Paddy Water Environ (2006) 4: 111–117
DOI 10.1007/s10333-006-0038-6

SHORT COMMUNICATION

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Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution

Received: 22 August 2005 / Accepted: 15 February 2006 / Published online: 12 April 2006

Abstract Burning of rice straw is a common practice in northwest India, where rice–wheat cropping system is extensively followed. The practice results in loss of nutrients, atmospheric pollution and emission of greenhouse gases. A field experiment was conducted at Indian Agricultural Research Institute, New Delhi, India during the rabi season (November to April) of 2002–2003 to evaluate the efficacy of the various modes of rice straw recycling in soil in improving yield and soil fertility and reducing not only carbon dioxide emission but also nitrous oxide (N_2O) emission. The treatment with no rice straw incorporation and application of recommended doses of fertilizer (120, 26 and 50 kg N, P and K ha^{-1}, respectively), gave the highest yield of wheat. Treatments with the incorporation of rice straw at 5 Mg ha^{-1} with additional amount of inorganic N (60 kg N ha^{-1}) or inoculation of microbial culture had similar grain yields to that of the treatment with no straw incorporation. The lowest yield was recorded in the plots where rice straw was incorporated in soil without additional inorganic N and with manure application. All the treatments with rice straw incorporation had larger soil organic C despite the effect on the mineralisation of soil organic matter. Emission of N_2O was more when additional N was added with rice straw and secondary when straw was added to the soil because of higher microbial activity. The study showed that burning of rice straw could be avoided without affecting yield of wheat crop by incorporating rice straw in soil with an additional dose of inorganic N or microbial inoculation. However, the reduction of N_2O emission due to avoiding burning is in part counterbalanced by an increase in emission during the subsequent wheat cultivation.

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Keywords Farmyard manure · Microbial inoculation · Nitrous oxide emission · Soil organic carbon

Introduction

Rice is the primary staple food for more than 40% of the world's population. Globally about 155 million ha of rice is harvested annually with a production of about 596 million tons (IRRI 2001). More than 90% of this is produced and consumed in Asia. India, with 42.25 million ha of land under rice, produces about 110 million tonnes of rice and 170 million tonnes of rice straw every year (FAI 2001). The disposal of such huge amount of rice straw is a major concern, particularly in the northwest India, where rice–wheat cropping system is extensively followed. Rice straw is not used as animal feed due to its low digestibility, low protein, high lignin and high silica contents. It is also not recycled in soil due to limited time (20–25 days) left before sowing of succeeding wheat crop. Within this short period of 20–25 days rice straw can not be completely decomposed in soil. Moreover, due to addition of large amount of organic C through rice straw, a net immobilization of N occurs in soil and the wheat crop suffers from N deficiency resulting in lower yield. Farmers in the northwest India, therefore, dispose a large part of rice straw by burning it in situ. In a recent survey it was observed that 60 and 82% of rice straw produced in the north-western states of Haryana and Punjab, respectively, are burned in the field (Punjab Agricultural University, unpublished). Burning of rice straw is also a major problem in Italy, Turkey and Spain, where large amounts of rice straw are burned in situ (L. Zavattaro, unpublished).

The burning of rice straw is environmentally unacceptable as it leads to (1) release of soot particles and smoke causing human health problems such as asthma or other respiratory problems, (2) emission of greenhouse gases such as carbon dioxide, methane and nitrous oxide (N_2O) causing global warming and (3) loss of plant nutrients such as N, P, K and S. Almost entire amounts of C and N, 25% of P, 50% of S and 20% of K present in straw are lost due to burning

(Dobermann and Fairhurst 2000). The gaseous emissions from burning of rice straw were 70% CO_2, 7% CO, 0.7% CH_4 and 2.1% N_2O (Yoshinori and Kanno 1997). It has been reported from the United Kingdom that 40–80% of wheat crop residue N is lost as ammonia when it is burned in the field and emissions of ammonia declined from 20 kt N $year^{-1}$ in 1981 to 3.3 kt N $year^{-1}$ in 1991 as a result of changes in agricultural practices because of an imposed ban on the burning of crop residues (Lee and Atkins 1994). Kumar et al. (2001) reported that for every ton of wheat residues burned, 2.4 kg of N was lost. Likewise, S losses from the burning of high-S and low-S rice crop residues in Australia were 60 and 40% of S content, respectively (Lefroy et al. 1994). Therefore, burning of crop residues should be avoided and alternate measures of disposal of residues should be found out.

One potential solution to the problem of rice straw burning would be its recycling in soil. Straw recycling can improve soil organic matter, therefore, the succeeding crops can benefit from this (Kumar and Goh 2000; Samra et al. 2003). Recycling of rice straw with high C:N (60–70), however, could accelerate immobilization of N causing N-deficiency to the following crop (Singh et al. 2001). To enhance the decomposition of straw microbial (fungi and bacteria) inoculation can be made. Another strategy to overcome the problem of net N-immobilization due to straw addition could be to apply additional amount of inorganic N so that the succeeding crop does not suffer from N-deficiency (Pathak and Sarkar 1994).

Emission of nitrous oxide (N_2O), a greenhouse gas accounting for approximately 5% of the enhanced global warming (Watson et al. 1996), from agriculture is a major environmental problem. The gas is also responsible for the destruction of the stratospheric ozone (Rodhe 1990). Atmospheric concentration of N_2O is increasing at a rate of 0.22% per year (Battle et al. 1996). Agricultural soils contribute 65% of anthropogenic N_2O emission (Mosier et al. 1998). Application of organic C, required for microbial growth, through rice straw could accelerate the emission of N_2O from soil (Pathak et al. 2002).

Prasad and Power (1991) and Kumar and Goh (2000) emphasized that no single residue management practice is superior under all conditions. Therefore, it is important to determine the benefits and adverse effects of residue management options before these are recommended to farmers for adoption. The objectives of the present study were to (1) evaluate the effect of various modes of rice straw recycling on the subsequent wheat crop, (2) assess the impact of straw recycling on soil fertility and (3) measure N_2O emission from soil due to rice straw recycling.

Materials and methods

Experimental site and soil

A field experiment was conducted at Indian Agricultural Research Institute, New Delhi farm during the rabi (November to April) season of 2002–2003. The site is located in the Indo-Gangetic alluvial tract at 28°40′N and 77°12′E, at an altitude of 228 m above mean sea level. The climate of the region is subtropical, semi-arid. The area receives an annual rainfall of 750 mm, about 80% of which occurs from June to September. The mean maximum and minimum temperatures from July to October (kharif season) are 35 and 18°C, respectively; while from November to April (rabi season) 22.6 and 6.7°C, respectively. The alluvial soil of experimental site was Typic Ustochrept with pH 8.0, loam in texture, bulk density 1.38 g cm^{-3}, electrical conductivity 0.43 dS m^{-1}, cation exchange capacity 7.3 cmol kg^{-1} and organic carbon 0.42% (Walkley and Black 1934). Alkaline $KMnO_4$-extractable N (Subbiah and Asija 1956), Olsen P (Olsen et al. 1954) and ammonium acetate extractable K (CSTPA 1974) contents of the soil were 232, 17 and 335 kg ha^{-1}, respectively. The site was under rice–wheat cropping system for the last 15 years.

Treatments and crop management

The experiment had six treatments with three replications in plots of 6 m long and 5 m wide in a randomised block design. The details of the treatments are given in Table 1. Rice straw containing C, N, P and K 480, 5.3,

Table 1 Treatments

Treatment	Details
1. NPK	N, P and K 120, 26 and 40 kg ha^{-1}, respectively; no rice straw incorporation.
2. NPK + straw	N, P and K 120, 26 and 40 kg ha^{-1}, respectively; rice straw (5 Mg ha^{-1}) incorporated after chopping into 5–6 cm pieces.
3. NPK + straw + urea	N, P and K 180, 26 and 40 kg ha^{-1}, respectively (extra 60 kg ha^{-1} inorganic N was applied to bring the C:N of rice straw to 20); rice straw (5 Mg ha^{-1}) incorporated after chopping into 5–6 cm pieces.
4. NPK + straw + FYM	N, P and K 120, 26 and 40 kg ha^{-1}, respectively; rice straw (5 Mg ha^{-1}) incorporated after chopping into 5–6 cm pieces; FYM at 5 Mg ha^{-1}.
5. NPK + straw + microbes	N, P and K 120, 26 and 40 kg ha^{-1}, respectively; rice straw (5 Mg ha^{-1}) incorporated after chopping into 5–6 cm pieces; microbial culture.
6. NPK + straw burnt	N, P and K 120, 26 and 40 kg ha^{-1}, respectively; rice straw (5 Mg ha^{-1}) burnt in the plot.

1.6 and 21.2 g kg^{-1}, respectively, was incorporated into the soil after chopping into 5–6 cm pieces. Farmyard manure (FYM) consisting of well-rotten cattle dung and cattle-shed wastes containing C, N, P and K 400, 9.6, 2.9 and 4.8 g kg^{-1}, respectively, was incorporated into the soil 2 weeks before sowing of wheat. Nitrogen, through urea, was applied in 3 equal splits, ½ at the time of sowing,¼ at crown root initiation stage and ¼ at maximum tillering stage. Phosphorus and K was incorporated into the soil at the time of sowing using single super phosphate (SSP) and muriate of potash (KCl), respectively. For microbial culture 50 g mycellial mat of *Aspergillus awamori*, 50 g mycellial mat of *Trichoderma viridii* and 1 L of *Bacillus polymyxa* (10^8 viable cells) per 100 kg of straw was applied. Wheat (cultivar HD 2329, 100 kg seed ha^{-1}) was sown in rows 22.5 cm apart. The plots were irrigated and weeds, pests, and diseases were controlled as per requirement.

Prior to the wheat crop, rice (cultivar Pusa 44) was grown in the field under lowland puddled condition. Nitrogen was applied through surface broadcast of urea in three splits of 60, 30 and 30 kg N ha^{-1} at 17, 37 and 62 days after transplanting of rice; while P (26.2 kg ha^{-1}) and K (50 kg ha^{-1}) were incorporated into the soil at the time of transplanting using SSP and KCl, respectively. The crop was harvested at maturity and the straw was removed from the field. Yield of rice was about 6.0 Mg ha^{-1}.

Collection and analysis of gas samples for nitrous oxide

Collection of gas samples was carried out by the closed-chamber technique (Hutchinson and Mosier 1981). Chambers of 50 cm × 30 cm × 100 cm (length × width × height) were made of 6 mm thick acrylic sheets. An aluminum channel of 15 cm height and 5 cm internal diameter placed in the field was used with each chamber. The channel was inserted at 10 cm depth in the soil. Before the collection of gas samples, the chamber was placed on the channel and the channel was filled with water to make the system air-tight. Once the samples were collected, the chamber was taken out. One 3-way stopcock was fitted at the top of the chamber to collect the gas samples. The chamber was thoroughly flushed several times with a 50-ml syringe to homogenize the inside air. Gas samples were drawn with 50-ml syringe with the help of a hypodermic needle (24 gauge) at 0, 1 and 2 h and syringes were made air-tight with a 3-way stopcock. Headspace volume inside the box was recorded to calculate flux of N_2O–N. Concentration of N_2O–N in the gas samples was estimated by Gas Chromatograph (Hewlett Packard 5890 Series II) fitted with an electron capture detector (ECD) and 6′ × 1/8′ stainless steel column (Porapak N). Column, injector, and detector temperatures were 50, 120 and 320°C, respectively. Carrier gas was N_2 with a flow rate of 14 ml min^{-1}. Gas samples were collected once in a week initially and then once in 2 weeks till the harvest of wheat crop.

Estimation of total N_2O emission during the crop season was done by successive linear interpolation of average N_2O emission on the sampling days assuming that N_2O emission followed a linear trend during the periods when no sample was taken (Majumdar et al. 2000; Pathak et al. 2002).

Estimation of wheat yield

Wheat grain and straw yields were recorded from the total plot area by harvesting all the plants excluding plants bordering the plot. Grain weights were expressed at 120 g kg^{-1} water content whereas straw weights were expressed on an oven-dry basis (65°C).

Soil sample analyses

Soil samples from the 0–15-cm soil layer in three locations in each plot were collected using a core sampler. Representative sub-samples were drawn to determine various physico-chemical properties of soils using standard procedures (Page et al. 1982).

Global warming potential

Global warming potential (GWP) 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. It is used to compare the effectiveness of each greenhouse gas to trap heat in the atmosphere relative to some standard gas, by convention CO_2. The GWP for N_2O (based on a 100-year time horizon) is 310 when for CO_2 the value is taken as 1. The GWP of different treatments were calculated using the following equation (Watson et al. 1996).

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}) = \text{N}_2\text{O (kg ha}^{-1}) \times 310$$

Data analysis

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

Results and discussion

Wheat yield

Yields of wheat ranged from 4.17 Mg ha^{-1} in NPK + rice straw treatment to 4.72 Mg ha^{-1} in NPK treatment where straw was removed from field and recommended levels of NPK were applied (Table 2). Lower yield in NPK +

Table 2 Effect of rice straw amendment in soil on yield and N uptake of wheat

Treatments	Grain (Mg ha^{-1})	Straw (Mg ha^{-1})	Biomass (Mg ha^{-1})	Harvest index	N uptake (kg ha^{-1})
NPK	4.72a	6.36a	11.08a	43a	102a
NPK + straw	4.17c	6.67a	10.84a	38a	90a
NPK + straw + urea	4.56a	6.40a	10.96a	42a	96a
NPK + straw + FYM	4.22b,c	6.78a	11.00a	38a	88a
NPK + straw + microbes	4.61a	6.22a	10.83a	43a	97a
NPK + straw burnt	4.50a,b	6.67a	11.17a	40a	95a

Note. The letters a, b or c are used with the mean values to show the significant difference between the values. Within a column, means followed by the same letter (a and a, for example) are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. On the other hand if they are followed by different letters (a and b, for example), they are significantly different. If the mean value is followed by more than one letter (a,b for example), it is statistically similar to all the mean values followed by either a or b or a,b

rice straw amended plot was due to immobilization of N because of addition of rice straw with high C:N (Kumar and Goh 2000). Production of some organic acids in the process of decomposition of rice straw could also cause lowering of yields in rice straw amended plots (Kumar and Goh 2000). Similar to the results of the present study, Verma and Bhagat (1992) found that incorporation of rice straw (5 Mg ha^{-1}) 30 days before sowing resulted in lower wheat yields than the removal or burning of straw. In the NPK + straw + urea treatment, additional amount of N overcame the problem of N immobilization resulting in higher yields (Table 2). Lower yields in NPK + straw + FYM treatment was due to slow release of N from FYM and net immobilization of N. Microbial inoculation enhanced the decomposition of rice straw and more N became available leading to larger yields in the NPK + straw + microbes treatment.

At Faislabad in Pakistan, the incorporation of rice straw into the soil produced significantly higher yields of wheat vis-à-vis when rice straw was removed (Salim 1995). Singh et al. (1996) reported that the incorporation of rice straw 3 weeks before sowing significantly increased wheat yield on clay loam soil but not on sandy loam soil. Studies conducted by Sharma et al. (1987) showed no adverse effect of straw incorporation on the grain yield of wheat and the following rice. Application of FYM (5 Mg ha^{-1}) along with rice straw increased average wheat yield by 40% over the rice straw treatment and exhibited a significant residual effect on the following rice crop. In a field experiment conducted at Ludhiana, Punjab, India using ^{15}N-labeled urea, grain yields of wheat and the following rice were not adversely affected by incorporation of rice straw at least 20 days before sowing (Singh et al. 2001).

Straw yield of wheat ranged from 6.22 Mg ha^{-1} in NPK + straw + microbes treatment to 6.78 Mg ha^{-1} in NPK + rice straw + FYM treatment (Table 2). However, different treatments did not show any significant effect on straw yield of wheat. Total biomass of wheat ranged from 10.84 Mg ha^{-1} in NPK + rice straw and NPK + straw + microbes treated plot to 11.17 Mg ha^{-1} in NPK + straw burnt plot. Like straw yield, different treatments were statistically on par in terms of total biomass yield. Uptake of N varied between 88 and 102 kg ha^{-1} but the treatments were statistically on par in terms of N uptake (Table 2).

Soil fertility

Organic carbon content of soil at wheat harvest ranged from 0.47% (NPK treatment) to 0.68% (NPK + straw + FYM treatment) (Table 3). The treatments NPK + straw, NPK + straw + urea and NPK + straw + microbes had larger soil organic C (0.56–0.59%) compared to NPK or NPK + straw burnt treatments. Thus application of rice straw significantly improved the organic carbon status of soil.

$KMnO_4$ extractable N (a measure of plant available N in soil) ranged from 233 kg ha^{-1} (NPK treatment) to 265 kg ha^{-1} (NPK + rice straw + urea treatment). But the difference in $KMnO_4$–N among different treatments was not significant (Table 3).

Olsen P content in soil ranged from 17.6 kg ha^{-1} (NPK + straw burnt) to 18.8 kg ha^{-1} (NPK treatment). Treatment with straw burnt had smaller Olsen P compared to the rest of the treatments (Table 3).

Ammonium acetate extractable K in different treatments ranged from 342 kg ha^{-1} (NPK plot) to 422 kg ha^{-1} (NPK + rice straw + FYM plot) (Table 3). The highest content of ammonium acetate extractable K in NPK + straw + FYM plot was due to addition of K through FYM. Higher value of available K in NPK + straw burnt plot than that of NPK plot was because of the ash left in the field after burning of straw contains a good amount of K.

Field experiments conducted in India on the rice–wheat cropping system showed that both nutrient contents and their availability increased with the incorporation of crop residues compared with their removal or burning. In an 11-year field experiment on a loamy sand soil in the Indian Punjab, the incorporation of residues of both crops in the rice–wheat cropping system increased the total P, available P and K contents in the soil over the removal of residues (Beri et al. 1995). In another study over a 5-year period on a silt loam soil in Himachal Pradesh, the incorporation of rice straw in wheat caused a slight increase in the availability of P, Mn and Zn and a marked increase in the availability of K (Verma and Bhagat 1992). Misra et al. (1996) also observed increased available N, P and K contents in soil with incorporation of crop residues in the rice–wheat rotation.

Crop residues also play an important role in maintaining soil physical conditions. Removal or burning of crop residues deteriorated soil physical properties (Prasad and Power 1991) while incorporation of crop residues into the

Table 3 Effect of rice straw amendment in soil on soil fertility

Treatments	Org. C (%)	$KMnO_4$ N (kg ha^{-1})	Olsen P (kg ha^{-1})	NH_4OAc K (kg ha^{-1})
NPK	0.47c	233a	18.8a	342c
NPK + straw	0.56b	243a	18.7a	385a
NPK + straw + urea	0.59b	265a	18.5a	377a,b
NPK + straw + FYM	0.68a	250a	18.8a	422a
NPK + straw + microbes	0.57b	251a	18.7a	377a,b
NPK + straw burnt	0.50c	240a	17.6b	362b

Note. The letters a, b or c are used with the mean values to show the significant difference between the values. Within a column, means followed by the same letter (a and a, for example) are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. On the other hand if they are followed by different letters (a and b, for example), they are significantly different. If the mean value is followed by more than one letter (a,b for example), it is statistically similar to all the mean values followed by either a or b or a,b

soil under rice-based cropping systems improved soil aggregation (Liu and Shen 1992; Meelu et al. 1994). In long-term experiments in the rice–wheat cropping system in sandy loam soil, the incorporation of both rice and wheat straw vis-à-vis their burning or removal increased both the infiltration rate and cumulative infiltration (Walia et al. 1995; Singh et al. 1996). Similarly, in another 5-year study on the rice–wheat cropping system on a loamy sand soil, Meelu et al. (1994) observed increased rates of infiltration on soil amended with green manure and crop residues. Moreover, regular addition of sufficient amounts of organic materials such as crop residues to the soil leads to the maintenance of microbial biomass and improvement of soil fertility (Patra et al. 1992; Sidhu et al. 1995; Malik et al. 1998; Samra et al. 2003).

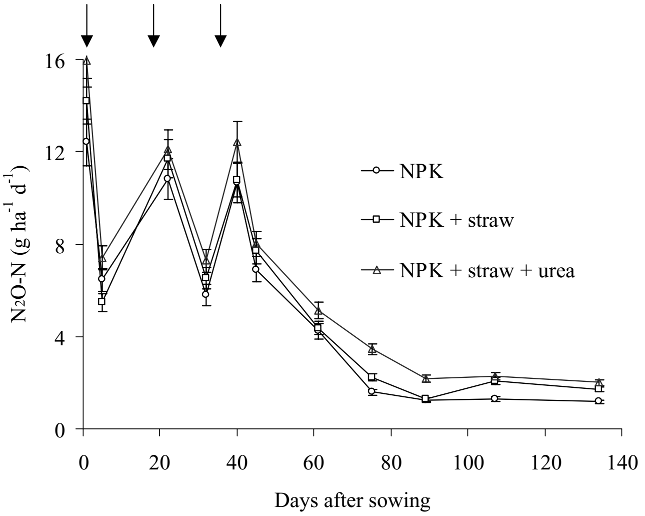

Fig. 1 Emission of nitrous oxide (N_2O) from soil under wheat with the various straw management practices. Arrows indicate application of N fertilizer

Nitrous oxide emission

Emission of N_2O on day 1 after sowing of wheat ranged from 12 to 16 g ha^{-1} d^{-1}, which reduced thereafter till the next dose of N was applied (Fig. 1). High emission of N_2O on day 1 was due to formation of N_2O during nitrification of 1) NH_4–N already present in soil as well as 2) NH_4–N produced by the hydrolysis of applied urea. A peak was observed in all the treatments following the addition of N through urea followed by a decline. Total emission of N_2O during the wheat season ranged from 588 g ha^{-1} with the NPK treatment to 749 g ha^{-1} with NPK + rice straw + urea treatment (Table 4). In terms of the total emission of nitrous oxide the treatments followed the sequence of NPK + straw + urea > NPK + straw = NPK + straw + FYM > NPK + straw + microbes > NPK + straw burnt = NPK. Application of additional amount of N through urea was responsible for higher N_2O emission in the NPK + rice straw + urea treatment (Pathak et al. 2002). In the straw amended plots, there were higher availability of organic carbon and greater microbial activity, which enhanced nitrification and denitrification (in microsites) resulting in higher emission of N_2O. Plant residues, green manure and farmyard manure have been reported to increase emission of N_2O (Aulakh 1988). Though emission of N_2O from soil during wheat was more in the straw amendment treatments compared to the straw burnt treatment, it may be expected that the latter emitted significant amount of N_2O during the burning of straw (Yoshinori and Kanno 1997). Moreover, straw amended treatments had more soil organic C. Thus carbon sequestration in these treatments could counter balance for the increased emission of N_2O due to straw incorporation in soil. The GWP of various treatments varied between 286 kg CO_2 equivalent ha^{-1} in the NPK treatment to 365 kg CO_2 equivalent ha^{-1} with NPK + straw + urea treatment (Table 4).

Conclusions

The study showed that rice straw could be managed in situ successfully. Additional inorganic N or microbial inoculation could avoid the problems of net N-immobilization and yield reduction of the subsequent crop due to rice straw amendment. Addition of FYM with rice straw is another option as it improves organic C and available nutrient status of soil offering advantages in

Table 4 Effect of rice straw amendment in soil on nitrous oxide emission and its global warming potential

Treatments	N_2O emission (g ha^{-1})	Global warming potential (kg CO_2 equivalent ha^{-1})
NPK	588c	286c
NPK + straw	646b	315b
NPK + straw + urea	749a	365a
NPK + straw + FYM	651b	317b
NPK + straw + microbes	623b,c	304b,c
NPK + straw burnt	601c	293c

Note. The letters a, b or c are used with the mean values to show the significant difference between the values. Within a column, means followed by the same letter (a and a, for example) are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. On the other hand if they are followed by different letters (a and b, for example), they are significantly different. If the mean value is followed by more than one letter (a,b for example), it is statistically similar to all the mean values followed by either a or b or a,b

the long-run. It was observed that the plots treated with additional inorganic N emitted maximum amount of N_2O but there may not be significant difference of N_2O emission between NPK and NPK + straw burnt plots as the later is expected to emit N_2O during straw burning. Moreover, increased emission of N_2O due to straw incorporation could be countered by carbon sequestration in soil. The study suggested that recycling of rice straw in soil offers good promise in reducing environmental pollution and improving yield and soil fertility. However, the hindrances of such a practice are the difficulty in chopping and spreading rice straw in the field. Suitable machinery, therefore, has to be developed to overcome this problem and farmers have to be made aware of the long-term benefit in terms of improved soil fertility due to straw recycling. The results give indication only on a short time period. The impact of such practices in a longer run should be studied.

Acknowledgement The authors acknowledge the Indian Agricultural Research Institute for supporting this study. H. Pathak is thankful to the Alexander von Humboldt Foundation, Germany, for providing a fellowship to carry out the work.

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