Simulation of rice crop performance and water and N dynamics, and methane emissions for rice in northwest India using CERES Rice model

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Simulation of rice crop performance and water and N dynamics, and methane emissions for rice in northwest India using CSM-CERES-Rice model

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Contents

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Summary

Crop growth simulation models provide a means to quantify the effects of climate, soil and management on crop growth, productivity and sustainability of agricultural production. These tools can reduce the need for expensive and time-consuming field experimentation as they can be used to extrapolate the results of research conducted in one season or location to other seasons, locations, or management. The development and application of system approaches and decision support methods can help to identify strategies for optimising resource use, increasing productivity, identifying yield gaps and reducing adverse environmental impacts.

The DSSAT (Decision Support Systems for Agro-technology Transfer) software facilitates the application of the various crop models. CSM-CERES-Rice, embedded within DSSAT, is a process-based, management-oriented model which simulates the growth and development of rice. The MERES (Methane Emission from Rice EcoSystems) model is a further development of CERES-Rice with additional processes for methane emission from rice fields.

The objectives of the present study were to:

- evaluate CSM-CERES-Rice ver. 4.0 for its ability to simulate rice growth and yield
- estimate potential yield and yield gaps in rice
- estimate and improve understanding of water and N dynamics and balances in the continuously flooded, continuously saturated and intermittently irrigated rice culture
- demonstrate potential applications of the model to improve understanding of sustainability issues related to water and N in various rice culture
- evaluate the ability of MERES to predict methane emission from rice culture in northwest India

Data generated from field experiments conducted in New Delhi, Ludhiana and Modipuram in northwest India were used for calibration and validation of the models. At Delhi experiment, there were 3 N (no added N, urea at 120 kg N ha^{-1}, and urea plus farmyard manure at 60 kg N ha^{-1} each) and two water management (saturated soil – SAT, and three alternating wetting and drying – AWD kept at 11-23 DAT, 30-48 DAT, and 57-78 DAT) treatments. In the SAT treatments 30 irrigations were provided to try and maintain saturation of the topsoil throughout the cropping period, and in the AWD, the soil surface was allowed to dry until fine cracks developed on the soil surface, with soil kept at saturation at other times. At Ludhiana, there were 3 N (no added N, 120 kg N ha^{-1} as urea in 3 equal splits, and 20 kg N ha^{-1} basal plus topdressing of 30 kg N ha^{-1} at a leaf colour chart reading of 4 and two water management (irrigated 1 or 3 days after the disappearance of the floodwater) treatments. At Modipuram, six N levels (as urea) and 3 varieties (Basmati-370, Saket-4 and Hybrid-6111) were compared, with soil kept at saturation throughout the experiment.

CSM-CERES Rice ver. 4.0 in its original form resulted in very high denitrification losses and no or very little loss of N through leaching, whereas reports of field studies suggested lower denitrification losses and significant leaching losses. The model was modified to improve the prediction of these losses by:

- including lag factors in nitrification/denitrification to simulate the effect of soil depth on oxygen availability, which prevented denitrification for 5 days following ponding;

- including a routine for leaching of soluble carbon, a prerequisite for denitrification.
- enabling the puddled soils to leach by adding a call to SATFLO in the puddled section of WATBAL, and adding the argument PUDPERC to set the maximum drainage rate

After incorporating these processes, CSM-CERES Rice ver. 4.0 generally simulated yield, and water- and N-related processes fairly satisfactorily.

Predicted grain yields agreed well with observed yields at all locations (RMSE=0.82 Mg ha^{-1}; d-stat=0.94), except for generally poor prediction (under prediction) of yields in unfertilised treatments. Simulated and observed total dry matter yields were also in reasonable agreement, though not as close as grain yields (RMSE=3.33 Mg ha^{-1}; d-stat=0.75). Observed and predicted N uptake by rice in Delhi (RMSE=21 kg ha^{-1}; d-stat=0.86) showed good agreement, especially for grain N uptake. However simulation of soil NH_4-N and NO_3-N in the surface soil layer (0-15 cm) was generally poor.

Simulated deep drainage below 120 cm on the Delhi loam was 1277 mm, more than double the loss of 561 mm by ET, consistent with observations from other studies in northwest India on sandy loam, loam and sandy soils. The model predicted N leaching losses similar to those reported in the literature with urea applied at 120 kg N ha^{-1}, but predicted higher denitrification and lower ammonia volatilisation losses than previous reports.

Emission of methane predicted by MERES ranged from 53 to 96 kg ha^{-1} during the rice season, and was much higher than the observed values of 28 to 45 kg ha^{-1}. MERES needs further improvement in terms of simulating soil water balance and redox potential to better predicting methane emissions.

The potential yield of rice as predicted by CSM-CERES Rice ver 4.0 at the 3 sites in northwest India ranged from 10.0 to 10.8 Mg ha^{-1}, with highest yield at Ludhiana and lowest at Modipuram. A wide gap exists between climatic potential yield and the yields obtained in research fields and farmers' fields. The gap between potential and on-station yields ranged from 28 to 38% and that between the potential and on-farm yields widened (48 to 68%) in all the locations. The analysis thus suggested that there is plenty of scope to improve the farmers' yields by adopting suitable water and N management strategies.

The model was tested for its sensitivity to a range of parameters such as time of planting and fertilizer and irrigation management. The model was sensitive to transplanting date, with highest potential yield (10.3 Mg ha^{-1} for early planting (1 May) and significantly lower yields after 20 July planting. Continuous ponding with 5 cm water or continuous saturation, each with 120 kg N ha^{-1}, yielded only ~7.0 Mg ha^{-1}. As irrigation applications were reduced, yields further decreased, with 3 prolonged drying events (AWD) decreasing yield by 21% compared to continuous submergence. Changing from continuous submergence to continuous saturation to 2 prolonged dryings reduced irrigation water amounts and increased water use efficiency. Increasing N application rate up to 300 kg ha^{-1} increased yields, but with only small increases at rates above 180 kg ha^{-1}. Recovery efficiency, internal-use efficiency, agronomic efficiency and utilization efficiency of applied N increased for N rates up to 150 kg ha^{-1}. The analysis suggests that water and N greatly limited the yield potential even the continuously flooded or saturated treatments, and that N rate be increased to at least 150 kg ha^{-1}.

The model was used to calculate components of in-season water and N balances in rice. Including initial soil water content of 369 mm to 120 cm depth, the total water input was 6381, 2522 and 1802 mm in the continuously flooded, saturated and drained treatments, respectively, at Delhi. Deep drainage was the main water loss at 5396, 1277 and 728 mm, respectively, compared with ETs of 637, 555 and 514 mm. The total N leaching loss was 15 to 16 kg ha^{-1} in the saturated soil, 12-13 kg ha^{-1} in AWD, and 21 kg ha^{-1} in the continuously flooded treatments. Total N loss due to volatilization was small and varied from 1 kg N ha^{-1} in the unfertilised treatment to 4 kg N ha^{-1} with application of 120 kg N ha^{-1} in the AWD and continuously flooded conditions. Denitrification was the largest source of N loss, and started from day 1 of the simulation due to denitrification of NO_3^- initially present in the soil profile. Total loss of N due to denitrification varied from 12 kg ha^{-1} in the unfertilised saturated soil to 54 kg ha^{-1} with application of 120 kg N ha^{-1} in AWD. Substitution of 50% of the urea N with farmyard manure (FYM) reduced the loss in both the irrigation treatments. Denitrification was greater in AWD than in saturated soil for the same N management. Soil organic carbon declined in all the treatments, with lowest decline in FYM amended plot under saturation and highest in the unfertilized control and in continuously flooded plots. The model simulated the time course of crop N uptake and N loss processes for various fertilizer and water regimes fairly realistically.

The cumulative probability functions (CPFs) based on 35 years of historical weather data for grain yield for Delhi showed that yields of Pusa 44 under the continuously flooded and saturated treatments were always higher than under AWD, and that in 75% of years yields with 120 kg N ha^{-1} through urea alone would be higher (6.2-7.4 Mg ha^{-1}) than with urea plus FYM (6.1-6.8 Mg ha^{-1}). With continuous flooding, in 90% of years yields were greater than 5.9 Mg ha^{-1}. Irrigation applied during the season ranged from 4933 to 5883 mm in the continuously flooded treatment compared with 1080 mm in AWD and 1800 mm in other non-ponded treatments. Rain exceeded 500 mm in at least 50% of years. The CPFs showed that drainage varied widely with water management, but was not affected by N treatment. Drainage of the saturated and drained treatments varied by ~1000 mm across seasons, whereas under continuous flooding, drainage was exceptionally high (5394 to 5452 mm) with little variation across years. Under continuous saturation, drainage ranged from 1428 to 2352 mm over 35 years, exceeding 1800 mm in 50% of years, while under AWD drainage ranged from 702 to 1654 mm, with at least 1100 mm in 50% of years.

Similar analysis using 30 years of historical weather data in Ludhiana showed that when N was not applied there was no significant difference in long-term yields of rice between 1- and 3-d drainage, with a 50% probability of getting yields of 1.7 Mg ha^{-1}. With N application, however, yields were higher (4.1-7.0 Mg ha^{-1}) for 1-d drainage compared to 3-d drainage (3.0-6.9 Mg ha^{-1}). Higher amounts of irrigation water (7140-8625 mm) were applied and higher drainage (6120-7500 mm) was observed at Ludhiana than at Delhi. The higher drainage was associated with slightly greater N leaching losses at Ludhiana. The analyses reveal that while rain is enough to meet ET requirements, irrigation is necessary at both sites because of the high permeability of the soil.

CSM-CERES Rice ver. 4.0 was generally able to capture the major effects of water, N and genotype on crop performance and water and N balances consistent with field determinations in northwest India. Potential applications of the model as described above and many others may be possible for other locations of northewest India and the IGP and thus CSM-CERES Rice ver. 4.0 would be a useful tool for decision making and for improving farmers' management in rice cropping systems.

Introduction

Rice is one of the world's most important food crops and has been grown for more than 6000 years in South Asia. The production of rice in South Asia, including northwest India, has increased markedly with the introduction and widespread adoption of modern crop production technologies such as early maturing and N responsive semi-dwarf cultivars, high use of inorganic fertilizers, especially N fertilizers, and pesticides, and the expansion of irrigation facilities. As a result, the removal of nutrients with harvested grain and straw has also increased. Most of the rice in Asia, including northwest India, is grown as a transplanted crop, where fields are flooded before planting and the soil is puddled to reduce percolation. The chemical environment of reduced soil and the extremely limited O_2 supply in the soil-floodwater system have a large influence on the soil nutrient dynamics of irrigated rice systems.

However, despite large research efforts and high inputs, rice yields are stagnant or declining (Cassmann et al., 1995; Nambiar, 1995; Brar et al., 1998; Yadav, et al., 1998, 2000; Duxbury et al., 2000; Regmi et al., 2002), and there are large gaps between potential, research station and farmers' yields. Suggested causes of yield decline include: gradual decline in the supply of soil nutrients causing nutrient (macro and micro) imbalances due to inappropriate fertilizer application, decline in soil organic matter (SOM) content, and adverse changes in bio-chemical and physical composition of SOM.

The major problems that northwest India is facing today include declining groundwater levels, increasing groundwater and atmospheric pollution (particulates, greenhouse gases), declining SOM, climate change and its adverse impacts on crop performance, water use requirement and water availability, and low N-use efficiency in flooded rice.

Soil organic matter, though usually comprising less than 5% of a soil's weight, is one of the most important components of soil. It serves as nutrient source, substrate for microbial activity, and major determinant for sustaining of increasing agricultural productivity. The rate and degree of mineralization of organic N to NH_4^+ and its subsequent transformation to NO_3^- can affect fertilizer requirements, maintenance of SOM, nitrate leaching, emissions of greenhouse gases, and N recycling. Unfortunately, in most of the sub-tropical rice growing areas of south Asia the SOM content has declined over time (Duxbury et al., 2000; Nambiar, 1994; Bronson and Hobbs, 1998; Yadav et al., 1998, 2000). In the major rice-wheat regions of northwest India the soil organic C in the topsoil has decreased from ~0.5% in 1960s to ~0.2% at present (Sinha et al., 1998). In Pakistan's Punjab average SOM decreased from 1.02% in 1971-74 to 0.72% in 1975-84, and further declined to 0.59% in the post green revolution period of 1985-94 (Ali and Byerlee, 2000).

Methane (CH_4) is one of the important greenhouse gases contributing to global warming (IPCC, 1996). Methanogenesis, the biogeochemically important process that occurs in all anaerobic environments in which organic matter undergoes decomposition, is responsible for CH_4 emission (Oremland, 1988). Wetland rice fields may account for approximately 20% of the global anthropogenic CH_4 annually produced (Cicerone and Oremland 1988; Roy and Conrad 1999). The CH_4 emission from wetland rice fields is estimated to be 60 Tg yr^{-1}, with a range of 20–100 Tg yr^{-1} (IPCC, 1996).

Water management is a major factor affecting CH_4 emission (Jain et al., 2000). While continuously submerged rice fields may emit substantial amounts of CH_4, emission from intermittently irrigated rice may be low (Mishra et al., 1997; Aulakh et al., 2001b). The cycle of aerobic and anaerobic conditions operating in the sandy loam soils of the northwest may considerably influence CH_4 emission. Application of FYM, ranging from 1 to 5 Mg ha^{-1} yr^{-1} (dry weight basis), is a common practice by the farmers of the IGP. Application of FYM plays an important role in CH_4 emission by adding organic carbon and N required for microbial growth. Precise estimates of methane emission have been difficult due to the large spatial and temporal variability in CH_4 measured at different sites due to the difference in climate, soil properties, duration, and pattern of flooding, rice cultivars and crop growth, organic amendments, fertilization, and cultural practices.

Northwest India is facing future water shortages due to the adoption of inefficient irrigation practices. Earlier the dominant cropping systems in this region were pearl millet-wheat, maize-wheat, fodder-wheat. With the introduction of the canal irrigation network the rice-wheat cropping system was introduced into the region. As the soils of the area are light to medium textured there are very high deep drainage losses of water and associated groundwater pollution. Reducing permeability by puddling enables rice production in these soils, but also results in hard pan formation and reduced fertility, while still consuming large amounts of water. The area receives an annual rainfall of 400-500 mm during the rice season, roughly matching evapotranspiration. However a substantial amount of additional irrigation water is required due to high drainage losses and lack of rain during the first part of the rice season. Many farmers, having access to the pumps and electricity subsidies, also pump from the ground water, which has resulted in a rapid decline in the water tables in large areas. Some farmers have also started practising a rice-rice-wheat cropping system, which requires further water. Unsustainable rates of exploitation of the water resource are incompatible with the desire for crop intensification in these areas. Many of the adverse effects of the rice-wheat cropping system on soil and water resources and air and water pollution can be reversed by better fertilizer and water management. Thus there is a strong need for adoption of improved water and nitrogen management techniques.

Nitrogen and water dynamics in rice in the Indo-Gangetic plain

Nitrogen is the major nutrient limiting rice yields, and also the most widely used,. The former results partly from the high cost of increasing N levels in soils and partly from the difficulty in forecasting how to adjust N fertilizer levels for different crop, soil and seasonal conditions. In some areas too much N may be applied as inorganic or organic fertiliser, with adverse impacts on yields, grain quality and ground and surface waters.

Improved fertiliser N management is one of the keys to increasing yield and N-use efficiency, and reducing the cost of N management, and N losses.

In the soil, N exists in a variety of inorganic and organic forms, with the majority present in organic forms. Organic N stored within wetland soils is the most stable pool of N and, as such, is not readily available for internal cycling. Inorganic stores of N are not very stable over time and generally comprise less than 1% of the total N within the rice paddies. The microbial biomass N is relatively small when compared with the total pool of organic N, yet microbial activity is the single greatest regulator of the stability of organic N. Microbial biomass N is typically 0.5 to 3% of total N. Soil N dynamics is closely linked to the soil organic carbon dynamics; these together determine the soil productivity to a greater extent.

Variability in soil water status is a major factor affecting N use efficiency. The alluvial soils (Ustochrept) of northwest India are sandy loam to loam with high percolation rates. Though maintenance of continuous submergence is recommended for higher yield and nutrient use efficiency (De Datta, 1981), it is often difficult to maintain continuous submergence in these soils. Thus farmers puddle the soil and irrigate frequently to keep the soil flooded or saturated with short periods of surface soil drying between irrigations. Application of frequent fresh irrigation water containing high concentrations of dissolved oxygen allows the soil to remain partially aerobic during the rice season.

Many of the processes affecting N dynamics in a rice cropping system are very sensitive to the availability of water and thus the N dynamics in flooded rice fields are very different from those of upland fields. When the soil is saturated, limited O_2 availability restricts nitrification and NH_4^+-N is the major form of N, and is vulnerable to loss through volatilization. Ammonia (NH_3) volatilization is one of the important losses affecting N use efficiency in rice (Fillery and Vlek, 1986), especially in tropical and sub-tropical regions due to high temperature. In the case of urea the process of hydrolysis forming NH_4^+ and HCO_3^- increases soil and floodwater pH, which promotes NH_3 volatilization loss. The main source of NH_3 loss from flooded rice is due to high levels of ammoniacal N in the floodwater after fertilizer application and elevated floodwater pH due to algal photosynthesis. Volatilization of NH_3 from agricultural systems is also a cause of environmental pollution. From the atmosphere it is washed out by clouds and redeposited on the terrestrial ecosystem (Ferm, 1998). The extent of volatilization depends on several soil, plant and climatic factors including the form and amount of N applied, soil and floodwater pH and temperature. In non-flooded situations, variability in soil water content is probably one of the most confounding factors affecting NH_3 loss (Fillery and Vlek, 1986). Ammonia volatilization increases with increasing soil water content from air dry to flooding (Patra et al., 1996). In general, maximum NH_3 loss is observed when the soil water content is at or near field capacity at the time of fertilizer application (Bouwmeestre et al., 1985). Estimates of NH_3 volatilisation losses from rice fields in northwest India range from 20-35 kg ha^{-1} (Banerjee et al., 2002; Katyal et al., 1987; Srivastava and Singh, 1996).

Nitrification rates generally increase with increasing soil water availability from air dry up to about 60–70% water filled pore space. At higher soil water contents oxygen availability is reduced and the rate of nitrification declines to negligible at about 90% water filled pore space. In contrast, denitrifying bacteria have little or no activity below 60% water filled pore space (Linn and Doran, 1984). Thus when water contents rise above the drained upper limit the rate of nitrification will generally decrease and denitrification will increase. Small changes in soil water content around this critical point will have large consequences on the availability of N. In the field this is often seen as large losses of N via nitrification followed by denitrification when periods of drying are followed by periods of flooding, especially where temperatures are high. Where water is managed to maintain soil water content below the critical water filled porosity, N can be preserved as nitrate and none lost to denitrification until prolonged ponding occurs. On the other hand, if marginally more water is applied and the soil water content stays above the critical water filled porosity, nitrification is blocked, and available N is present as ammonium, avoiding loss by denitrification.

Denitrification occurs when nitrate is present in soil with anaerobic sites that develop as a result of microbial demand for oxygen exceeding supply. This may well occur where oxygen diffusion is impeded by water, either at the centres of soil particles or in water saturated regions or wherever the local oxygen demand is exceptionally high. Movement of nitrate into anaerobic microsites or into a thick reduced layer that is often beneath the aerobic soil surface in flooded rice results in N loss through denitrification, reducing N-use efficiency (Aulakh et al., 1992). The drying of the soil that normally occurs at the end of the rice crop favours aerobic N transformations resulting in nitrification. Accumulated NO_3-N is prone to losses by denitrification and leaching during soil flooding for the next rice crop (Buresh et al., 1989; George et al., 1992). A few results have been reported from northwest India where N losses were estimated through the difference method, where the unaccounted for N was considered to be lost through denitrification (Srivastava and Singh, 1996; Bijay-Singh et al., 2001). Using the acetylene inhibition intact soil core technique, Aulakh et al. (2001a) estimated that 23-33% of N applied to rice was lost via denitrification. In other study in northwest India, denitrification loss ranged from 10 to 40 kg ha^{-1} (Aulakh et al., 1992). Leaching is also a major loss process in the coarse-textured soils of northwest India, with estimates of leaching losses ranging from 10 to 18 kg ha^{-1} (Bijay-Singh and Sekhon, 1976; Bijay-Singh et al., 1991,a,b).

Role of a systems approach for sustainable rice production

A systems approach can be defined as “the systematic and quantitative analysis of agricultural systems and the synthesis of comprehensive, functional concepts of these systems” (Kropff et al., 1994). The central idea of systems research is to identify, define, and understand the system sufficiently to be able to influence it in a predictable manner. The modelling tool as a systems approach serves to highlight gaps in knowledge and to point the direction of further research. Simulation modelling can be used for the following purposes.

Estimation of potential production

Potential yield is defined as the maximum yield of a variety restricted only by the season specific climatic conditions. This assumes that other inputs (nutrient, water, pests, etc.) are not limiting and cultural management is optimal. Thus the potential yield of a crop is dependent upon temporal variation in solar radiation and maximum and minimum temperatures during the crop season, and physiological characteristics of the variety. Mechanistic crop growth models are routinely used for estimation of potential yield and determination of yield gaps, and assessing yields with the impacts of climate change.

Optimization of water management

Efficient use of water is of prime concern all over the world. Many parts of the world are facing the problem of water deficit. It is difficult to give general recommendations for deficit irrigation because of the uniqueness of each situation and the influence of several factors on irrigation requirement. Dynamic crop growth models can be used efficiently to compare and develop strategies for water management (Sankaran, 1994). For example, Kalra et al. (1993) used WTGROWS simulation model to evaluate the effect of different levels of water and N on the growth and yield of wheat in India. Likewise, Ramasamy (1993), using ORYZA model, showed that an effective drainage in wetland rice soils increases the activity of roots and improves N uptake and crop yield.

Optimization of N management

Efficient use of N is of prime concern in irrigated rice production. Knowledge of when and how much N to apply is essential on two counts: N input has an economic cost as well as an environmental cost. The amount of N needed and its ultimate fate are important issues regardless of the source of N, either organic or inorganic. A common approach for fertilizer recommendation has been to do field experiments and study the response of crops to increasing rates of N fertilizer and then fit a mathematical equation to the data. This information, although useful, offers limited information for deriving N recommendations in another year or at another site.

To improve N fertilizer management and provide recommendations, 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 water and N dynamics in the soil-plant system should include the major soil water (flood and soil evaporation, infiltration, runoff, and drainage), soil and fertilizer N (mineralization, immobilization, nitrification, ammonia volatilization, denitrification, and their movement, and fixation and release) and above and below-ground plant processes (phenology, root and shoot growth, and N and water uptake). The ability of C/N cycling models to make projections of future outcomes of management scenarios with respect to key environmental areas such as nitrate leaching, carbon sequestration, and emissions of greenhouse gases has generated intense interest in using them as regulatory tools.

Estimation of methane emission from soil

Several models have been developed in the recent years to predict emissions of CH_4 from rice. Early models used regression relationships between rates of emissions and either the crop biomass (Kern et al., 1997) or grain yield (e.g. Anastasi et al., 1992). These relationships were based on the assumption that higher the biomass production of the crop, the more substrate would be available for CH_4 production, either from increased crop residues or from higher rates of rhizo deposition.

Cao et al. (1995) presented a more mechanistic model describing CH_4 production and oxidation in rice fields. In this model, soil organic carbon was assumed to be partitioned between three main pools based on their rate of decomposition. The seasonal pattern of Eh was required as an input in the model. Huang et al. (1998) used two pools in their model to represent soil organic matter, with different potential decomposition rates for each; these were modified by multipliers representing the influence of soil texture and temperature. As with the Cao et al. (1995) model, CH_4 production was affected directly by soil Eh, although this was simulated by a negative power function of rather than as a model input. Lu et al. (2000) developed a model for CH_4 production derived from incubation studies. Matthews et al. (2000a) developed MERES (Methane Emission in Rice EcoSystems) model for simulating methane emissions from rice fields based on CERES-Rice, a model for simulating growth and development of a rice crop. The denitrification–decomposition (DNDC) model (Li et al., 1997) consisting of the soil climate, crop growth, and decomposition, nitrification, denitrification, and fermentation submodels, predicts NH_3, NO, N_2O, and CH_4 fluxes based on the soil environmental variables.

Models Available

DSSAT models

The Decision Support Systems for Agro-technology Transfer (DSSAT) models, developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Jones et al., 1998), follow a systems approach to agronomic research. The DSSAT models help decision-makers by reducing the time and human resources required for analyzing complex alternative decisions. They also provide a framework for scientific cooperation through research to integrate and apply new knowledge to research questions (Tsuji et al., 1998).

DSSAT includes 17 process-based, mechanistic and management oriented models and simulate growth and development of various crops grown in temperate and tropical environments throughout the world (Tsuji et al., 1994; Jones et al., 2003, Porter et al., 2003). These include CERES-Rice (Singh et al., 1993; Ritchie et al., 1998), which simulates the growth and development of rice. The model operates on a daily time-step and calculates biomass production, which is then partitioned to the leaves, stems, roots and grain, depending on the phenological stage of the plant. Sub-models calculate the water balance and N transformations in the soil, and crop uptake of water and N. Under fully irrigated conditions, the height of the surrounding bund and the initial floodwater depth can be specified, subsequent floodwater depth is simulated taking into account inputs from rainfall or irrigation and losses from evapo-transpiration, percolation, and runoff over the bund.

The Cropping System Model (CSM) released with DSSAT v4.0 represents a major departure from previously released DSSAT crop models (Jones et al., 2003; Porter et al., 2003). The computer source code for the model has been extensively restructured into a modular format in which components separate along scientific discipline lines and are structured to allow easy replacement or addition of modules (Jones et al., 2003). CSM now incorporates all crops as modules using a single soil model and a single weather module. The major modules in the new version (Batchelor, 2003; Jones et al., 2003; Porter et al., 2003) are:

1. Soil module- includes a soil water balance sub-module and two soil nitrogen/organic matter modules.
2. CROPGRO plant growth template module – simulates different crops by defining species characteristics in input files.
3. Plant growth interface for adding additional individual crop models, which are not included in the CROPGRO template approach. Currently this includes rice, maize, millet, sorghum, wheat, barley and potato.
4. Weather module – reads or generates daily weather data

5. Soil-Plant-Atmosphere module - deals with competition for light and water among the soil, plants, and atmosphere

New components and capabilities that have been added to the CSM system of models include (Porter et al., 2003):

1. Two additional ET routines (FAO Penman Monteith PET - FAO-56 and Penman Monteith PET using dynamic canopy height and LAI)
2. Addition of the CENTURY SOM simulation as an option for modeling SON and SOC processes
3. A soil-plant-atmosphere module
4. Pest damage simulation for maize, millet, and sorghum
5. A soil fertility factor for maize, millet and sorghum
6. Combination of several crop growth routines into a single model

Earlier versions of the CERES Rice model have been validated in the rice-wheat growing environments of South Asia (Timsina et al., 1995, 1997a,b, 1998; Hundal and Kaur, 1996; Lal, 1999; Aggarwal and Mall, 2002; Mall and Aggarwal, 2002; Timsina and Humphreys, 2003). Though there were some deficiencies, there was generally good agreement in the simulated and observed time course in growth, and phenological development, and grain yield. The model has been extensively used to simulate growth, development of rice in Asia and Australia (Timsina and Humphreys, 2003). The water and nitrogen sub-modules are briefly discussed below.

Soil water balance sub-module

The soil water balance model of DSSAT is a one-dimensional model and computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes (Jones et al., 2003). The soil has parameters that describe its surface conditions and layer-by-layer soil water holding and conductivity characteristics. The model uses a 'tipping bucket' approach for computing soil water drainage when a layer's water content is above a drained upper limit parameter. Upward unsaturated flow is also computed using a conservative estimate of the soil water diffusivity and differences in volumetric soil water content of adjacent layers (Ritchie, 1998). Soil water infiltration during a day is computed by subtracting surface runoff from rainfall that occurs on that day. The SCS method (Soil Conservation Service, 1972) is used to partition rainfall into runoff and infiltration, based on a 'curve number' that attempts to account for texture, slope, and tillage. The modification to this method that was developed by Williams et al. (1984) used in the model accounts for layered soils and soil water content at the time when rainfall occurs. When irrigation is applied, the amount applied is added to the amount of rainfall for the day to compute infiltration and runoff. Drainage of water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer, if this parameter is provided. If the saturated hydraulic conductivity of any layer is less than computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer. The details of soil water balance sub-module are given in Ritchie (1998) and Jones et al. (2003).

Nitrogen sub-module

In the DSSAT 4.0 N submodel, the major processes simulated are mineralization and immobilization (influenced by soil temperature, soil water, C/N ratio), nitrification (influenced by soil temperature, soil water, soil pH, NH_4 concentration), denitrification (influenced by soil temperature, soil water, soil pH, soil C, and NO_3^- concentration), NO_3^- leaching (influenced by drainage and NO_3^- concentration), ammonia volatilization (influenced by soil temperature, soil pH, surface evaporation, NH_4 concentration), and crop uptake (influenced by soil water, inorganic N, crop demand, root length density). In the model mineralization of N is linked to the routines describing the decomposition of organic matter. The soil profile is characterized by its initial organic matter and N content, water-holding properties and texture. Transport of N through the soil to lower layers is based on water movement obtained from the soil water balance module. Details of nitrogen sub-module are given by Godwin and Jones (1991) and Godwin and Singh (1998).

MERES Model

Matthews et al. (2000a) argued that a mechanistic model for simulating methane emission should include 1) crop growth and rhizodeposition over the season, 2) soil organic matter decomposition under anaerobic conditions, 3) the effect of alternative electron acceptors in the soil such as NO^{3+}, Mn^{4+}, Fe^{3+}, SO_4^{2-} ions, 4) a mechanistic description of CH_4 oxidation and fluxes of CH_4 from the soil, and 5) the influence of crop management practices such as water management and application of organic and inorganic fertilizers. They developed MERES model by employing the existing routines of CERES-Rice first to simulate SOM decomposition and to predict the amount of substrate available for methanogenesis, and to simulate methane emissions from rice fields. For this, they linked CERES Rice to an existing submodel of Arah and Kirk (2000), which is a transport reaction scheme governing the behaviour of any non-adsorbed substance which simultaneously moves through and reacts in an effectively homogeneous soil-plant system. The MERES model calculates 1) growth and development of rice crop using CERES-Rice, 2) decomposition of SOM, 3) rhizodeposition i.e., root exudates and root death, 4) the effect of alternative electron acceptors on CH_4 production, 5) methane production, 6) methane oxidation, 7) plant-mediated gaseous transport, 8) diffusion, 9) leaching, and 10) ebullition (Matthews et al., 2000a,b).

Objectives

The objectives of the present study were to evaluate and apply CSM-CERES Rice ver. 4.0 and MERES for rice culture in northwest India. The specific objectives were to:

- evaluate CSM-CERES-Rice ver. 4.0 for its ability to simulate rice growth and yield
- estimate potential yield and yield gaps in rice
- estimate and improve understanding of water and N dynamics and balances in the continuously flooded, continuously saturated and intermittently irrigated rice culture
- demonstrate potential applications of the model to improve understanding of sustainability issues related to water and N in various rice culture
- evaluate the ability of MERES to predict methane emission from rice culture in northwest India

Materials and Methods

Field Experiments

Sites

Observations from rice field experiments conducted at three sites (New Delhi, Ludhiana and Modipuram) were used to validate the CSM-CERES Rice v. 4.0 and MERES models (Figure 1). All three sites are on alluvial soils of the Indo-Gangetic Plains in northwest India, ranging from loam at Delhi to sandy loam at Modipuram to loamy sand at Ludhiana (Table 1). The climate is semi-arid sub-tropical at all three sites, with mean annual rainfall of 750-800 mm, 75 to 80% of which falls during the rice season. Mean maximum temperatures over the rice season at all three sites are similar (34-35^{o}C over July to October), while the mean minimum is higher at Modipuram (24^{o}C) compared with 18^{o}C at the other two sites.

At all sites rice was grown in rotation with wheat. The soil was puddled and P (as single superphosphate or diammonium phosphate) and K (as KCl) were broadcast onto the puddled soil prior to transplanting. Three rice seedlings (25-30 days old) were transplanted at 20 cm x 15 cm spacing. At all sites, all treatments were ponded continuously for the first two weeks following transplanting. Weeds, pests and diseases were controlled.

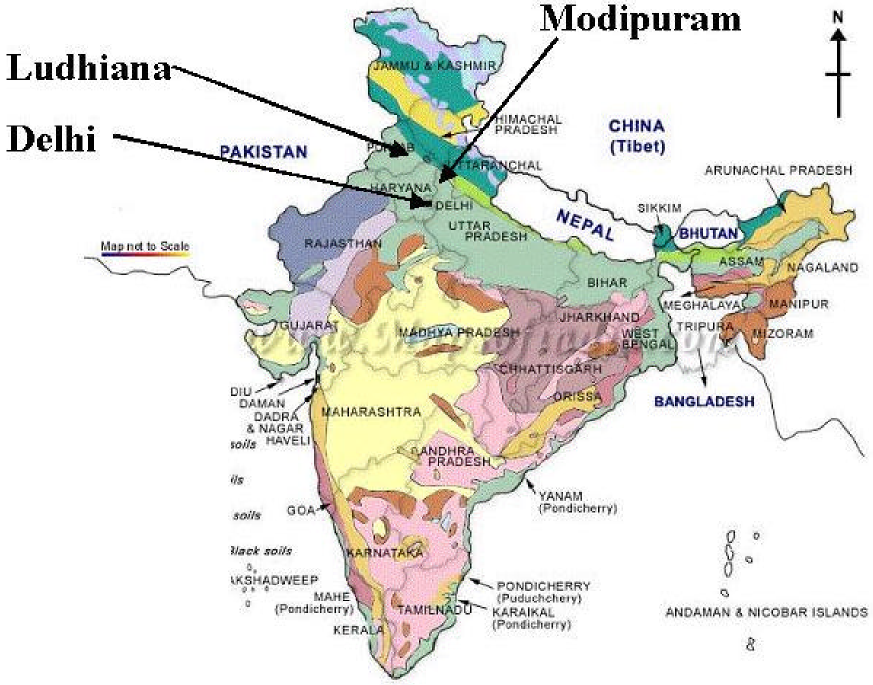

Fig. 1. Experimental sites used for model validation and simulation in northwest India

Treatments

The experiments at Delhi and Ludhiana included water management and N management treatments in a factorial design, while variety x N management was evaluated at Modipuram (Table 2).

At Delhi the N management treatments included: 1) no added N (0N), 2) urea at 120 kg N ha^{-1}, and 3) urea plus farmyard manure (FYM) at 60 kg N ha^{-1} each. There were two water management treatments: 1) “saturated soil” (SAT), and 2) three alternating wetting and drying events (AWD). FYM (0.1%N, 0.03%P, and 0.05%K) was incorporated 2 weeks before puddling and transplanting. Urea was broadcast in 3 splits (1/2 at 11 days after transplanting (DAT), 1/4 at 30 DAT and 1/4 at 64 DAT). In the SAT treatments 30 irrigations were provided to try and maintain saturation of the topsoil throughout the cropping period but still the surface soil became drier than saturated between irrigations. This treatment was in between treatments 1 and 3 (i.e., irrigated 2 days after the disappearance of floodwater) of the Ludhiana experiment (see below).

Table 1. Climate and soil properties at the three sites.

Soil type	Soil name	Depth cm	Bulk density g/cm^3	$\theta_{0.3\ bars}$ cm^3/cm^3	$\theta_{15\ bars}$ cm^3/cm^3	θ_{sat} cm^3/cm^3	Clay %	Silt %	Sand %	pH 1:2 soil:water	Organic C %	Total N %	Ksat cm/hr
Delhi - Indian Agricultural Research Institute *28°40’N, 77°12’E, 228 m ASL*													
Loam	Typic Ustochrept	0-15	1.38	0.17	0.06	0.36	21	33	46	8.0	0.45	0.03	1.13
		16-45	1.45	0.14	0.06	0.34	21	30	49	7.0	0.25	0.02	0.12
		46-75	1.50	0.14	0.06	0.33	21	30	49	7.0	0.15	0.01	0.09
		76-120	1.50	0.14	0.05	0.32	20	30	50	7.0	0.10	0.01	0.06
Modipuram, Meerut – Directorate of Cropping Systems Research *29°4’N, 77°46’E, 237 m ASL*													
Sandy loam (Sobhapur sandy loam)	Typic Ustochrept	0-15	1.46	0.35	0.17	0.43	16	19	65	7.4	0.54	0.07	1.1
		16-45	1.56	0.33	0.14	0.45	17	20	63	7.4	0.51	0.06	0.2
		46-75	1.56	0.33	0.14	0.44	17	20	63	7.4	0.51	0.05	0.2
Ludhiana – Punjab Agricultural University *30°55’N, 75°51’E, 247 m ASL*													
Loamy sand (Fatehpur loamy sand	Typic Ustipsamment	0-15	1.58	0.22	0.06	0.40	8	15	77	6.5	0.39		
		16-45	1.72	0.22	0.06	0.38	8	18	74	7.1	0.14		
		46-75	1.68	0.22	0.05	0.35	7	10	83	7.1	0.21		
		76-120	1.68	0.21	0.04	0.34	6	4	90	7.2	0.13		
		90-120	1.68	0.20	0.04	0.33	6	8	86	7.2	0.11		

For the intermittent drying treatments, the soil surface was allowed to dry until fine cracks developed on the soil surface, and the soil was kept at saturation at other times (Pathak et al., 2002). The three drying events were from 11-23 DAT, 30-48 DAT, and 57-78 DAT (Table 2; Appendix Table 1).

At Ludhiana the N management treatments included: 1) 0N, 2) 120 kg N ha^{-1} as urea in 3 equal splits, and 3) 20 kg N ha^{-1} basal plus topdressing of 30 kg N ha^{-1} at a leaf colour chart (LCC) reading of 4. There were two water management treatments irrigated 1 or 3 days after the disappearance of the floodwater (Appendix Table 2). The use of the LCC is based on the principle that leaf chlorophyll content and its N content are closely related (Balasubramanian et al., 2003) and can be used to assess the leaf N status of crops at different growth stages to determine the need for N topdressing (Bijay-Singh et al., 2002a).

At Modipuram six fertilizer N (as urea) management treatments based on the LCC scores of = 2, 3, and 4 (60, 120 and 160 kg N ha^{-1}) for Basmati-370 and = 3, 4, and 5 (60, 120 and 160 kg N ha^{-1}) for Saket-4 and Hybrid-6111 were compared with two farmers' N rates (120, and 150 kg N ha^{-1}) and a 0N control. In the farmer treatments N was applied in three equal splits at transplanting (basal), mid-tillering and panicle initiation (Appendix table 3). The soil was maintained at saturation throughout the experiment (Shukla et al., 2004).

Table 2. Treatments and cultural practices used for model evaluation at the three sites

Treatments/ operation	**Delhi (loam)**	**Modipuram (sandy clay loam**	**Ludhiana (loamy sand)**
Treatments	*Water management* 1. Soil saturated continuously (sat) 2. 3 periods of soil drying (drained) *N management* 1. None (0N) 2.120 kg N ha^{-1} as urea (120 N) 3. 60 kg N ha^{-1} as urea + 60 kg kg N ha^{-1} as farmyard manure (FYM).	*Variety* 1. Basmati 370 2. Saket 4 3. Hybrid 6111 *N management* 1. 0N 2. 120 kg N ha^{-1} as urea (120N) 3. 150 kg N ha^{-1} as urea (150N) 4-9. Urea at LCC scores of : ≤2, 3, 4 (60, 120, 160 kg N ha^{-1} as urea) for Basmati ≤3, 4, 5 (60, 120, 180 kg N ha^{-1} as urea) for Saket and Hybrid	*Water management* 1 Irrigation 1 d after flood water disappeared ("1-d drainage") 2. Irrigation 3 d after flood water disappeared ("3-d drainage") *N management* 1. 0N 2. 120 kg N ha^{-1} as urea (120 N) 3. 20 kg N ha^{-1} as urea basal plus 30 kg N ha^{-1} as urea at LCC of 4
Transplanting dates	15 July 1999 18 July 2000	6 July 2001 12 July 2002	9 June 2001
Variety /Duration	Pusa 44 (semi-dwarf)/ 125 d	Basmati 370 (traditional, tall, scented)/ 155 d Saket 4 (inbred, semi -dwarf)/ 110 d Hybrid 6111 (semi-dwarf)/ 130 d	PR114 (semi -dwarf)/ 145 d
Plant population/m^2	35	35	33
Row spacing	20 cm	20 cm	20 cm
Transplanting depth	~2-3 cm	~2-3 cm	~2-3 cm
Total irrigation amount (mm)	1. Saturated - 1800 mm 2. 3 dryings - 1080 mm	Saturated 1560 mm	1. 1-d drainage - 1750 mm 2. 3-d drainage - 1050 mm
Rain during rice season	1999 (352 mm) 2000 (495 mm)	2001 (264 mm) 2002 (257 mm)	2001 (839 mm)

Fertilizer and water use efficiency parameters

Fertilizer and water use efficiency parameters, based on the simulation results, were calculated as follows.

1. Agronomic efficiency (kg grain kg^{-1} N applied) – AE (Nova and Loomis, 1981)

$$AE = \frac{\text{grain yield in N plot (kg ha}^{-1}\text{) - yield in no N plot (kg ha}^{-1}\text{)}}{\text{N rate (kg ha}^{-1}\text{)}}$$

2. Recovery efficiency (%) – RE (Cassman et al., 1998)

$$RE = \frac{\text{plant N in N plot (kg ha}^{-1}\text{) - plant N in no N plot (kg ha}^{-1}\text{)}}{\text{N rate (kg ha}^{-1}\text{) x 100}}$$

3. Internal efficiency (kg grain kg^{-1} nutrient in plant dry matter)- IE (Witt et al., 1999)

$$IE = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{\text{N uptake (kg ha}^{-1}\text{)}}$$

4. Physiological efficiency ((kg grain kg^{-1} plant N) – PE (Novoa and Loomis, 1981)

$$PE = \frac{\text{grain yield in N plot (kg ha}^{-1}\text{) - grain in no N plot (kg ha}^{-1}\text{)}}{\text{plant N in N plot (kg ha}^{-1}\text{) – plant N in no N plot (kg ha}^{-1}\text{)}}$$

5. Water use efficiency parameters were calculated as follows:

a. Water use efficiency (WUE), i.e., weight of produce per unit of consumptive water over a unit area (kg grain mm^{-1} ha^{-1}) (Prihar and Sandhu, 1987)

$$WUE = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{\text{[rain (mm) + irrigation (mm) + soil water use (mm) – drainage (mm)]}}$$

b. Water expense efficiency (WEE), i.e., ratio between production and the water spent to obtain that over a unit area (kg grain mm^{-1} ha^{-1}) (Prihar et al., 1976).

$$WEE = \frac{\text{[grain yield (kg ha}^{-1}\text{)]}}{\text{[rain (mm) + irrigation (mm) + soil water use (mm)]}}$$

c. Irrigation use efficiency (IUE), i.e., weight of produce per unit of irrigation water over a unit area (kg grain mm^{-1} ha^{-1})

$$IUE = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{\text{irrigation (mm)}}$$

Simulation Modelling

Model modification

In the earlier version of CERES-Rice, there was very high loss of N due to denitrification, most of which occurred on the day of flooding. This may be the case in the continuously flooded heavy clay soils with very low percolation rates and anaerobic conditions such as that exist in Australian and Philippine rice soils. However, this is not the case in permeable coarse-textured soils of northwest India, where continuous flooding is difficult to maintain and frequent irrigation is required to maintain soil saturation (Bijay-Singh et al., 2002b; Pathak et al., 2003a).

Another limitation of the original version of the model was no or very little percolation of water or leaching of N. This is quite an unlikely scenario as even in the puddled condition there will be substantial percolation, especially in the highly permeable sandy loam and loamy soils of northwest India where leaching of N is one of the major loss mechanisms (Aulakh and Bijay-Singh, 1997).

Thus the original version of CERES-Rice was modified as follows:

1. Include lags in nitrification/denitrification to simulate the effect of soil depth on oxygen availability:

```
IF (DS(L) .GT. 50.) THEN
      NITRIF_DEPTH(L)   = AMIN1 (1.0, 50./(DS(L)-DLAYR(L)))
      DENITRIF_DEPTH(L) = 1.0
ELSE
      NITRIF_DEPTH(L)   = 1.0
      DENITRIF_DEPTH(L) = 0.5 + (DS(L)-DLAYR(L))/100.
```

```
  ENDIF
 NITRIF_LIMIT = AMAX1(0.0, AMIN1(1.0, TFACTOR *
&                     WF2 * PHFACT * TLAG* NITRIF_DEPTH(L)))
NITRIF      = NITRIF_LIMIT * NH4(L) * SOILBIO_FACT
```

Denitrification occurs only if SW > DUL and a lag factor is used to eliminate denitrification for 5 days to allow for suitable conditions. However, first the availability and possible leaching of water soluble carbon is checked. For that, a soluble carbon leaching routine (CLEACH) is called from NTRANS routine.

```
CALL CLEACH (CW, CFLOW, SW, NLAYR, DLAYR, DRN,
  &    HUMC, FPOOL, FAC, TOTAL_CLEACH)
DENITRIF = 6.0 * 1.E-04 * CW(L) * NO3(L) * WFDENIT *
  &              TFDENIT *DENITRIF_DEPTH(L) / FAC(L)
DENITRIF = AMAX1 (DENITRIF, 0.0)

 WFDENIT = 1. - (SAT(L) - SW(L)) / (SAT(L) - DUL(L))
 WFDENIT = MAX (MIN (WFDENIT, 1.), 0.)
 IF (WFDENIT .GT. 0.0) THEN
         DLAG = DLAG + 1
       ELSE
         DLAG = 0.0
 ENDIF

 IF (DLAG .LT. 5.0) THEN
         WFDENIT = 0.0
 ENDIF
```

2. Enable the puddled soils to leach by adding a call to SATFLO in the puddled section of WATBAL and adding the argument PUDPERC to set the maximum drainage rate. First water available for infiltration (WINF) is calculated. For the puddled field, the model first fills the soil profile and limits drainage to PUDPERC.

Saturated flow is calculated for days with no irrigation or rain through the SATFLO routine. Drainage is reduced when the flux exceeds the rate allowed by the saturated soil hydraulic conductivity, assuming unit gradient. This allows for perched water tables in the profile and prevents the flux from exceeding the most limiting layer below it. If the saturated hydraulic conductivity values are missing (or negative) no perching of water table is assumed.

```
CALL SATFLO( DLAYR, DUL, NLAYR, SAT, SW, SWCN, SWCON,       !Input
   &   DRAIN, DRN, SWDELTS)
IF (PUDDLED) THEN
       WINF = MAX(0.0, FLOOD + IRRAMT + RAIN)
       Swcn(2)=Pudperc*0.004167  ! this is 1/24 for hours and 1/10 for mm to cm
        Swcn(1)=3.0
    DRAIN = MIN(PUDPERC, WINF - INFILT)
    INFILT = INFILT + DRAIN
```

Model calibration

Derivation of genetic coefficients

The genetic coefficients for different cultivars are used as model inputs to describe crop phenology in response to temperature and photoperiod (Hunt and Boote, 1994, 1998). The genetic coefficients for the cultivars in this study were estimated from independent and separate treatments with water and N non-limiting (Daryai, 2002; Pathak et al., 2002; A.K. Shukla, unpublished data; Bijay-Singh, unpublished data) by adjusting the coefficients until close matches were achieved between simulated and observed phenology and yield.

Calibrating the rate of mineralization

The original version of the model mineralised soil organic matter slowly. For example, the simulated cumulative amount of N mineralized during the rice crop in Delhi was 16-18 kg ha^{-1}, which is much lower than generally observed (Pathak and Sarkar, 1994). Other research has shown net mineralization of 50-80 kg N ha^{-1} in the soils of tropics during the rice season (Pathak et al., unpublished). Using the MANAGE-N model ten

Berge et al. (1996) calculated seasonal soil N supply rates ranging from 0.3 to 1.2 kg ha^{-1} d^{-1} with a total of about 70-80 kg ha^{-1} season^{-1}. The rate constant for decomposition of SOM used in DSSAT is 0.000083 day^{-1}, based on the findings of Seligman and van Keulen (1981). Godwin and Singh (1998) argued that this value should not be universally applied to all soils and proposed the use of a modifier (DMOD) in the equation to modify the mineralization rate. In the present study the value of the modifier (DMOD) was used as 3.7, 2.2, and 2.0 for Delhi, Ludhiana and Modipuram, respectively to increase the cumulative mineralization in the unfertilised treatment to 45-60 kg N ha^{-1}.

Atmospheric CO_2 concentration

In the earlier versions of DSSAT models the carbon dioxide (CO_2) concentration in the atmosphere is set at a default value of 330 ppm whereas the actual concentration in the past decade has been around 356 ppm (Bachelet et al., 1993; IPCC, 2001). Therefore, the actual CO_2 concentration was used by adjusting the CO_2 concentration in the environment modification section of the input file (File X) with an increment of 26 ppm from a base CO_2 concentration of 330 ppm (Appendix 1).

Model validation

Rice growth, development and yield at Ludhiana, Modipuram and Delhi were simulated using soil data for the sites from the published and unpublished literature (Ludhiana, Bijay-Singh et al., unpublished; Delhi, Pathak et al., 2002; Modipuram, Shukla et al., 2003 and Pal, S. personal communication), and daily weather data (solar radiation, maximum and minimum temperatures, and rainfall) from the meteorological observatories located at each site. Input data used for the model validation at the three sites are presented in Appendix Tables 1 to 4.

Estimation of potential yields and yield gap analysis

Potential yield of the most important rice varieties in each of the 3 regions - Pusa 44 (Delhi), PR 114 (Ludhiana), and Saket 4 (Modipuram), was simulated by switching “Off” the water and N in the simulation control section of File X.

The district average grain yields of rice for each region were collected from the regional statistics of the Fertilizer Association of India, New Delhi (FAI, 2000). Yield gaps were estimated for each site by subtracting the district yield from potential yield and research station yield.

Sensitivity analyses

Sensitivity of the model to changes in planting date, amount and timing of N fertilizer and irrigation applications on rice yield was done for the Delhi site using the weather data of 1999-2000 and other inputs given in Appendix Table 1.

Data analysis

The model was evaluated using the root mean square error (RMSE) and index of agreement (d-stat) statistics (Willmott, 1982). The d-stat of a "good" model should approach unity and the RMSE approach zero. The RMSE is considered as the "best" overall measure of model performance as it summarises the mean difference in the units of oserved and predicted values (Willmott, 1982; Toit and Toit, 2003). Standard deviations were used to compare the long-term simulation means of various scenarios.

Results and Discussion

Calibration of the model

Genetic coefficients

Genetic coefficients used in the model for rice cultivars are given in Table 3. The juvenile phase coefficient (P1), photoperiodism coefficient (P2R) and grain filling duration coefficient (P5) of the cultivars varied from 650 to 980 degree days (^{o}C), 180 to 295 degree days h^{-1}, and 330 to 720 degree days (^{o}C), respectively. Because of its longer duration basmati rice had the highest juvenile phase and grain filling duration coefficients. The critical photoperiod (P20) was 12 hours for all cultivars. Grain weight (G2) was least for basmati rice, and is the main cause of lower yield of this scented rice cultivar. The high grain weight (G2) of hybrid rice is responsible for its higher yield.

Table 3. Genetic coefficients of rice cultivars used in the CSM-CERES-Rice ver 4.0 model

Genetic coefficient[a]	Cultivars				
	Pusa 44	PR 114	Basmati 370	Saket 4	Hybrid 6111
Juvenile phase coefficient (P1), GDD[b]	800	650	980	700	750
Photoperiodism coefficient (P2R), GDD h^{-1}	280	180	250	220	250
Grain filling duration coefficient (P5), GDD	370	500	720	440	640
Critical photoperiod (P20), h	12	12	12	12	12
Spikelet number coefficient (G1)	55	59	40	55	55
Single grain weight (G2), g	0.022	0.025	0.023	0.025	0.029
Tillering coefficient (G3)	1.0	1.0	1.0	1.0	1.0
Temperature tolerance coefficient (G4)	1.0	1.0	1.0	1.0	1.0

[a] For definition of these coefficients see Hunt and Boote (1994, 1998)

[b] GDD, growing degree days (°C)

Mineralization of N

Using the new modifier of 3.7 the average N mineralization rate at Delhi increased to 0.4 kg ha^{-1} d^{-1} while with FYM it increased to 0.6 kg ha^{-1} d^{-1}. Thus cumulative mineralised N during the season ranged from 46.2 to 48.6 kg ha^{-1} without organic amendment and from 74.0 to 79.6 kg ha^{-1} with FYM amendment (Fig. 2). Using the InfoCrop model, Pathak et al. (unpublished data) also calculated N mineralization from soil with 0.5% organic carbon to be 0.5 kg ha^{-1} d^{-1}.

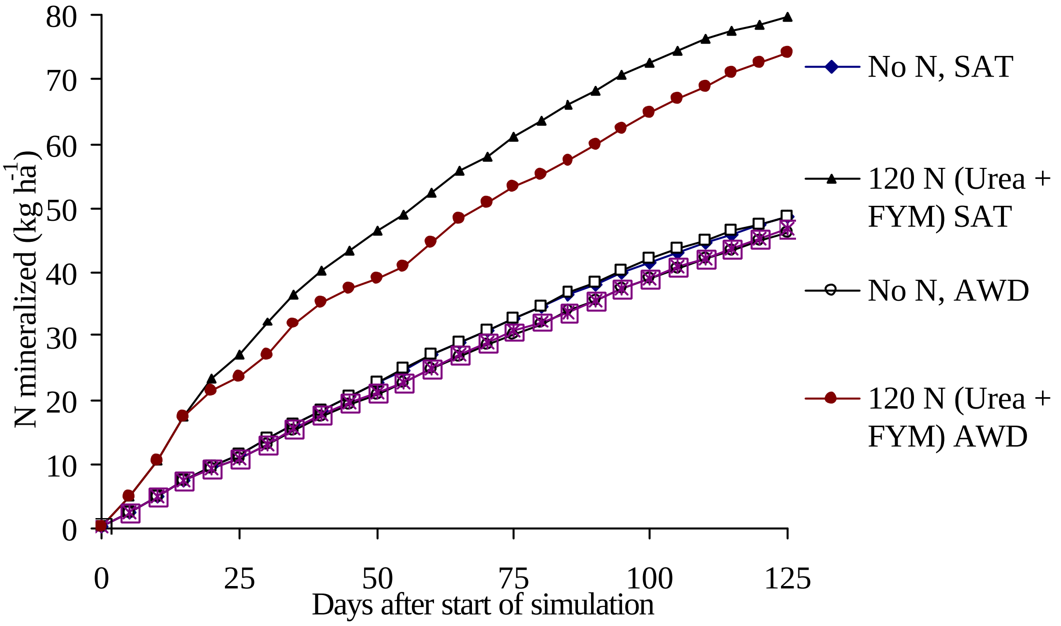

Fig. 2. Simulated seasonal cumulative mineralization of N in rice during 1999 in Delhi as influenced by N, FYM and water management (AWD = 3 soil drying events) (No N SAT and 120 N SAT mineralized same amount, and No N AWD and 120 N AWD mineralized same amount, so only one 2 treatments are shown in the legend).

Validation of the model

The data set for validation of the model included a range of water management treatments from soil saturation (frequent irrigations) to frequent intermittent wetting and drying to prolonged periods of drying, and a range of N regimes from zero to recommended to supra-optimal. Predicted grain yields in all locations agreed well with observed yields (RMSE=815 kg ha^{-1}; d-stat=0.94) (Fig. 3a). There was, however, generally poor prediction of yields in the unfertilised treatments. Removing the unfertilised treatments from the analysis improved the relationship (RMSE=643 kg ha^{-1}; d-stat=0.94) (Fig. 3b). The agreement between simulated and observed total dry matter yields was also reasonable, but not as good as for grain yields (RMSE=3330 kg ha^{-1}; d-stat=0.75) (Fig. 4).

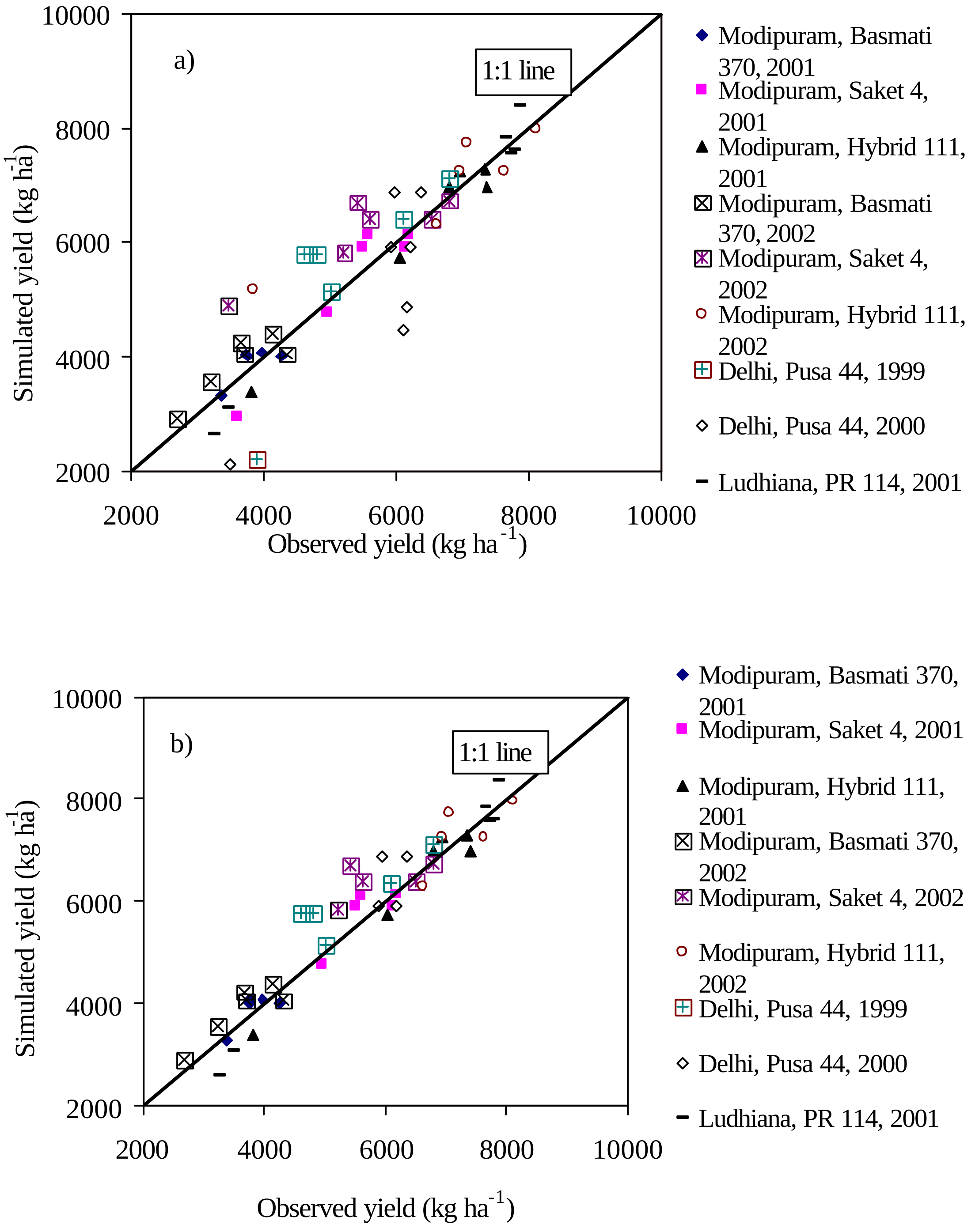

Fig. 3. Simulated and observed grain yields of rice with a) all treatments and b) without 0 N treatments

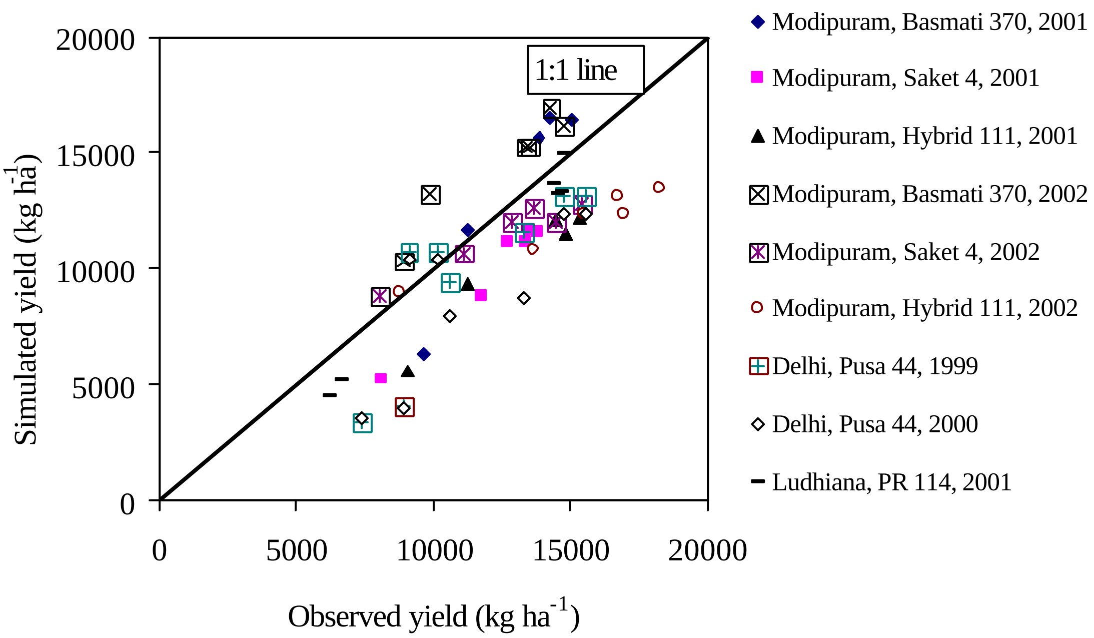

Fig. 4. Simulated and observed total dry matter yield of rice (all N and irrigation treatments)

Evaluation of the model to simulate N uptake was done for Delhi only due to the non-availability of data for other locations. There was reasonably good agreement between observed and simulated N uptake by rice (cultivar Pusa 44) especially for grain N uptake (RMSE=21 kg ha^{-1}; d-stat=0.86) (Fig. 5).

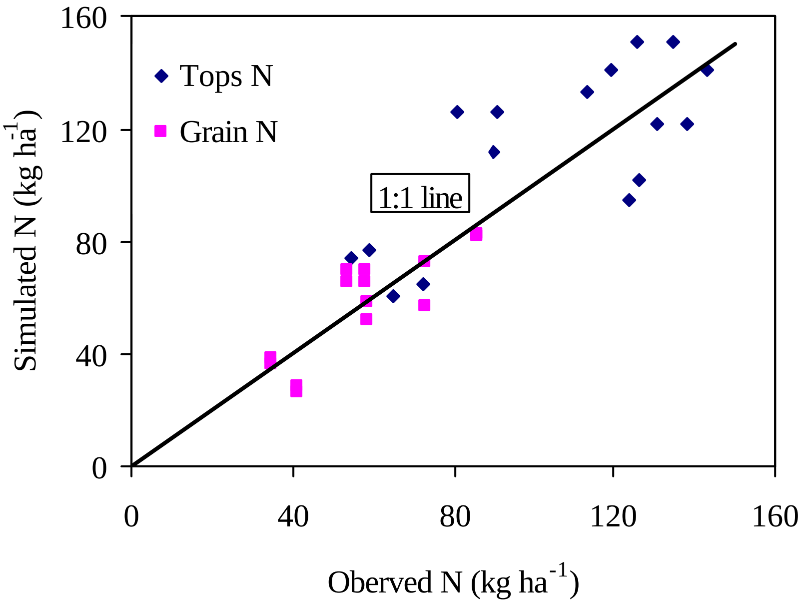

Fig. 5. Simulated and observed total N uptake by rice (cultivar Pusa 44) in Delhi in 1999 and 2000 (all N and irrigated treatments)

Model predictions of soil mineral N were compared against a very limited set of observations at Delhi. Nitrogen was applied at 11, 30 and 64 days after transplanting (DAT). Simulated and observed soil NH_4-N (Fig. 6) and NO_3-N in the surface soil layer (Fig. 7) differed considerably. Simulated NH_4-N peaked at 18-24 DAT, 37-38 DAT and 70 DAT, about a week after each N top-dressing suggesting that the rate of urea hydrolysis in the model was too low. Simulated NH_4-N declined rapidly after top dressing compared with higher observed values. Simulated NO_3-N peaked at 1, 24 and 71 DAT. Observed NO_3-N concentrations were always around 10 kg ha^{-1}, whereas the model predicted levels close to zero for most of the time, except at 24 DAT and for a brief period after the third top-dressing suggesting that the rate of urea hydrolysis in the model was too low. This suggests that the model is probably underestimating nitrification rates and/or overestimating denitrification and/or NO_3-N leaching.

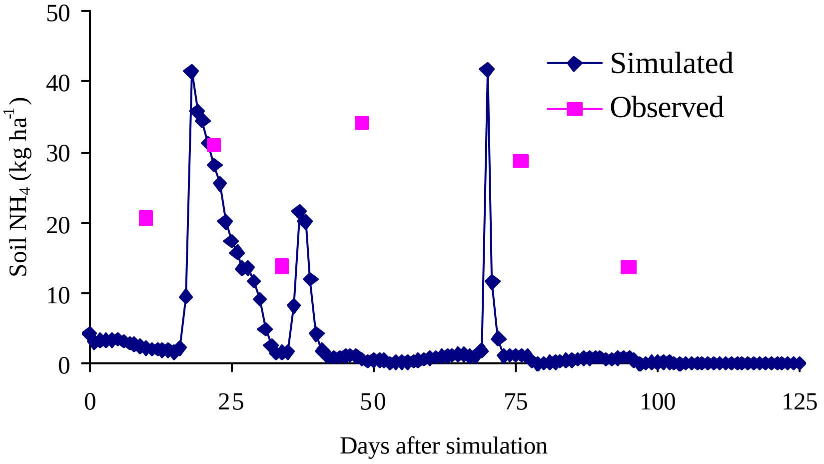

Fig. 6. Simulated and observed soil NH_4-N at 0-15 cm depth in saturated soil with urea at 120 kg N ha^{-1} in Delhi (transplanting occurred 4 days after the start of simulation)

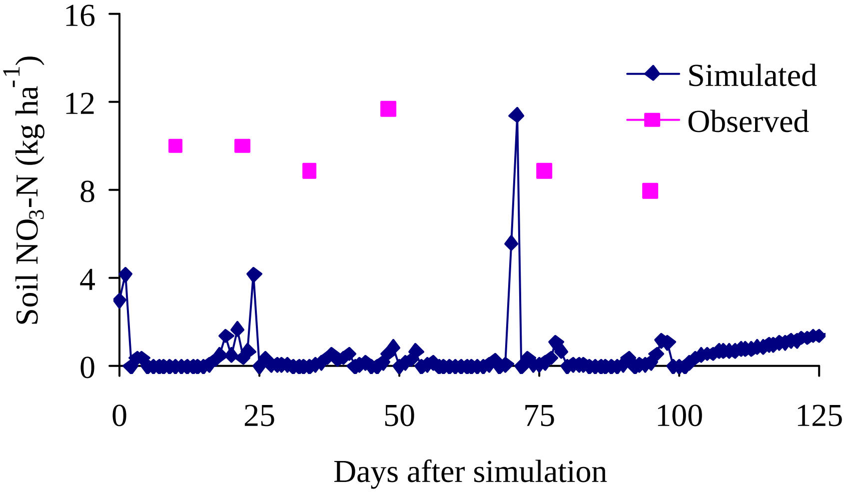

Fig. 7. Simulated and observed soil NO_3-N at 0-15 cm depth in saturated soil with urea at 120 kg N ha^{-1} in Delhi in 1999.

The model predicted total N leaching losses similar to those observed in various other experiments with urea applied at 120 kg N ha^{-1}, but higher denitrification and lower ammonia volatilisation losses. Mean losses of N due to leaching, ammonia volatilization and denitrification from continuously flooded rice fields in northwest India are about 15, 25 and 30 kg ha^{-1}, respectively (Aulakh et al., 2001a,b; Banerjee et al., 2002; Bijay Singh et al., 1991a,2002b; Katyal et al., 1985,1987; Pathak et al., 2002), while the simulated values were 14, 4, and 48 kg ha^{-1} (Table 4). Ammonia volatilization losses from rice grown under frequent irrigation to achieve soil saturation is likely to be lower than from continuously flooded culture as in the former case the urea is topdressed onto the soil surface prior to irrigation and transported into the soil. The frequent wetting and drying of the surface soil is also more likely to promote nitrification and subsequent denitrification.

Simulated deep drainage below 120 cm on the Delhi loam was very high at 1277 mm, more than double the loss of 561 mm by ET, consistent with observations for deep drainage and ET from other studies in northwest India on sandy loam, loam and sandy soils (Prihar and Sandhu, 1987 as cited by Hira and Khera, 2000).

Table 4. Simulated and observed losses of N (kg ha^{-1}) from rice in northwest India

Losses	Observed[a]	Simulated[b]
Denitrification	30 (10-40)	48
Leaching	15 (10-18)	14
Volatilization	25 (20-35)	4

[a] Means (range) for saturated and AWD treatments with recommended N (120 kg ha^{-1}) from Aulakh et al. (2001a,b); Katyal et al. (1985,1987); Bijay-Singh et al. (2002b); Pathak et al. (2002); Banerjee et al. (2002); Srivastava and Singh (1996)

[b] Means for saturated and AWD treatments with 120 kg N ha^{-1} through urea in Delhi.

Methane emissions using the MERES model

Total emission of methane during the rice season for the three N treatments in the Delhi experiment ranged from 28 to 45 kg ha^{-1}, while the simulated total emission ranged from 53 to 96 kg ha^{-1} (Table 5). For the saturated soil with 120 kg N ha^{-1} the simulated daily emissions were much higher than the observed emissions (Fig. 8). The simulated daily emissions for the three N treatments were different and varied from 0 to 22 kg ha^{-1} d^{-1} (Fig. 9). The detailed methane related outputs (not shown) suggest that, among many factors influencing methane emissions, the model perhaps needs improvement in terms of simulating soil water status and soil redox potential for better prediction of methane emissions. This was also observed by Matthews et al. (2000a,b).

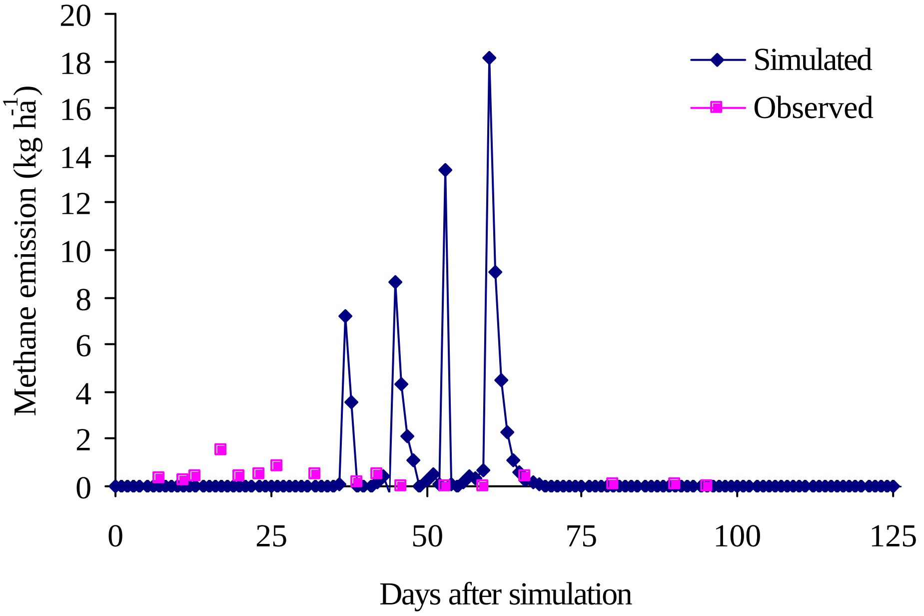

Fig. 8. Simulated and observed daily methane emission from the saturated soil with urea at 120 kg N ha^{-1} urea in Delhi during the rice season in 1999

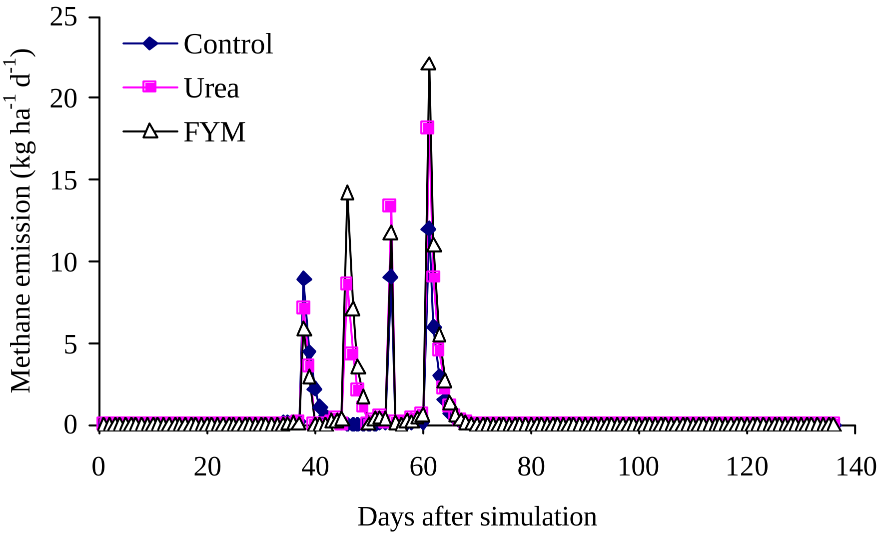

Fig. 9. Simulated daily methane emission during the rice season in Delhi in 1999

Table 5. Simulated and observed methane emission in saturated soil treatment at Delhi.

Treatments	Methane emission	
	Simulated[a]	Observed[b]
Control 0 N	53	24
120 kg N (Urea)	80	28
120 kg N (FYM + Urea)	96	45

[a]Using MERES model

[b]data from Pathak et al. (2003c)

Sensitivity analyses

The model was tested for its sensitivity to a range of parameters such as time of planting, N fertilizer rate and water management. The baseline data (soil, variety, location and other inputs) used for the sensitivity analyses are from the Delhi site as presented in Appendix Table 1.

Time of planting

The effect of transplanting date for Delhi revealed that the potential yield is highest (10.3 Mg ha^{-1}) with planting on 1 May, and decreases as planting is delayed (Fig. 10). However, from 1 May to 20 July the yield decline is small. Farmers, however, prefer to transplant rice in May because of labour availability, saving time for other field operations, and expecting higher yield. Later planted crops are also disadvantage by the build up of pests and diseases. Early planting requires more irrigation water because of very high evaporative demand in May and June. As the availability of irrigation water is limited and the groundwater table is receding due to over exploitation, it is desirable to delay planting until July when the monsoon starts and evaporative demand is less. Planting after July 20 reduces yield potential by 0.08 Mg ha^{-1} for each day delay in planting, hence planting after that date should be avoided. Low temperature during the reproductive stages and low solar radiation during grain filling are probably responsible for this yield decline. Reduction in rice yield due to late transplanting for various medium and short duration cultivars for various locations of Punjab has also been observed in some field experiments in Punjab (Hira and Khera, 2000). Aggarwal et al.

(2000a,b) also predicted similar yield declining trends in rice for northwest India using CERES-Rice v. 3.0.

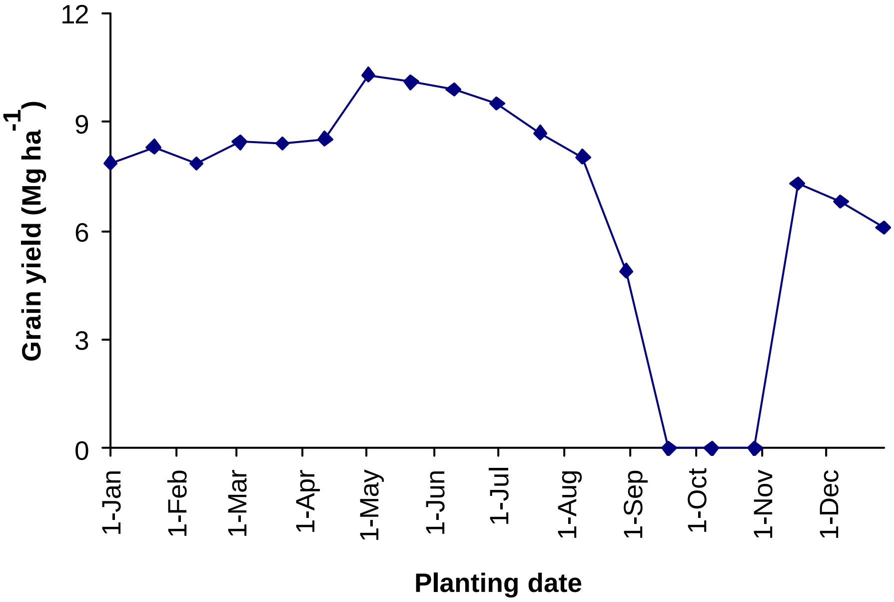

Fig. 10. Effect of planting date on simulated potential yield of rice (Variety Pusa 44) in Delhi in 1999.

Amount of irrigation application

The effect of water management (ranging from rainfed to intermittent dryings to continuous submergence) on grain yield of rice was simulated for 120 for kg N ha^{-1} Delhi in 1999 (Table 6). All treatments received irrigation for puddling prior to transplanting and were ponded for two weeks with 5 cm water depth after transplanting for establishment, prior to the start of the water management treatments. Continuous saturation treatment received irrigation after 2 days of disappearance of ponded water (2-d drainage). The three intermittent drying treatments had one (11-23 DAT), two (11-23 DAT and 30-48 DAT) and three (11-23 DAT, 30-48 DAT, and 57-78 DAT) drying events. Urea in all treatments was applied at 120 kg N ha^{-1} in 3 splits. Continuous submergence with 5 cm water and continuous saturation gave the highest yield (7.1 and 7.0 Mg ha^{-1}, respectively), and yield decreased as water application decreased from submergence to rainfed conditions. Yields were reduced by 10-15% for the mid-season drying treatments as compared to ponding. Irrigation water requirement for continuous submergence was substantially higher (5669 mm) compared to continuous saturation (1800 mm) and other mid-season drying treatments (1080 to 1560 mm). ET ranged from 418 mm (rainfed) to 575 mm (continuous saturation). Drainage was substantially higher for continuous submergence (5396 mm) compared to other treatments (996 to 1691 mm). High irrigation increases the cost of production due to increased cost of pumping water and excessive deep drainage increases groundwater pollution. If the groundwater is too saline or polluted for reuse, then deep drainage is also a net loss of water. Irrigation efficiency, water expense and irrigation amount also decreased going from submergence to 3 mid-season dryings. Water-use efficiency was similar for all irrigation treatments, but lower for the rainfed treatment.

N application rate

The effect of N rate (from 0 to 330 kg ha^{-1}) on grain yield of rice was simulated for saturated soil moisture regime for Delhi in 1999 (Table 7). Nitrogen was broadcast at 3 splits (1/2 at 11 DAT, ¼ at 30 DAT and ¼ at 64 DAT). Yield increased with application rate up to 300 kg N ha^{-1}, but with only small increases at rates above 180 kg ha^{-1}. Nitrogen losses increased as application rate increased beyond 150 kg ha^{-1}, whereas increasing the rate from 60 to 150 kg ha^{-1} did not increase N losses, presumably because applying N increased the plant sink size in proportion with the increase in N application rate. Therefore, a balance between yield gain and environmental pollution is required. Recovery efficiency and internal efficiency of applied N increased for N rates up to 150 kg ha^{-1}, while agronomic use efficiency was also high with 150 kg N ha^{-1}. All measures of efficiency decreased beyond this level of N, whereas the present fertilizer N recommendation is 120 kg N ha^{-1}. These results reveal that current level of N recommendation is not sufficient and should be increased to 150 kg ha^{-1}.

Table 6. Impact of different water regimes on simulated rice yield and water use efficiency with urea at 120 kg ha^{-1} N in Delhi in 1999.

Water regime	Grain yield (Mg ha^{-1})	N uptake (kg ha^{-1})	Rain (mm)	Irrigation (mm)	Drainage (mm)	Soil water use (mm)	ET (mm)	Water use efficiency (kg mm^{-1} ha^{-1})	Water expense efficiency (kg mm^{-1} ha^{-1})	Irrigation use efficiency (kg mm^{-1} ha^{-1})
Continuous submergence	7.1	140	353	5659	5396	22	540	11	2	1
Continuous saturation (2-d drainage)	7.0	135	353	1800	1691	42	575	13	4	3
1 mid-season drying	6.9	117	353	1560	1457	39	491	13	4	4
2 mid-season dryings	6.6	115	353	1320	1229	40	483	12	5	4
3 mid-season dryings	5.6	112	353	1080	996	40	475	11	5	4
Rainfed	2.1	96	353	0	92	157	418	7	3	-

Table 7. Impact of different rates of urea N on simulated rice yield, N losses and N use efficiency with saturated soil moisture regime in Delhi in 1999.

Nitrogen dose (kg ha^{-1})	Grain yield (Mg ha^{-1})	Dry matter yield (Mg ha^{-1})	N uptake (kg ha^{-1})	Leaching (kg ha^{-1})	Volatilization (kg ha^{-1})	Denitrification (kg ha^{-1})	Added N lost (%)[1]	Agronomic efficiency (kg kg^{-1})	Recovery efficiency (%)	Internal efficiency (kg kg^{-1})	Utilization efficiency (kg kg^{-1})
0	2.0	3.7	67	12	0	15	-	-	-	29	-
30	3.3	6.0	78	13	2	14	7	43	37	42	118
60	4.7	8.5	99	15	6	17	18	45	53	47	84
90	5.6	10.3	118	16	6	19	15	40	57	47	71
120	7.0	12.8	147	17	9	21	17	42	67	47	62
150	8.0	15.1	171	18	9	23	15	40	69	47	58
180	8.8	16.5	189	20	12	28	18	38	68	46	56
210	9.2	17.6	209	21	14	32	19	34	68	44	51
240	9.4	18.4	227	22	16	38	21	31	67	41	47
270	9.5	18.8	236	24	19	50	24	28	63	40	45
300	9.6	18.9	238	24	23	71	30	25	57	40	45
330	9.6	19.1	242	25	27	91	35	23	53	40	44

[1] Losses in 0N plot are from soil N and the soil N losses are assumed to be same in all treatments.

Interaction of water and N

Three irrigation treatments (saturated, and 1 and 2 mid-season dryings) and four N levels (0, 120, 150 and 180 kg ha^{-1}) were selected to analyse the interactions between water and N on yield and water and N-use efficiencies (Table 8). Yield and N uptake increased from 0 to 180 kg N ha^{-1} in all water management treatments. Maximum yield and N uptake were similar for all irrigation treatments. Irrigation amount ranged from 1056 mm (2 intermittent dryings) to 1440 mm (saturation) and drainage from 922 (180 kg N ha^{-1} with 2 intermittent dryings) to 1307 mm (0N with saturation). ET ranged from 439 mm (0N with 2 intermittent dryings) to 573 mm (180 kg N ha^{-1} with saturation). Water expense efficiency and agronomic efficiency were higher with 1 or 2 midseason dryings treatments, but recovery efficiency was higher for saturated treatment. Two mid-season drainage events saved 384 mm irrigation water without increasing N losses or reducing N use efficiency.

Model applications

Once the model is calibrated and validated for a particular location it can be used for several purposes such as yield forecasting, yield trend and gap analyses, devising crop management strategies, studying the impact of climatic change, estimation of greenhouse gas emissions, pest and disease management and policy formulation. The DSSAT crop models have been widely used over the last 20 years by many researchers for many different applications. Recent review by Timsina and Humphreys (2003) give sa good account of this. Many applications have studied management options, including fertilizer, irrigation and pest management, and site-specific farming. Using the calibrated and validated model we estimated and analysed potential yields and yield gaps in rice, and water and nitrogen dynamics and balance, for the three locations in northwest India.

Table 8. Impact of different levels of water and N on simulated rice yield, and water and N use efficiencies in Delhi in 1999.

Water regime	N added (kg ha^{-1})	Grain yield (Mg ha^{-1})	N uptake (kg ha^{-1})	Irrigation (mm)	Drainage (mm)	ET (mm)	Water-use efficiency (kg mm^{-1} ha^{-1})	Water-expense efficiency (kg mm^{-1} ha^{-1})	Agronomic efficiency (kg kg^{-1})	Recovery efficiency (%)
Saturated	0	2.0	67	1440	1307	482.7	3	1		
Saturated	120	7.0	147	1440	1277	555.7	11	4	42	67
Saturated	150	8.0	171	1440	1284	566	13	4	40	69
Saturated	180	8.8	189	1440	1284	573.4	14	5	38	68
1 Intermittent drying	0	1.6	75	1248	1132	465.8	3	1		
1 Intermittent drying	120	6.9	146	1248	1095	531.4	11	4	44	59
1 Intermittent drying	150	7.9	168	1248	1106	543.8	13	5	42	62
1 Intermittent drying	180	8.8	190	1248	1102	559.2	14	5	40	64
2 Intermittent dryings	0	1.4	72	1056	964	439	3	1		
2 Intermittent dryings	120	6.6	140	1056	909	524.8	11	4	43	57
2 Intermittent dryings	150	7.9	166	1056	922	536.7	13	5	43	63
2 Intermittent dryings	180	8.8	189	1056	922	552.6	14	6	41	65

Yield gap analysis

Potential yield

Simulated average potential yield (mean of 20 years) of rice at the 3 sites in northwest India ranged from 10.0 to 10.8 Mg ha^{-1} (Table 9). Yield of rice was highest in Ludhiana because of higher solar radiation, while the lower yield at Modipuram was due to lower solar radiation and higher daily minimum temperature resulting in decreased photosynthesis, increased respiration, and shortened vegetative and grain filling periods (Horie et al., 1995; Pathak et al., 2003b). Aggarwal et al. (2000a) and Pathak et al. (2003b) estimated similar potential yields using CERES Rice V 3.0 in the same region. In the Kapurthala district of Punjab in the upper Gangetic plains potential rice yield was estimated to be 10.5 Mg ha^{-1} using ORYZA1, compared with much lower potential yield (7.1 Mg ha^{-1}) in Cuttack, Orissa, in the lower IGP (Mohandas et al., 1995)

Table 9. Climatic potential, on-station and on-farm yields of rice (Mg ha^{-1}) and yield gaps in rice for three sites in India.

Site	Potential yield[a]	Actual yields		Yield gap (%)	
		On-station[a]	On-farm[b]	1[c]	2[c]
	(A)	(B)	(C)	(A-B)/A*100	(A-C)/A*100
Ludhiana	10.8	7.8	5.6	28	48
Delhi	10.3	7.1	3.3	31	68
Modipuram	10.0	6.2	3.5	38	65

[a] The commonly grown inbred, short stature cultivars PR114, Pusa 44 and Saket 4 were used for potential and on-station yield estimation at Ludhiana, Delhi and Modipuram, respectively.

[b] Average yield of the whole district with different water and nitrogen management

[c] Yield gap 1 is the gap between the potential and on-station yields whereas 2 is the gap between the potential and on-farm yields.

On-station yield

The highest on-station yield occurred at Ludhiana (7.8 Mg ha^{-1}) and the lowest at Modipuram (6.2 Mg ha^{-1}) (Table 9). The higher yield at Ludhiana occurred inspite of lower soil fertility (SOC 0.40%) than that at Modipuram (SOC, 0.54%) and Delhi (SOC, 0.44%) and the same amount of applied N (120 kg ha^{-1}). Higher solar radiation (Pathak et al., 2003b) could be responsible for the higher yield at Ludhiana.

On-farm yield

The on-farm average yields of rice varied from 3.3 Mg ha^{-1} at Delhi to 5.6 Mg ha^{-1} at Ludhiana (Table 9). Among other factors, a more favourable climate, better irrigation facilities and better socio-economic conditions of the farmers, are responsible for the higher yields at Ludhiana. Narang and Virmani (2001) also observed higher on-farm yields of rice in Punjab in the upper IGP compared to the lower transects.

Yield gap

A wide gap exists between climatic potential yields and the yields obtained on research stations and in farmers' fields. The gaps between potential and research station yields (yield gap 1) ranged from 28 to 38% of potential yield, or 3.0 to 3.8 t/ha (Table 9). Ludhiana had a lower yield gap compared to the other two sites. The gap between potential and on-farm yields was greater than the gap between potential and research station yields at all locations. For example, it increased from 28% to 48% at Ludhiana and from 31% to 68% at Delhi. It is important to identify and address the yield gap constraints to increase food production. In India, socio-economic factors causing the yield gap on farmers' fields are very important (Aggarwal et al., 2000a,b; Ladha et al., 2003).

The analysis suggests that there is plenty of scope to increase farmers' yields by improved crop management. Research must now focus on increasing potential yield of the cultivars to increase overall productivity. At the same time dissemination of successful management options among farmers through appropriate communication strategies for wider impact is required to increase farmers' yields. An effective extension infrastructure is required to address the problems and to provide technical support to the farmers. Raising the awareness of yield gaps and factors causing yield gaps among all stakeholders (farmers, extension staff, researchers, government decision-makers, etc.) is an important step towards narrowing the gap.

In-crop season analysis of water and N dynamics

The validated model was run to study in-crop season analyses of water and N dynamics for Delhi conditions.

Components of the water balance

The model calculates components of the water balance (transpiration, evaporation, runoff, infiltration, drainage, and changes in stored soil water) (e.g. Table 10) and water deficit stress effects on phenology and growth processes. In fine-textured soils, percolation losses are generally low, while in light-textured soils there are generally high losses of water due to deep percolation. Figure 11 shows seasonal pattern of actual cumulative irrigation and rainfall, and simulated drainage during the rice season in 1999 for the Delhi experiment. Rainfall during the rice season was 353 mm. Irrigation was applied daily and totals of 1800, 1080 and 5659 mm of irrigation water were applied during the season in the saturated, alternate wetting and drying (AWD) with 3 mid-season dryings, and continuously flooded treatments, respectively (Table 10).

Including initial soil water content of 369 mm over the soil profile of 120 cm, the total water input was 2522, 1802 and 6381 mm, respectively in those treatments. Simulated ET (transpiration, soil evaporation and flood pool evaporation) in those treatments were 503, 475 and 637 mm, respectively. Drainage was the largest loss at 1691, 996 and 5396 mm in the saturated, AWD, and continuously flooded treatments, respectively, on this permeable loam soil. High irrigation water requirement (3100 mm) for unpuddled continuously saturated soil has been reported for a sandy loam soils in Punjab (Prihar et al., 1976) and from 1000 to 2500 mm for loam to sandy loam soils at various places in India (Prihar and sandhu, 1987). High drainage rates (up to 1500 mm or even higher) in puddled rice fields on alluvial sandy loam soils of northwestern India have been reported by several authors (Bhatti and Kijne, 1992; Hira and Khera, 2000; Tripathi, 1992; Velayutham et al., 1999). Prihar and Sandhu (1987) reported 94-184% of irrigation water lost through percolation from sandy loam and loamy sand soils in various places in India.

The simulated water content in surface layer (0-5 cm) as influenced by the irrigation treatments is shown in Fig. 12. With three drying events the soil moisture fell to wilting point at three stages during the season, which resulted in water stress and lower yield of rice. In the continuously flooded treatment, as expected, water content was always at or near saturation.

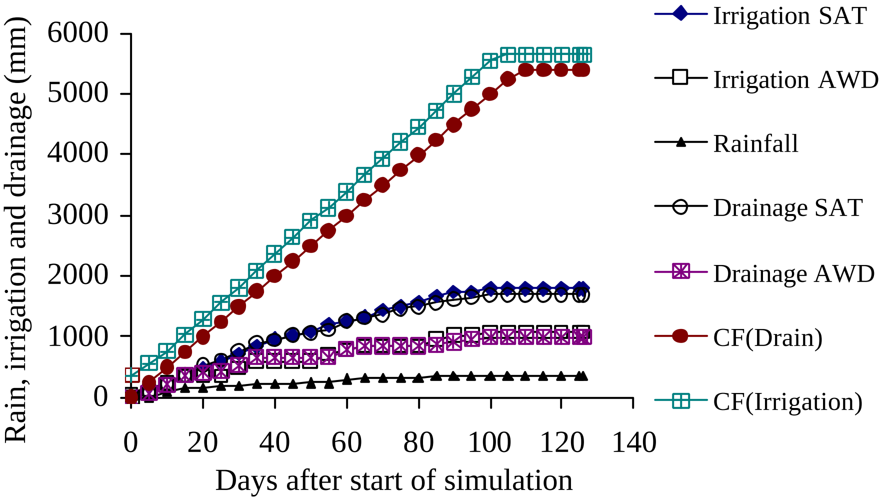

Fig. 11. Simulated seasonal cumulative components of the water balance in rice with urea at 120 kg N ha^{-1} in Delhi in 1999 (SAT, saturated soil; AWD, 3 drying events; CF, continuously flooded).

Table 10. Water balance components (mm) with 120 kg N ha^{-1} applied to rice in Delhi in 1999.

Components	Continuously flooded	Saturated soil	AWD
Input			
Initial soil water	369	369	369
Irrigation	5659	1800	1080
Precipitation	353	353	353
Total	6381	2522	1802
Output			
Transpiration	414	333	316
Soil evaporation	18	137	135
Flood pool evaporation	205	85	63
Drainage	5396	1277	728
Runoff	0	0	0
Final soil water	347	323	331
Total	6380	2161	1585

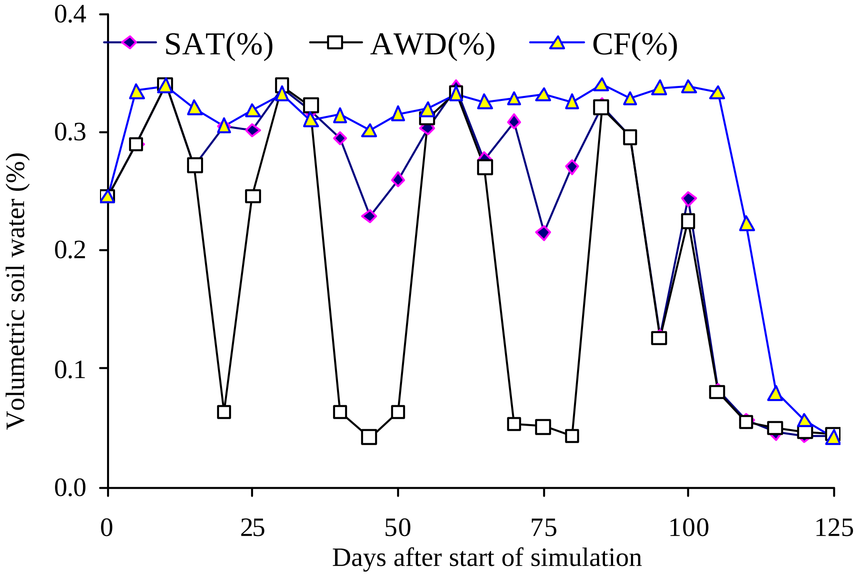

Fig. 12. Simulated daily volumetric soil water content (0-5 cm layer) as influenced by water management with 120 kg N ha^{-1} in rice in Delhi in 1999.

Components of the nitrogen balance

The model calculates the components of N balance such as N inputs through soil humus, mineralization, litter, residue, fertilizer and irrigation water, and N outputs through uptake, leaching, volatilisation, denitrification and runoff. The components N balance for the Delhi experiment in 1999 are summarised in Table 11.

Leaching loss of N

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. Total leaching loss of N over the season varied from 13 kg ha^{-1} in 0N with three mid-season dryings to 21 kg ha^{-1} in the 120 kg N ha^{-1} with continuous flooding (Table 11). Losses were similar for N applied as urea or urea plus FYM. Seasonal patterns of leaching loss in rice for various N and water regimes for Delhi soil are shown in Fig. 13. The loss was similar (9. to 9.4 kg N ha^{-1}) in all treatments during the first 20 days of simulation. Those losses were due to the presence of NO_3^- prior to ponding for puddling, with the soil remaining ponded for two weeks after transplanting for crop establishment. Nitrogen leaching during the season then increased in all treatments with highest leaching (21.3 kg N ha^{-1}) in the continuously flooded treatment. The presence of soil NO_3^- prior to rice is to be expected in rice-upland cropping systems like the rice-wheat system where the soil is aerobic during the wheat and fallow periods after rice. Any residual NO_3-N is prone to losses by denitrification and leaching during soil flooding for rice (Buresh et al. 1989; George et al. 1992).

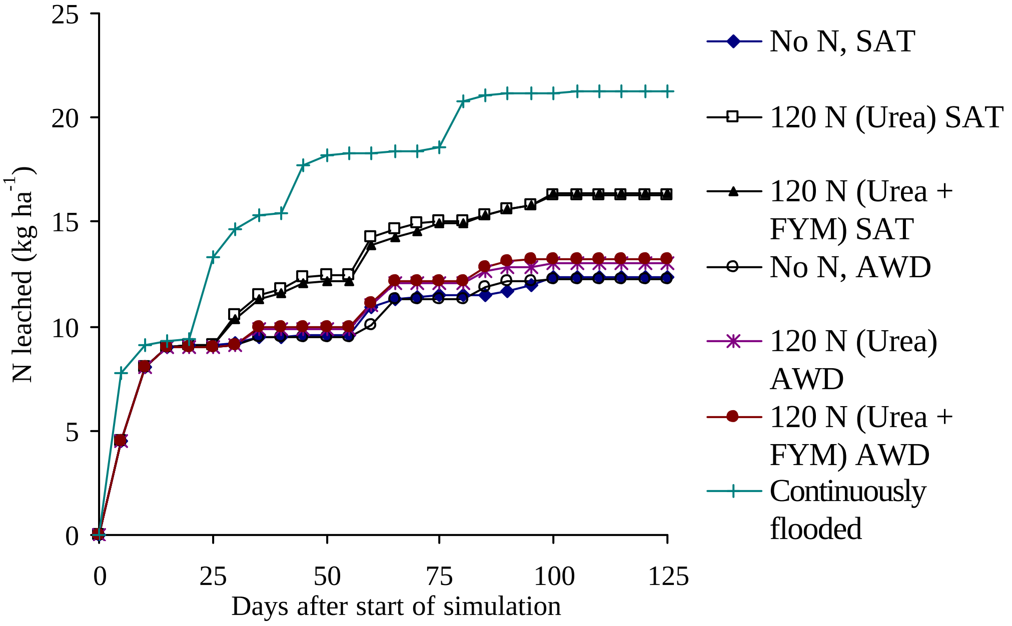

Fig. 13. Simulated seasonal cumulative leaching loss of N as influenced by N and water management in rice in Delhi in 1999.

Table 11. Applied N inputs and simulated N balance (kg ha^{-1}) in rice with various N sources and water management practices in Delhi in 1999.

Components	Saturated soil			Three mid-season drying events			Continuou flooded
N source	Nil	Urea[a]	Urea + FYM[b]	Nil	Urea[a]	Urea + FYM[b]	Urea[a]
Input							
Soil humus N	2835	2835	2835	2835	2835	2835	2835
Soil NO_3^-	22	22	22	22	22	22	22
Soil NH_4^+	21	21	21	21	21	21	21
Soil litter N	1	1	1	1	1	1	1
N in residues	2	2	2	2	2	2	2
Organic N added	0	0	60	0	0	60	0
Fertilizer N added	0	120	60	0	120	60	120
Irrigation water N	10	10	10	10	10	10	10
Total	2897	3017	3017	2897	3017	3017	3017
Output							
Uptake	31	118	111	26	106	101	136
Leached	15	16	16	12	13	13	21
Volatilized	<1	3	2	2	4	<4	4
Denitrified	12	43	27	17	54	35	21
Runoff	0	0	0	0	0	0	0
Soil NO_3^-	4	5	5	5	7	6	2
Soil NH_4^+	15	12	13	18	11	12	16
Soil humus N	2817	2817	2830	2818	2819	2832	2815
Soil litter N	2	2	12	3	3	15	1
Total	2897	3017	3017	3017	3017	3017	3017

[a] 120 kg N ha^{-1} through urea

[b] 60 kg N ha^{-1} through urea + 60 kg N ha^{-1} through FYM

Ammonia volatilization

Loss of N due to volatilization was very low and ranged from <1 kg ha^{-1} in the unfertilized saturated to 4 kg ha^{-1} in 120 N ha^{-1} treatments (Table 11). Substitution of 50% of the urea N with FYM slightly reduced the loss of N in both the saturated and AWD treatment. This was probably due to the fact that FYM is incorporated into the soil and thus the NH_4^+ is released slowly with little diffusion into the floodwater whereas urea is broadcast onto the soil surface after puddling resulting in a higher concentration of ammonical N in solution at the surface. All the AWD treatments had slightly higher N volatilisation than their counterparts in saturated soil. Seasonal patterns revealed that every application of N resulted in a very small flux of ammonia (Fig. 14). FYM reduced ammonia volatilization by about 20% due to slow mineralization and low soil NH_4^+ N (Banerjee et al., 2002). Banerjee et al. also found lower ammonia volatilisation in 0N plot due to lower amount of soil NH_4^+ N.

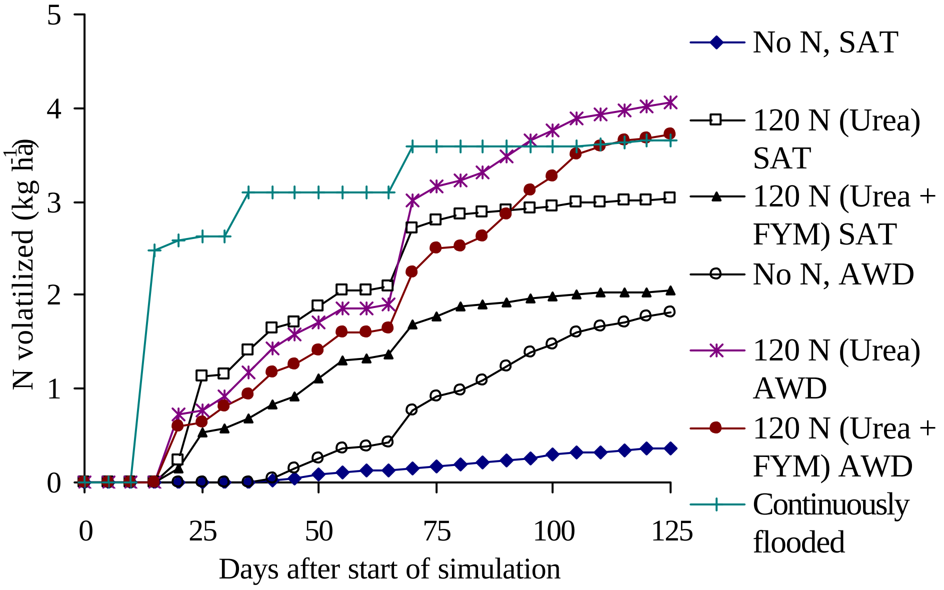

Fig. 14. Simulated seasonal cumulative volatilization loss of N as influenced by N and water management in rice in Delhi in 1999.

Denitrification

The highest N loss (ranging from 12 kg ha^{-1} in 0N, saturation to 54 kg ha^{-1} in 120 kg N, AWD) was due to denitrification. Denitrification loss started from day 1 of the simulation (Fig. 15). Denitrification loss was least in the continuous flooded treatment with 120 kg N at 21 kg N ha^{-1}. Substitution of 50% of the urea N with FYM reduced the loss by about 40% in saturated and drained treatments. Denitrification loss from the drained treatments was higher than from the saturated treatment for the same N management due to nitrification during drained periods, followed by denitrification upon reflooding. High denitrification loss of N immediately after flooding of dry soil has also been reported by Buresh et al. (1989) and George et al. (1992).

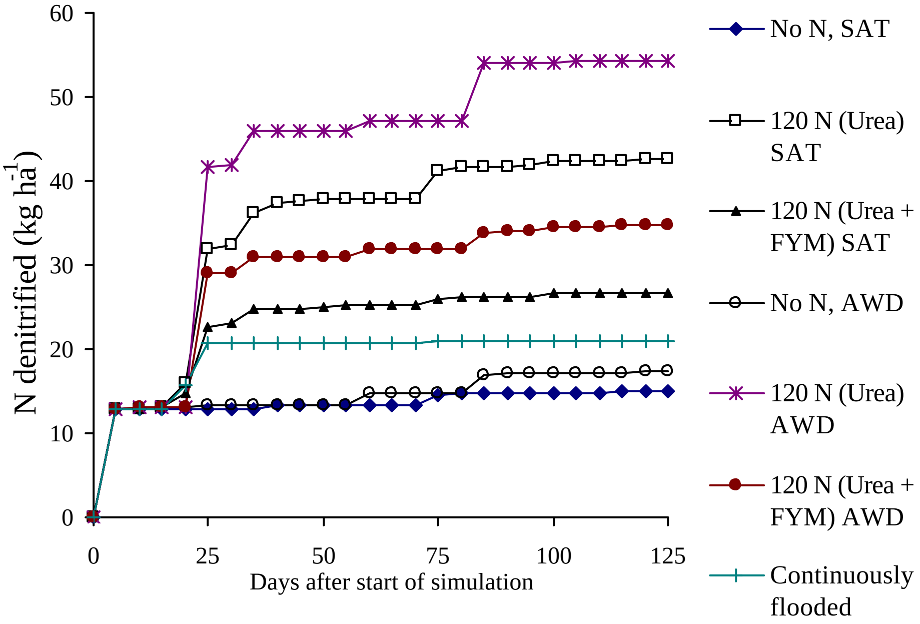

Fig. 15. Simulated seasonal cumulative denitrification loss of N as influenced by N and water management in rice in Delhi in 1999.

Dynamics of organic carbon

The simulation of soil organic carbon (SOC) showed a decline of SOC in all the treatments ranging from 28 to 43 kg ha^{-1} in the surface layer (0-5 cm), except in the urea+FYM treatment where there was a slight increase in SOC (Fig. 16). Decline in SOM has also been reported in the long-term experiments from the major rice-wheat regions of north west India (Sinha et al., 1998; Ladha et al., 2003) and the Pakistan’s Punjab (Ali and Byerlee, 2000). The model was not able to mimic the observed decline in field condition quite satisfactorily. High temperature resulting in high decomposition rate of organic matter makes the build up of SOC very difficult in tropical and sub-tropical soils.

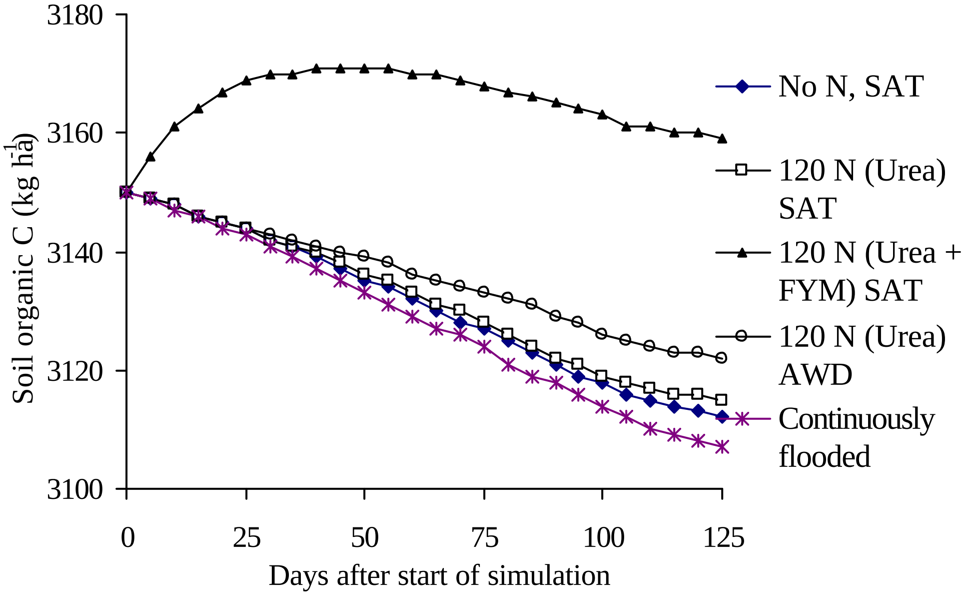

Fig. 16. The effect of N and water regimes on simulated soil organic C (0-5 cm layer) in rice season in Delhi in 1999.

Time course of N uptake

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 mineral N during this period. The pattern of N uptake by rice with different levels and sources of N is shown in Fig. 17. In the fertilized treatments the crop rapidly took up N following fertilization 15 days after the start of simulation (DAS) until 40 DAS when the rate of uptake decreased, presumably having exhausted the supply of available N. During that 25-day period the crop took up about 80 kg N ha^{-1} in urea+FYM and urea only treatments. Further rapid uptake occurred during 70-75 DAS following fertilization. Total uptake was greatest in the continuously flooded treatment throughout the growing season. In the unfertilized treatments N uptake continued steadily throughout the season. The total uptake was about 42, 118, 111 and 136 kg N ha^{-1} in the unfertilized, urea, and urea +FYM, and continuously flooded treatments (Fig. 17). Such information can be used to guide fertilizer management to attain better synchrony between N supply and demand.

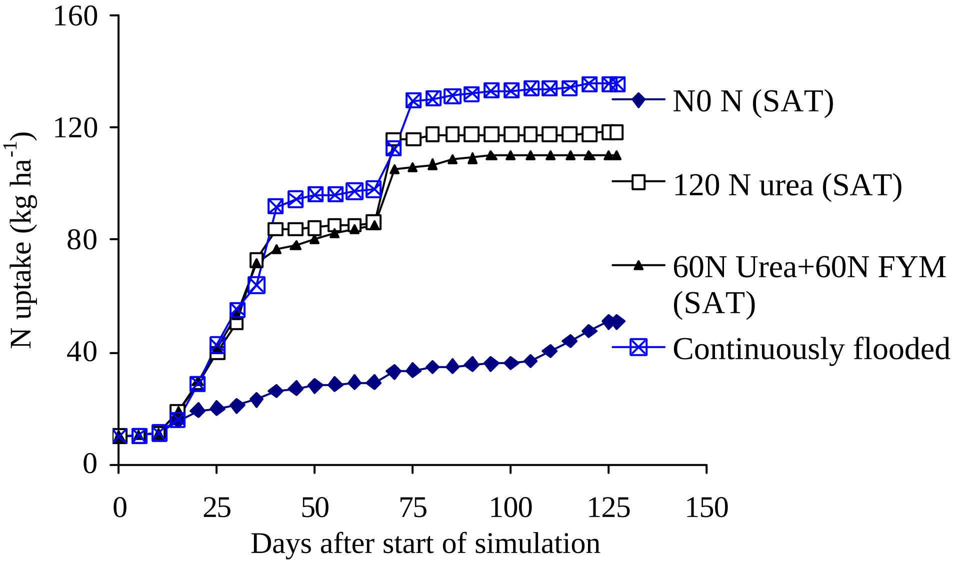

Fig. 17. Simulated cumulative N uptake by rice with different N treatments at saturated soil and a continuously flooded treatments in Delhi in 1999

Effects of weather variability in Delhi

Cumulative probability distributions of yield and other parameters were developed from the results of simulations for 34 years (1968-2002) of Delhi weather data. Three N and two water management treatments were analysed with 5 scenarios: 1) No N – saturation; 2&3) N applied at 120 kg ha^{-1} through urea - saturation & AWD; 4) N applied as urea and FYM (60 kg ha^{-1} each) – saturation; and 5) N applied at 120 kg ha^{-1} through urea alone- continuously flooded. With the exception of weather, all other model inputs, such as soils, cultivar, crop and management were identical. Fixed amount of irrigation was applied on fixed days each year thus any variability in yield and other parameters was associated with variations in seasonal weather conditions. The simulation was carried out for Pusa 44 transplanted on 15 July each year. Details of crop, irrigation and fertilizer inputs are presented in Appendix Table 5, and soil inputs in Appendix Table 4.

Yields of the fertilized treatments varied by up to 2 Mg ha^{-1} across the years, reflecting the variation in seasonal conditions. Yield variation was less in unfertilized treatments. The cumulative probability functions (CPFs) for grain yield showed that yields under saturation were always higher than under AWD with the same N management, by an average of 0.3 to 0.4 Mg ha^{-1}. Yields with 120 kg N ha^{-1} through urea alone were higher than with urea+FYM by an average of 0.5 to 0.6 Mg ha^{-1}. In 90% of years, yields with 120 kg N ha^{-1} through urea were between 5.4 and 7.4 Mg ha^{-1} with saturated soil, while application of N through urea plus FYM gave lower yields (3.4-6.9 Mg ha^{-1}). In 90% of the years, rice yields in the unfertilized soil in the saturated treatment ranged from 1.0 to 2.7 Mg ha^{-1} while yields in continuously flooded treatment were between 5.9 to 8.0 Mg ha^{-1} (Fig. 18). Irrigation applied during the season in various years ranged from 4933 to 5883 mm in continuously flooded treatment. It was 1080 mm in AWD and 1800 mm in other treatments.

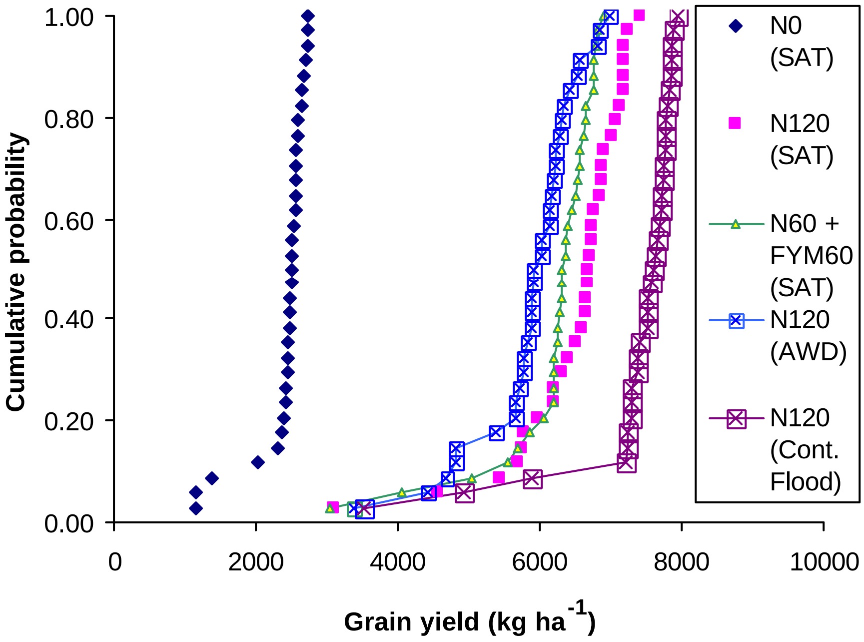

Fig. 18. Simulated CPFs for grain yield in Delhi as affected by N and water regimes (standard deviations of 397, 850, 785, 740, and 893 kg ha^{-1}, respectively for N0 (SAT), N120 (SAT), N60+FYM60 (SAT), N120 (AWD), and N120 (continuous Flood) treatments).

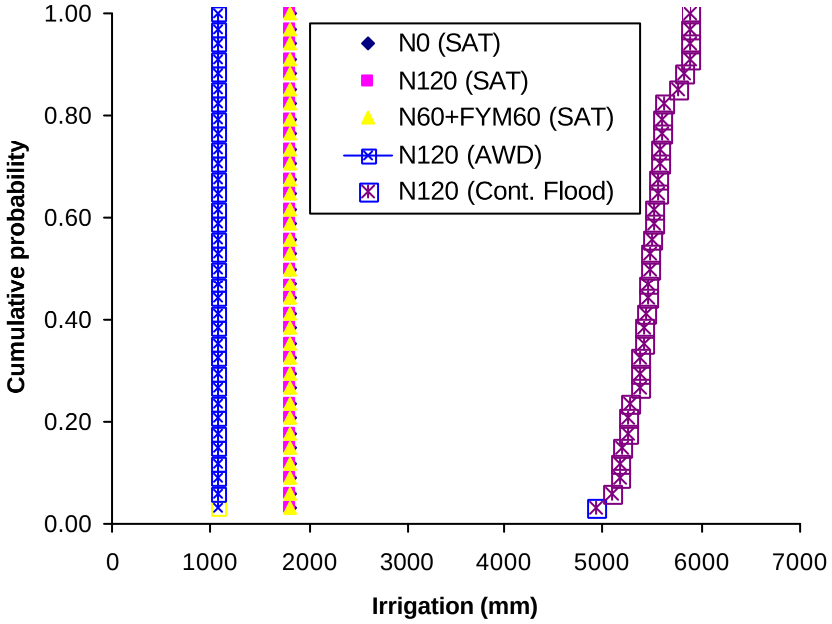

Fig. 19. Simulated CPFs for cumulative irrigation as affected by N and water (standard deviation of 236 mm for N120 (continuous Flood) and zero for others).

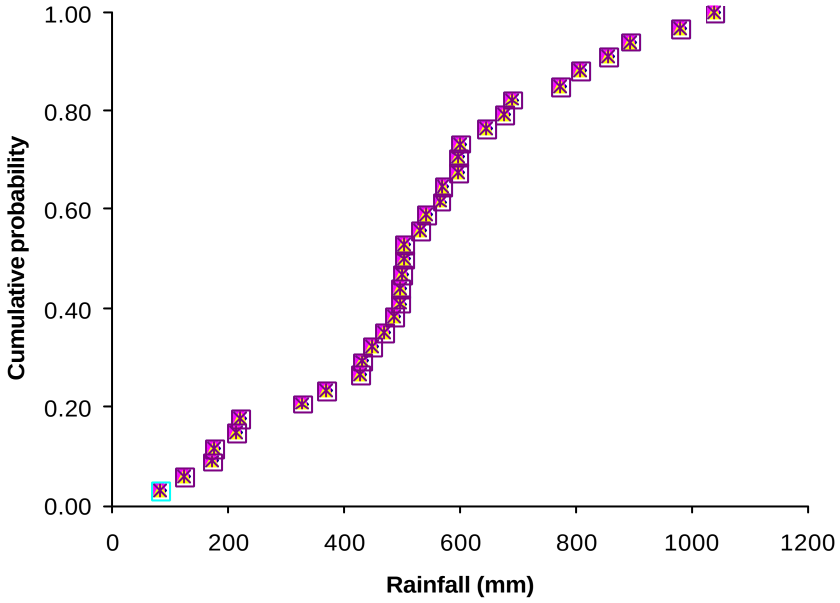

Fig. 20. Simulated CPFs for seasonal rain in Delhi (standard deviation = 236 mm).

In 50% of years, rainfall exceeded 500 mm during the rice season (Fig. 20) and in those years leaching losses were also higher. The CPFs showed that drainage varied widely with water management, but no differences between N treatments (Figure 21). Drainage of the saturated and drained treatments varied by ~1000 mm across seasons, whereas under continuous flooding, drainage was exceptionally high (5394 to 5452 mm) with little variation across years. Under continuous saturation, drainage ranged from 1428 to 2352 mm over 35 years, exceeding 1800 mm in 50% of years, while under AWD drainage ranged from 702 to 1654 mm, with at least 1100 mm in 50% of years. As a result, the leaching loss of applied N was also higher under saturation than with AWD (Fig. 22).

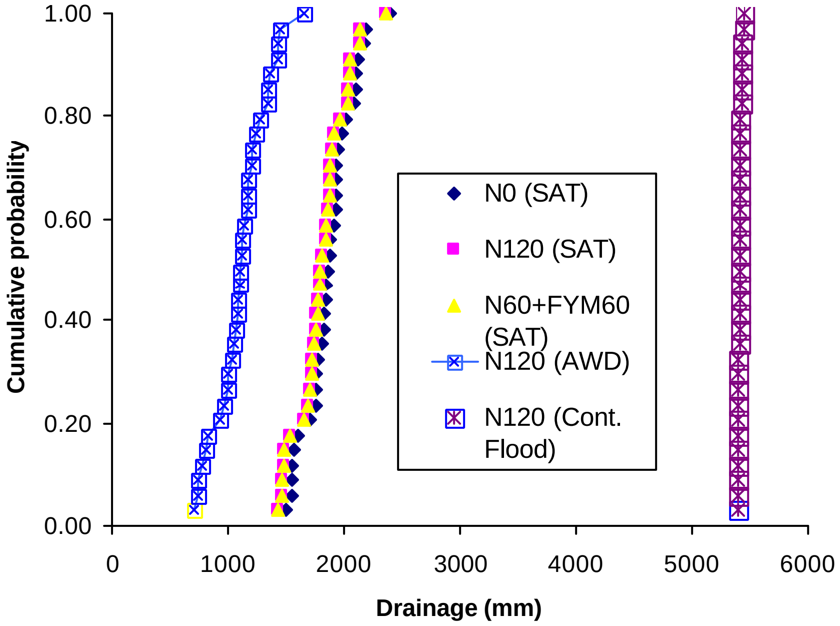

Fig. 21. Simulated CPFs for seasonal drainage in Delhi as affected by N and water regimes (standard deviations of 208, 215, 215, 224, and 14 mm, respectively for N0 (SAT), N120 (SAT), N60+FYM60 (SAT), N120 (AWD), and N120 (continuous Flood) treatments).

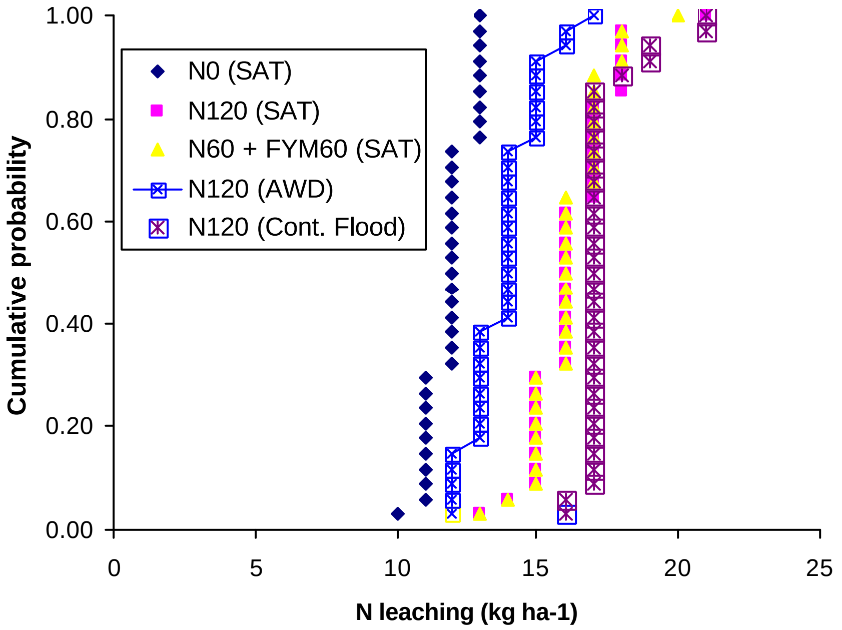

Fig. 22. Simulated CPFs for leaching losses of N in Delhi as affected by N and water regimes (standard deviations of 0.8, 1.5, 1.3, 1.2, and 1.1 kg ha^{-1}, respectively for N0 (SAT), N120 (SAT), N60+FYM60 (SAT), N120 (AWD), and N120 (continuous Flood) treatments).

There was 10-13 kg ha^{-1} season^{-1} loss of N through leaching in the unfertilized treatment. In saturated treatment with 120 N, it was 13-21 kg ha^{-1}, compared with 12-17 kg ha^{-1} for AWD with 120 N. In the continuous flooding with 120 N, it was 16-21 kg ha^{-1}.

Evapotranspiration ranged from 318 to 578 mm across treatments and years (fig. 23). ET was highest (433-578 mm) for saturation with 120 kg ha^{-1} N, intermediate (381-496 mm) for continuous flooding with 120 N, and lowest (318-421 mm) for saturation with 0N treatments. ET for N120 (AWD) and N60+FYM60 (SAT) were similar to N120 (SAT). The analysis showed that while rain was enough to meet ET requirements, irrigation was necessary because of the high drainage losses on this highly permeable soil.

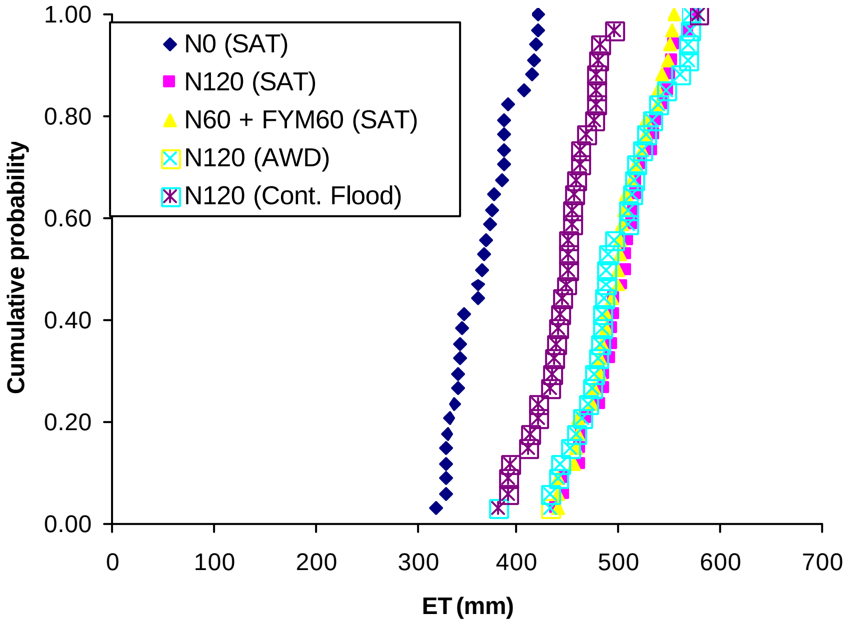

Fig. 23. Simulated CPFs for seasonal ET in Delhi as affected by N and water regimes (standard deviations of 31, 36, 34, 41, and 37 mm, respectively for N0 (SAT), N120 (SAT), N60+FYM60 (SAT), N120 (AWD), and N120 (continuous Flood) treatments).

Effects of weather variability in Ludhiana

In Ludhiana, five water x N management scenarios were simulated using 30 years of historical weather data from 1970-2000. The five scenarios involved 2 N application rates (0 and 120 kg N ha^{-1} as urea) each under 2 water regimes (1-d drainage and 3-d drainage) and the fifth treatment with 120 kg N under continuous flooding. The popular rice cultivar PR114 was transplanted on 9 June in each year. Fixed amount of irrigation was applied on fixed days each year thus any variability in yield and other parameters was associated with variations in seasonal weather conditions. Details of crop, water and fertilizer inputs are summarised in Appendix Table 6, and soil inputs in Appendix Table 4.

Simulated yields of rice across treatments and years in Ludhiana ranged from 1.1 to 8.9 Mg ha^{-1}. Under the continuous flooding, yields ranged from 7.4 to 8.9 Mg ha^{-1}, with

>8.5 Mg ha^{-1} in 50% of years (Fig. 24). Long-term simulated yields were different for 1-d and 3-d drainage treatments when N was applied at 120 kg ha^{-1}, but without N application, yields were almost similar in all years for both drainage treatments (1.1-2.6 Mg ha^{-1}). With 120 kg N ha^{-1}, yields were >6.0 Mg ha^{-1} for 1-d drainage in 90% of years compared with only 30% of years for 1-d drainage.

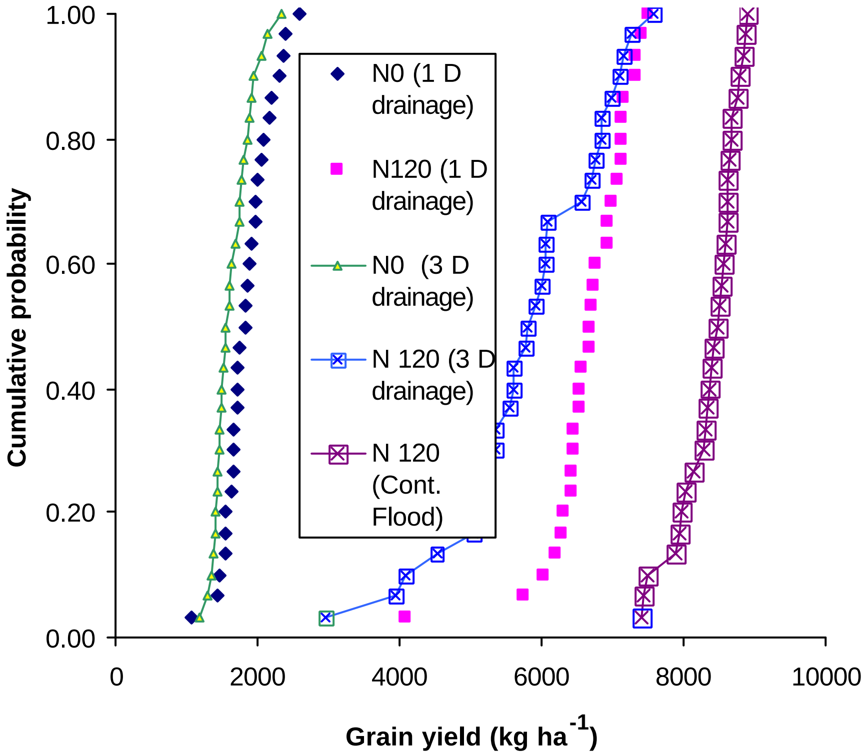

Fig. 24. Simulated CPFs for rice grain yield in Ludhiana as affected by N and water regimes (standard deviations of 347, 648, 266, 1080, and 416 kg ha^{-1}, respectively for 0N (1D), 120N (1D), 0N (3D), 120N (3D), and continuous flooding treatments).

Irrigation water applied was 1050 and 1750 mm for 3-d and 1-d drainage, respectively. Under continuously flooded treatment, however, significantly high more water (7140 to 8625 mm) was applied (Fig. 25). Rainfall ranged from 167 to 1183 mm, with 574 mm or more rain occurring in 50% years (Fig. 26). Cumulative seasonal drainage was always much lower with 3-d drainage (425-1363 mm) compared with 1-d drainage (1098-2022 mm). In continuous flooding treatment, it ranged from 6120 to 7500 mm (Fig. 27).

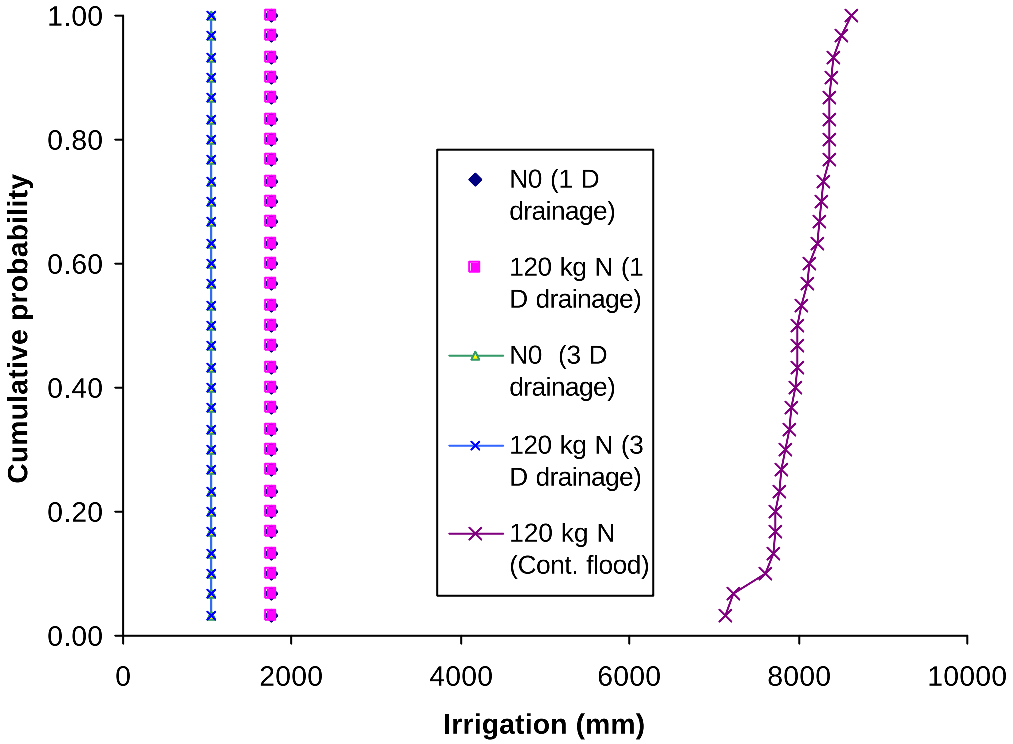

Fig. 25. Simulated CPFs for seasonal irrigation in Ludhiana as affected by N and water regimes (standard deviations of 57, 73.1, 46.5, 70.7, and 85 kg ha^{-1}, respectively for 0N (1D), 120N (1D), 0N (3D), 120N (3D), and continuous flooding treatments).

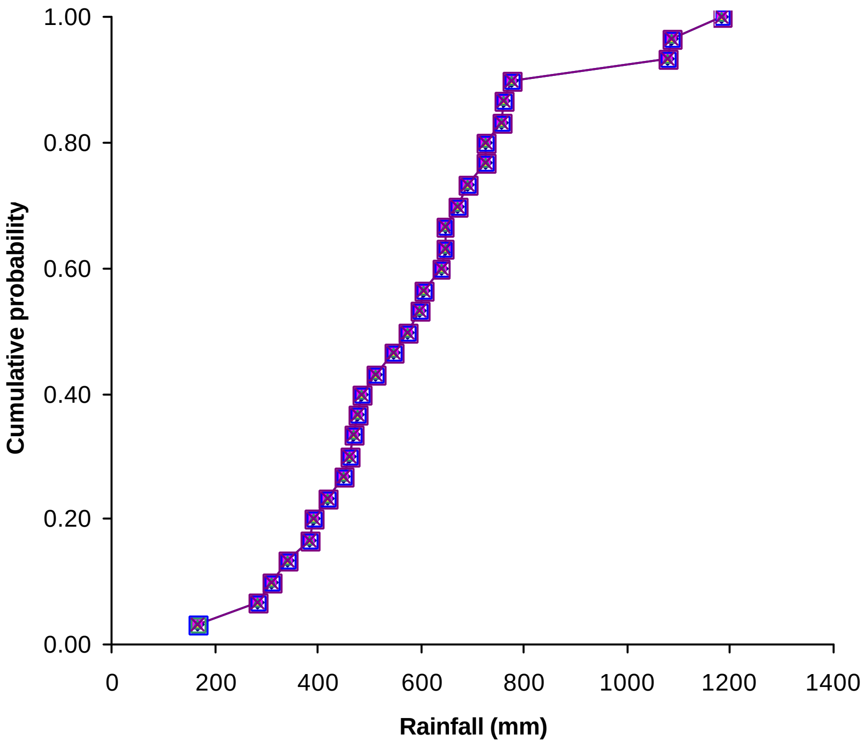

Fig. 26. Simulated CPFs for seasonal rain during rice in Ludhiana (standard deviation=235.4).

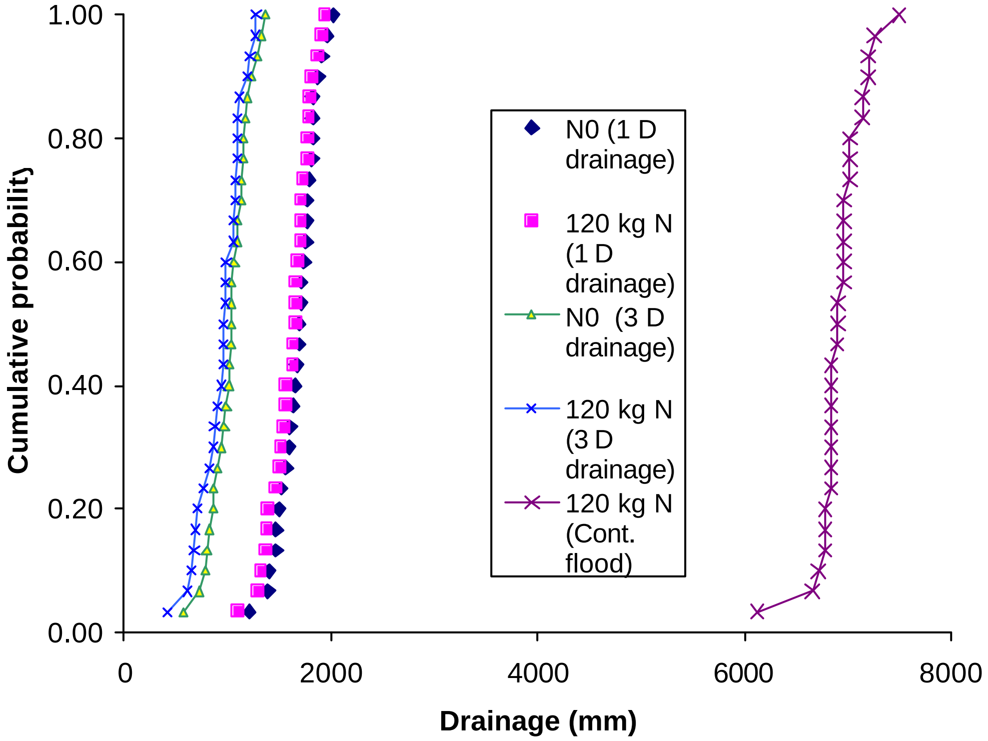

Fig. 27. Simulated CPFs for seasonal drainage during rice in Ludhiana as affected by N and water regimes (standard deviations of 203, 211, 200, 218, and 210 mm, respectively for 0N (1D), 120N (1D), 0N (3D), 120N (3D), and continuous flooding treatments).

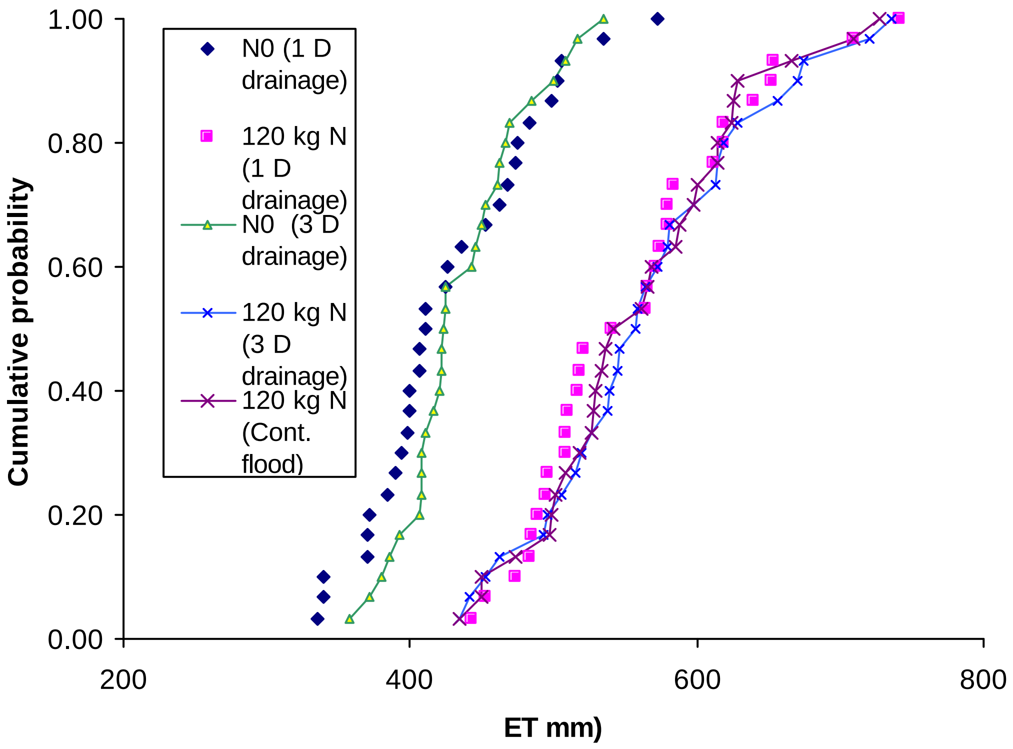

Fig. 28. Simulated CPFs for seasonal ET for rice with 120 kg N in Ludhiana as affected by water regimes (standard deviations of 57, 73.1, 46.5, and 70.7 mm, respectively for 1 d and 3 d drainage with 0 N and 120 kg N through urea, and continuous flooding with 120 kg N treatments).

Under continuous flooding, ET ranged from 336 to 742 mm. ET was similar for 1-d and 3-d drainage, but was considerably higher for 120 kg N (443-742 mm) than for 0 N (336-572 mm) treatments (Fig. 28). Cumulative seasonal N leaching ranged from 11 to 22 kg ha^{-1} across treatments, with higher leaching for 120 kg N (12-19 kg ha^{-1}) than for 0 N (11-16 kg ha^{-1}) treatments (Fig. 29). Under 120 kg N, leaching was slightly higher for 1-d drainage but under 0N, opposite was the case.

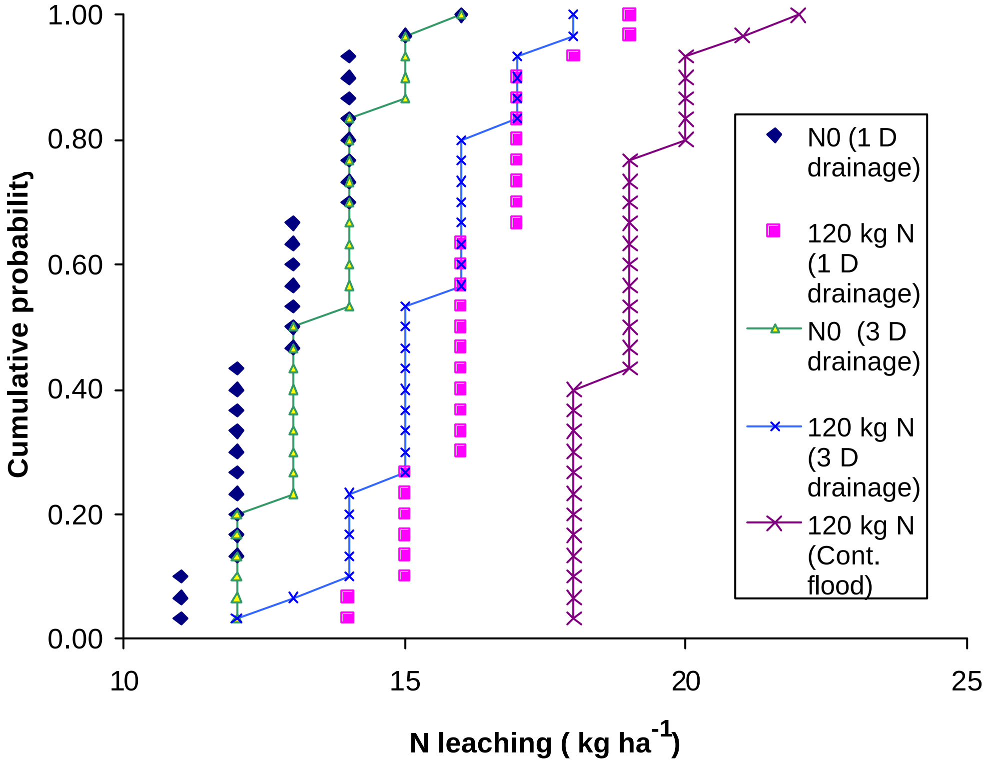

Fig. 29. Simulated CPFs for seasonal N leaching during rice in Ludhiana as affected by N and water regimes (standard deviations of 1.5, 1.1, 1.3, 1.4, and 1.6 kg ha^{-1}, respectively for 1 d and 3 d drainage with 0 N and 120 kg N through urea, and continuous flooding with 120 kg N treatments).

The model simulations help 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 presentation of simulated data using CPFs helps to depict the potential tradeoff between a benefit and an environmental cost, i.e., greater yield due to applied N versus potential leaching of NO3-N to groundwater. In the above analyses, whereas both Delhi and Ludhiana soils show a yield response to applied N, leaching losses are likely to be much greater on loamy sands of Ludhiana than loams of Delhi. Singh and Thornton (1992) also used such approach to quantify the weather related risks for different N management options.

Conclusions

The latest version of CSM-CERES-Rice (ver 4.0) generally predicted grain yields, above-ground biomass yields and total N uptake fairly satisfactorily across a range of data sets covering varying levels of water and N management at three sites in northwest India. The performance of model was, however, better for N-added treatments than zero-N treatments. Simulation of soil NH_4-N and NO_3-N in the surface soil layer (0-15 cm) was generally poor. Simulated deep drainage below 120 cm, and ET and N leaching were in consistent with, but denitrification and ammonia volatilisation losses were inconsistent with, observations from field experiments in northwest India on sandy loam, loam and sandy soils. Emission of methane predicted by MERES was much higher than the observed values.

CSM-CERES-Rice ver. 4.0 was useful in identifying gaps between potential (dictated by weather and genotype) and research and farmers' field yields, suggesting that there is plenty of scope to increase farmers' yields by improved crop management.

The model was generally able to capture the major effects of water and N on crop performance and water and N dynamics and balances as seen from the in-season analysis of water and N dynamics for Delhi and long-term analysis at Delhi and Ludhiana differing in climate and soils. The analysis suggested that though CSM-CERES-Rice ver 4.0 can be applied for studying the variety, water and N related issues in fully and intermittently irrigated rice cropping systems of northwest India, it needs further improvements for better prediction of growth and development and N- and water-related processes. Adequate and good quality experimental data would be required for further improvements of key model processes and for further evaluation of the model. Likewise, MERES needs further improvement in terms of simulating soil water balance and soil redox potential for better prediction of methane emissions.

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Appendix Table 1. Experimental FileX for Delhi

```
*EXP.DETAILS: INDL0001RI IARI 1999-2000

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 0 0 Control 0 N (SAT-99)       1  1  1  1  1  1  1  0  0  0  1  0  1
 2 1 0 0 120 urea (SAT-99)          1  1  1  1  1  1  2  0  0  0  1  0  1
 3 1 0 0 120 kg N FYM (SAT-99)      1  1  1  1  1  1  3  1  0  0  1  0  1
 4 1 0 0 Control 0 N (AWD-99)       1  1  1  1  1  2  1  0  0  0  1  0  1
 5 1 0 0 120 kg N urea (AWD-99)     1  1  1  1  1  2  2  0  0  0  1  0  1
 6 1 0 0 120 kg N FYM (AWD-99)      1  1  1  1  1  2  3  1  0  0  1  0  1
 7 1 0 0 Control 0 N (SAT-00)       1  1  2  2  2  3  4  0  0  0  2  0  2
 8 1 0 0 120 urea (SAT-00)          1  1  2  2  2  3  5  0  0  0  2  0  2
 9 1 0 0 120 kg N FYM (SAT-00)      1  1  2  2  2  3  6  2  0  0  2  0  2
10 1 0 0 Control 0 N (AWD-00)       1  1  2  2  2  4  4  0  0  0  2  0  2
11 1 0 0 120 kg N urea (AWD-00)     1  1  2  2  2  4  5  0  0  0  2  0  2
12 1 0 0 120 kg N FYM (AWD-00)      1  1  2  2  2  4  6  2  0  0  2  0  2

*CULTIVARS
@C CR INGENO CNAME
 1 RI IA0001 PUSA 44

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL    FLNAME
 1 MB14 C   DELH        -99     0 IB000     0     0 00000 -99     50  IBWH980011 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 1         0.00000         0.00000      0.00               0.0   0.0   0.0   0.0

*SOIL ANALYSIS
@A SADAT  SMHB  SMPX  SMKE  SANAME
```

```
 1 99193   -99   -99   -99  -99
@A  SABL  SADM  SAOC  SANI SAPHW SAPHB  SAPX  SAKE
 1    15   1.4  0.44  0.04   8.1 -99.0  10.0  45.0
@A SADAT  SMHB  SMPX  SMKE  SANAME
 2 00196   -99   -99   -99  -99
@A  SABL  SADM  SAOC  SANI SAPHW SAPHB  SAPX  SAKE
 2    15   1.4  0.44  0.04   8.1 -99.0  10.0  45.0

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    WH 99193   200   -99  1.00  1.00 -99.0   200  0.40  0.00   100    15 -99
@C  ICBL  SH2O  SNH4  SNO3
 1    15 0.320   4.2   3.0
 1    30 0.320   2.3   1.8
 1    45 0.320   1.3   1.0
 1    60 0.300   0.8   1.0
 1    90 0.300   0.3   0.8
 1   120 0.300   0.3   0.8
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 2    WH 00193   200   -99  1.00  1.00 -99.0   200  0.40  0.00   100    15 -99
@C  ICBL  SH2O  SNH4  SNO3
 2    15 0.320   4.3   3.0
 2    30 0.320   2.5   2.1
 2    45 0.320   1.5   1.0
 2    60 0.300   0.8   1.0
 2    90 0.300   0.3   0.8
 2   120 0.300   0.3   0.8

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL  PLNAME
 1 99196   -99  35.0 -99.0     T     H    20     0   2.0     0    22  36.0   3.0   0.0     -99
```

```
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL  PLNAME
 2 00199   -99  35.0 -99.0     T     H    20     0   2.0     0    22  36.0   3.0   0.0      -99

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1  0.80   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 1 99192 IR008  30.0     0
 1 99192 IR009 150.0     0
 1 99192 IR010   0.0     0
 1 99192 IR003  60.0     0
 1 99195 IR003  60.0     0
 1 99198 IR003  60.0     0
 1 99201 IR003  60.0     0
 1 99205 IR003  60.0     0
 1 99207 IR003  60.0     0
 1 99209 IR003  60.0     0
 1 99211 IR003  60.0     0
 1 99215 IR003  60.0     0
 1 99217 IR003  60.0     0
 1 99219 IR003  60.0     0
 1 99221 IR003  60.0     0
 1 99223 IR003  60.0     0
 1 99226 IR003  60.0     0
 1 99229 IR003  60.0     0
 1 99232 IR003  60.0     0
 1 99235 IR003  60.0     0
 1 99240 IR003  60.0     0
 1 99244 IR003  60.0     0
 1 99247 IR003  60.0     0
 1 99250 IR003  60.0     0
```

```
 1 99253 IR003  60.0     0
 1 99258 IR003  60.0     0
 1 99262 IR003  60.0     0
 1 99264 IR003  60.0     0
 1 99270 IR003  60.0     0
 1 99274 IR003  60.0     0
 1 99277 IR003  60.0     0
 1 99282 IR003  60.0     0
 1 99289 IR003  60.0     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 2   0.8   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 2 99192 IR008  30.0     0
 2 99192 IR009 150.0     0
 2 99192 IR010   0.0     0
 2 99192 IR003  60.0     0
 2 99195 IR003  60.0     0
 2 99198 IR003  60.0     0
 2 99201 IR003  60.0     0
 2 99205 IR003  60.0     0
 2 99207 IR003  60.0     0
 2 99219 IR003  60.0     0
 2 99221 IR003  60.0     0
 2 99223 IR003  60.0     0
 2 99226 IR003  60.0     0
 2 99244 IR003  60.0     0
 2 99247 IR003  60.0     0
 2 99250 IR003  60.0     0
 2 99253 IR003  60.0     0
 2 99274 IR003  60.0     0
```

```
 2 99277 IR003  60.0     0
 2 99282 IR003  60.0     0
 2 99289 IR003  60.0     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 3  0.80   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 3 00194 IR008  30.0     0
 3 00194 IR009 150.0     0
 3 00194 IR010   0.0     0
 3 00194 IR003  60.0     0
 3 00197 IR003  60.0     0
 3 00198 IR003  60.0     0
 3 00201 IR003  60.0     0
 3 00205 IR003  60.0     0
 3 00209 IR003  60.0     0
 3 00215 IR003  60.0     0
 3 00219 IR003  60.0     0
 3 00223 IR003  60.0     0
 3 00229 IR003  60.0     0
 3 00235 IR003  60.0     0
 3 00244 IR003  60.0     0
 3 00247 IR003  60.0     0
 3 00250 IR003  60.0     0
 3 00253 IR003  60.0     0
 3 00258 IR003  60.0     0
 3 00262 IR003  60.0     0
 3 00266 IR003  60.0     0
 3 00270 IR003  60.0     0
 3 00274 IR003  60.0     0
 3 00277 IR003  60.0     0
```

```
 3 00282 IR003  60.0     0
 3 00289 IR003  60.0     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 4   0.8   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 4 00194 IR008  30.0     0
 4 00194 IR009 150.0     0
 4 00194 IR010   0.0     0
 4 00194 IR003  60.0     0
 4 00197 IR003  60.0     0
 4 00198 IR003  60.0     0
 4 00201 IR003  60.0     0
 4 00205 IR003  60.0     0
 4 00209 IR003  60.0     0
 4 00219 IR003  60.0     0
 4 00223 IR003  60.0     0
 4 00235 IR003  60.0     0
 4 00247 IR003  60.0     0
 4 00253 IR003  60.0     0
 4 00262 IR003  60.0     0
 4 00270 IR003  60.0     0
 4 00274 IR003  60.0     0
 4 00282 IR003  60.0     0
 4 00289 IR003  60.0     0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 99207 FE005   -99     5     0   -99   -99   -99   -99   -99 -99
 1 99226 FE005   -99     5     5   -99   -99   -99   -99   -99 -99
 1 99260 FE005   -99     5     5   -99   -99   -99   -99   -99 -99
```

```
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 2 99207 FE005   -99     5    60   -99   -99   -99   -99   -99 -99
 2 99226 FE005   -99     5    35   -99   -99   -99   -99   -99 -99
 2 99260 FE005   -99     5    35   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 3 99207 FE005   -99     5    30   -99   -99   -99   -99   -99 -99
 3 99226 FE005   -99     5    20   -99   -99   -99   -99   -99 -99
 3 99260 FE005   -99     5    20   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 4 00210 FE005   -99     5     0   -99   -99   -99   -99   -99 -99
 4 00241 FE005   -99     5     5   -99   -99   -99   -99   -99 -99
 4 00272 FE005   -99     5     5   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 5 00210 FE005   -99     5    60   -99   -99   -99   -99   -99 -99
 5 00241 FE005   -99     5    35   -99   -99   -99   -99   -99 -99
 5 00272 FE005   -99     5    35   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 6 00210 FE005   -99     5    30   -99   -99   -99   -99   -99 -99
 6 00241 FE005   -99     5    20   -99   -99   -99   -99   -99 -99
 6 00272 FE005   -99     5    20   -99   -99   -99   -99   -99 -99

*RESIDUES AND ORGANIC FERTILIZER
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 1 99192 RE003  6000   1.0   -99   -99   -99    15   -99 -99
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 2 99195 RE003  6000   1.0   -99   -99   -99    15   -99 -99
```

```
*ENVIRONMENT MODIFICATIONS
@E ODATE EDAY  ERAD  EMAX  EMIN  ERAIN ECO2  EDEW  EWIND ENVNAME
 1 99191 A 0.0 A 0.0 A 0.0 A 0.0 A 0.0 A26.0 A 0.0 A 0.0
@E ODATE EDAY  ERAD  EMAX  EMIN  ERAIN ECO2  EDEW  EWIND ENVNAME
 2 00194 A 0.0 A 0.0 A 0.0 A 0.0 A 0.0 A26.0 A 0.0 A 0.0

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     1     S 99191  2150 IARI,New Delhi
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL  CARBO
 1 OP              Y     Y     Y     N     N     N     N     N      Y
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 1 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 1 OU              N     Y     Y     5     Y     Y     Y     Y     Y     Y     Y     Y     Y

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          99190 99200   -99   -99   -99    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR            -99   -99   -99 IB001 IB003   -99  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 IB001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01205    10     0
```

```
*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 2 GE              1     1     S 00194  2150 IARI,New Delhi
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL  CARBO
 2 OP              Y     Y     Y     N     N     N     N     N      Y
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 2 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 2 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 2 OU              N     Y     Y     5     Y     Y     Y     Y     Y     Y     Y     Y     Y

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 2 PL          00199 00200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 2 IR             30    50   100 IB001 IB001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 2 NI             30    50    25 IB001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 2 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01205    10     0
```

Appendix Table 2: Experimental FileX for Ludhiana

```
*EXP.DETAILS: PULU0101ri PAU LUDHIANA JUNE 2001 N X W INTERACTION

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 0 0 Control 0 N(1 D DRAINAGE)  1  1  0  1  1  1  0  1  0  0  0  0  1
 2 1 0 0 120 kgN as urea(40+40+40)  1  1  0  1  1  1  1  1  0  0  0  0  1
 3 1 0 0 20 kg N/ha basal + LCC4    1  1  0  1  1  1  2  1  0  0  0  0  1
 4 1 0 0 Control 0 N(3 D Drainage)  1  1  0  1  1  2  0  1  0  0  0  0  1
 5 1 0 0 120 kgN urea(40+40+40)3D   1  1  0  1  1  2  1  1  0  0  0  0  1
 6 1 0 0 20 kg N basal + LCC4 3D    1  1  0  1  1  2  2  1  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 RI IB0050 PR 114

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST  SLTX  SLDP ID_SOIL    FLNAME
 1 PULU0101 LUDH       -99     0 DR000     0     0 00000  LOSA   150 PULU010001 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 1         0.00000         0.00000      0.00               0.0     0   0.0   0.0

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    WH 01150   -99   -99   -99   -99 -99.0     0  0.00  0.00   100    15 -99
@C  ICBL  SH2O  SNH4  SNO3
 1    15 0.250   4.2   5.6
 1    30 0.300   4.2   2.8
 1    45 0.310   3.5   3.5
 1    60 0.320   2.8   1.4
```

```
 1    75 0.310   4.2   1.4

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL PLNAME
 1 01160   -99  33.0  33.0     T     H    20     0   3.0     0    35  30.0   2.0   0.0    -99

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1 -99.00   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 1 01160 IB010     0     0
 1 01160 IB008    50     0
 1 01160 IB009   150     0
 1 01160 IB003    70     0
 1 01162 IB003    70     0
 1 01164 IB003    70     0
 1 01168 IB003    70     0
 1 01170 IB003    70     0
 1 01176 IB003    70     0
 1 01178 IB003    70     0
 1 01180 IB003    70     0
 1 01193 IB003    70     0
 1 01201 IB003    70     0
 1 01204 IB003    70     0
 1 01211 IB003    70     0
 1 01213 IB003    70     0
 1 01216 IB003    70     0
 1 01218 IB003    70     0
 1 01225 IB003    70     0
 1 01229 IB003    70     0
 1 01232 IB003    70     0
```

```
 1 01241 IB003    70     0
 1 01243 IB003    70     0
 1 01246 IB003    70     0
 1 01250 IB003    70     0
 1 01253 IB003    70     0
 1 01257 IB003    70     0
 1 01260 IB003    70     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 2 -99.00   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 2 01160 IB010     0     0
 2 01160 IB008    50     0
 2 01160 IB009   150     0
 2 01160 IB003    70     0
 2 01162 IB003    70     0
 2 01164 IB003    70     0
 2 01168 IB003    70     0
 2 01170 IB003    70     0
 2 01176 IB003    70     0
 2 01178 IB003    70     0
 2 01204 IB003    70     0
 2 01213 IB003    70     0
 2 01218 IB003    70     0
 2 01232 IB003    70     0
 2 01241 IB003    70     0
 2 01246 IB003    70     0
 2 01253 IB003    70     0
 2 01260 IB003    70     0

*FERTILIZERS
```

```
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 01162 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 1 01183 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 1 01201 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 2 01162 FE005 AP001     0    20   -99   -99   -99   -99   -99 -99
 2 01177 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99
 2 01194 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99
 2 01221 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99

*RESIDUES AND OTHER ORGANIC MATERIALS
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 1 01159 RE001   300  0.50  0.07  0.50   100    15   -99 -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     3     S 01150  2150 PAU, LUDHIANA, JUN 01 NXW
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL
 1 OP              Y     Y     N     N     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 1 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 1 OU              N     Y     Y     1     Y     Y     Y     Y     N     N     Y     N     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          01155 01200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 IB001 IB001    10  0.75
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
```

```
 1 NI              30    50    25 IB001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE             100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA               0 01365   100     0
```

Appendix Table 3: Experimental input FileX for Modipuram

```
*EXP.DETAILS: MODIPURAM, UTTAR PRADESH, INDIA, LCC EXPT. RICE 2001

*GENERAL
@ADDRESS: PDCSR, MODIPURAM, UTTAR PRADESH, INDIA

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 1 0   0 kg N as urea(N0        1  1  0  1  1  1  0  0  0  0  0  0  1
 2 1 1 0  60 kg N as urea(LCC 2     1  1  0  1  1  1  1  0  0  0  0  0  1
 3 1 1 0 120 kg N as urea(LCC 3     1  1  0  1  1  1  2  0  0  0  0  0  1
 4 1 1 0 160 kg N as urea(LCC 4     1  1  0  1  1  1  3  0  0  0  0  0  1
 5 1 1 0 120 kg N as urea(REC       1  1  0  1  1  1  4  0  0  0  0  0  1
 6 1 1 0 150 kg N as urea(FP        1  1  0  1  1  1  5  0  0  0  0  0  1
 7 1 1 0   0 kg N as urea(N0        2  1  0  1  1  1  0  0  0  0  0  0  1
 8 1 1 0  60 kg N as urea(LCC 3     2  1  0  1  1  1  1  0  0  0  0  0  1
 9 1 1 0 120 kg N as urea(LCC 4     2  1  0  1  1  1  2  0  0  0  0  0  1
10 1 1 0 160 kg N as urea(LCC 5     2  1  0  1  1  1  3  0  0  0  0  0  1
11 1 1 0 120 kg N as urea(REC       2  1  0  1  1  1  4  0  0  0  0  0  1
12 1 1 0 150 kg N as urea(FP        2  1  0  1  1  1  5  0  0  0  0  0  1
13 1 1 0   0 kg N as urea(N0        3  1  0  1  1  1  0  0  0  0  0  0  1
14 1 1 0  60 kg N as urea(LCC 3     3  1  0  1  1  1  1  0  0  0  0  0  1
15 1 1 0 120 kg N as urea(LCC 4     3  1  0  1  1  1  2  0  0  0  0  0  1
16 1 1 0 160 kg N as urea(LCC 5     3  1  0  1  1  1  3  0  0  0  0  0  1
17 1 1 0 120 kg N as urea(REC       3  1  0  1  1  1  4  0  0  0  0  0  1
18 1 1 0 150 kg N as urea(FP        3  1  0  1  1  1  5  0  0  0  0  0  1
19 1 1 0   0 kg N as urea(N0        1  1  0  2  2  2  0  0  0  0  0  0  2
20 1 1 0  60 kg N as urea(LCC 2     1  1  0  2  2  2  6  0  0  0  0  0  2
21 1 1 0 120 kg N as urea(LCC 3     1  1  0  2  2  2  7  0  0  0  0  0  2
22 1 1 0 160 kg N as urea(LCC 4     1  1  0  2  2  2  8  0  0  0  0  0  2
```

```
23 1 1 0 120 kg N as urea(REC       1  1  0  2  2  2  9  0  0  0  0  0  2
24 1 1 0 150 kg N as urea(FP        1  1  0  2  2  2 10  0  0  0  0  0  2
25 1 1 0   0 kg N as urea(N0        2  1  0  2  2  2  0  0  0  0  0  0  2
26 1 1 0  60 kg N as urea(LCC 3     2  1  0  2  2  2  6  0  0  0  0  0  2
27 1 1 0 120 kg N as urea(LCC 4     2  1  0  2  2  2  7  0  0  0  0  0  2
28 1 1 0 160 kg N as urea(LCC 5     2  1  0  2  2  2  8  0  0  0  0  0  2
29 1 1 0 120 kg N as urea(REC       2  1  0  2  2  2  9  0  0  0  0  0  2
30 1 1 0 150 kg N as urea(FP        2  1  0  2  2  2 10  0  0  0  0  0  2
31 1 1 0   0 kg N as urea(N0        3  1  0  2  2  2  0  0  0  0  0  0  2
32 1 1 0  60 kg N as urea(LCC 3     3  1  0  2  2  2  6  0  0  0  0  0  2
33 1 1 0 120 kg N as urea(LCC 4     3  1  0  2  2  2  7  0  0  0  0  0  2
34 1 1 0 160 kg N as urea(LCC 5     3  1  0  2  2  2  8  0  0  0  0  0  2
35 1 1 0 120 kg N as urea(REC       3  1  0  2  2  2  9  0  0  0  0  0  2
36 1 1 0 150 kg N as urea(FP        3  1  0  2  2  2 10  0  0  0  0  0  2


*CULTIVARS
@C CR INGENO CNAME
 1 RI IT0001 BASMATI 370
 2 RI CS0001 SAKET 4
 3 RI IR0130 HYBRID 6111

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX   SLDP ID_SOIL    FLNAME
 1 PDCSR    MODI     -99.0     0 IB000     0     0 00000 SALO    120 IBWH980112  -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 1         0.00000         0.00000      0.00               0.0     0   0.0   0.0
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX   SLDP ID_SOIL    FLNAME
 2 PDCSR    MODI     -99.0     0 IB000     0     0 00000 SALO    120 IBWH980112  -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 2         0.00000         0.00000      0.00               0.0     0   0.0   0.0
```

```
*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    RI 01183   200   -99  1.00  1.00 -99.0     0  0.40  0.00   100    15  -99
@C  ICBL  SH2O  SNH4  SNO3
 1    30 0.430   4.2   2.7
 1    60 0.410   2.4   1.9
 1   120 0.410   1.2   1.0

@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID
 2    RI 02188   200   -99  1.00  1.00 -99.0     0  0.00  0.00   100    15
@C  ICBL  SH2O  SNH4  SNO3
 2    30 0.430   4.0   2.6
 2    60 0.410   2.2   2.0
 2   120 0.410   1.0   1.0


*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
 1 01187   -99    35   -99     T     H    20     0   2.0   -99    23  36.0   3.0
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH
 2 02193   -99    35   -99     T     H    20     0   2.0   -99    23  36.0   3.0

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT
 1   0.8   -99   -99   -99   -99   -99    10
@I IDATE  IROP IRVAL  IIRV
 1 01183 IR008  30.0     0
 1 01183 IR009 150.0     0
 1 01183 IR010   0.0     0
 1 01186 IR003  60.0     0
```

```
 1 01189 IR003  60.0     0
 1 01192 IR003  60.0     0
 1 01195 IR003  60.0     0
 1 01197 IR003  60.0     0
 1 01199 IR003  60.0     0
 1 01205 IR003  60.0     0
 1 01209 IR003  60.0     0
 1 01213 IR003  60.0     0
 1 01217 IR003  60.0     0
 1 01221 IR003  60.0     0
 1 01223 IR003  60.0     0
 1 01226 IR003  60.0     0
 1 01229 IR003  60.0     0
 1 01235 IR003  60.0     0
 1 01238 IR003  60.0     0
 1 01242 IR003  60.0     0
 1 01244 IR003  60.0     0
 1 01247 IR003  60.0     0
 1 01250 IR003  60.0     0
 1 01253 IR003  60.0     0
 1 01258 IR003  60.0     0
 1 01262 IR003  60.0     0
 1 01266 IR003  60.0     0
 1 01270 IR003  60.0     0
 1 01274 IR003  60.0     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT
 2   0.8   -99   -99   -99   -99   -99    10
@I IDATE  IROP IRVAL  IIRV
 2 02187 IR010   0.0     0
 2 02187 IR008  30.0     0
```

```
 2 02187 IR009 150.0     0
 2 02187 IR003  60.0     0
 2 02190 IR003  60.0     0
 2 02195 IR003  60.0     0
 2 02197 IR003  60.0     0
 2 02202 IR003  60.0     0
 2 02208 IR003  60.0     0
 2 02211 IR003  60.0     0
 2 02221 IR003  60.0     0
 2 02223 IR003  60.0     0
 2 02226 IR003  60.0     0
 2 02238 IR003  60.0     0
 2 02242 IR003  60.0     0
 2 02247 IR003  60.0     0
 2 02258 IR003  60.0     0
 2 02262 IR003  60.0     0
 2 02270 IR003  60.0     0
 2 02274 IR003  60.0     0
 2 02277 IR003  60.0     0
 2 02280 IR003  60.0     0
 2 02286 IR003  60.0     0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 1 01194 FE005 AP000     5    30    26    25   -99   -99   -99
 1 01227 FE005 AP000     5    15     0     0   -99   -99   -99
 1 01257 FE005 AP000     5    15     0     0   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 2 01194 FE005 AP000     5    60    26    25   -99   -99   -99
 2 01227 FE005 AP000     5    30     0     0   -99   -99   -99
 2 01257 FE005 AP000     5    30     0     0   -99   -99   -99
```

```
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 3 01194 FE005 AP000     5    60    26    25   -99   -99   -99
 3 01227 FE005 AP000     5    50     0     0   -99   -99   -99
 3 01257 FE005 AP000     5    50     0     0   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 4 01194 FE005 AP000     5    60    26    25   -99   -99   -99
 4 01227 FE005 AP000     5    30     0     0   -99   -99   -99
 4 01257 FE005 AP000     5    30     0     0   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 5 01194 FE005 AP000     5    60    26    25   -99   -99   -99
 5 01227 FE005 AP000     5    50     0     0   -99   -99   -99
 5 01257 FE005 AP000     5    40     0     0   -99   -99   -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 6 02200 FE005 AP000     5    30   -99   -99   -99   -99   -99
 6 02233 FE005 AP000     5    15   -99   -99   -99   -99   -99
 6 02263 FE005 AP000     5    15   -99   -99   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 7 02200 FE005 AP000     5    60   -99   -99   -99   -99   -99
 7 02233 FE005 AP000     5    30   -99   -99   -99   -99   -99
 7 02263 FE005 AP000     5    30   -99   -99   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 8 02200 FE005 AP000     5    60   -99   -99   -99   -99   -99
 8 02233 FE005 AP000     5    50   -99   -99   -99   -99   -99
 8 02263 FE005 AP000     5    50   -99   -99   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
 9 02200 FE005 AP000     5    60   -99   -99   -99   -99   -99
 9 02233 FE005 AP000     5    30   -99   -99   -99   -99   -99
 9 02263 FE005 AP000     5    30   -99   -99   -99   -99   -99
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD
10 02200 FE005 AP000     5    60   -99   -99   -99   -99   -99
```

```
10 02233 FE005 AP000     5    50   -99   -99   -99   -99   -99
10 02263 FE005 AP000     5    40   -99   -99   -99   -99   -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE              1     1     S 01186  2150 PDCSR, MODIPURAM
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL
 1 OP              Y     Y     N     N     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 1 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     N     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 1 OU              N     Y     Y     3     Y     Y     Y     Y     N     N     Y     N     N

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 2 GE              1     1     S 02186  2150 PDCSR, MODIPURAM
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL
 2 OP              Y     Y     N     N     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 2 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 2 MA              R     R     R     N     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 2 OU              N     Y     Y     3     Y     Y     Y     Y     N     N     Y     N     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          01179 01183    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
```

```
 1 IR              30    50   100 IB001 IB001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI              30    50   25  FE001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE             100     1    20
@N HARVEST     HFRST  HLAST HPCNP HPCNR
 1 HA               0  01365   100     0

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 2 PL          02179 02183    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 2 IR              30    50   100 IB001 IB001    10  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 2 NI              30    50   25  FE001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 2 RE             100     1    20
@N HARVEST     HFRST  HLAST HPCNP HPCNR
 2 HA               0  02365   100     0
```

Appendix Table 4: Soil input file for three sites

```
*IBWH980011  IARI Delhi          120       Loam
@SITE        COUNTRY          LAT     LONG SCS FAMILY
 DELHI       India           28.6     77.2
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
   -99  0.18   5.0   0.7    70  1.00   1.0 IB001 IB001 IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB SCEC
    15   -99 0.063 0.165 0.360 1.000  1.13  1.38  0.45    21    33     0  0.03   8.2   8.0  7.3
    45   -99 0.057 0.140 0.340 1.000  0.12  1.45  0.25    21    30     0  0.02   8.1   7.0  -99
    75   -99 0.057 0.140 0.330 1.000  0.09  1.50  0.15    21    30     0  0.01   8.1   7.0  -99
   120   -99 0.050 0.135 0.320 0.820  0.06  1.50  0.10    20    30     0  0.01   8.1   7.0  -99

*IBWH980112  PDCSR FIELD         150      Sandy CLAY Loam
@SITE        COUNTRY          LAT     LONG SCS FAMILY
 MODIPURAM   India           29.4     77.4
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
   -99  0.18   5.0  0.70  70.0  1.00  1.00 IB001 IB001 IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB SCEC
    15   -99  0.17  0.35  0.43 1.000   1.1  1.46  0.54  16.0  19.0  00.0 0.071   7.4   8.2 12.2
    45   -99  0.14  0.33  0.45 1.000   0.2  1.56  0.51  17.0  20.0  00.0 0.061   7.4   8.2  -99
   120   -99  0.14  0.33  0.44 1.000   0.2  1.56  0.51  17.0  20.0  00.0 0.051   7.4   8.2  -99

*PULU010001   SOILSPAU     LOSA     150 ENTISOL, Typic Ustipsamment, Fatehpur Series
@SITE        COUNTRY          LAT     LONG SCS FAMILY
 LUDHIANA    INDIA          30.55    75.51 Typic Ustipsamment
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
   -99  0.20   5.0  0.60  60.0  1.00  0.90 SA001 SA001 SA006
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB SCEC
    15   -99  0.06  0.22  0.40  1.00   -99  1.58  0.39  0.08  0.15  0.77   -99   6.5   -99 10.3
    30   -99  0.06  0.22  0.38  0.90   -99  1.72  0.14  0.08  0.18  0.74   -99   7.1   -99  9.8
```

```
45    -99  0.05  0.22  0.35  0.75   -99  1.68  0.21  0.07  0.10  0.83   -99   7.1   -99  8.4
60    -99  0.04  0.21  0.34  0.50   -99  1.68  0.13  0.06  0.04  0.90   -99   7.2   -99  7.7
75    -99  0.04  0.20  0.33  0.25   -99  1.68  0.11  0.06  0.08  0.86   -99   7.2   -99  7.2
```

Appendix Table 5: Seasonal analysis input file for Delhi

```
*EXP.DETAILS: INDL0001RI IARI 1999-2000 GREENHOUSE GAS EMISSION STUDIES


*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 0 0 Control 0 N (SAT-99)       1  1  1  1  1  1  1  0  0  0  1  0  1
 2 1 0 0 120 urea (SAT-99)          1  1  1  1  1  1  2  0  0  0  1  0  1
 3 1 0 0 120 kg N FYM (SAT-99)      1  1  1  1  1  1  3  1  0  0  1  0  1
 4 1 0 0 120 kg N DcD (SAT-99)      1  1  1  1  1  1  2  0  0  0  1  0  1
 5 1 0 0 Control 0 N (AWD-99)       1  1  1  1  1  2  1  0  0  0  1  0  1
 6 1 0 0 120 kg N urea (AWD-99)     1  1  1  1  1  2  2  0  0  0  1  0  1
 7 1 0 0 120 kg N FYM (AWD-99)      1  1  1  1  1  2  3  1  0  0  1  0  1
 8 1 0 0 120 kg N DCD (AWD-99)      1  1  1  1  1  2  2  0  0  0  1  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 RI IA0001 PUSA 44

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL    FLNAME
 1 MB14 C   DELH       -99     0 IB000     0     0 00000 -99     50  IBWH980011 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 1         0.00000         0.00000      0.00               0.0   0.0   0.0   0.0

*SOIL ANALYSIS
@A SADAT  SMHB  SMPX  SMKE  SANAME
 1 68193   -99   -99   -99  -99
@A  SABL  SADM  SAOC  SANI SAPHW SAPHB  SAPX  SAKE
 1    15   1.4  0.44  0.04   8.1 -99.0  10.0  45.0
```

```
*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    WH 68193   200   -99  1.00  1.00 -99.0   200  0.40  0.00   100    15 -99
@C  ICBL  SH2O  SNH4  SNO3
 1    15 0.320   4.2   3.0
 1    30 0.320   2.3   1.8
 1    45 0.320   1.3   1.0
 1    60 0.300   0.8   1.0
 1    90 0.300   0.3   0.8
 1   120 0.300   0.3   0.8

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL  PLNAME
 1 68196   -99  35.0 -99.0     T     H    20     0   2.0     0    22  36.0   3.0   0.0      -99

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1  0.80   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 1 68192 IR008  30.0     0
 1 68192 IR009 150.0     0
 1 68192 IR010   0.0     0
 1 68192 IR003  60.0     0
 1 68195 IR003  60.0     0
 1 68198 IR003  60.0     0
 1 68201 IR003  60.0     0
 1 68205 IR003  60.0     0
 1 68207 IR003  60.0     0
 1 68209 IR003  60.0     0
 1 68211 IR003  60.0     0
```

```
 1 68215 IR003  60.0     0
 1 68217 IR003  60.0     0
 1 68219 IR003  60.0     0
 1 68221 IR003  60.0     0
 1 68223 IR003  60.0     0
 1 68226 IR003  60.0     0
 1 68229 IR003  60.0     0
 1 68232 IR003  60.0     0
 1 68235 IR003  60.0     0
 1 68240 IR003  60.0     0
 1 68244 IR003  60.0     0
 1 68247 IR003  60.0     0
 1 68250 IR003  60.0     0
 1 68253 IR003  60.0     0
 1 68258 IR003  60.0     0
 1 68262 IR003  60.0     0
 1 68264 IR003  60.0     0
 1 68270 IR003  60.0     0
 1 68274 IR003  60.0     0
 1 68277 IR003  60.0     0
 1 68282 IR003  60.0     0
 1 68289 IR003  60.0     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 2   0.8   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 2 68192 IR008  30.0     0
 2 68192 IR009 150.0     0
 2 68192 IR010   0.0     0
 2 68192 IR003  60.0     0
 2 68195 IR003  60.0     0
```

```
 2 68198 IR003  60.0     0
 2 68201 IR003  60.0     0
 2 68205 IR003  60.0     0
 2 68207 IR003  60.0     0
 2 68219 IR003  60.0     0
 2 68221 IR003  60.0     0
 2 68223 IR003  60.0     0
 2 68226 IR003  60.0     0
 2 68244 IR003  60.0     0
 2 68247 IR003  60.0     0
 2 68250 IR003  60.0     0
 2 68253 IR003  60.0     0
 2 68274 IR003  60.0     0
 2 68277 IR003  60.0     0
 2 68282 IR003  60.0     0
 2 68289 IR003  60.0     0

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 68207 FE005   -99     5     0   -99   -99   -99   -99   -99 -99
 1 68226 FE005   -99     5     5   -99   -99   -99   -99   -99 -99
 1 68260 FE005   -99     5     5   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 2 68207 FE005   -99     5    60   -99   -99   -99   -99   -99 -99
 2 68226 FE005   -99     5    35   -99   -99   -99   -99   -99 -99
 2 68260 FE005   -99     5    35   -99   -99   -99   -99   -99 -99

@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 3 68207 FE005   -99     5    30   -99   -99   -99   -99   -99 -99
 3 68226 FE005   -99     5    20   -99   -99   -99   -99   -99 -99
```

```
 3 68260 FE005   -99     5    20   -99   -99   -99   -99   -99 -99

*RESIDUES AND ORGANIC FERTILIZER
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 1 68192 RE003  6000   1.0   -99   -99   -99    15   -99 -99

*ENVIRONMENT MODIFICATIONS
@E ODATE EDAY  ERAD  EMAX  EMIN  ERAIN ECO2  EDEW  EWIND ENVNAME
 1 68191 A 0.0 A 0.0 A 0.0 A 0.0 A 0.0 A26.0 A 0.0 A 0.0

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE             34     1     S 68191  2150 IARI,New Delhi
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL  CARBO
 1 OP              Y     Y     Y     N     N     N     N     N      Y
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 1 ME              M     S     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 1 OU              Y     Y     Y     5     Y     Y     Y     Y     Y     Y     Y     Y     Y

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          68190 68200   -99   -99   -99    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR            -99   -99   -99 IB001 IB003   -99  1.00
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 IB001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
```

```
@N HARVEST      HFRST HLAST HPCNP HPCNR
 1 HA               0 01205    10     0
```

Appendix Table 6: Seasonal analysis input file for Ludhiana

```
*EXP.DETAILS: PULU0101ri PAU LUDHIANA JUNE 2001 N X W INTERACTION  (NATP)
@ADDRESS
 PUNJAB AGRIL UNIVERSITY, LUDHIANA , INDIA

*TREATMENTS                        -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 0 0 Control 0 N(1 D DRAINAGE)  1  1  0  1  1  1  0  1  0  0  0  0  1
 2 1 0 0 120 kgN as urea(40+40+40)  1  1  0  1  1  1  1  1  0  0  0  0  1
 3 1 0 0 20 kg N/ha basal + LCC4    1  1  0  1  1  1  2  1  0  0  0  0  1
 4 1 0 0 Control 0 N(3 D Drainage)  1  1  0  1  1  2  0  1  0  0  0  0  1
 5 1 0 0 120 kgN urea(40+40+40)3D   1  1  0  1  1  2  1  1  0  0  0  0  1
 6 1 0 0 20 kg N basal + LCC4 3D    1  1  0  1  1  2  2  1  0  0  0  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 RI IB0050 PR 114

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST  SLTX  SLDP ID_SOIL    FLNAME
 1 PULU7001 LUDH       -99     0 DR000     0     0 00000  LOSA   150 PULU010001 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS
 1         0.00000         0.00000      0.00               0.0     0   0.0   0.0

*INITIAL CONDITIONS
@C   PCR ICDAT  ICRT  ICND  ICRN  ICRE  ICWD ICRES ICREN ICREP ICRIP ICRID ICNAME
 1    WH 01150   -99   -99   -99   -99 -99.0     0  0.00  0.00   100    15 -99
@C  ICBL  SH2O  SNH4  SNO3
 1    15 0.250   4.2   5.6
 1    30 0.300   4.2   2.8
```

```
 1    45 0.310   3.5   3.5
 1    60 0.320   2.8   1.4
 1    75 0.310   4.2   1.4

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV  PLPH  SPRL PLNAME
 1 70160   -99  33.0  33.0     T     H    20     0   3.0     0    35  30.0   2.0   0.0    -99

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1 -99.00   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 1 70160 IB010     0     0
 1 70160 IB008    50     0
 1 70160 IB009   150     0
 1 70160 IB003    70     0
 1 70162 IB003    70     0
 1 70164 IB003    70     0
 1 70168 IB003    70     0
 1 70170 IB003    70     0
 1 70176 IB003    70     0
 1 70178 IB003    70     0
 1 70180 IB003    70     0
 1 70193 IB003    70     0
 1 70201 IB003    70     0
 1 70204 IB003    70     0
 1 70211 IB003    70     0
 1 70213 IB003    70     0
 1 70216 IB003    70     0
 1 70218 IB003    70     0
 1 70225 IB003    70     0
```

```
 1 70229 IB003    70     0
 1 70232 IB003    70     0
 1 70241 IB003    70     0
 1 70243 IB003    70     0
 1 70246 IB003    70     0
 1 70250 IB003    70     0
 1 70253 IB003    70     0
 1 70257 IB003    70     0
 1 70260 IB003    70     0

@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 2 -99.00   -99   -99   -99   -99   -99   -99 -99
@I IDATE  IROP IRVAL  IIRV
 2 70160 IB010     0     0
 2 70160 IB008    50     0
 2 70160 IB009   150     0
 2 70160 IB003    70     0
 2 70162 IB003    70     0
 2 70164 IB003    70     0
 2 70168 IB003    70     0
 2 70170 IB003    70     0
 2 70176 IB003    70     0
 2 70178 IB003    70     0
 2 70204 IB003    70     0
 2 70213 IB003    70     0
 2 70218 IB003    70     0
 2 70232 IB003    70     0
 2 70241 IB003    70     0
 2 70246 IB003    70     0
 2 70253 IB003    70     0
 2 70260 IB003    70     0
```

```
*FERTILIZERS
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 70162 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 1 70183 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 1 70201 FE005 AP001     0    40   -99   -99   -99   -99   -99 -99
 2 70162 FE005 AP001     0    20   -99   -99   -99   -99   -99 -99
 2 70177 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99
 2 70194 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99
 2 70221 FE005 AP001     0    30   -99   -99   -99   -99   -99 -99

*RESIDUES AND OTHER ORGANIC MATERIALS
@R RDATE  RCOD  RAMT  RESN  RESP  RESK  RINP  RDEP  RMET RENAME
 1 70159 RE001   300  0.50  0.07  0.50   100    15   -99 -99

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME....................
 1 GE             30     1     S 70150  2150 PAU, LUDHIANA, JUN 70 NXW
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL
 1 OP              Y     Y     N     N     N     N     N     N
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
 1 ME              M     M     E     R     S     C     R     1     G
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT MIOUT DIOUT  LONG CHOUT OPOUT
 1 OU              Y     Y     Y     1     Y     Y     Y     Y     N     N     Y     N     N

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          70155 70200    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
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 1 IR              30    50   100 IB001 IB001     10  0.75
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI              30    50    25 IB001 IB001
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE             100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA               0 70365   100     0
```