −0.043 kg ha^{-1}. During the wheat growth season, CH_4 emission was observed in only two sampling days in negligible amount (ranging from 0.2 to 1.1 μg C m^{-2} h^{-1}). In general, CH_4 uptake was observed with the uptake in the range of −0.1 to −6.5 μg C m^{-2} h^{-1} under ONM, −0.4 to −10.2 μg C m^{-2} h^{-1} under NPK, and −0.3 to −7.9 μg C m^{-2} h^{-1} under INM treatment (Fig. 4b). The seasonal cumulative values over the wheat season were in the range of −0.092 to −0.167 kg ha^{-1}. The uptake in most part of the wheat growth season was due to absence of any continuous rainfall events (Fig. 1) and relatively lower soil moisture content than the soybean season (Fig. 3b).

CH_4 flux depends on the activity of methanogens and methanotrophs, which in turn is primarily decided by the redox potential in the soil. A lowered redox potential caused due to submergence or higher soil moisture content suppresses the activity of methanotrophs, and thus, a net CH_4 flux is observed under higher soil wetness. During most parts of crop season, the anaerobic condition required for the formation of CH_4 was not prevailing. Among agricultural soils, wet land rice paddies have received attention as a net source of CH_4, whereas well-aerated agricultural soils are presumed to have low or negligible CH_4 uptake capacity (Li et al. 2004; Mosier et al. 2006). However, recently, Ho et al. (2015) reported unexpected CH_4 uptake in well-aerated agricultural soils (sandy loam and clay texture) with addition of sewage sludge and compost as ammendments. On an average, a net CH_4 sink capacity as observed in both the crop growth periods are in agreement with findings of Ho et al. (2015). However, during the transient phases of high soil wetness, CH_4 efflux was higher under organic treatments, which was in the line of findings of Mishra et al. (1997), Singh et al. (1998), and Lu et al. (2000). In flooded rice soils of eastern India, higher CH_4 emission was reported under combined application of rice straw and green manure as compared to application of urea only (Bhattacharyya et al. 2012). Bhatia et al. (2012) reported

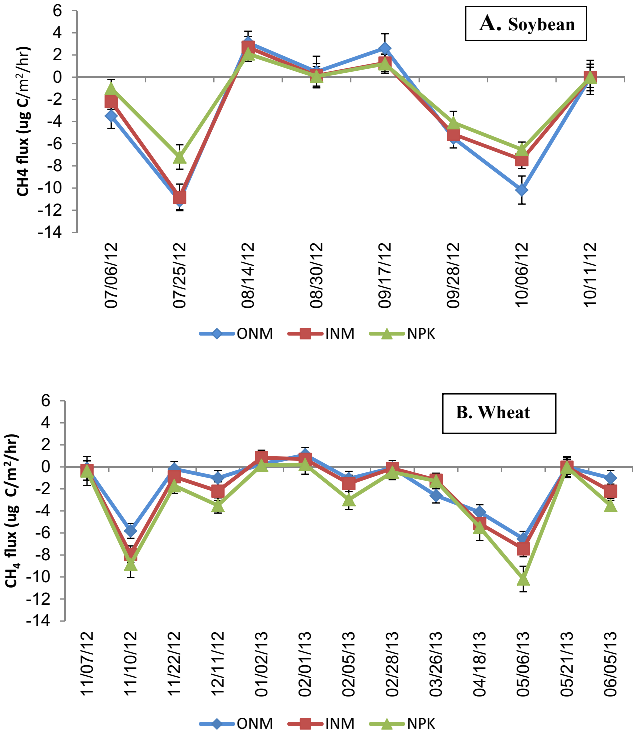


Fig. 4 Effect of 9 years of nutrient mangement on CH_4 emission in **a** soybean and **b** wheat during 2012–2013 crop season. *Error bars* indicate standard error of mean

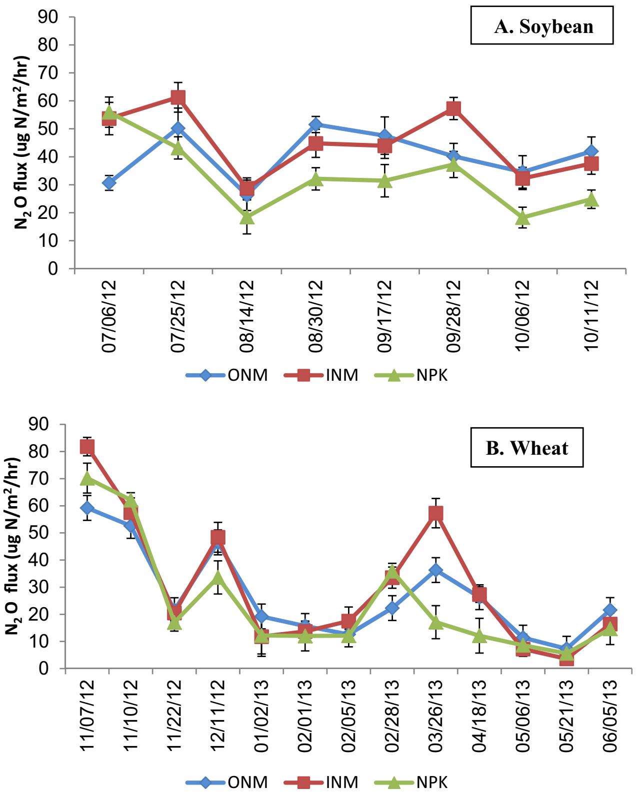


Fig. 5 Effect of 9 years of nutrient mangement on N_2O emission in **a** soybean and **b** wheat during 2012–2013 crop season. *Error bars* indicate standard error of mean

CH_4 emission in the range of 31–35 kg ha^{-1} in rice crop and a net uptake (−0.03 to −0.17 kg ha^{-1} in wheat crop in semi-arid climate of Delhi). During the efflux phase, application of organic amendments enhanced CH_4 emission by providing additional C substrate as compared to urea alone treatment (Lu et al. 2000). Additional amount of organic matter added through the organic amendments serves as a source of electrons (Singh et al. 1998) creating more anaerobic conditions (Mishra et al. 1997) and thus higher CH_4 flux.

Nitrous oxide (N_2O) flux

The soil N_2O flux during the soybean crop (Table 2) was significantly higher under INM, followed by ONM and NPK treatments. The N_2O flux ranged from 26 to 52, 18 to 56, and 29 to 61 μg N_2O-N m^{-2} h^{-1} under ONM, NPK, and INM, respectively (Fig. 5a). The N_2O emission from soil was not only influenced by the addition of carbon and nitrogen, but was also affected by soil moisture content. Higher emission was observed during the first two sampling dates followed by secondary peaks observed at higher soil moisture content (Figs. 3a and 5a). The seasonal cumulative values varied from 1.02 kg ha^{-1} under NPK to 1.36 kg ha^{-1} under INM treatment.

The wheat crop showed similar trend of N_2O flux as in soybean, with the seasonal cumulative values varying from 1.36 kg ha^{-1} under INM to 1.15 kg ha^{-1} under NPK treatment (Table 2). In contrast to the N_2O emission data in the present study, a lower N_2O emission was reported by Bhatia et al. (2012) in both rice (0.28 to 0.73 kg ha^{-1}) and wheat (0.39 to 0.83 kg ha^{-1}) crops. In all the treatments, the N_2O emission was highest at sowing followed by reduced emission (Fig. 5b). However, as in the soybean crop, emission peaks were observed after first basal application of fertilizers or manures, which declined thereafter with decrease in air temperature from November to January. Short-term increase in N_2O flux immediately after N fertilization has also been reported by Maljanen et al. (2003) and Mosier et al. (2006). The three critical factors governing N_2O emission are substrate availability, soil moisture, and air temperature (Mosier et al. 2006). As observed in the present study, the N_2O emission positively correlated with air temperature (Meng et al. 2005; Fu et al. 2012; Lenka and Lal 2013). At flowering with increase in air temperature during March, the N_2O emission was higher and a decline in fluxes at the later stage of wheat growth till harvest, possibly due to very dry soil conditions.

In legume-based cropping systems, internal N_2 fixation is a critical factor to affect the flux dynamics of GHGs, particularly N_2O flux. A comparison in terms of N_2O flux across annual cropping systems showed that it is the high N availability in soil rather than fertilizer or tillage that affects the N_2O flux (Robertson et al. 2000). This was corroborated in their study by the high N_2O emission from alfalfa crop despite it not receiving any fertilizer. However, flux dynamics and the global warming potential of legume-based systems under arable cropping are likely to be under the interactive effect of fixed N and added N received by the cropping system. In the present study, long-term application of organic amendments combined with or without NPK stimulated soil N_2O emissions due to high N availability in soil. The current findings showing lower N_2O flux under NPK than ONM or INM are in agreement with that of Robertson et al. (2000) and Yang et al. (2003).

Grain yield of crops

The average grain yield during five consecutive crop seasons (2010–2011 to 2014–2015) of soybean and wheat was taken into account for the study (Table 3). The average soybean yield over the last 5 years was significantly higher under ONM followed by INM and NPK treatments. However, in the wheat crop, the ONM and INM yields were at par but were higher than the NPK treatment. The observed trend might be due to a number of ancillary benefits, such as better soil physical properties, improved soil aggregation, better microbial activity etc. under organic and INM treatments. The soybean grain yield in the ONM treatment was higher by 19 and 29% over INM and NPK treatments, respectively. The corresponding values in wheat crop were 6 and 13% indicating the difference in the grain yield between the treatments to be lower in wheat crop. This was due to the fact that soybean was grown under rainfed condition while wheat crop was irrigated. In soybean, the organic treatment showed better performance in both dry years as well as in years with high rainfall, which is possibly due to the fact that higher soil organic matter content contributes to water retention in dry conditions and towards good drainage in wet situations. The soil of the study region being heavy textured with clay content of about 52% often witnesses drainage problem during heavy rainfall and soybean being a legume is susceptible to waterlogging conditions.

In terms of wheat equivalent yield, non-significant difference between the ONM and INM treatments was observed, though numerically higher values were obtained under ONM treatment. However, both the treatments were statistically superior to NPK treatment. Similar results with improvement in crop yield under organic treatments are also reported by Behera et al. (2007) and Monsefi et al. (2014) on soybean–wheat cropping system in central India. In the short term, organically managed plots yields less as compared to treatments receiving complete inorganic fertilization (Randall et al. 2000; Griffin et al. 2002; Lenka and Singh 2011), though the effect of organic farming on crop productivity is realized with time (Lenka et al. 2014).

Table 3 Average crop grain yield under different nutrient management treatments in soybean–wheat system during five crop seasons (2010–2011 to 2014–2015)

Treatment	Soybean yield* (kg ha^{-1})	Wheat yield* (kg ha^{-1})	Wheat equivalent grain yield* (kg ha^{-1})
ONM	611a	3071a	4011a
NPK	474c	2715b	3440b
INM	515b	2883a	3673a

ONM 100% organic, *NPK* 100% inorganic, *INM* 50% organic + 50% inorganic

*In a column, values followed by the same letter are not significantly different at $p < 0.05$ by Duncan's multiple range test

Global warming potential

The GWP of the soybean–wheat cropping system was computed by taking into account the emission of CH_4 and N_2O in the individual crop seasons and their respective GWP coefficients (Table 2). The GWP in the three nutrient management treatments varied significantly, with the highest GWP under INM (1126 kg CO_2 ha^{-1}) followed by the organic (1002 kg CO_2 ha^{-1}) and the least under inorganic treatment (896 kg CO_2 ha^{-1}). This was due to the higher N_2O emission under INM followed by ONM or NPK treatment. Though a net N_2O flux was observed, all the treatments were observed to be net sinks for CH_4 in the soybean–wheat cropping system. Typically, except waterlogged rice soils, agricultural soils are low emitters and often small sinks for CH_4 (Mosier et al. 2006). The results reported by this study were much lower than the GWP values of about 4500 kg CO_2 eq ha^{-1} in rice-wheat season as reported by Linquist et al. (2012) from the meta-analysis of 57 studies. In other words, the soybean–wheat cropping system was observed to have lower GWP. Higher GWP values as compared to the present study was reported by Bhatia et al. (2005) and Bhatia et al. (2012) under rice–wheat system in the Indo-Gangetic plains of northern India, which was due to higher CH_4 emission and thus its contribution towards the total GWP. The soybean–wheat cropping system showed net uptake of CH_4 and thus probably a lower GWP. The trends in the variation of GWP between nutrient management treatments were slightly different, with the GWP of organic and INM treatments were at par in the study of Bhatia et al. (2005). However, in our study, the INM treatment was clearly observed to have a significantly higher GWP than the organic and the least with NPK treatment. In Indian wetland rice soils, Bhattacharyya et al. (2012) reported significant difference among nutrient management methods with highest GWP under rice straw + green manure, followed by rice straw + urea, and the least under urea only, though the computation method was different with inclusion of CO_2 in their study.

Assessing GHG emissions in terms of per unit yield, rather than per unit land area, is a better indicator and aids in trade-off decisions for enhancing crop production with reduced GHG emissions (Zheng et al. 2014). The GWP per unit crop

Table 4 Global warming potential (GWP) expressed in terms of GHG emission under nutrient management practices in soybean–wheat system

Treatment	GWP* in soybean (kg CO_2 eq ha^{-1})	GWP in wheat (kg CO_2 eq ha^{-1})	Annual GWP (kg CO_2 eq ha^{-1})	GWP per unit grain yield (kg CO_2 eq Mg^{-1})
ONM	497b	505b	1002b	250b
NPK	423c	473c	896c	261b
INM	564a	562a	1126a	307a

ONM 100% organic, *NPK* 100% inorganic, *INM* 50% organic + 50% inorganic

*In a column, values followed by the same letter are not significantly different at $p < 0.05$ by Duncan's multiple range test

yield varied from 250 under ONM to 261 and 307 kg CO_2 eq Mg^{-1} grain yield under NPK and INM treatments, respectively (Table 4). The GWP per unit crop yield was statistically similar under ONM and NPK treatments but was significantly higher under INM treatment. This type of result was observed due to consistently higher grain yield under fully organic plots despite a relatively lower GWP as compared to that in case of the INM treatment. The INM treatment, even though produced similar grain yield as that of ONM treatment, resulted in a significantly higher GWP. On the other hand, under NPK treatment, both grain yield and GWP were lower, and thus, a lower GWP per unit grain yield was observed. The results observed in our study were slightly different from that of Lynch et al. (2011) where lower GWP per grain yield was reported under organic than inorganic plots. The data observed in this study is similar to that reported by Linquist et al. (2012) though the GWP per unit grain yield in case of rice crop was higher. The yield scaled GWP of rice and wheat was 657 and 166 kg CO_2 eq Mg^{-1} grain yield (Linquist et al. 2012).

Conclusions

The study involving the GHG accounting in terms of emission of three greenhouse gases, GWP, and yield scaled GWP from a long-term nutrient management experiment has shown GWP of the non-rice-based (soybean–wheat) cropping system in central India. There was net uptake of CH_4 in the cropping system under all the treatments. Emission of CO_2 and N_2O was highest under INM followed by organic and the chemical nutrient management method. Despite a significantly higher GWP under organic treatment than the fully inorganic treatment, better crop yield resulted in a lower yield scaled GWP in the organic treatment. However, it would be appropriate to undertake a full life cycle analysis of manures as well as synthetic fertilizers for a conclusive assessment of mitigation potential of the two commonly used nutrient management practices.

Acknowledgement This work was supported by a research grant from Madhya Pradesh Council of Science and Technology, Bhopal, India.

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