Research Note

SOIL MANAGEMENT FOR BETTER NUTRITION OF LOWLAND RICE

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ABSTRACT

Some experiments were conducted in field conditions at Rampur, Nepal between 2001 and 2003 to assess the potential of wheat straw management with grain and green manure legumes in the lowland areas on soil N dynamics, crop yields and systems' N balances. Two levels of wheat straw incorporation (0 and 2 Mg ha^{-1}) with four types of land management (bare fallow control, mucuna, mungbean and maize) treatments were randomly allotted in the 10 m^2 plots in the fields. When the land was left bare during the transition season, N_{min} was initially building up of *50-80 kg of nitrate-N* and subsequently lost by nitrate leaching and denitrification, resulting in low N uptake of rice. The application of wheat straw during DWT significantly reduced soil N_{min} at the same rate as soil microbial biomass-N increased and resulted in <1 kg ha^{-1} of nitrate leaching and minimal nitrous oxide emissions from the soil. Growing cover crops during transition period reduced leaching losses by half and nitrous oxide emissions by two thirds of those in the bare fallow control, and BNF-N additions by legumes ranged from 27 to 56 kg ha^{-1}. Depending on the type of legume, this resulted in increased crop N uptake and grain yield. The lower N benefits were associated with the grain legume because about 50% of the N assimilation was removed by grain harvest, while the high benefits were obtained with green manures. When DWT is sufficiently long, the cultivation of legumes appears economically and ecologically beneficial and should be encouraged. Combinations of straw amendment and green manure use during DWT provide the largest benefits in terms of grain yield, and N balance with possible longe-term benefits for system's productivity.

Key words: Soil, nutrient management, lowland rice

INTRODUCTION

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) provide food for about 400 million people in South Asia (Swaminathan, 1984) and for 23 million people in Nepal alone (Ladha *et al.*, 2003). These two crops are often grown in the same field in an annual rotation. The rice-wheat annual double cropping system covers about 13.5 million hectares in the Indo-Gangetic Plain (IGP) and about 0.5 million hectares in Nepal (Hobbs and Morris, 1996). The reported maximum grain yield of rice was 8 Mg ha^{-1} in mid hill research station at Khumaltar (Pandey *et al.*, 1999). Long-term monitoring on experimental stations and farmers' field indicates that at constant inputs, the grain yields of both the crops are declining (Giri and Hobbs, 1994). Currently, the mean yields of rice and wheat are 2 Mg ha^{-1} and 1.3 Mg ha^{-1} respectively (Pandey *et al.*, 1999). To provide food for a rapidly growing population, Nepal needs to increase the production of rice by 1 Mg ha^{-1} and that of wheat by 0.6 Mg ha^{-1} by the end of 2020 (Hobbs and Adhikari, 1997; Gami *et al.*, 2001). The gap between the maximum observed and national average yield as well as the declining yield trend in long-term experiments require urgent research attention.

Many factors have been associated with the current low and even declining productivity of the system. A diagnostic field survey conducted in the Terai area of Nepal identified both short-term problems as nutrient deficiencies, especially N, early season water logging, and late season drought (Gami *et al.*, 2001) and long-term key problems comprise the declining soil fertility (mainly associated with declining soil organic matter and soil N supplying capacity) and the build up of insect pest problems in the rice-wheat system (Harrington *et al.*, 1993). However, the average mineral N uses by rice-wheat farmers in 2000 was less than 30 kg ha^{-1} yr^{-1} (Pandey and Joshy, 2000), while the recommendation for both rice and wheat amounts to more than 100 kg N ha^{-1}. Consequently, the N nutrition of both rice and wheat is largely based on the native soil N supply. Under such circumstances, the efficient use of systems' internal resources such as the recycling of crop residues and manures, minimization of nutrient losses, and the addition of N by biological nitrogen fixation (BNF) must be exploited to a much larger extent than at present. Maximization of the benefits from these internal resources require an improved understanding of: i) the seasonal native soil N-dynamics and its under-lying processes as well as the extent and mechanisms of N losses (leaching, denitrification and ammonia volatilization), ii) the potential and the benefits from inter-season legume crops, and iii) the development of possible technical options to improve N use efficiency at systems level. This study attempts to fill these knowledge gaps by addressing the subject of diagnosis and management of seasonal soil N dynamics. Thus, we hypothesize that an improved understanding of N mineralization, immobilization and loss mechanisms will help to sustain soil N supply, increase N use efficiency of rice and enhance the productivity of small-holder rice-wheat systems in the short term with possible long-term benefits. A series of experiments were conducted at Rampur, Chitwan to quantify the effect of management options on soil N mineralization, nitrate-N leaching. N_2O emissions and N immobilization in microbial biomass and growing crops and evaluate soil N dynamics during the wet season, involving N uptake by rice.

MATERIALS AND METHODS

Field experiments were conducted in a rice-wheat growing field site in Nepal to study the seasonal soil N dynamics, the extent and mechanism of N losses and the possibilities to improve the N use efficiency and the yield of lowland rice evaluating different crops and straw management options during the dry-to-wet season transition period under new management system. The treatments applied were two levels of wheat straw as 0 and 2 $Mgha^{-1}$ and 4 levels of land management options as bare fallow, mucuna, mungbean and maize. All treatments were randomely allotted in $10m^2$ plot of each replication in the field located at 27°37' N latitude and 84°25' E longitude with an elevation of 240-260 meter above sea level, representative of the tropical and subtropical lowland area of the Terai in Chitwan. Soil at the experimental field site is classified as sandy loam with the soil pH range of 6.1-6.8, organic carbon of 1.1-1.5% and N of 0.1%. The green manure *Mucuna puriens* var *utilis* L. and grain legume mungbean were seeded during transition period under upland conditions. A maize variety Arun-2 was seeded as reference crop to calculate biological nitrogen fixation. At the end of DWT, all crop residues except pods of grain legume and maize cobs were recycled in the respective plots before puddling. A lowland rice variety Masuli of 21-day-old seedlings were transplanted at 20x20 cm spacing with three seedlings per hill. Soil samples were taken at 15-day intervals to evaluate the mineralization of the recycled crop residues during DWT. Grain and straw yield of rice were determined from a central 2 m x 3 m harvest area and reported at 14% grain moisture. The N uptake by rice grain and straw was determined at harvest. Treatment effects on the N nutrition of the succeeding crop of rice were evaluated by the N uptake at harvest and the grain yield. At the end of DWT, the above ground plant biomass was cut at the ground level and dry matter was determined based on 1 m^2 harvest areas of each plot. Oven dried material was fine ground (<0.1 mm) for chemical analysis. The total N was determined by micro-Kjeldahl procedure and ^{15}N was analysed using mass spectrometry (ANCA SL coupled to 20-20 stable isotope analyser IRMS, Europa scientific/ PDZ now Sercon Ltd., UK). The natural abundance of the staple isotope ^{15}N was determined in fine ground plant samples.

$$\text{o/oo } \delta 15 \text{ N excess} = \frac{\text{atom \% } \delta^{15}\text{N sample - atom \% } \delta^{15}\text{N atmosphere}}{\text{atom \% } \delta^{15}\text{Natmosphere}}$$

The share of biological nitrogen fixation was calculated as,

$$\text{Ndfa \%} = 1 - \frac{\delta^{15}\text{N excess in the sample}}{\delta^{15}\text{N excess in the referenc plant} + \beta} \times 100$$

The β-values for natural discrimination against 15N were taken from Becker and Johnson (2001). Soil samples were extracted with 2M KCl after shaking for two hours at 100 r.p.m. Ammonium and nitrate in soil extracts were determined colorimetrically using an EC standard Autoanalyser III, Bran+Luebbe, Norderstedt, Germany. Soil moisture content was determined by using Time Domain Refractometer (TDR). The amount of NO3-N leached from the topsoil during DWT was determined in mixed ion-exchange resin cores (Rohm and Haas, France, SAS) with a resin density of 0,8 $g.cm^3$. The effect of straw amendment on temporary immobilization of soil N_{min} (NO_3-N +NH_4-N) in the microbial biomass was quantified using the chloroform fumigation technique. Nitrous oxide emitted from soils during the DWT was collected using closed chambers at regular bi-weekly intervals as well as after each rainfall event. Collected gas was analysed using gas chromatography (SRI

[Torrance, CA] 8610C) with a back flush system to eliminate water vapour and on an electron capture detector (ECD) for N_2O. The gas chromatograph was operated at a column temperature of 40°C, an ECD temperature of 320°C, and gas flow rates (nitrogen 5.0) were adjusted to 35 ml min^{-1} for the carrier gas and 6 ml min^{-1} for the ECD. Data were subjected to analysis of variance. Mean separation was done by Duncans Multiple Range Test (DMRT), using SPSS 10.0 for Windows. Microsoft Excel and Sigma Plot were used to prepare graphs.

RESULTS AND DISCUSSION

N-dynamics during dry-to-wet transition season

A gradual increment in soil moisture resulted changes in the available forms of N_{min} in the soil. The initial NH_4-N content in the bare soil decreased from 21.2 to 5.9 kg ha-1 and from 12.3 to 9.3 kg ha^{-1} at 6 weeks after wheat harvesting in the years 2001 and 2003, respectively. At soil saturation by the monsoon rains, the NH_4-N content gradually increased to 26.4 and 28.8 kg ha^{-1} 14th week after wheat harvesting in the years 2001 and 2003, respectively. A reverse pattern was observed in the case of NO_3-N in both years. Nitrate peak of 51 kg ha^{-1} and 75.3 kg ha^{-1} were observed in the bare fallow soil in the years 2001 and 2003, respectively. With the onset of monsoon rain, the soil was saturated by water and almost all NO_3-N disappeared from the soil. The initial increment in NO_3-N in the bare fallow soil during the aerobic phase was possibly associated with the oxidation of NH_4-N to NO_3-N, while the sharp decline in NO_3-N at the end of DWT at soil saturation by monsoon rain was associated with N losses by denitrification and leaching. The NH_4-N and NO_3-N content in the bare soil showed an inverse relation.

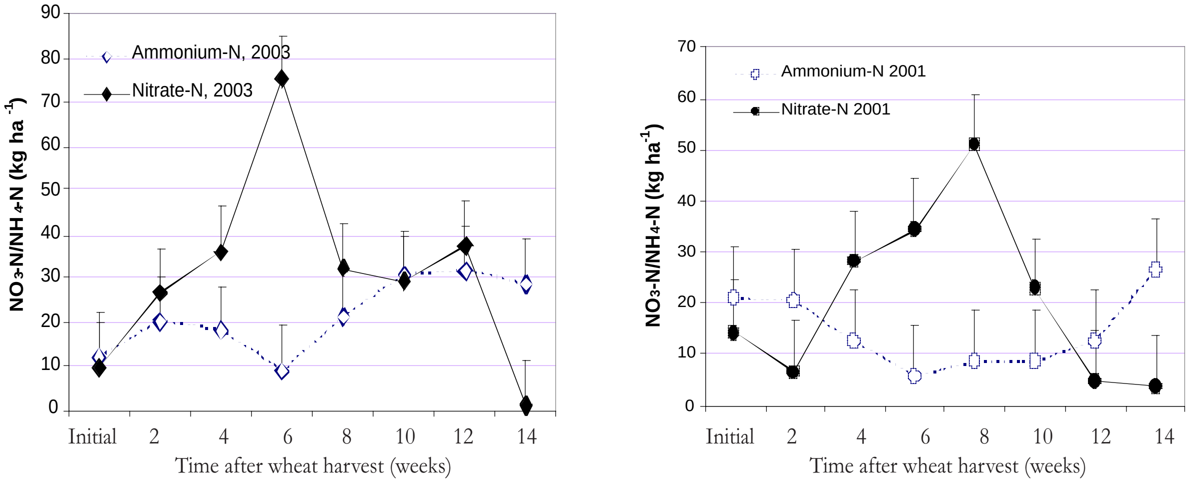

Figure 1. Soil N_{min} dynamics in the bare fallow soil during the dry-to-wet season transition period at the lowland field sites (field experiment, Rampur, Chitwan province, Nepal, 2001 and 2003). Bars present standard errors of the mean (n=4)

As reported by Hynes (1986), and Kanal (1995), soil organic matter decomposition and N mineralization show complex interactions with microbial populations and environmental factors, particularly with soil moisture and temperature. In the present study, soil N dynamics were linked to variations in soil moisture content, a modification of the C:N-ratio via straw addition (temporary microbial N immobilization), and N uptake by crops grown during the transition season (N immobilization in the plant biomass. Soil N mineralization showed high temporal dynamics and was strongly affected by management options. Generally, the highest NO_3-N built up was observed at soil moisture content of 60-75% FC under bare fallow management (farmers' practice). Other workers (Inubushi *et al.*, 1996) observed peak microbial activities at similar soil moisture levels under incubation studies at 60% FC and Flessa *et al.* (1996) and Bollmann and Conrad, (1998) observed peak microbial activities under field conditions at <80% FC). Thus, it appears that 60-75% FC is most favourable for the activity of nitrifying bacteria. This peak of soil NO_3-N observed in 2003 was much higher than in 2001 in the same plot. In 2003, the soil drying and wetting cycles were more frequent and more severe than in 2001. Larger soil N_{min} peaks under frequent soil drying and wetting than under continuous soil moisture conditions have been linked to an enhanced activity of nitrifying bacteria resulting in large amounts of NO_3-N built up in the soil (Müller, *et al.*, 2002; Sehy, *et al.*, 2004).

A number of studies on the N dynamics in seasonally flooded soils of South Asia, Southeast Asia, and West Africa highlighted the occurrence of the Birch effect (N mineralization peak) after the first rains and the near complete disappearance of the nitrate fraction at the beginning of the main wet season (Pande and Becker, 2003; Shrestha and Ladha, 1998). Estimated amounts of N lost in the course of soil flooding ranged from 20 to 90 kg ha^{-1}.

The incorporation of wheat straw at the rate of 2 Mg ha^{-1} reduced the build up of soil NO_3-N from 51 kg ha^{-1} in the bare fallow to 12.8 kg ha^{-1} in the year 2001. After soil saturation, the NH_4-N was increased from 26 kg ha^{-1} to 32.1 kg ha^{-1} in the straw amended bare fallow plots. Similar results were observed in the year 2003. Crop residues with a wide C: N ratio such as straw can temporarily immobilize soil N in the microbial biomass, resulting in less soil N_{min} available for plant uptake but also for microbial transformation or physical movements. Nitrogen immobilization in lowland soils after application of crop residues with a wide carbon to nitrogen (C:N) or lignin to nitrogen ratio (L:N) has been reported (Becker *et al.*, 1994, 1996, Haynes, 1986). A temporary immobilization of soil N after application of Municipality Solid Waste Compost with a C: N ratio of 40:1 in an Alfisol (George *et al.*, 1998) has been reported. In the present study, the peak of soil NO_3-N reduced by 50-75% after incorporation of wheat straw at the rate of 2 Mg ha^{-1}. A reduction in soil Nmin after the application of wheat straw was linked to a parallel increase in the amount of soil microbial biomass N. The soil microbial biomass N in the bare soil ranged from 0.4 to 2.4 mg kg^{-1} soil. The largest amount of soil microbial biomass N (4.8 mg N kg^{-1} soil) was observed with wheat straw incorporation. The largest microbial biomass N of 2.4 mg N kg^{-1} soil was observed in the bare fallow control at 75% FC. Soil incorporation of wheat straw may provide more energy substrates and larger surface area to microbial population. The peak of soil NO_3-N reduction after incorporation of wheat straw was linked to the microbial biomass N present in the soil. Malik *et al.* (1998) observed a large increase in soil microbial biomass after incorporation of organic substrates as wheat straw and green manure. Beri *et al.* (1992) and Sidhu *et al.* (1995) observed 5-10 times more soil aerobic bacteria and 1.5 to 11 times more soil fungi in crop residue amended soils than in soils where crop residue had been removed or burned. Stevenson (1986) observed soil N immobilization with the application of low quality crop residues associated with an increase in soil microbial biomass. The present study showed increased soil microbial biomass N (SMB-N) with wheat straw incorporation. Similar results were observed by Kumar and Goh (2000), Malik *et al.* (1998), and Sidhu *et al.* (1995). However, the size and the composition of the microbial community depend on the quality of the residues applied (Broder and Wagner, 1988). Campbell *et al.* (1991) observed increased fungal community after application of non-legume residues and increased bacterial populations after application of legume residues to the soil. In the present field experiments both wheat straw (non-legume) and green manure (legume) residue were incorporated, thus both fungal and bacterial communities are likely to be increased.

The growth of the transition season crops reduced the soil NO_3-N peak from 51 in bare fallow to 25, 27 and 32 kg ha-1 in 2001 and 75 kg ha^{-1} in the bare fallow to 34.9, 36.6 and 29.4 kg ha^{-1} in 2003 in the treatments with maize, mungbean and mucuna respectively. A combination of wheat straw and the growth of transition season crops further reduced NO_3-N in the soil. The low NO_3-N content observed in the straw amended mucuna treatment is likely to be associated with the immobilization of soil N_{min} both in the plants and in the microbial biomass. Compared to the bare fallow control (farmers' practice in Nepal), growth of the "nitrate catch crops" mucuna, maize and mungbean during DWT reduced soil NO_3-N by by 67-86% and that was closely related to the N uptake by the crops from the soil pool. Shrestha and Ladha (1998) reported 10 to 68% reduction in soil nitrate from rice-sweet pepper cropping system when crops (maize, indigo, and mungbean) were grown as N-catch crops during DWT on an Inceptisol. George *et al.* (1995) reported a reduction in nitrate-N losses from 107 to less than 20 kg ha^{-1} when green manure legumes occupied the field during DWT on a Mollisol in rainfed lowlands of the Philippines. Buresh and De Datta (1989) observed an inverse relation between N accumulation by dry season crops (legumes and weeds) and NO_3-N content in the soil. Hartemink *et al.* (1996) observed significantly ($P \leq 0.05$) reduced NO_3-N content in the topsoil when growing sesbania, maize and weeds rather than leaving the land to bare fallow in the humid zone of Kenya. Similarly, our observations in Nepal showed an inverse relation between N accumulation by plant and soil nitrate concentration.

Soil NO_3-N leaching during DWT determined by ion-exchange resin capsules placed at 30 cm soil depth showed large differences in NO_3-N leaching from the top soil were among DWT treatments. The highest amount of 12 kg NO_3-N ha^{-1} leached from the topsoil was observed in the bare fallow control treatment, followed by the straw amended fallow with 3.02 kg NO_3-N ha^{-1}. Thus, wheat straw amendment significantly ($P \leq 0.05$) reduced the nitrate N leaching. The lowest amount of 0.57 kg ha^{-1} of NO_3-N leaching was observed in the wheat straw amended mucuna treatment and was associated with the immobilization of soil N_{min} in both microbial and plant biomass. As NO_3-N is negatively charged and not sorbed onto clay particles, it is prone to losses, particularly by leaching in sandy soils but also by denitrification, particularly in saturated clay soils (Bacon *et al.,* 1986; Davidson *et al*., 1986).

In present study, large differences in nitrous oxide emissions on applied treatments were observed from the lowland fields of rice-wheat annual rotation system in during DWT. With the onset of sporadic spring rains, several cycles of soil drying and wetting occurred. The change in soil moisture status resulted in an increase in N_2O emission from the soil. With a further increase in soil moisture to >43% FC, N_2O emission was increased. However, both prolonged drying and prolonged wetting periods decreased the emission. A first peak of N_2O emission of 27 μg N m^{-2} h^{-1} was observed at 63 % FC soil moisture in the bare fallow treatment. This N_2O emission peak was related with the maximum of NO_3-N in the soil and was possibly associated with the oxidation of NH_4-N (nitrification). After the onset of monsoon the soil got saturated and the highest amount of N_2O emission of 48 μg N m^{-2} h^{-1} was observed in the bare fallow treatment. This second peak was associated with a rapid reduction in the NO_3-N content in the soil was possibly associated with microbial reduction of NO_3-N under anaerobic soil moisture condition (denitrification). The application of wheat straw significantly reduced the emissions and was further reduced by a combination of DWT crop with wheat straw application, possibly the result of the combined effects of N immobilization in the soil microbial biomass with wheat straw application and N uptake by growing crops.

About 50% of N_2O production is derived from the soil and agricultural activities (Bauwman, 1990). In an incubation study, Hütsch *et al.* (1999) observed a significantly higher amount of emission by changing the soil water content from 60% to 120% FC. Inubushi *et al.* (1996) observed an increased N_2O emission in NH_4-N amended soil with a sharp declining NH_4-N and increasing NO_3-N concentrations in soil at 60% FC. Flessa *et al.* (1996) and Bollmann and Conrad (1998) determined nitrification as the main determining process for N_2O emission in soil with < 80% FC. Abbasi *et al.* (2003) observed a significantly reduced NO_3-N formation and reduced N_2O emission in the soil after application of nitrification inhibitor nitrapyrin in incubation experiments. Linn and Doran (1984), Parton *et al.* (1996) observed the best condition for nitrifiers at 60% FC with large associated N_2O emissions. In rice fields, high emissions occurred with alternate drying and rewetting provided that mineral N was present in the soil before rewetting (Davidson, 1992; Yue *et al*., 1997). By alternate draining and flooding in rice fields Xing and Zhu (1997) observed 4 times higher N_2O emission than with continuous flooding in southern China. The present study showed peaks of N_2O emissions in bare fallow during DWT at soil moisture of 75% FC as well as immediately after soil flooding. The initial peak was probably associated with nitrification and the later peak with denitrification. Application of wheat straw and growth of DWT crops significantly ($P \leq 0.05$) reduced both NO_3-N built-up in the soil as well as N_2O emissions. The lowest emissions were recorded in wheat straw amended mucuna plots where both N_{min} immobilizations by plants and in the microbial biomass resulted in a massive reduction of soil N_{min}. In Nepalese context, the use of nitrification inhibitor nitrapyrin is impracticable and growth of DWT crops like mucuna in combination with wheat straw could be the best option to reduce the nitrate built up in the lowland fields.

Kladivko *et al.* (2004) observed reduced nitrate leaching from a topsoil of Indiana by growing nitrate trap crops in corn-soybean rotation system during the fallow period. Shrestha and Ladha (1998) observed significantly ($P \leq 0.05$) reduced NO_3-N leaching from the plots where maize, indigo, and mungbean were grown as N-catch crops during DWT than bare fallow control. In present study, the highest amount of NO_3-N leaching was observed in the bare fallow treatment during DWT. The application of wheat straw significantly ($P \leq 0.05$) reduced the leaching loss and it could be associated with the reduced build up of NO_3-N in the soil caused by immobilization of soil Nmin in the microbial biomass N. The lowest amount of leached NO_3-N was observed in the wheat straw amended mucuna treatment where the combined effects of soil N immobilization in the microbial biomass N and efficient uptake of soil N_{min} by the growing mucuna crop have minimized the potential for N losses to occur. This conservation of native soil N during DWT may help in N nutrition of succeeding crops.

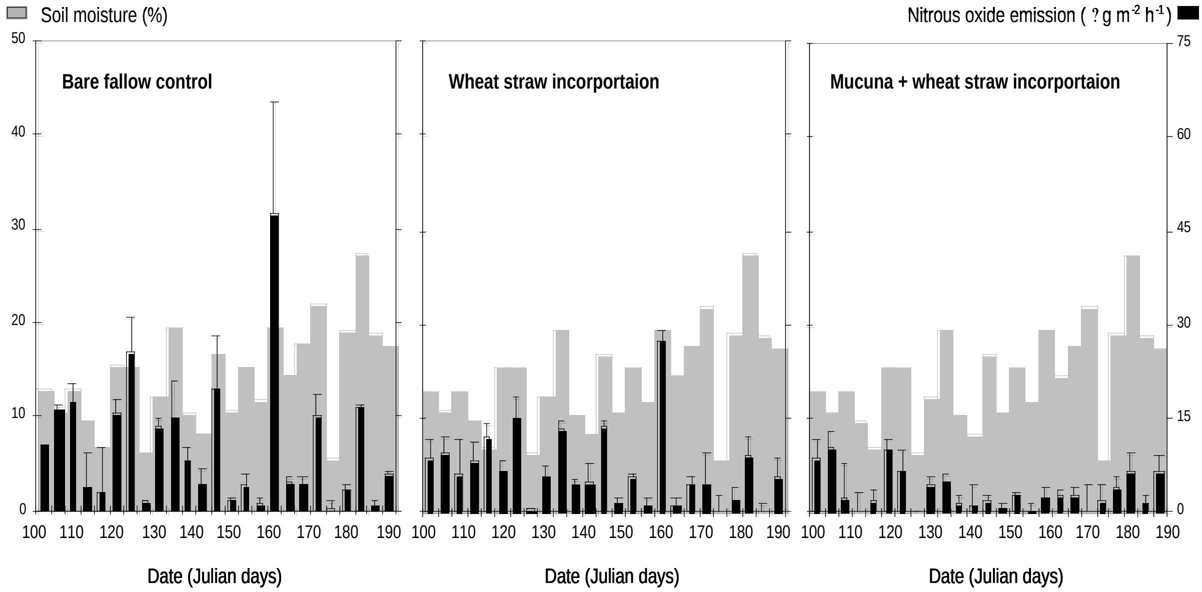

Figure 2. Effects of straw incorporation and crop management (mucuna +straw) on the N_2O emissions from the lowland fields during the dry-to-wet season transition period (field experiments, Rampur, Chitwan 2003). Bars present standard errors of the mean (n=4)

Crops grown during DWT showed large differences in N accumulation. Total N accumulation by maize was 86 kg N ha^{-1} in 2001 and was significantly ($P\leq0.05$) reduced to 74 kg N ha^{-1} by wheat straw application. The grain legume mungbean and the green manure legume mucuna accumulated 53 and 80 kg N ha^{-1} respectively in the absence of wheat straw, while 66 and 92 kg ha^{-1}, respectively with wheat straw amendment. Hence, application of wheat straw resulted significantly ($P\leq0.05$) higher N accumulation by legumes. Nitrogen-15 analysis indicated that the major portion of this N was derived from biological nitrogen fixation. Determination of the N accumulation by DWT crops in 2003 also showed significantly large differences in plant N uptake as in 2001. The total N accumulation by mucuna, mungbean and maize were 108, 80 and 54 kg ha^{-1}, respectively. Wheat straw application reduced the N uptake by maize from 54 kg ha^{-1} to 48 kg ha^{-1}, however, that further enhanced the total N accumulation by both legumes (mucuna and mungbean). The highest amount of 116 kg N ha^{-1} was accumulated by the straw amended mucuna. The increased N accumulation by legumes was due to the increased atmospheric N fixation under wheat straw application.

Rice grain yield responded to the N savings and/or N adding effects (BNF) of the dry-to-wet transition season treatments. The lowest rice grain yield of 1.7 Mg ha^{-1} (average of 2001 and 2003) was obtained from the plots where rice was grown after a bare fallow and where large amounts of NO_3-N disappeared during DWT by leaching and denitrification. The application of wheat straw alone significantly increased the rice grain yield to 2.6 Mg $ha^{-1}$and straw application in combination with maize, mungbean and mucuna resulted in 2.5, 2.9 and 3.7 Mg ha^{-1} (average of 2001 and 2003), respectively. The highest grain yields of 3.61 Mg ha^{-1} in 2001 and of 3.79 Mg ha^{-1} in 2003 were observed in the wheat straw-amended mucuna treatment. Similar to the grain yield, large differences in N uptake by wet season rice were observed among treatments. The lowest N uptake of 32 kg ha^{-1} was determined in the bare fallow pre-treatment and the highest N uptake of 77 kg ha^{-1} was determined where mucuna biomass had been incorporated together with previously applied wheat straw. The application of wheat straw in the fallow land during DWT enhanced rice N uptake by 62% compared to bare fallow. It could be the reflection of N savings during DWT by means of temporary immobilization of N_{min} and remineralization during rice growing wet season. Nitrogen accumulation by a crop depends upon the amounts of mineral N present in the soil, the prevailing climatic conditions and the capacity and efficiency of the plant for N uptake. Growing legumes and recycling their biomass can improve soil fertility, increase the yield of the subsequent rice crop and reduces the requirement for chemical N fertilizer (Pande and Becker, 2001; Ladha and Reddy, 2003; Becker 2002). The nitrogen fertilizer equivalence (NFE) for green manures and grain legume residues range from 37 to 120 kg ha^{-1} (Peoples *et al.*, 1995; Becker, 2002). Differences in the N accumulation by legumes, in the recovery of incorporated N by rice and in the synchrony between residue N supply and crop N demand may explain the wide range in NFE (Becker and Ladha, 1996). Synchronization between N mineralization and plant uptake has been shown previously to contribute to reduced N losses and more increased N use efficiency by rice (Becker *et al*., 1994). In present study, the highest rice yields were observed in straw amended green manure plots. In this case, wheat straw not only conserved soil N during DWT, but may also have improved the synchrony between the N supply from the soil with the N demand of rice as reflected in the increased agronomic use efficiency of applied green manure N. Similar findings were reported from studies by Malik *et al.* (1998) in India.

The reported results demonstrate the large potential for further productivity gains in rice-wheat systems of Nepal with improved DWT crop and residue management. Although the research results presented here are highly encouraging, the grain yield of rice is still low compared to the South Asian average and the production potential of 8 Mg ha^{-1} reported from Nepal (Rajbhandari and Upreti, 1997). Further development of site-, system- and season-specific management options in a range of environments are required. Finally, to ensure the adoption of proposed options, farmers' participation in further activities will be imperative.

CONCLUSIONS

Massive loss of native soil nitrogen occurs in rice-wheat rotations when fields are left to bare fallow during the dry-to-wet season transition period (conventional system). Returning wheat straw into the plots (instead of removal and burning) can reduce N_2O emission and nitrate leaching losses by temporary N immobilization in the microbial biomass. This, "preserved" soil N results in increased yields and improved N uptake of succeeding rice crop. Growing crops during the transition season immobilize soil N in the plant biomass and add N from BNF. Reduced amounts of available soil N_{min} as a result of crop growth during DWT results in reduced N losses.

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