

Greenhouse gas mitigation in rice–wheat system with leaf color chart-based urea application

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Abstract Conventional blanket application of nitrogen (N) fertilizer results in more loss of N from soil system and emission of nitrous oxide, a greenhouse gas (GHG). The leaf color chart (LCC) can be used for real-time N management and synchronizing N application with crop demand to reduce GHG emission. A 1-year study was carried out to evaluate the impact of conventional and LCC-based urea application on emission of nitrous oxide, methane, and carbon dioxide in a rice–wheat system of the Indo-Gangetic Plains of India. Treatments consisted of LCC scores of ≤ 4 and 5 for rice and wheat and were compared with conventional fixed-time N splitting schedule. The LCC-based urea application reduced nitrous oxide emission in rice and wheat. Application of 120 kg N per hectare at LCC ≤ 4 decreased nitrous oxide emission by 16% and methane by 11% over the conventional split application of urea in rice. However, application of N at LCC ≤ 5 increased nitrous oxide emission by 11% over the LCC ≤ 4 treatment in rice. Wheat reduction of nitrous oxide at LCC ≤ 4 was 18% as compared to the conventional method. Application of LCC-based N did not affect carbon dioxide emission from soil in rice and wheat. The global warming potential (GWP)

were 12,395 and 13,692 kg CO₂ ha⁻¹ in LCC ≤ 4 and conventional urea application, respectively. Total carbon fixed in conventional urea application in rice–wheat system was 4.89 Mg C ha⁻¹ and it increased to 5.54 Mg C ha⁻¹ in LCC-based urea application (LCC ≤ 4). The study showed that LCC-based urea application can reduce GWP of a rice–wheat system by 10.5%.

Keywords Carbon efficiency ratio · Carbon equivalent emission · Demand driven N application · Global warming potential · Methane · Nitrous oxide

Introduction

Consumption of nitrogen (N) fertilizer has been steadily increasing over the years, but low N-use efficiency (NUE) continues to be a problem in the rice–wheat cropping system of the Indo-Gangetic Plains (IGP) (Ladha et al. 2005). One of the reasons for low N-use efficiency could be inefficient timing of N application and the use of N in excess to crop requirement. The commonly practiced split application of N at specified growth stages of rice and wheat does not offer a very good match of the N supply from applied fertilizer with crop demand because of large variations in crop N requirements and soil N supply (Balasubramanian et al. 2003). In many field situations, more than 60% of applied N is lost because of the lack of synchrony of plant demand

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with N supply (Singh and Singh 2003). Site-specific nutrient management approach for rice has been evaluated at numerous locations in Asia and has been found to be more efficient than the conventional methods (Wang et al. 2001; Dobermann et al. 2002). The leaf color chart (LCC), developed by the International Rice Research Institute (IRRI), is a simple and easy-to-use tool that enhances productivity, NUE, and farmer's profit (Singh et al. 2002). Due to its low cost for farmers, LCC has shown much promise in real-time N management studies conducted in India and elsewhere (IRRI 2005; Pathak 2010). The use of the LCC has also been advocated to minimize the fertilizer-related pollution of surface and ground water (Ladha et al. 2005).

Nitrous oxide (N_2O) emission from agriculture has increased by nearly 17% from 1990 to 2005 (IPCC 2007). Soil receiving chemical fertilizer N contributes to not only the emission of N_2O , but may also impact the emission of carbon dioxide (CO_2) and methane (CH_4), the two other major greenhouse gases (GHGs) contributing towards enhanced global warming (IPCC 2007). Improved N fertilizer application techniques, therefore, are required to reduce N_2O emission and increase crop yield. The LCC-based N application may be helpful in reducing GHG emission, particularly N_2O emission from soil and also improve crop yields. There are, however, no studies on the use of LCC on soil N content and its impact on the emission of GHGs from fertilized soil. The objectives of the study were to (1) assess the influence of LCC-based urea application in mitigating GHG emission and (2) quantify its impact on global warming potential (GWP), carbon equivalent emission, and carbon efficiency ratio in the rice–wheat cropping system of the IGP.

Materials and methods

Experimental site and soil

A field experiment was conducted growing rice in kharif (rainy season) followed by wheat in rabi (winter season) during 2004–2005 in a silty clay loam (Typic Ustochrept) soil at the experimental farm of the Indian Agricultural Research Institute, New Delhi, India. The site is located in the Indo-Gangetic alluvial tract at $28^\circ 40' \text{ N}$ and $77^\circ 12' \text{ E}$, at an altitude

of 228 m above mean sea level. The climate of the region is subtropical and semi-arid. The area receives an annual rainfall of 750 mm, about 80% of which occurs from June to September. The soils are well drained with the groundwater table at 6.6- and 10-m deep during the rainy and summer seasons, respectively. The mean maximum and minimum temperatures from July to October are 35°C and 18°C while from November to April, 22.6°C and 6.7°C , respectively. The alluvial soil of the experimental site had a bulk density of 1.49 g cm^{-3} , pH (1:2, soil to water ratio) of 8.04, electrical conductivity of 0.37 dS m^{-1} , CEC of $7.3 \text{ C mol (p}^+) \text{ kg}^{-1}$, and organic carbon, total N, Olsen P, and ammonium acetate extractable K contents of 5.3 g kg^{-1} , 0.32 g kg^{-1} , 0.008 g kg^{-1} , and 0.14 g kg^{-1} , respectively. The experimental soil was under conventional rice–wheat rotation for the past many years.

Treatments and crop management

In rice and wheat crops, LCC-based N application was evaluated and compared with the conventional split application of N. The LCCs, manufactured by IRRI, India, consisting of six shades from yellowish green to dark green were used in this study. The experiment included four treatments with five replications in completely randomized design in plots of 6-m long and 5-m wide (Table 1). The treatments included (1) no-N control; (2) conventional N application (120 kg ha^{-1}) in three equal splits at transplanting, mid-tillering, and panicle initiation stages in rice, and at sowing (basal), crown root initiation stage (CRI), and panicle initiation stages in wheat; (3) $\text{LCC} \leq 4$ (30 kg N ha^{-1} was applied when the leaf color reading fell below the critical value of 4 in the leaf color panel) (4) $\text{LCC} \leq 5$ (30 kg N ha^{-1} was applied when the leaf color reading fell below the critical value of 5 in the leaf color panel). The LCC readings were taken at weekly intervals from the ten randomly selected topmost fully expanded leaves starting at 7 days after transplanting of rice until flowering. In wheat, ten disease-free plants were chosen in each plot, and the color of the youngest fully expanded leaf was measured from CRI stage (21 days after sowing (AS) till flowering. When the LCC value of six out of ten leaves fell below the critical level, 30 kg N ha^{-1} of urea was top dressed on the same day. No basal N was applied in the LCC-based plots in rice and wheat. A basal dose of

Table 1 Treatments in the field experiment on rice–wheat system

Number	Treatment in rice/wheat	No. of splits	Total N applied kg N ha ⁻¹	Time of urea application		Time of irrigation wheat (days AS)
				Rice (days AT)	Wheat (days AS)	
T1	Unfertilized control	0	0			20, 41, 61, 76, 95
T2	Conventional urea application (N applied in three equal splits)	3	120	1, 30, 55	B ^a , 21, 62	20, 41, 61, 76, 95
T3	LCC-based urea application, 30 kg N ha ⁻¹ at LCC≤4, no basal N	4	120	14, 28, 42, 63	21, 43, 62, 77	20, 41, 61, 76, 95
T4	LCC-based urea application, 30 kg N ha ⁻¹ at LCC≤5, no basal N	5	150	14, 28, 42, 56, 70	21, 43, 56, 62, 77	20, 41, 55, 63, 76, 95

^aBasal N application

26 kg P ha⁻¹, 50 kg K ha⁻¹ was applied to all the treatments in both rice and wheat and 10 kg Zn ha⁻¹ was applied at the time of transplanting rice.

The land was prepared by two criss-cross plowings and two harrowing, leveled and then puddled for rice transplanting. Rice (variety Pusa Sugandh-3) was raised in a nearby nursery, and 30-day-old seedlings were transplanted in to the puddled field on the 13th of July at a spacing of 20×15 cm. Wheat (variety PBW 343, 100 kg of seed per hectare) was sown in rows 22.5-cm apart on the 23rd of November. The plots were irrigated on alternate days in rice. In wheat, five irrigations were given in T1, T2, and T3 treatments on 20, 41, 61, 76, and 95 days AS, and six irrigations were given in T4 treatment on 20, 41, 55, 63, 76, and 95 days AS (Table 1). Weeds, pests, and diseases were controlled as required.

Soil sampling and analysis

Soil samples were collected from 0- to 15-cm soil layers at three locations from each plot prior to puddling 10, 20, 33, 46, 60, 75, and 116 days after transplanting (AT), in rice and before sowing, 10, 20, 30, 40, 50, 60, 84, 99 and 119 days AS in wheat using a core sampler of 8-cm diameter. The entire volume of soil was weighed and mixed thoroughly, and 10 g of soil was used for making extracts with 2 M KCl. These extracts were used for estimation of inorganic N, viz., NH₄⁺ and NO₃⁻ content. Initial soil samples were air-dried, sieved through a 2-mm screen, mixed, and used to determine various physicochemical properties using standard procedures (Page et al. 1982).

Plant sampling and analysis

Plant samples were collected at harvest to calculate the biomass, fresh weights, and dry weights. The dried grain samples were ground and used to analyze the N content using standard procedures (Page et al. 1982).

Collection and analysis of gas samples

Collection of gas samples was carried out by the closed-chamber technique (Pathak et al. 2002). Chambers of 50×30×100 cm (length × width × height) made of 6-mm thick acrylic sheets were placed over the plants for sampling of CH₄ and N₂O. An aluminum channel having 50×30×15 cm (length × width × height) and 5-cm internal diameter placed in the soil was used with each chamber. The channels were inserted at a 10-cm depth in the soil and filled with water to make the system airtight. For CO₂, the chamber and channel of the size 15×15×50 cm (length × width × height) were inserted between the rows without the plants. One three-way stopcock was fitted at the top of the chamber to collect gas samples. A small rotary fan was fixed in each chamber for mixing of air inside the chamber. Gas samples were drawn with a 50-ml syringe with a hypodermic needle (24 gauge) at 0, 15, and 30 min for CH₄ and 0, 30, and 60 min for N₂O and CO₂. The syringes were made air tight with a three-way stopcock. Headspace volume inside the boxes was recorded to calculate flux of N₂O, CH₄, and CO₂. The concentration of CH₄ and CO₂ in the gas samples was estimated by a gas chromatograph (GC) fitted with a

flame ionization detector (FID), and N₂O samples were analyzed using GC with an electron capture detector. For CO₂, the gas samples were converted to CH₄ using a methanizer (Ni catalyst, 320°C) and then analyzed using an FID (Kotsyurbenko et al. 2004).

Samples for GHG analysis were collected from each treatment replicate by placing one box per replicate 2 days prior to transplanting; on 1, 3, 4, 6, 10, 12, 17, 23, 26, 29, 33, 45, 48, 57, 59, 66, 67, 73, 79, 85, 88, 93, and 108 days AT in rice; 1 day prior to sowing; and on 1, 2, 6, 12, 16, 21, 22, 23, 30, 37, 44, 47, 51, 57, 64, 65, 77, 83, 86, 87, 89, 99, 103, 106, 117, and 123 days AS in wheat. Estimation of total N₂O, CH₄, and CO₂ emissions during the crop season was done by successive linear interpolation of average emission on the sampling days assuming that emission followed a linear trend during the periods when no sample was taken (Pathak et al. 2002).

Estimation of yields of rice and wheat

Rice and wheat yields were determined from the total plot area by harvesting all the hills excluding the hills bordering the plot. The grains were separated from the straw, dried, and weighed. Grain moisture was determined immediately after weighing, and subsamples were dried in an oven at 65°C for 48 h. The rice and wheat grains contained 14% and 12% moisture, respectively.

$$\text{CER} = \text{Grain yield (in terms of C) of the rice – wheat system} / \text{CEE of rice – wheat system} \quad (2)$$

Results and discussion

Nitrous oxide emission in rice

Total N applied in LCC_{≤4} treatment (T3) was the same as in conventional application of urea (120 kg N ha⁻¹, Table 1). Lower N₂O fluxes were recorded in the LCC-based urea treatments than for conventional application of urea. The fluxes of N₂O were low before transplanting of rice in all the treatments. Application of the first dose of urea (40 kg N ha⁻¹) in conventional treatment (T2) increased N₂O flux and a peak of 18.9 g N₂O–N per

Data analysis

Statistical analyses of the data were performed using the MSTAT-C (version 1.41), developed by Crop and Soil Science Division, Michigan State University, USA. Duncan's Multiple Range Test was carried out to test whether the differences between means were statistically significant.

Global warming potential, carbon equivalent emission, and carbon efficiency ratio

Global warming potential is an index defined as the cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now. The GWP for CH₄ (based on a 100-year time horizon) is 25, while that for N₂O is 298 when GWP for CO₂ is taken as 1. The GWP of different treatments were calculated using the following equation (IPCC 2007).

$$\text{GWP} = \text{CO}_2 + \text{CH}_4 \times 25 + \text{N}_2\text{O} \times 298 \quad (1)$$

The carbon equivalent emission (CEE) was 27.3% (12/44) of the GWP. Carbon efficiency ratio (CER) is an index of efficiency of a treatment. It is a ratio of carbon fixed in terms of grain yield to the carbon emitted from soil in a particular treatment. In our study, the carbon efficiency ratio, i.e., carbon (C) fixed in grain by rice and wheat per unit of C emitted from soil was calculated using the following equation.

hectare per day was observed for 4 days AT (Fig. 1a). The emissions were higher than 10 g ha⁻¹ in T2 treatment till 10 days AT and subsequently declined till the next dose of urea application. Three peaks of N₂O, corresponding to the date of urea application, were obtained in the conventional treatment (T2). The hydrolysis of urea resulted in the availability of ammonical N (NH₄⁺–N) in the fertilized treatments for crop uptake, nitrification, and denitrification (NO₃⁻–N) processes (Banerjee et al. 2002). In the soil, both the processes might have occurred simultaneously, as frequent irrigation carried dissolved O₂ in water making the soil partially aerobic

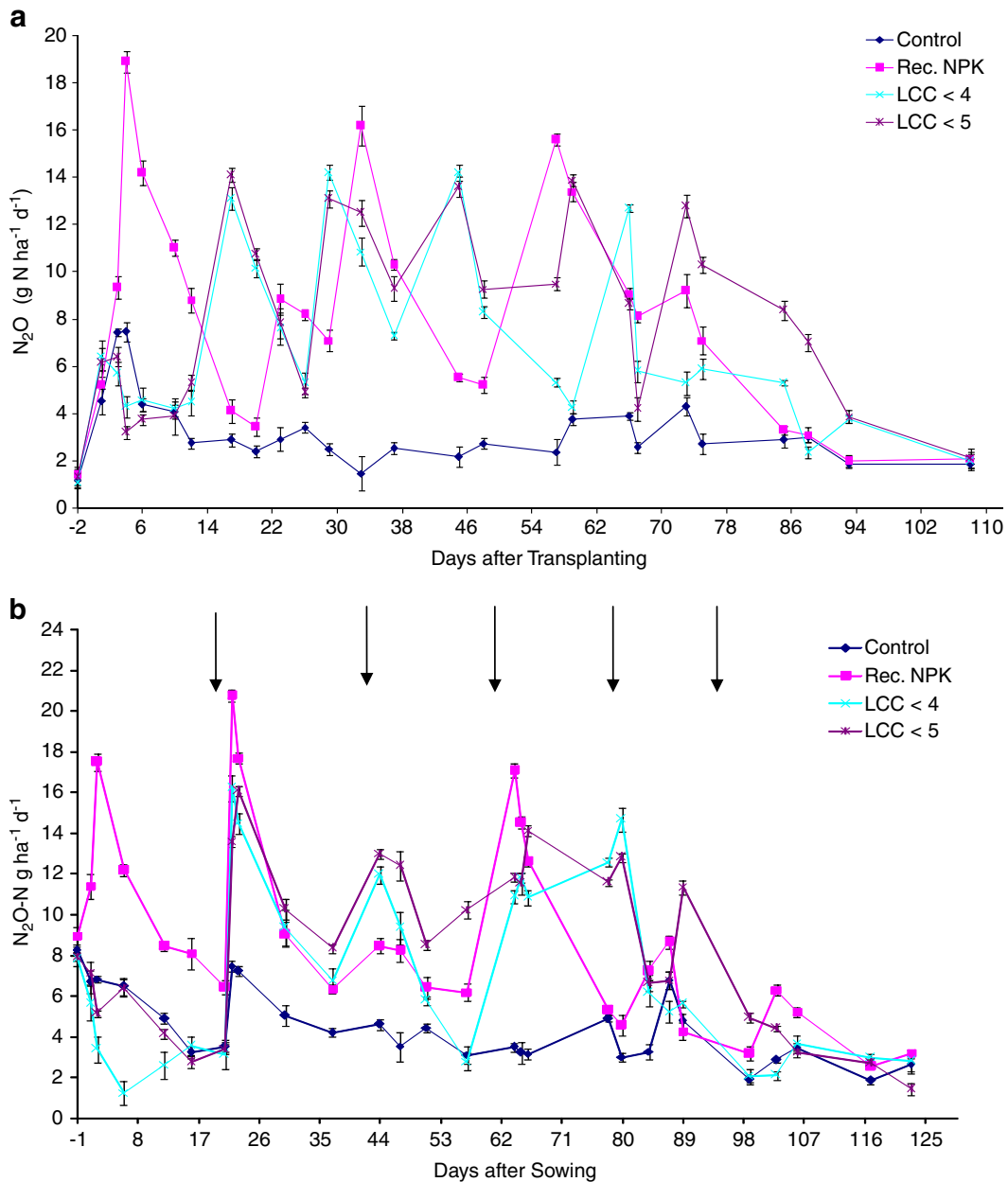


Fig. 1 Emission of N_2O in **a** rice and **b** wheat under different N management options. Downward-pointing arrows indicate the days of irrigation in wheat

(Majumdar et al. 2000). The initial low fluxes of N_2O (1 to 6 g N_2O-N ha⁻¹) in the control (T1) and LCC treatments (T3 and T4) were probably due to nitrification of NH_4^+-N present in soil, whose concentration reduced in T1, T3, and T4 treatments (Fig. 2a). After application of 30 kg N ha⁻¹ on 14 days AT in LCC≤4 (T3) and LCC≤5 (T4)

treatments, peaks of 13.4 and 14.1 g N_2O-N ha⁻¹, respectively, were obtained on 17 days AT. The peaks of N_2O flux were obtained 2–3 days after application of 30 kg N ha⁻¹ urea based on LCC. In the case of LCC≤5 treatment (T4), five peaks of N_2O flux were obtained as N was added in five splits, and in LCC≤4 treatment (T3), four peaks of

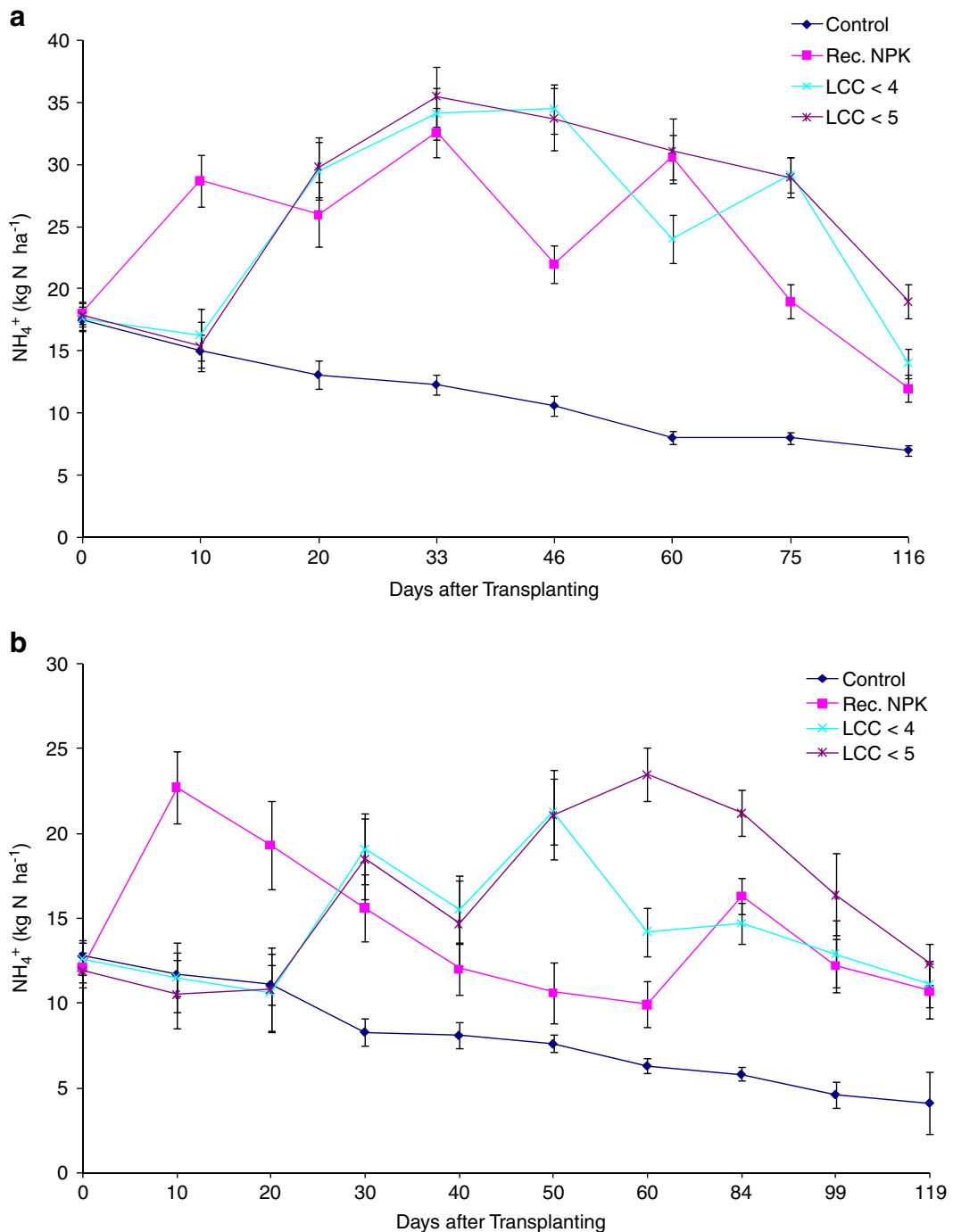


Fig. 2 NH_4^+ concentration in **a** rice and **b** wheat under different N management options

N_2O flux were obtained (Fig. 1a). The magnitudes of the peaks of N_2O flux obtained in LCC treatments were lower than the peaks obtained in the conventional treatment.

Total emission of N_2O during rice crop ranged from 285 g ha^{-1} in the unfertilized control plots (T1) to 788 g ha^{-1} in conventional split application of urea (Table 2). Cumulative emissions

Table 2 Effect of various options of N management on emission of methane, nitrous oxide, carbon dioxide, and carbon equivalent emissions in rice–wheat system

Treatment	CH ₄ emission in rice (kg ha ⁻¹)	CH ₄ emission in wheat (kg ha ⁻¹)	N ₂ O emission in rice (kg N ha ⁻¹)	N ₂ O emission in wheat (kg N ha ⁻¹)	CO ₂ emission in rice (kg C ha ⁻¹)	CO ₂ emission in wheat (kg C ha ⁻¹)	GWP of rice–wheat system ^a (kg CO ₂ ha ⁻¹)	Carbon equivalent emission ^b (CEE) (kg C ha ⁻¹)
T1	31.0a	-0.09a	0.285a	0.389a	1,092a	1,441a	10,619a	2,896a
T2	35.6b	-0.06a	0.788d	0.917d	1,483b	1,635b	13,692c	3,734c
T3	32.1c	-0.03a	0.665b	0.751b	1,348b	1,505b	12,395b	3,380b
T4	34.1b	-0.17a	0.735c	0.832c	1,431b	1,558b	13,061c	3562c

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

^a $GWP = CO_2\text{emission} + (CH_4\text{emission in rice} \times 25 + CH_4\text{uptake in wheat} \times 25) + (N_2O\text{ emission in rice} + N_2O\text{ emission in wheat}) \times 298$

^b Carbon equivalent emission = $GWP \times 12/44$

of N₂O were lower in both the LCC-based treatments (T3 and T4) as compared to conventional treatment (T2). Daily average emissions of N₂O were 8.1, 6.7, and 7.7 g ha⁻¹ per day in the T2, T3, and T4 treatments respectively during rice crop. On an average, 4.2, 3.2, and 3.7 g ha⁻¹ of N₂O–N emissions were obtained per kilogram of urea–N applied in the conventional (T2), LCC≤4 (T3) and LCC≤5 (T4) treatments, respectively. The application of urea based on LCC≤4 and LCC≤5, lowered the cumulative N₂O emissions by 15.6% and 6.7%, respectively over the conventional N application. These results indicated that N application starting at 14 days AT in rice, based on crop need as determined by the LCC, was more efficient in increasing N-use efficiency. Demand-driven application eliminated wastage of N by avoiding application when the crop did not require it and prevented excessive application of N, which could leak from rice fields to contaminate water bodies and emit as GHG in the atmosphere (Wang et al. 2007).

Nitrous oxide emission in wheat

Application of water in the dry soil before sowing of wheat triggered off the activity of the nitrifying microbes resulting in greater fluxes of N₂O before sowing (Fig. 1b). Fluxes of N₂O on 1 day AS ranged from 5.6 to 11.4 g ha⁻¹ per day, and declined subsequently, when NH₄⁺ contents in soil decreased (Fig. 2b) as a result of nitrification in aerobic conditions of wheat except in T2 plots where a basal dose of urea was applied. After every dose of urea

application, N₂O flux increased due to the availability of substrate for nitrification. The NH₄⁺ concentrations increased in the soil after each application of N fertilizer. Three, four, and five peaks of N₂O fluxes were obtained in the conventional (T2), LCC≤4 (T3), and LCC≤5 (T4) treatments, respectively after application of N fertilizer. Lower fluxes of N₂O were obtained in LCC-based plots as compared to conventional application of N. The levels of NH₄⁺–N were lower in wheat (Fig. 2b) than in rice (Fig. 2a). The N₂O emissions observed in aerobic conditions of wheat were primarily a result of nitrification, except during short periods after each irrigation event when creation of anoxic soil conditions for a short period resulted in enhanced denitrification activity (Arah and Smith 1989) and a slight increase in N₂O flux was observed. The NO₃–N levels (result not shown here) remained higher over a longer duration in the LCC-based urea application treatments resulting in higher N uptake as compared to conventional application.

Magnitude of N₂O fluxes was higher in conventional plots as compared to the LCC-based urea application treatments. The first peak of N₂O flux was obtained 2 days AS in the T2 treatment only as no basal application of fertilizer was carried out in LCC treatments T3 and T4. The highest peak flux of 20.7 g ha⁻¹ N₂O–N was obtained in the T2 treatment 23 days AT, after fertilizer application 21 days AT, whereas the N₂O fluxes remained lower than 16.1 g ha⁻¹ in the T3 and T4 treatments throughout the crop growth period. Peak fluxes of 16.1, 13.1, 10.2, 11.9, and 12.8 g ha⁻¹ N₂O–N were obtained in the LCC≤5 treatment on 23, 44, 57, 64, and 80 days

AS after the application of 30 kg N ha⁻¹ on 21, 43, 56, 62, and 77 days AS (Fig. 1b). In LCC≤4 treatment, four peaks of N₂O–N flux were observed after the application of 30 kg N ha⁻¹ on 21, 43, 62, and 77 days AS. Total emission of N₂O during wheat crop ranged from 389 g ha⁻¹ in the unfertilized treatment (T1) to 917 g ha⁻¹ in the conventional treatment (T2) (Table 2). As in the case of rice, significantly lower cumulative emission of N₂O (18% for LCC≤4) were obtained in LCC-based urea application in wheat as compared to the conventional urea application implying better N-use efficiency.

Methane emission in rice

Fluxes of CH₄ fluctuated between 0.001 and 1.40 kg ha⁻¹ per day during the crop growing period. Methane emissions from N-treated plots were higher than from unfertilized plots. Peak flux of 1.40 kg ha⁻¹ per day was observed 34 days AT in the LCC≤5 treatment (T4) followed by 1.24 kg ha⁻¹ per day in the conventional treatment (T2) (Fig. 3a). Largest peak of methane flux in all treatments coincided with the active tillering phase in rice (34 days AT). The daily average flux of CH₄ ranged from 0.33 kg ha⁻¹ per day in unfertilized control to 0.41 kg ha⁻¹ per day in conventional N application. Four peaks of CH₄ flux were observed during the rice crop. These coincided with the continuous soil submergence because of rainfall and irrigation events. Three to four days after application of N, a marginal increase in the CH₄ flux was observed in all the treatments. This is because applied N might have increased the activity of the microorganisms, involved in the production of CH₄ (Singh et al. 1998; Jain et al. 2000) resulting in marginally increased emission.

Application of 120 kg urea per hectare based on LCC reduced the CH₄ emission significantly. The seasonally integrated flux of CH₄ was higher in the conventional urea application as compared to the LCC≤4 and LCC≤5 treatments (Table 2).

Methane uptake in wheat

In wheat, negative fluxes of CH₄ were observed on most days (Fig. 3b) resulting in a net consumption of CH₄ (Table 2). This indicated that aerobic soil condition during wheat favored the growth of methanotrophs and consumption of CH₄ (Sriegel et al. 1992; Lessard et al. 1994). There was no significant difference in the CH₄

uptake in the LCC-and the conventional treatments. A similar pattern of CH₄ uptake in soil under wheat crop was observed by Singh et al. (1996).

Carbon dioxide emission from rice soil

Initial soil CO₂ fluxes before transplanting rice were in the range of 12 to 14 kg C ha⁻¹ per day (Fig. 4a). During puddling of soil, the soil aggregates were broken releasing CO₂ trapped in the soil. The CO₂ flux decreased subsequently in the control and treated plots. Generally, the N application method had no significant effect on CO₂ emission rate, except on a few days. Peak fluxes of CO₂ emission appeared to be related to soil moisture and temperature conditions. High temperature during the kharif season was ideal for decomposition of soil organic carbon. Due to high porosity of the experimental soil, moisture levels went below saturation many times resulting in aerobic soil condition that favored decomposition of soil organic carbon into CO₂. The highest CO₂ flux of 15.6 kg C ha⁻¹ per day was observed in the conventional treatment (T2). The lowest average flux of CO₂ was observed in the unfertilized treatment (T1).

Cumulative seasonal emissions of CO₂ ranged from 1,092 in the control to 1,483 kg C ha⁻¹ in the conventional treatment (Table 2). Application of urea based on LCC did not affect the CO₂ emission. However, additional N (30 kg N ha⁻¹) application in the LCC≤5 treatment (T4) increased the CO₂ emissions marginally over the LCC≤4 treatment (T3). In LCC≤4 treatment, CO₂ emission was 23% more as compared to the unfertilized control treatment. The N available to microbial population in the fertilized treatments might have accelerated the decomposition of soil organic carbon leading to higher CO₂ emission.

Carbon dioxide emission from wheat soil

The fluxes of CO₂ were lower on day 1 in wheat than in the previous rice crop and ranged from 11 to 12 kg ha⁻¹ per day (Fig. 4b). The temporal emissions of CO₂ increased in the conventional treatment (T2), whereas a decline was observed in the LCC-based treatments. The application of N in three splits in T2 and four and five splits in T3 and T4 treatments, respectively, did not have a significant impact on the flux of CO₂. The average daily flux of CO₂ was at par in all the fertilized treatments. A marginal increase in the CO₂ flux was

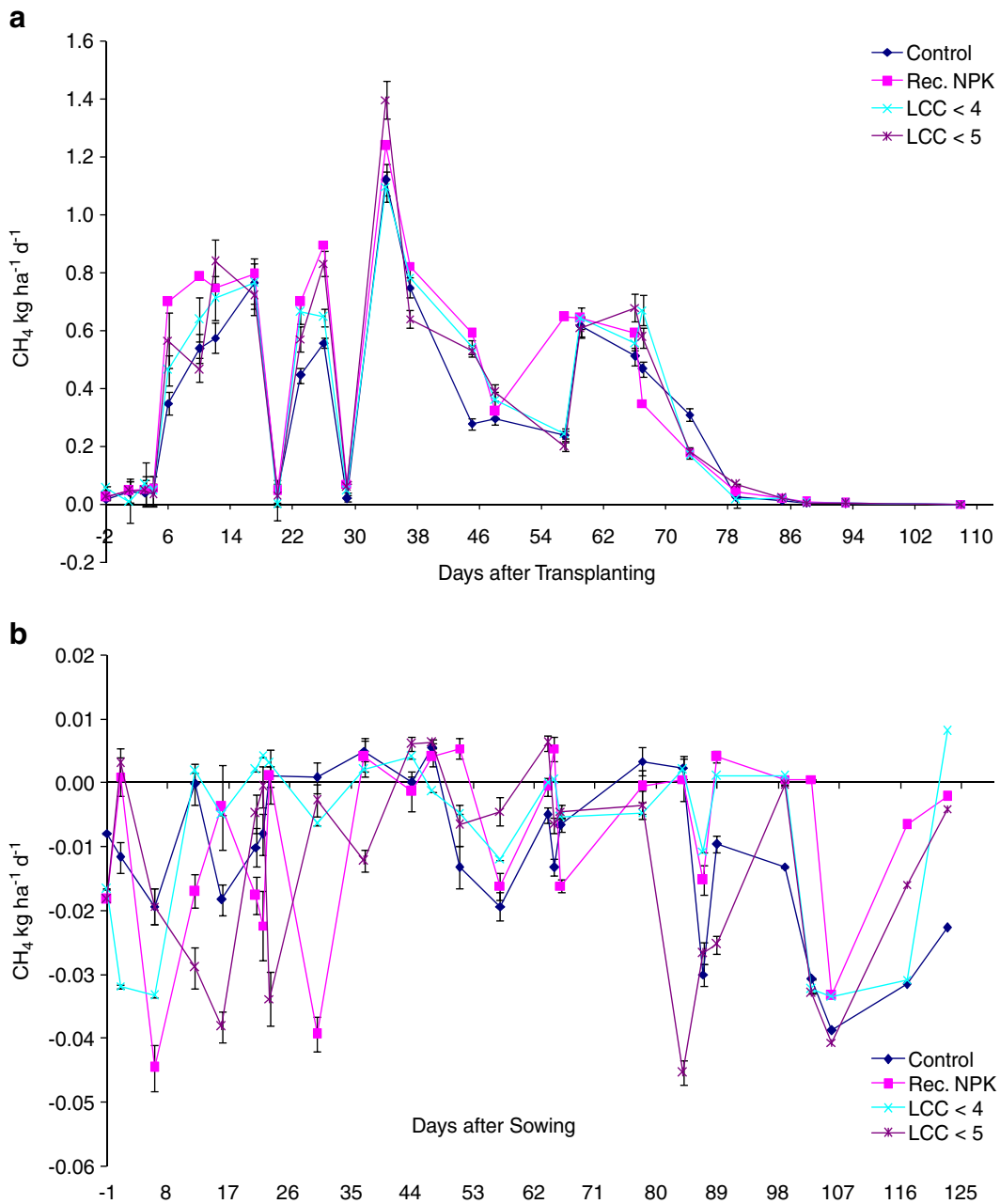


Fig. 3 Emission of CH₄ in **a** rice and **b** uptake of CH₄ in wheat under different N management options

observed with every split of urea application indicating that more availability of N increased soil respiration. Soil microbial activity may increase due to N fertilization as a result of increased biomass production, which stimulates soil biological activity (Dick 1992). Small peaks were observed after every irrigation event, indicating that soil moisture played a crucial role in the emission of CO₂. An increase in soil water content

resulted in increased CO₂ evolution probably due to greater availability of water to soil microbes and more diffusion of CO₂ from soil to the atmosphere.

In wheat, higher cumulative seasonal emissions were obtained in all the treatments than the preceding rice crop (Table 2). The CO₂ emissions in conventional (T2) and LCC-based N application (T3 and T4) treatments were at par. Application of N increased the CO₂

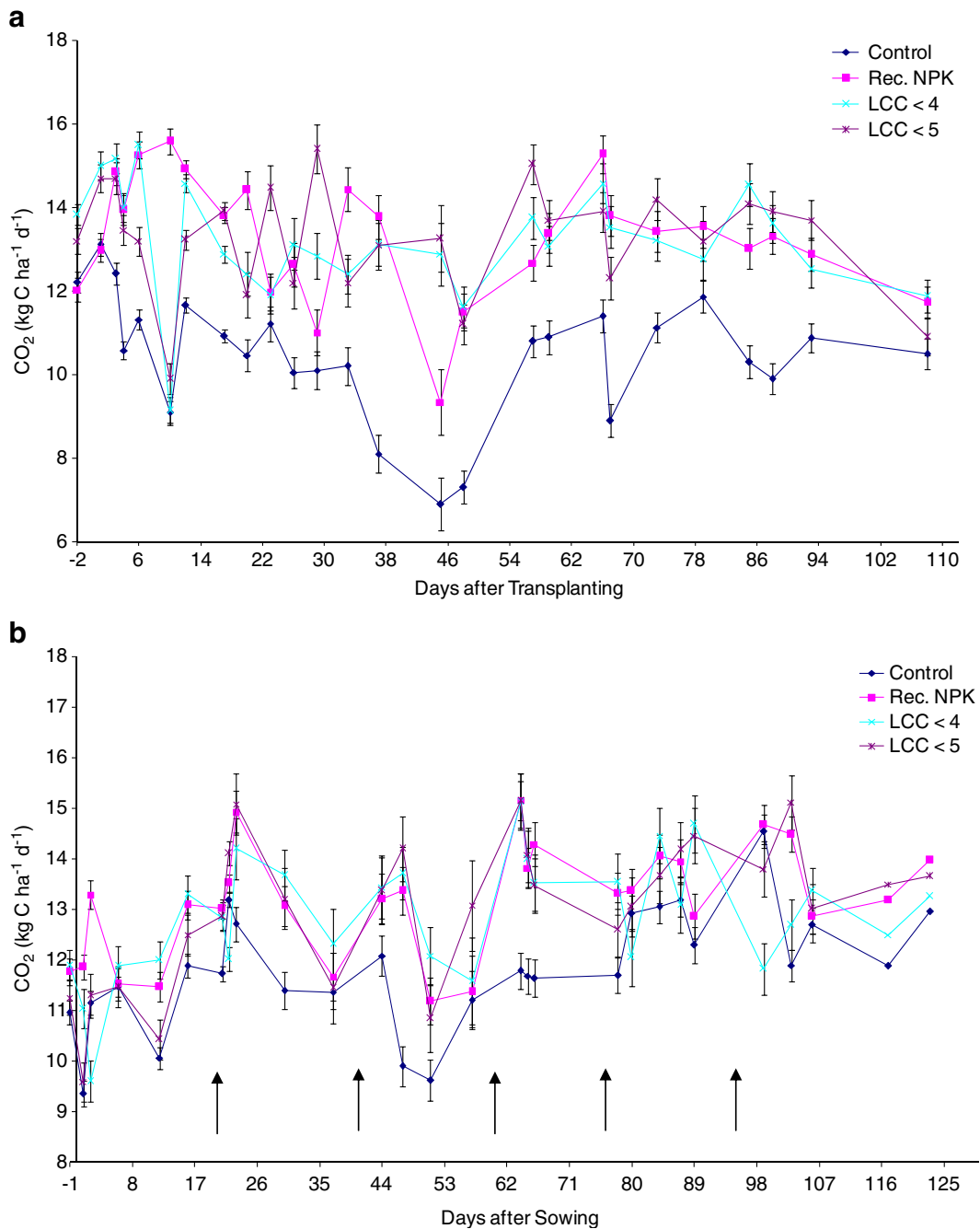


Fig. 4 Emission of CO_2 in **a** rice and **b** wheat under different N management options. *Upward-pointing arrows* indicate the days of irrigation in wheat

emission by 13% over the unfertilized control. Grace et al. (2003) reported that the CO_2 emissions from soil decreased with the application of fertilizer, whereas in our field conditions, the reverse pattern was observed and the emissions increased with the application of nitrogen fertilizer.

Yields of rice and wheat and plant N uptake

Grain yield in rice ranged from 2.95 to 6.55 Mg ha^{-1} , while yield of wheat varied from 2.7 to 6.1 Mg ha^{-1} (Table 3). The LCC-based urea application (T3 and T4) led to higher yields than split application of urea

Table 3 Yield and N uptake of rice and wheat as affected by various options of N management

Treatment	Grain yield rice (Mg ha ⁻¹)	Grain yield wheat (Mg ha ⁻¹)	Total C fixed in R-W ^a (Mg ha ⁻¹)	C efficiency ratio	Biomass in rice (Mg ha ⁻¹)	Biomass in wheat (Mg ha ⁻¹)	N uptake in rice (kg ha ⁻¹)	N uptake in wheat (kg ha ⁻¹)
T1	2.95a	2.7a	2.71a	0.94a	7.36a	7.11a	51a	58a
T2	5.3b	4.9b	4.89b	1.31b	13.22b	12.15b	105b	114b
T3	5.95c	5.6c	5.54c	1.64c	14.64b	13.75b	121c	132c
T4	6.55d	6.1d	6.06d	1.70c	15.28b	14.50b	133c	141c

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

^a Carbon content in rice=0.487 and in wheat 0.471

in both rice and wheat. Application of urea based on $LCC \leq 4$ produced 12% and 14% higher yield in rice and wheat, respectively than the conventional urea application, whereas $LCC \leq 5$ was found to be superior with 24% and 25% increase in rice and wheat yields, respectively. A number of studies in the IGP (Alam et al. 2004; Varinderpal-Singh et al. 2010) showed that critical shade of LCC for real time N management in rice to be $LCC \leq 4$, but it was found to be $LCC \leq 5$ in the present study. In another study conducted by Shukla et al. (2004), LCC-based N use for different rice and wheat genotypes produced higher yield than farmers’ practice and $LCC \leq 5$ gave higher yields compared to $LCC \leq 4$. Total carbon fixed in rice–wheat system in $LCC \leq 4$ treatment was 5.54 Mg C ha⁻¹ per year as compared to 4.89 Mg C ha⁻¹ per year in conventional urea application (Table 3). Pham et al. (2000) observed that adjusting N application and indigenous N supply was the key to get a higher yield of rice. They observed that N application with the help of LCC not only increased yield up to 10% but also saved 20–25 kg N ha⁻¹.

Uptake of N was higher with LCC-based urea application in both rice and wheat (Table 3) due to availability of N as per crop requirement. Abdulrachman et al. (2002) also obtained increased N uptake (13% to 22%) on site-specific nutrient management in rice. Application of additional 30 kg N ha⁻¹ in the $LCC \leq 5$ treatment in rice led to a higher biomass yield (Table 3). The results indicated that there was no need for any basal application of N in wheat as higher yields were obtained in the LCC-based urea application treatments where no basal N was applied. It was also observed that there was hardly any yield benefit of applying a basal dose of N to rice. However, due to the tight relationship between crop growth and N uptake, more significant

gains in yield and N-use efficiency appear to require field-specific, real-time N management to improve the congruence between N supply and crop N demand (Peng et al. 1996).

Global warming potential, carbon equivalent emission, and carbon efficiency ratio

The GWP of various treatments in the rice–wheat system varied between 10,619 kg CO₂ ha⁻¹ in the unfertilized treatment (T1) to 13,692 kg CO₂ ha⁻¹ with conventional urea application (T2) (Table 2). The LCC-based urea application ($LCC \leq 4$) reduced the GWP of the rice–wheat system by 10.5%. An increase in GWP with the application of additional 30 kg N ha⁻¹ in $LCC \leq 5$ treatment was due to the increase in N₂O emissions.

The CEE in the rice–wheat system varied from 2,896 to 3,734 kg C ha⁻¹ (Table 2). Even though there was an additional application of 30 kg N ha⁻¹ in the $LCC \leq 5$ treatment, the CEEs were at par with the conventional treatment (T2). Grace et al. (2003) estimated an annual GWP of 3,496 to 7,137 kg C ha⁻¹ of irrigated rice–wheat system in the IGP depending on crop management practices.

The CER in $LCC \leq 4$ (T3) was higher than in the conventional urea treatment (T2) (Table 3). The lowest CER (0.94) was observed in unfertilized treatment as this had the lowest CEE and also the least amount of C fixed in rice and wheat. Application of additional 30 kg N ha⁻¹ in the $LCC \leq 5$ treatment (T4) significantly increased grain yield but increased the CEE marginally, resulting in the highest CER (1.7). In comparison with the conventional urea splits, the LCC treatment ($LCC \leq 4$) gave 13% higher net return in the rice–wheat system. An increase in N by

30 kg ha⁻¹ (LCC≤5) increased the farmers' return by Rs 13,000 ha⁻¹. The demand-driven approach for managing fertilizer N will thus increase profit for farmers by achieving high crop yields and better efficiency of crop N use.

Conclusions

More studies are required to evaluate the GHG mitigation potential of LCC-based urea application in other cropping systems. The use of LCC reduced the global warming potential of rice–wheat cropping system and also significantly increased crop yields, N-use efficiency, and carbon efficiency ratio. Thus, it may provide a win–win option for the farmers for real-time N management to reduce GHG emission and optimize N application with crop demand.

References

- Abdulrachman, S., Gines, H. C., Nagarajan, R., Satawathananont, S., Son, T. T., Tan, P. S., et al. (2002). Variation in the performance of site-specific nutrient management among different environments with irrigated rice in Asia. *Better Crops International*, 16, 18–23.
- Alam, M. M., Buresh, R. J., Ladha, J. K., & Khan, A. H. (2004). *Site-specific nutrient management (SSNM) for rice: recommendations and user guidelines*. Gazipur: Bangladesh Rice Research Institute.
- Arah, J. R. M., & Smith, K. A. (1989). Steady state denitrification in aggregated soils: a mathematical model. *Journal of Soil Science*, 40, 139–149.
- Balasubramanian, V., Ladha, J. K., Gupta, R. K., Naresh, R. K., Mehla, R. S., Bijay-Singh, et al. (2003). In J. K. Ladha et al. (Eds.), *Improving the productivity and sustainability of rice–wheat systems: Issues and impact* (pp. 115–118). Madison: ASA. ASA Spec Publ 65.
- Banerjee, B., Pathak, H., & Aggarwal, P. K. (2002). Effects of dicyandiamide, farmyard manure and irrigation on ammonia volatilization from an alluvial soil in rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system. *Biology and Fertility of Soils*, 36, 207–214.
- Bijay-Singh, & Yadvinder-Singh. (2003). Efficient nitrogen management in rice–wheat system in the Indo-Gangetic plains. In Yadvinder-Singh, Bijay-Singh, V. K. Nayyar, & J. Singh (Eds.), *Nutrient management for sustainable rice–wheat cropping system. National Agricultural Technology Project* (pp. 99–114). New Delhi: Indian Council of Agricultural Research.
- Bijay-Singh, Yadvinder-Singh, Ladha, J. K., Bronson, K. F., Balasubramanian, V., Singh, J., et al. (2002). Chlorophyll meter and leaf color chart-based nitrogen management for rice and wheat in northwestern India. *Agronomy Journal*, 94, 821–829.
- Dick, R. P. (1992). A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. *Agriculture, Ecosystems and Environment*, 40, 25–36.
- Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H. C., Nagarajan, R., et al. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research*, 74, 37–66.
- Grace, P. R., Harrington, L., Jain, M. C., & Robertson, G. P. (2003). Long term sustainability of tropical and subtropical rice–wheat system: an environmental perspective. In J. K. Ladha et al. (Eds.), *Improving the productivity and sustainability of rice–wheat systems: Issues and Impacts* (pp. 27–41). Madison: ASA. ASA Spec Publ 65.
- IPCC. (2007). The physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.
- IRRI (International Rice Research Institute). (2005). *Accelerating technology adoption to improve rural livelihoods in the rainfed Eastern Gangetic Plains. IRRI technical report, ref. DPPC2002-27*. Los Baños: IRRI.
- Jain, M. C., Kumar, S., Wassmann, R., Mitra, S., Singh, S. D., Singh, J. P., et al. (2000). Methane emissions from irrigated rice fields in Northern India (New Delhi). *Nutrient Cycling in Agroecosystems*, 58, 75–83.
- Kotsyurbenko, O. R., Chin, K. J., Glagolev, M. V., Stubner, S., Simankova, M. V., Nozhevnikova, A. N., et al. (2004). Acetoclastic and hydrogenotrophic methane production and methanogenic populations in an acidic West-Siberian peat bog. *Environmental Microbiology*, 6, 1159–1173.
- Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Advances in Agronomy*, 87, 85–176.
- Lessard, R., Rochette, P., Topp, E., Pattey, E., Desjardins, R. L., & Beaumont, G. (1994). Methane and carbon dioxide fluxes from poorly drained adjacent cultivated and forest sites. *Canadian Journal of Soil Science*, 74, 139–148.
- Majumdar, D., Kumar, S., Pathak, H., Jain, M. C., & Kumar, U. (2000). Reducing nitrous oxide emission from rice field with nitrification inhibitors. *Agriculture, Ecosystems and Environment*, 81, 163–169.
- Page, A. L., Miller, R. H., & Keeney, D. R. (1982). *Methods of soil analysis. Part 2, chemical and microbiological properties* (2nd ed., p. 1159). Madison: ASA-SSSA.
- Pathak, H. (2010). Mitigating greenhouse gas and nitrogen loss with improved fertilizer management in rice: quantification and economic assessment. *Nutrient Cycling in Agroecosystems*. doi:10.1007/s10705-010-9350-z.
- Pathak, H., Bhatia, A., Prasad, S., Singh, S., Kumar, S., Jain, M. C., et al. (2002). Emission of nitrous oxide from soil in rice wheat systems of Indo-Gangetic plains of India. *Environmental Monitoring and Assessment*, 77, 163–178.
- Peng, S., Garcia, F. V., Laza, R. C., Sanico, A. L., Visperas, R. M., & Cassman, K. G. (1996). Increased N-use efficiency

- using a chlorophyll meter on high-yielding irrigated rice. *Field Crops Research*, 47, 243–252.
- Pham, S. T., Tuyen, T. Q., Huan, T. T. N., Khuong, T. Q., Diep, L. N., Dung, H. T., et al. (2000). Site-specific nutrient management in intensive nutrient rice ecosystems: a case study in Omon district, Cantho province. *Omon Rice*, 8, 64–74.
- Shukla, A. K., Ladha, J. K., Singh, V. K., Dwivedi, B. S., Balasubramanian, V., Gupta, R. J., et al. (2004). Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. *Agronomy Journal*, 96, 1606–1621.
- Singh, J. S., Singh, S., Raghubanshi, A. S., Singh, S., & Kashyap, A. K. (1996). Methane flux from rice/wheat agro-ecosystem as affected by crop phenology, fertilization and water level. *Plant and Soil*, 183, 323–327.
- Singh, J. S., Raghubanshi, A. S., Reddy, V. S., Singh, S., & Kashyap, A. K. (1998). Methane flux from irrigated paddy and dryland rice fields, and from seasonally dry tropical forest and savanna soils of India. *Soil Biology and Biochemistry*, 30, 135–139.
- Sriegel, R. G., McConnaughey, T. A., Thorsteson, D. C., Weeks, E. P., & Woodward, J. C. (1992). Consumption of atmospheric methane by desert soils. *Nature*, 357, 145–147.
- Varinderpal-Singh, B.-S., Yadvinder-Singh, T. H. S., & Gupta, R. K. (2010). Need based nitrogen management using the chlorophyll meter and leaf colour chart in rice and wheat in South Asia: a review. *Nutrient Cycling in Agroecosystems*, 88, 361–380.
- Wang, G. H., Dobermann, A., Witt, C., Sun, Q. Z., & Fu, R. X. (2001). Performance of site-specific nutrient management for irrigated rice in southeast China. *Agronomy Journal*, 93, 869–878.
- Wang, G., Zhanga, Q. C., Witt, C., & Buresh, R. J. (2007). Opportunities for yield increases and environmental benefits through site-specific nutrient management in rice systems of Zhejiang province China. *Agricultural Systems*, 94, 801–808.