Environ Monit Assess (2007) 131:451–465
DOI 10.1007/s10661-006-9491-3

Simulation of Nitrogen Dynamics in Soil Using Infocrop Model

K. N. Ebrayi · H. Pathak · Naveen Kalra · Arti Bhatia · Niveta Jain

Received: 1 February 2006 / Accepted: 15 September 2006 /

Abstract Nitrogen is the most widely used fertilizer nutrient, and it is a universally deficient nutrient too, which often severely restricts the growth and yield of crops. To improve N fertilizer management, soil–plant system models can be applied to simulate adequate N supply for both, optimal crop growth and minimal N losses. The likely impact of climate change on the cereal production is of paramount importance in the planning strategies to meet the future growing needs on sustainable grounds. In this scenario models are the effective tools to foresee the probable impacts and for choosing appropriate land use options. The study reported in this thesis, employs field experiments and use of simulation tools to understand the dynamics of soil N balance and relate growth and yield of rice under varying nitrogen inputs. The InfoCrop model was used in this study, which was calibrated with the historic data sets, and subsequently validated with the field experiment conducted at IARI Farm, New Delhi. Simulated results matched well with the observed values in terms of growth and yield of rice and seasonal nitrogen uptake. The components of soil nitrogen balance differed among varying nitrogen level treatments, which was also captured by use of InfoCrop. The model was then taken to climate change impact analysis. The results clearly revealed that when temperature increased, the soil N losses, like denitrification, volatilization, N2O emission increased, whereas grain and biomass yields decreased. The further scope of the study is to validate the study in contrasting agroenvironments.

Keywords Simulation · InfoCrop · Nitrogen balance components

1 Introduction

Rice is the world's most important food crop, more than 40% of the world's population depends on rice as the major source of calories and 155 million ha of rice, of which 79 million ha is irrigated, are harvested annually with a production of about 596 million metric tons (IRRI 2001). As the primary staple food, it provides more than 50% of total calorie intake in many Asian countries. To meet the increasing demand of food for increasing population, the production of rice has to be increased. Moreover, the coming years will probably witness major changes in rice production with the introduction and adoption of a new generation of cultivars with improved water and nutrient management strategies, which include site-specific knowledge of crop nutrient requirement, recovery of applied fertilizer nutrients and indigenous nutrient supply (Dobermann and White 1999).

Nitrogen is the most widely used fertilizer nutrient, and it is a universally deficient nutrient too, which

K. N. Ebrayi · H. Pathak · N. Kalra (✉) · A. Bhatia · N. Jain
Indian Agricultural Research Institute,
New Delhi 110012, India
e-mail: kal_naveen@yahoo.co.in

often severely restricts the crop yields. This results partly from the high cost of increasing nitrogen levels in soils and partly from the difficulty in forecasting how to adjust N fertilizer levels for differences in crops and soils. In some areas too much nitrogen may be applied as fertilizer or as organic manures, and when this happens, both yield and crop quality can be severely depressed and the concentration of nitrate in the drainage water may rise sufficiently to cause public concern. Efficient utilization of fertilizer is one of the keys to increase economic crop yield, increase N use efficiency, and reduce losses of N.

Nitrogen fertilizers are petroleum-based products, vulnerable to political and economic fluctuations in the oil markets. They are expensive inputs, costing agriculture more than US$ 45 billion per year. Biological N fixation is the primary source of reactive N in nature. In recent years, however, chemical N fixation has become equally important in agriculture, as meeting the growing demand for food has forced large increases in the use of chemical N. The continuing increasing use of N has altered the global cycle of N. About 60% of excess reactive N used in the industrial era is believed to have accumulated on land, causing serious disruptions in ecosystem functioning. It is clear, that the environmental costs associated with N fertilization are high. Crops use fertilizer N inefficiently, and generally more than 50% of the N applied is not assimilated by the plants (Dobermann and Cassman 2004). Furthermore, many cropping systems particularly in developing countries have reached the point of diminishing returns to fertilizer-N applications, and there is a decline in global cereal production per unit of application of N fertilizer. This trend is not sustainable, and indicates higher economic and environmental costs for each unit of food produced. The distribution of the new, reactive N inputs to the landscape is also not uniform across the globe. Natural sources of inputs, driven by BNF in forests and uncultivated lands, dominate the N budgets in Africa (79%), Oceania (79%), and Latin America (72%). In contrast, anthropogenic N sources dominate the overall N budgets in Asia (74%), North America (61%), and Europe/former Soviet Union (FSU) (59%) (Boyer et al. 2004).

To improve N fertilizer management, soil–plant system models can be applied to simulate adequate N supply for both, optimal crop growth and minimal N losses. A good model for N dynamics in the soil–plant system should include the soil N processes, processes pertaining to above ground plant growth, N and water uptake. Most models correctly describe crop N demands and N uptake; description of the soil N turnover cycle remains difficult. In particular, data on the quality of organic fertilizers and of remaining plant residues, including decaying roots following crop harvest, is often incomplete. For the present study InfoCrop model was used.

InfoCrop is a generic crop model that has been developed to provide a platform to scientists to build their applications around it and to meet the goals of stakeholders' need for information. The models for various crops are designed to simulate the effects of weather, soils, agronomic management (including planting, nitrogen, residues and irrigation) and major pests on crop growth and yield. Its general structure is based on a large number of earlier models, and the knowledge base of the tropics. In particular, it is based on MACROS (Penning de Vries et al. 1989), WTGROWS (Aggarwal and Kalra 1994) and ORYZAI (Kropff et al. 2000) models.

The InfoCrop model calculates the transformations, movement, leaching, gaseous losses of N, and crop N uptake from various soil layers in daily time step. The model computes the dynamics of N in soil through the following processes; mineralisation, immobilization, urea hydrolysis, nitrification, volatilization, denitrification, nitrous oxide emission, N movement in soil, uptake by crops. In the model total soil N pool is divided into organic N, NH_4-N and NO_3-N. The following sources of N are considered: indigenous soil N, which is derived from soil organic matter, and NH_4-N and NO_3-N present in soil at the time of start of simulation; inorganic fertilizer, organic manure, irrigation, rainfall, biological N fixation. The sinks of N include plant uptake and losses of N including leaching, ammonia volatilization, denitrification and nitrous oxide emission. Mass balance of N between various sources and sinks has been used with time coefficients (or rate constants) to calculate the rates of flow. Components of soil nitrogen balance in the model need to be tested for crops, cropping systems and diverse agro- and production environments.

The Inter-Governmental Panel on Climatic Change (IPCC) of the United Nations (UN) in its recent report has confirmed the global warming trend and projected that the globally averaged temperature of the air above the earth's surface would rise by 1.4–5.8°C over the next 100 years (IPCC 2001). IPCC has recently compiled the magnitude of change in temperature, rainfall and carbon dioxide for different parts of the world (Watson et al. 1998). According to this, by 2010, CO_2 level will increase to 397–416 ppm from the current (2000) level of approximately 360 ppm. This will further increase to 605–755 ppm by 2070. There is considerable uncertainty in the magnitude of change in rainfall and temperature. The climate change effects on organic carbon, microbial activity and nutrient availability have not been exhaustively worked out for crops. These trends could be used in InfoCrop model to simulate the impacts of climatic change on N dynamics. The present study was carried out to assess the influence of various nitrogen management practices on rice yield and nitrogen dynamics in soil through field experiment and simulation modelling and to evaluate the impact of global warming on nitrogen dynamics in Indian soils using simulation model.

2 Materials and Methods

2.1 Field experiment

A field experiment was carried out to quantify the nitrogen dynamics in the rice crop. The details of location, climate and weather condition of the experimental site and methodology for estimation of different parameters and procedure for model validation and calibration are described in this chapter.

2.1.1 Location

The experiment was carried out in a silty clay loam (Typic Ustochrept) soil of main block (14B) of the Indian Agricultural Research Institute farm, New Delhi during 2003 *kharif* season.

2.1.2 Weather and soil

Geographically the experimental site is situated between latitude 28°37′ and 28°39′N and longitude 77°9′ and 77°11′E at an altitude of 225.7 m above mean sea level. It is characterized by semi arid type of climate with mean maximum temperatures varying from 43.9 to 45.0°C. The mean minimum temperature ranges from 6 to 8°C. There is occasional occurrence of frost in December and January. The mean summer and mean winter temperatures were 33.0 and 17.3°C, respectively. The mean annual rainfall is around 750 mm of which a substantial amount is received during July to September.

Table 1 Physico-chemical properties of the experimental soil

Soil parameters	Depth (m)	
	0–0.15	0.15–0.30
Texture	Silty clay loam	Clay loam
Sand (%)	31.7	35.1
Silt (%)	40.8	36.0
Clay (%)	27.5	28.9
pH (1:2 soil:water)	8.2	7.5
Electrical conductivity (dS m^{-1})	0.37	0.24
Bulk density (Mg m^{-3})	1.49	1.52
Hydraulic conductivity (cm hr^{-1})	0.38	0.51
Field capacity (%, vol.)	29.1	31.4
Wilting point (%, vol.)	10.9	10.9
Organic carbon (%)	0.53	0.43
Ammo. acetate extractable K (kg ha^{-1})	361.8	373.4
Olsen P (kg ha^{-1})	31.6	27.4
Min. N (kg ha^{-1})	52.2	42.1

The soils are well drained with the groundwater table at 6.6 and 10 m deep during the rainy and summer seasons, respectively. The alluvial soil of experimental site was Typic Ustochrept with pH 8.2 and silty clay loam in texture (Table 1).

2.1.3 Field operation and treatments

The field was puddled and farmyard manure (FYM) was incorporated into T_3 plots at 12 t ha^{-1} to supply the recommended dose of N i.e., 120 kg N ha^{-1}. Farmyard manure, consisting of well rotten cattle dung was incorporated into the soil one day before transplanting of rice. In T_2, T_4 and T_5 plots diammonium phosphate (DAP) was added to supply full dose of P and a portion of N on the day of transplanting. Remaining N was applied through urea. In T_2 plots K was supplied through muriate of potash (KCl) to supply full dose (50 kg ha^{-1}) of K basally on the day of transplanting. Rice (variety Pusa Sugandh-3) was raised in a nearby nursery and 30 days old seedlings were transplanted in to the puddled field at a spacing of 20×15 cm. The plots were irrigated in alternate days. The treatments in the field experiment

Table 2 Various treatments in the field experiment

Treatment	Name	Details
T1	Unfertilized control	No fertilizer or manure applied
T2	Recommended fertilizer practice	120:26:50 kg N:P:K ha^{-1}
T3	Organic manuring	FYM @12 t ha^{-1}, no inorganic fertilizer added
T4	Farmers' practice	120:26:0 kg N:P ha^{-1}, no K applied
T5	Leaf colour chart (LCC) based N application	150:26:0 kg N:P:K ha^{-1} (based on weekly leaf colour chart readings), no K applied based upon initial soil test

to evaluate the N dynamics in soil are given in Table 2.

2.1.4 Soil sampling and analysis

Soil samples from 0–15 and 15–30 cm soil layers at three locations from each plot were collected prior to puddling, 25 DAT, 35 DAT, 45 DAT, 75 DAT, 90 DAT, before and after fertilizer application and after the rice harvest using a core sampler of 8-cm diameter. The entire volume of soil was weighed and mixed thoroughly and 10 g of soil was weighed and used for making extracts with 2M KCl. These extracts were used for estimation of inorganic N viz. NH_4^+ and NO_3^- content. Initial soil samples were air-dried, sieved through a 2-mm screen, mixed and used to determine various physico-chemical properties using standard procedures (Page et al. 1982).

2.1.5 Plant sampling and analysis

Plant samples were collected from all the plots at following stages viz. seedlings, 30 DAT, 45 DAT, 75 DAT, 90 DAT and at Harvest. The samples were collected from representative rows @ 10 hills per plot. To estimate the biomass accumulation at different stages of the crop, fresh weights and dry weights were recorded. The dried samples were ground and used to estimate the N content. N content of the seedlings, grain, straw were also estimated using standard procedures Kjeldhal method.

2.1.6 Collection of gas samples

Collection of gas samples was carried out by closed chamber technique (Majumdar et al. 2000). Chambers of 50 cm × 30 cm × 100 cm made of 6 mm acrylic sheets were used. Aluminum channels placed in the field are used with each chamber. The aluminum channels were inserted 10 cm inside the soil and the channels were filled with water to make the system air-tight. A battery operated fan was fixed inside the chamber to homogenize the inside air. A thermometer was also inserted inside to monitor the inside temperature. One three-way stopcock (Eastern Medikit Ltd. India) was fitted at the top of chamber to collect gas samples. The chamber was thoroughly flushed several times with a 50 ml syringe. Gas samples were drawn with the help of hypodermic needle (24 gauges). After drawing the sample, syringes were made air tight with a three-way stopcock. Samples of three replications of each treatment were taken from the plots and the average was taken as representative value for the treatment. Head space volume inside the box was recorded, which was used to calculate flux of nitrous oxide. Gas samples at 0, 1/2 and 1 h are collected from the chamber.

2.1.7 Analysis of nitrous oxide in the gas samples

Nitrous oxide concentration in the gas samples collected from the fields was estimated by Gas Chromatograph fitted with an electron capture detector (ECD) and 6′ × 1/8″ stainless steel column (Porapak Q). Column, injector, and detector temperatures were 50°C, 120°C, and 350°C, respectively. The carrier gas was N_2 with a flow rate of 35 ml min^{-1}. An integrator was used to plot and measure the peak area.

2.1.8 Final biomass and yield

Rice grain and straw yields were recorded from all the plots by harvesting 1 m^2 representative area from all the plots. Total biomass weight was estimated and the grains were separated from the straw using a plot thresher and weighed.

Table 3 Total dry matter yield of rice crop at various growth stages

Treatment	Total dry matter (Mg ha^{-1})				
	33 DAT	45 DAT	77 DAT	90 DAT	Harvest
Control	0.94	1.47	5.16	5.99	6.05
Recommended NPK	1.88	2.63	10.55	12.81	13.10
Organic manuring	1.43	2.05	7.20	10.11	10.28
Farmers' practice	1.92	2.57	10.50	12.59	12.97
LCC based N use	1.73	2.51	10.71	14.70	14.92
LSD ($P<0.05$)	0.093	0.056	0.311	0.533	0.386

DAT Days after transplanting

2.1.9 Data analysis

Statistical analyses of the data were done using the Microsoft Excel statistical package (1998). Analysis of variance was done to test whether the differences were statistically significant. Unless indicated otherwise, differences were considered only when significant at $P<0.05$.

2.2 Calibration and validation of InfoCrop model

Data required for calibration and validation of InfoCrop model are crop data, soil data, daily weather data and crop management data. From these data thermal time in degree-days for the vegetative, grain filling, panicle initiation are determined. The values describing growth and grain development were also determined. The procedure for determining genetic coefficients initially involves running the model with values, derived elsewhere and then rerunning the model using a range of values for each coefficient until and satisfactory level of agreement between simulated and observed value is reached. The soil and plant data collected from the literature were used for calibration of the InfoCrop model and the data generated through field experiment were used to validate the calibrated model.

2.3 Estimation of impact of climatic change on N dynamics

The Inter-Governmental Panel on Climatic Change (IPCC) of the United Nations in its recent report has confirmed the global warming trend and projected that the globally averaged temperature of the air above the earth's surface would rise by 1.4–5.8°C over the next 100 years (IPCC 2001). IPCC has recently compiled the magnitude of change in temperature, rainfall and carbon dioxide for different parts of the world (Watson et al. 1998). According to this, by 2010, CO_2 level will increase to 397–416 ppm from the current (2000) level of approximately 370 ppm. This will further increase to 605–755 ppm by 2070. There is considerable uncertainty in the magnitude of change in rainfall and temperature predicted for India. Relatively, the increase in temperature is projected to be less in kharif than in rabi. The rabi rainfall will, however, have larger uncertainty. Kharif rainfall is likely to increase by as much as 10%. To evaluate the impact of climatic change on N dynamics on Indian soils, these scenarios will be given in to the model and the impacts will be simulated.

Table 4 Grain and straw yield of rice crop at harvest

Treatment	Grain yield (Mg ha^{-1})	Straw yield (Mg ha^{-1})	Harvest index
Control	3.07	5.36	0.36
Recommended NPK	6.80	8.70	0.43
Organic manuring	4.53	6.80	0.4
Farmers' practice	6.56	8.54	0.43
LCC based N use	6.95	9.63	0.42
LSD ($P<0.05$)	0.35	1.08	NS

Table 5 Biomass N content (%) at different stages of rice crop

Treatment	33 DAT	45 DAT	Grain at harvest
Control	1.12	1.32	0.91
Recommended NPK	2.06	2.31	1.14
Organic manuring	1.96	2.21	1.03
Farmers' practice	2.03	2.28	1.10
LCC based N use	2.13	2.38	1.18
LSD ($P<0.05$)	0.27	0.46	0.13

3 Results and Discussion

3.1 Total dry matter of rice crop

In rice, periodical changes in dry weight are shown in Table 3. In every growth stage, the dry weight increased with increasing N dose. Biomass increased with each successive increase in N level up to 0.15 Mg ha^{-1}. Biomass increased from 6.0 Mg ha^{-1} in control treatment to 14.9 Mg ha^{-1} in LCC based crop N use at harvest, and treatment with organic source of N showed a biomass of 10.2 Mg ha^{-1}.

3.2 Grain yield and its attributes

Grain yield of rice crop under different nitrogen levels are presented in Table 4. In rice, highest grain yield was obtained with LCC based N use of 150 kg N ha^{-1}, which was 6.95 Mg ha^{-1}; where as recommended and farmers' practice (of 120 kg N with and without K) showed relatively lower yield, which were 6.8 Mg ha^{-1} and 6.65 Mg ha^{-1} respectively.

A better grain yield with higher amount of N was due to increased photosynthetic efficiency of crop leading to production of more number of spikes per square metre, more number of grains per spike. Effects of better N status of soil on grain yield of rice were also reported by Channabasappa et al. (1998), Singandhupe and Rajput (1990), Singh and Singh (2000), and Thakur (1993).

3.3 Plant N uptake

The results pertaining to the percentage of nitrogen content in above-ground biomass at different stages of the crop and final grain and straw masses at harvest of the crop is presented in Table 5. Total nitrogen uptake by the above ground plant under each treatment is given in Table 6. Significant increase in N content in grains was observed with increasing N levels. Grain N at harvest varied from 0.61% in control, 0.73% in organic N treatment to 1.18% at LCC based application of 150 kg N ha^{-1}. Nitrogen content in the straw at harvest also showed considerable variation between different N treatments, it was found to be 0.39% in case of control and 0.63% in LCC based application of 150 kg N ha^{-1}; organic N treatment also showing increase in N compared to control i.e. 0.46%. Total N uptake (kg ha^{-1}) increased significantly with increase in applied N.

Table 6 Plant N uptake (kg ha^{-1}) at different stages of rice

Treatment	33 DAT	45 DAT	Harvest
Control	21	35	53
Recommended NPK	50	78	126
Organic manure	40	66	88
Farmers' practice	50	75	118
LCC based N use	51	83	142
LSD (P<0.05)	7.6	14.8	8.6

Increase in total N uptake by the plant with increasing N rate may be attributed to production of more dry matter, grain yield and increase in per cent N content in different plant part and increased availability of nitrogen. More N uptake by rice and with increasing N rate has been reported by several workers (Jaiswal and Singh 2001; Sharma et al. 1990). Higher N uptake under continuous submergence has been reported by Islam et al. (1986) and Timsina et al. (1998). Higher N uptake with increase in number of irrigation has been reported by Sharma et al. (1990) and Singh and Das (1985). Higher N uptake by both rice and wheat with higher N rate has been reported by Gangiah and Prasad (1999).

3.4 Nutrient status of soil

Soil fertility status in terms of soil organic carbon, $NH_4^+ - N$, $NO_3^- - N$ as affected by different N levels and FYM application are descried below:

3.4.1 Soil organic carbon content

The SOC content determined in various treatments at harvest of each crop has been presented in Table 7. The

Table 7 Soil organic carbon (%) in different treatments at harvest

Treatment	0–15 m depth	0.15–0.30 m depth
Control	0.61	0.40
Recommended NPK	0.73	0.46
Organic manure	0.82	0.51
Farmers' practice	0.72	0.45
LCC based N use	0.75	0.48
LSD (P<0.05)	0.10	NS

Table 8 NH_4-N content (kg ha^{-1}) in the surface layer (0–15 cm) at different stages of rice crop

Treatment	NH_4 (kg ha^{-1})					
	26 DAT	40 DAT	48 DAT	78 DAT	88 DAT	Harvest
Control	20	14	12	8	8	7
Recommended NPK	44	34	24	28	23	18
Organic manure	32	21	20	19	17	13
Farmers' practice	46	36	26	30	24	20
LCC based N use	48	47	48	34	27	23
LSD ($P<0.05$)	11	5	3	2	3	2

distribution of SOC in the soil profile was in conformity with the general observation of being highest in the surface layer (Monreal et al. 1995). It decreased significantly with depth up to 30 cm. Application of nitrogen enhanced the SOC content significantly. Substitution of the entire required dose of N by FYM was found to be more effective in enhancing SOC content than inorganic fertilizer N treatments. The SOC content at FYM treatment was significantly higher than all other treatments, whereas SOC at 120 kg N ha^{-1} and 150 kg N ha^{-1} were significantly higher than control.

Higher SOC content at higher N level can be attributed to increase in crop growth and consequent increased addition of biomass to the soil by way of roots and crop residues. The increase in organic carbon content in the FYM treatment is attributed to direct incorporation of the organic matter in the soil (Subramaniam and Kumarswamy 1989; Swarup 1991). Similar beneficiation effect of FYM in increasing SOC content has been reported by several workers (Brar and Dhillon 1994; Kesavan et al. 1995; Sudhir et al. 1998; Tembhare et al. 1998; Yadav et al. 2000). But due to higher temperatures in the tropical and subtropical region of our country, the extent of its degradation also is expected to be higher, but would give benefit to the existing crop.

3.4.2 Inorganic nitrogen content ($NH_4^+ - N$ *and* $NO_3^- - N$)

Ammoniacal and nitrate-N distribution in the soil up to 30 cm depth was studied at various stages of crop growth viz. 26, 40, 48, 78, 88 days after transplanting and at harvest.

3.4.2.1 $NH_4^+ - N$ In rice crop, $NH_4^+ - N$ is dominant over $NO_3^- - N$. This difference was observed for all the depths and all nitrogen treatments. However, amount of $NH_4^+ - N$ present in soil declined with crop growth, being least at harvest. It was 20 kg ha^{-1} in control at 26 DAT, reduced to 12 kg ha^{-1} at 48 DAT and attained a minimal value of 7 kg ha^{-1} at the time of harvest in the surface layer (0–15 cm). In case of FYM treatment the same trend was observed i.e. a maximum of 32 kg ha^{-1} at 26 DAT and declined to a minimum value of 13 kg ha^{-1} at the time of harvest. The same declining trend was observed in other treatments also (Table 8).

At any specific stage of crop, $NH_4^+ - N$ content decreased with increase in soil depth. In recommended NPK at 26 DAT stage, it was 32 kg ha^{-1} in the surface layer (0–15 cm) and reduced to 11 kg ha^{-1} at the time of harvest in the 15–30 cm layers. The same

Table 9 NH_4-N content in subsoil layer (15–30 cm) at different stages of rice

Treatment	NH_4-N (kg ha^{-1})					
	26 DAT	40 DAT	48 DAT	78 DAT	88 DAT	Harvest
Control	19	7	9	6	5	4
Recommended NPK	32	34	22	25	20	15
Organic manure	25	17	13	12	15	11
Farmers' practice	35	33	20	25	22	16
LCC based N use	36	36	34	29	24	19
LSD ($P<0.05$)	3	6	4	3	5	4

Table 10 NO_3-N content in the surface layer at different stages of rice crop

Treatment	NO_3-N, kg ha^{-1}					
	26 DAT	40 DAT	48 DAT	78 DAT	88 DAT	Harvest
Control	1.9	1.5	1.5	0.8	1.0	2.3
Recommended NPK	3.6	3.7	2.3	2.7	2.7	3.7
Organic manure	2.9	2.4	1.5	2.1	1.8	2.9
Farmers' practice	3.9	3.8	2.3	2.7	2.3	3.7
LCC based N use	4.5	4.3	4.7	3.4	2.9	4.0
LSD (P<0.05)	0.4	0.4	0.2	0.4	0.4	0.4

trend was observed in case of organic treatment and LCC based application.

Application of nitrogen in rice increased $NH_4^+ - N$ content in soil from 20 kg ha^{-1} in control to 48 kg ha^{-1} in LCC based application of 150 kg N ha^{-1}, and 32 kg ha^{-1} in organic treatment (Table 8). Same trend was noticed in 15–30 cm soil layer and also at other growth stages (Table 9).

3.4.2.2 $NO_3^- - N$ $\mathrm{NO_3^- - N}$ distribution also followed the same pattern as that of $\mathrm{NH_4^+ - N}$. But it was observed that the concentration at harvest was almost on par or little higher in some cases with that at 26 DAT. $\mathrm{NO_3^- - N}$ content increased significantly with increasing levels of nitrogen (Table 10).

The $\mathrm{NO_3^- - N}$ at 26 DAT was found to be 1.9, 2.9, 3.6, and 4.5 kg ha^{-1} in case of control, organic application, N_{120}, and N_{150} treatments respectively at 0–15 cm depths. But the concentration at harvest was 2.3, 2.9, 3.7, and 4.0 kg ha^{-1} respectively. In contrast to $NH_4^+ - N$, NO_3^- *N* showed an increasing trend with depth up to 30 cm. NO_3^- *N* content at 26 DAT was found to be 2.6 kg ha^{-1} in case of control, 3.6 kg ha^{-1} in case of 120 kg-N, 3.5 kg ha^{-1} in organic, and 4.8 kg ha^{-1} in case of 150 kg-N in the depth of 15–30 cm (Table 11).

3.5 N_2O emission

Nitrification and denitrification are the major soil processes, which yield to N_2O emission from soil. N_2O emission has not only agricultural concern but also environmental consequence, since it is a green house gas. N_2O emission showed an increasing trend with increasing N application it was least with no nitrogen application i.e. 308 g ha^{-1} and maximum with 150 kg N ha^{-1} treatment i.e. 1,016 g ha^{-1}, through out the crop period (Table 12).

3.6 Calibration and validation of InfoCrop

The model was calibrated using the data available from published literature, and the data generated through the field experiment was used to validate the model.

3.6.1 Model calibration

3.6.1.1 Derivation of genetic coefficients The genetic coefficients for the cultivar in this study was estimated from field observations by repeated iterations until close matches were observed between simulated and observed phenology and yield. Genotypic coefficients used in the model for rice

Table 11 NO_3-N content at 15–30 cm soil layer at different stages of rice crop

Treatments	NO_3 (kg ha^{-1})					
	26 DAT	40 DAT	48 DAT	78 DAT	88 DAT	Harvest
Control	2.6	1.9	1.6	1.5	1.3	2.7
Recommended NPK	3.9	3.8	3.0	3.2	3.5	4.0
Organic manure	3.5	3.1	2.4	2.8	2.9	3.4
Farmers' practice	4.9	4.6	3.2	3.0	3.1	3.9
LCC based N use	4.8	4.7	5.3	4.2	3.6	4.6
LSD (P<0.05)	0.3	0.3	0.6	0.3	0.5	0.6

Table 12 N_2O emission throughout the rice crop period

Treatment	N_2O emission (g ha^{-1})
Control	308
Recommended NPK	788
Organic manure	513
Farmers' practice	795
LCC based N use	1,016
LSD ($P<0.05$)	29.1

cultivar is given in Table 13. Because of the longer duration it has the highest juvenile phase and grain filling duration coefficients. The time taken for the completion of various physiological growth stages has been given in Table 14.

3.6.1.2 Calibration for crop yields Banerjee (2003) used InfoCrop model to simulate the grain yield and biomass yield of rice in case of saturated moisture regime. The grain and biomass yields were well simulated by the model for control as well as NPK treatment. There was, however, generally poor prediction of yields in the unfertilised treatment. Removing the values of the unfertilised treatments from the analysis considerably improved the predictability. Results of the field experiments conducted by Pathak et al. (2002, 2003b) showed that the predicted grain yield in 120 kg N treatment is in good agreement with the simulated yield (Mean error= 4.4). Simulated and observed total dry matter yields also had a reasonable agreement, though lower than that for grain yields (Banerjee 2003). The long-term simulation performed for Delhi with three levels of N showed that the yields with 120 kg N ha^{-1} through urea would be between 5.8 and 7.4 Mg ha^{-1} (Pathak et al. 2003b).

Table 13 Genetic coefficients of rice cultivar derived through the study

Genetic coefficient[a]	Pusa Sugandh 3
Juvenile phase coefficient (TTVG), GDD[b]	2,300
Grain filling duration coefficient (TTGF), GDD	370
Grain number coefficient (GNOCF)	58,000
Potential grain weight (POTGWT), g for thousand	22

[a] For definition of these coefficients see Aggarwal et al. (2004)

[b] GDD, growing degree days (°C-d)

Table 14 Duration (days) of different physiological growth stages of the crop

Treatment	Vegetative growth		Grain filling stage	
	Observed	Simulated	Observed	Simulated
Control	109	106	22	23
Recommended NPK	108	106	23	23
Farmers' practice	101	106	24	25
Organic manure	106	106	23	21
LCC based N use	101	106	25	24

3.6.1.3 Calibration for plant N uptake The results of the two different years of field experiments (Pathak et al. 2002, 2003b) shows that, with 120 kg N application the average N uptake by rice crop under same condition is in good agreement with the observed values (Mean error=4).

3.6.1.4 Calibration for components of soil N dynamics The major soil N dynamic processes are denitrification, leaching, and volatilization. The model simulated these processes and shows closer agreement with the observed values (Bijay-Singh et al. 2002; Katyal et al. 1987; Pathak et al. 2002, 2003b). In case of denitrification and volatilization the difference is meager, but it is a little wider in case of leaching (Table 15).

3.6.1.5 Calibration for nitrous oxide emission N_2O emission from rice field is a way of N loss and it is very important because N_2O is a greenhouse gas. Pathak et al. (2002, 2003b) had estimated the average loss of N as N_2O gas in a rice-growing season. The simulated results are almost on par with the observed quantities of the emission.

Table 15 Simulated components of soil N balance, kg ha^{-1}

Treatment	Leaching	Denitrification	Volatilization
Control	8.0	13.0	3.0
Recommended NPK	16.5	30.4	15.5
Farmers' practice	16.5	30.4	15.5
Organic manure	9.0	20.0	9.0
LCC based N applied	19.5	38.0	17.0

Table 16 Simulated versus observed grain yield of rice

Treatment	Observed Mg ha^{-1}	Simulated Mg ha^{-1}	Deviation (%)
Control	3.07	2.52	16.2
Recommended NPK	6.80	6.02	11.4
Farmers' practice	6.56	6.02	8.2
Organic manure	4.53	4.77	−5.2
LCC based N use	6.95	7.26	−4.4
Mean error (%)			9.1

3.6.2 Model validation

3.6.2.1 Validation for crop yields Predicted grain yields in all the treatments were in good agreement with the observed yields (Mean error=9.1%) (Table 6). There was, however, generally poor prediction of yields in the unfertilised treatments. Removing the values of the unfertilised treatments from the analysis considerably improved the predictability (Mean error=7.3). Model also failed to capture the difference in yield due to K application. Simulated and observed total dry matter yields also had a reasonable agreement, which is better than that of grain yield (Mean error=6.1) (Table 7). In this case also removal of unfertilized control improves the predictability (Mean error=3.6) (Table 16 and 17)

3.6.2.2 Validation for soil N dynamics Pathak et al. (2003a) had simulated the extent of N losses from rice fields in similar conditions using DSSAT model. After calibrating the model it has been observed that the predicted values for denitrification, leaching and volatilization are in good agreement with these observed values (Table 18).

3.6.2.3 Validation for nitrous oxide emission Predicted values in case of N_2O emission is in good agreement with observed values in case of 120 kg N (Error %=2.3), where as other treatments shows high variability (Mean error %=10.3). In all these cases model simulates lesser values for N_2O emissions (Table 19).

Table 17 Simulated versus observed total dry matter yield

Treatment	Dry matter (Mg ha^{-1})		Deviation %
	Observed	Simulated	
Control	6.50	5.53	16.4
Recommended NPK	13.10	12.76	2.6
Farmers' practice	12.68	12.76	4.6
Organic manure	10.81	10.03	−1.2
LCC based N use	14.18	14.46	5.8
Mean error			6.1

Table 18 Simulated and observed losses of N during growth of rice (kg ha^{-1})

Losses	Observed[a]	Simulated	Deviation, %
Denitrification	33	30.4	7.9
Leaching	16	16.5	−3.1
Volatilization	12	15.5	−29.1

[a] Pathak et al. (2003a)

3.6.2.4 Validation for N uptake N uptake by the crop with different N treatments has been simulated. The observed results shows good agreement with the simulated results (Mean error=11.4%) (Table 20). The unfertilised control treatment shows a wider variability followed by organic treatment in compar-ison to the other treatments. The predictability of the model can be improved by removing the control and organic treatments (Mean error=5.4 %).

3.7 Impacts of global warming on rice growth and N-dynamics

Calibrated and validated model was then used to simulate the possible impacts of climate change on crop growth as well as different processes. Temperature plays dominant role on crop growth. It determines the potential length of the growing seasons, and generally has a strong effect on the timing of developmental processes and on rates of expansion

Table 19 N_2O emission through the rice crop growing period

Treatment	N_2O emission (g ha^{-1})		Deviation (%)
	Observed[a]	Simulated	
Control	308	260	15.5
Recommended NPK	788	777	1.4
Farmers' practice	795	777	2.3
Organic manure	513	436	17.7
LCC based N use	1,016	869	14.5
Mean error			10.3

[a] Present study

Table 20 Total N uptake by the crop (kg ha^{-1})

Treatments	Observed[a]	Simulated	Deviation %
Control	53	65	−22.6
Recommended NPK	126	130	−3.2
Farmers' practice	118	130	10.2
Organic manure	88	104	−18.2
LCC based N use	142	146	−2.8
Mean			11.4

[a] Present study

of plant leaves. The latter, in turn, affects the time at which a crop canopy can begin to intercept solar radiation and, thus, the efficiency with which solar radiation is used to make plant biomass. The impacts of temperature rise by 1, 2 and 3°C from the ambient air temperature were simulated with the application of 60, 120 and 180 kg N ha^{-1}. In addition to duration of the crop, grain yield and biomass, various nitrogen transformation processes like denitrification, leaching, volatilization, N_2O emission and N uptake were also simulated.

Increase in temperature decreased crop duration in all the N treatments (Fig. 1). It can be seen that different N treatments did not change in their duration with same temperature. Rise in temperature reduced the grain yield considerably and continuously (Fig. 2). The total biomass yield also showed similar trend as noticed in case of yield (Fig. 3).

As far as N dynamics is concerned, the rise in temperature increased the N losses like N_2O emission (Fig. 4), denitrification (Fig. 5), volatilisation (Fig. 6) with all levels of N treatments. In case of N uptake, it is found to be decreasing (Fig. 7).

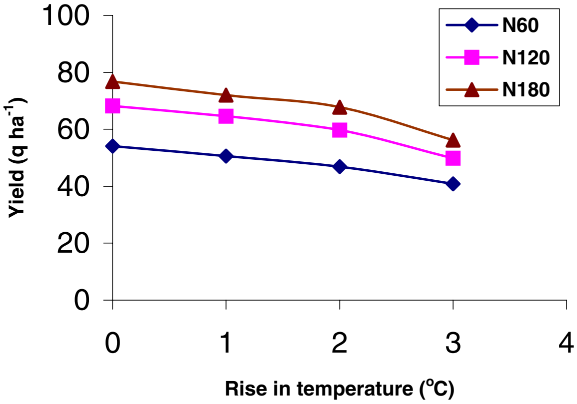

Fig. 2 Impact of temperature rise on yield of rice under different nitrogen application treatments

3.8 Discussion

The model simulations help to evaluate N management options, i.e., the increase in yield due to applied N versus potential loss of N to the groundwater and atmosphere. Bowen and Baethgen (1998) suggested that such tradeoff curves could be successfully used to define a critical value for nitrate beyond which leaching losses were not permitted.

Loss of N due to volatilization was found to be very low in the unfertilized treatment but application of N through inorganic or organic sources resulted in considerable loss. Every application of N resulted in a flux of ammonia. Total loss of N due to volatilization

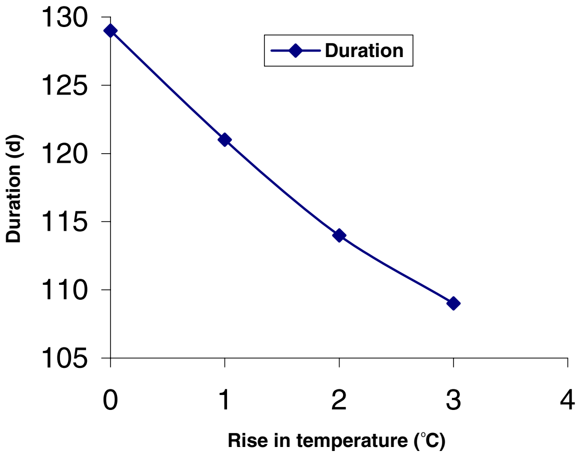

Fig. 1 Impact of temperature rise on crop duration

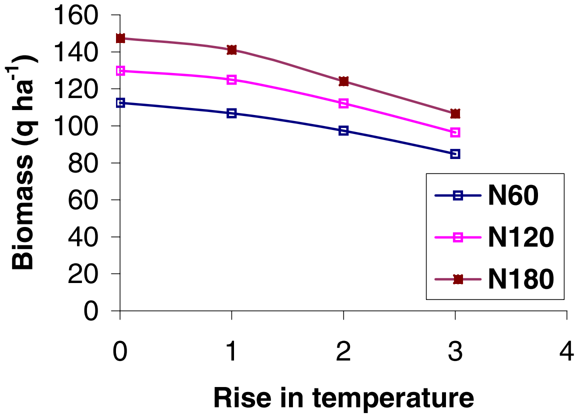

Fig. 3 Impact of temperature rise on final rice biomass under different nitrogen application treatments

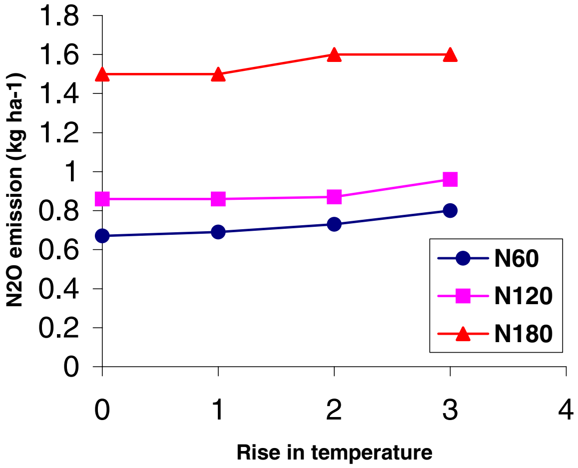

Fig. 4 Impact of temperature rise on N_2O emission in rice under different nitrogen application treatments

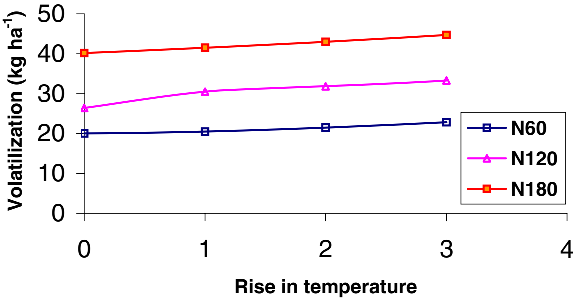

Fig. 6 Impact of temperature rise on volatilization in rice grown under various nitrogen application treatments

varied from 3 kg ha^{-1} in the unfertilized treatment to 15.5 kg ha^{-1} with application of 120 kg N ha^{-1} in three splits in the saturated condition (Table 18).

In ideal lowland rice fields with fine-textured soils leaching losses of N are low due to restricted percolation. In coarse textured permeable soils, however, the loss of N through leaching can be substantial. There were high losses of N during the first early days of the simulation due to ponding for puddling and leaching of nitrate, already present in the soil. This is expected in rice-upland cropping systems like the rice–wheat system. The drying of the soil that normally occurs at the end of the rice crop favours aerobic N transformations resulting in nitrification, and the accumulated NO_3-N at wheat harvest and subsequent fallow period is prone to losses by denitrification and leaching during soil flooding for rice (Buresh et al. 1989; George et al. 1992). Water application through irrigation and rainfall and its subsequent drainage dictates the leaching of N.

Among all N-loss processes, the highest N loss was due to denitrification. Denitrification started from the day 1 of the simulation. As the soil is submerged for puddling and rice transplanting, the anaerobic condition starts developing and the denitrification process is initiated. High denitrification loss of N immediately after flooding of dry soil has been reported by Buresh et al. (1989) and George et al. (1992). The total loss of N due to denitrification varied from 13 kg ha^{-1} in the unfertilized treatment in saturated soil to 38 kg ha^{-1} with application of 150 kg N ha^{-1} in the saturated soil condition (Table 18). A few results have been reported from India where N losses through denitrification are estimated through the difference method, e.g. the unaccounted for N is considered to be lost through denitrification (Bijay-Singh et al. 2002; Srivastava and Singh 1996). Aulakh et al. (2001) estimated that 23%–33% of N applied through fertilizer is lost via denitrification during rice cropping.

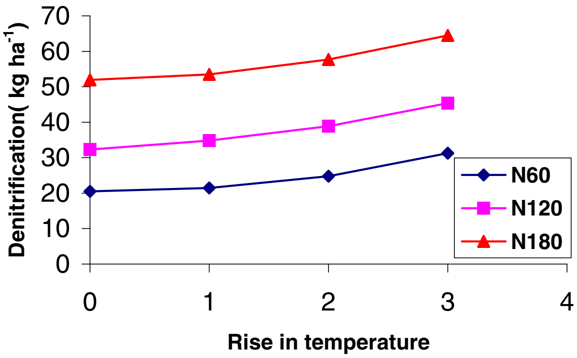

Fig. 5 Impact of temperature rise on denitrification in rice under various nitrogen application treatments

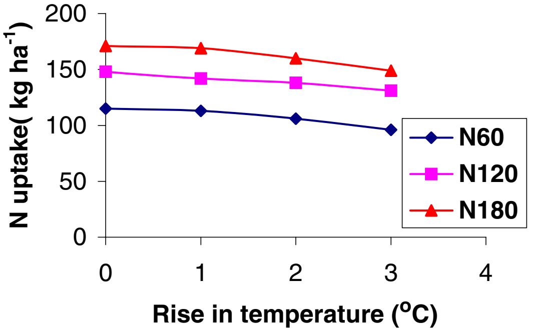

Fig. 7 Impact of temperature rise on N uptake for rice under different nitrogen application treatments

Models can be used to study the time course or pattern of N uptake by the crop and identify the most active period of N uptake. Crop management should then aim to provide sufficient amount of available soil N during this period. The pattern of N uptake by rice (cultivar Pusa Sugandh 3) in Delhi showed differential behaviour with different levels of N. The total uptake was about 65, 130 and 104, 146 kg N ha^{-1} in the unfertilized, 120 kg N, Organic and 150 kg N ha^{-1} treatments (Table 20). Such information can be used to attain a better synchrony between supply and demand of N of the crop for a particular situation.

The likely impact of climate change on the cereal production is of paramount importance in the planning strategies to meet the increased demands. In this scenario models are the effective tools to foresee the probable impacts and go for long term planning. Probable impact of climate change on N dynamics in soil and crop yield in general has been simulated with three levels of N viz. 60, 120, and 180 kg ha^{-1}. Values for three different years i.e. 1999, 2000, and 2003 have been averaged. The results show that with each degree rise in temperature yield and biomass yield will be reduced (Figs. 2 and 3). The effect of increased temperature on crop production would largely be negative because of increased respiration and a shortened vegetative and grain-filling period (Horie et al. 1995; Penning de Vries 1993). The processes, which lead to soil N losses such as volatilization, denitrification, N2O emission etc, will be increased (Figs. 4, 5, 6); this in turn will make crop production more expensive. Under increasing temperature conditions crop N uptake shows decreasing trend (Fig. 7), this will make the food crops less nutritious.

4 Conclusion

InfoCrop model was able to capture the major effects of water, N and genotype on crop performance and water and nitrogen balance. Observed grain and total dry matter yields were in agreement with the predicted values. Further, there was poor prediction of yields in the unfertilised treatments. A good agreement was observed between simulated and predicted N uptake by rice. It was noticed that as temperature increased, the duration of the crop decreased and yield and total biomass yield also decreased with different levels of N application. Increase in temperature increased different soil N losses such as N_2O emission, denitrification and volatilization that had direct bearings on economic crop production and environmental consequences. Further scope of the study can be the validation of this model for the components of SPAC in varying agroenvironments.

References

Aggarwal, P. K., & Kalra, N. (1994). Analyzing the limitations set by climatic factors, genotype, and water and nitrogen availability on productivity of wheat. II. Climatically potential yields and optimal management strategies. *Field Crops Research, 38*, 93–103.

Aggarwal, P. K., Kalra, N., Subhash, C., & Pathak, H. (2004). *InfoCrop: A generic model for annual crops in tropical environments*. New Delhi: Indian Agricultural Research Institute.

Aulakh, M. S., Khera, T. S., Doran, J. W., & Bronson, K. F. (2001). Denitrification, N_2O and CO_2 fluxes in rice–wheat cropping system as affected by crop residues, fertilizer N and legume green manure. *Biology and Fertility of Soils, 34*, 375–389.

Banerjee, B. (2003). *Carbon dynamics in rice–wheat systems* (pp. 108). Ph. D. thesis. New Delhi: Indian Agricultural Research Institute.

Bijay-Singh, Gajri, P. R., Timsina, J., Yadvinder-Singh, & Dhillon, S. S. (2002). Some issues on water and nitrogen dynamics in rice–wheat sequences on flats and beds in the Indo-Gangetic plains. In E. Humphrey, & J. Timsina (Eds.), *Modelling irrigated cropping systems, with special attention to rice–wheat sequences and raised bed planting*. Report 25/02. (pp. 1–15). CSIRO Land and Water tech. Proc. Workshop CSIRO, Griffith, 25–28 Feb, 2002.

Bowen, W. T., & Baethgen, W. E. (1998). Simulation as a tool for improving nitrogen management. In G. Y. Tsuji et al. (Eds.), *Understanding options for agricultural production* (pp. 189–204). The Netherlands: Kluwer.

Boyer, E., Howarth, R. H., Galloway, J. N., Dentener, F. J., Cleveland, C., Asner, G. P., et al. (2004). Current nitrogen inputs to world region. In A. R. Mosier, J. K. Syers, & J. R. Freney (Eds.), *Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment* (pp. 221–230). Washington, DC: Island.

Brar, S. S., & Dhillon, N. S. (1994). Effect of FYM application of yield and soil fertility in rice–wheat rotation. *International Rice Research, Note(Philippines), 19*(2), 23.

Buresh, R. J., Woodhead, T., Shepherd, K. D., Flordelis, E., & Cabangon, R. C. (1989). Nitrate accumulation and loss in a mung bean–lowland rice cropping system. *Soil Science Society of America Journal, 53*, 477–482.

Channabasappa, K. S., Reddy, B. G. M., Patil, S. G., & Kumar, M. D. (1998). Response of late transplanted rice to age, number of seedlings and fertilizer levels. *Indian Journal of Agronomy, 43*(3), 636–638.

Dobermann, A., & Cassman, K. G. (2004). Environmental dimensions of fertilizer nitrogen: What can be bone to increase nitrogen use efficiency and ensure global food security? In A. R. Mosier, J. K. Syers, & J. R. Freney (Eds.), *Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment*. Washington, DC: Island.

Dobermann, A., & White, P. F. (1999). Strategies for nutrient management in irrigated & rainfed rice systems. *Nutrient Cycling in Agroecosystems, 53*, 1–18.

Gangiah, B., & Prasad, R. (1999). Effects of fertilizers on the productivity and NPK removal of a rice–wheat cropping system. *Acta Agronomica Hungarica, 47*(4), 405–412.

George, T., Ladha, J. K., Buresh, R. J., & Garrity, D. P. (1992). Managing native and legume fixed N in lowland rice based cropping systems. *Plant and Soil, 141*, 69–91.

Horie, T., Yajima, M., & Nakagawa, H. (1995). Yield forecasting. *Agricultural Systems, 40*(1:3), 211–236.

IPCC (International Panel on Climate Change). (2001). *Climate change—2000. The science of climate change* (XII). Cambridge, UK: Cambridge University Press.

IRRI. (2001). *Annual reports 2000–2001. Rice research: The way forward* (pp. 71). Los Banos, Philippines: International Rice Research Institute.

Islam, M. Z., Haq, K., & Bhuiyan, L. R. (1986). Effect of different water management practices on grain yield, wed population and recovery of applied nitrogen in rice cultivation. *Bangladesh Journal of Agriculture, 11*(3), 57–64.

Jaiswal, V. P., & Singh, G. R. (2001). Effects of planting methods, source and levels of nitrogen on the growth and yield of rice (*Oryza sativa*) and on succeeding wheat (*Triticum aestivum*). *Indian Journal of Agronomy, 46*(1), 5–11.

Katyal, J. C., Bijay-Singh Vlek, P. L. G., & Buresh, R. J. (1987). Efficient nitrogen use as affected by urea application and irrigation sequence. *Soil Science Society of America Journal, 5*(1), 366–370.

Kesavan, S. P., Sharma, N. K., Khadikar, P. V., & Verma, G. P. (1995). Effect of long term input and intensive cropping on aggregation of a black clay soil. *Crop Research, 9*(2), 258–265.

Kropff, M. J., Bouma, J., & Jones, J. W. (2000). Systems approaches for the design of sustainable agro-ecosystems. *Agricultural Systems, 70*(2:3), 369–393.

Majumdar, D., Rastogi, M., Kumar, S., Pathak, H., Jain, M. C., & Kumar, U. (2000). Nitrous oxide emissions from an alluvial soil with different nitrogenous fertilizers and nitrogen levels. *Journal of Indian Society of Soil Science, 48*(4), 732–741.

Monreal, C. M., Schintizer, M., Schulten, H. R., Campbell, C. A., & Anderson, D. W. (1995). Soil organic structures in macro and micro aggregates of a cultivated brown chernozem. *Soil Biology & Biochemistry, 27*(6), 845–853.

Page, A. L., Miller, R. H., & Keeney, D. R. (1982). *Methods of soil analysis. Part 2, Chemical and microbiological properties* (2nd ed.). Agronomy no. 9. Madison, WI, USA: ASA-SSSA.

Pathak, H., Arti, B., Shiv, P., Sushil, K., Shalini, S., Jain, M. C., et al. (2003b). Effect of DCD, FYM and moisture regimes on nitrous oxide emission from alluvial soil in rice–wheat cropping system. *Journal of the Indian Society of Soil Science, 51*, 139–144.

Pathak, H., Bhatia, A., Shiv Prasad, Jain, M. C., Kumar, S., Singh, S., & Kumar, U. (2002). Emission of nitrous oxide from soil in rice–wheat systems of Indo-Gangetic plains of India. *Environmental Monitoring and Assessment, 77*(2), 163–178.

Pathak, H., Timsina, J., Humphreys E., Godwin, D. C., Bijay-Singh, Shukla, A. K., et al. (2003a). *Simulation of rice crop performance and water, nitrogen and carbon dynamics in northwest India using CERES Rice 4.0 model*. CSIRO Land and Water Technical Report. Griffith, Australia: CSIRO.

Penning de Vries, F. W. T. (1993). Rice production and climate change. In F. W. T. Penning de Vries et al. (Eds.), *Systems approaches for agricultural development* (pp. 175–189). Netherlands: Kluwer.

Penning de Vries, F. W. T, Jansen, D. M, ten Berge, H. F. M, & Bakema, A. (1989). *Simulation of eco-physiological processes of growth in several annual crops* (p. 64). Los Banos, Philippines/Wagningen, the Netherlands: International Rice Research Institute/Pudoc.

Sharma, S. K., Yadav, M. P., & Tripathi, H. P. (1990). Effect of planting methods under various levels of nitrogen on yield and N-use efficiency of rice. *Narendra Deva Journal of Agricultural Research, 5*(1), 42–45.

Singandhupe, R. B., & Rajput, R. K. (1990). Nitrogen use efficiency in rice under varying water regimes, sources and levels in semi reclaimed sodic soil. *Indian Journal of Agronomy, 90*(1–2), 73–81.

Singh, C., & Das, D. K. (1985). Nitrate-nitrogen distribution in soil and nitrogen uptake by wheat under varying levels of water and nitrogen supply. *Annals of Agricultural Research, 6*(1), 91–97.

Singh, V. P., & Singh, V. K. (2000). Effect of sowing date and nitrogen level on the productivity of spring sown rice (*Oryza sativa*) varieties in low hills of Uttaranchal. *Indian Journal of Agronomy, 45*(3), 560–563.

Srivastava, P. C., & Singh, T. A. (1996). Nitrogen in soils and transformation of fertilizer nitrogen. In H. L. S. Tandon (Ed.), *Nitrogen research and crop production* (pp. 14–31). New Delhi: FDCO.

Subramaniam, K. S., & Kumarswamy, K. (1989). Effect of continuous cropping and fertilization on chemical properties of soil. *Journal of the Indian Society of Soil Science, 37*, 171–173.

Sudhir, K., Mariaswamy Gowda, S. M., & Srikanta, K. (1998). Long term effects of continuous cropping and fertilizer use on sustenance of productivity and fertility of an alfisol under irrigated finger millet hybrid maize systems. In A. Swarup, D. Reddy, & R. N. Prasad (Eds.), *Long-term soil fertility management through integrated plant nutrient supply* (pp. 139–145). Proceedings of a National Workshop, 2–4 April, 1998, IISS, Bhopal.

Swarup, A. (1991). Long-term effects of green manuring (*Sesbania aculeata*) on soil properties and sustainability of rice and wheat yield on a sodic soil. *Journal of the Indian Society of Soil Science, 39*, 777–780.

Tembhare, B. R., Dwivedi, A. K., & Tiwari, A. (1998). Effect of continuous cropping and fertilizer use on crop yields and fertility of a Typic Haplustert. In A. Swraup, D. Reddy, & R. N. Prasad (Eds.), *Long-term soil fertility management through integrated plant nutrient supply* (pp. 221–228). Proceedings of a National Workshop, 2–4 April, 1998, IISS, Bhopal.

Thakur, R. B. (1993). Performance of summer rice (*Oryza sativa*) to levels of nitrogen. *Indian Journal of Agronomy, 38*(2), 187–190.

Timsina, J., Singh, U., Badaruddin, M., & Meisner, C. (1998). Cultivar, nitrogen and moisture effects on rice–wheat sequence. Experimentation and simulation. *Agronomy Journal, 90*(2), 119–130.

Watson, R. T., Zinyowera, M. C., & Moss, R. H. (Eds.). (1998). *The regional impacts of climate change. An assessment of vulnerability* (IPCC II report) (p. 517). Cambridge: Cambridge University Press.

Yadav, R. L., Dwivedi B. S., & Pandey, P. S. (2000). Rice–wheat cropping system, assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crop Research, 65*, 15–30.