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InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. II. Performance of the model

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Abstract

InfoCrop, a generic crop model, simulates the effects of weather, soils, agronomic management (planting, nitrogen, residues and irrigation) and major pests on crop growth, yield, soil carbon, nitrogen and water, and greenhouse gas emissions. This paper presents results of its evaluation in terms of its validation for rice and wheat crops in contrasting agro-environments of tropics, sensitivity to the key inputs, and also illustrates two typical applications of the model. Eleven diverse field experiments, having treatments of location, seasons, varieties, nitrogen management, organic matter, irrigation, and multiple pest incidences were used for validation. Grain yields in these experiments varied from 2.8 to 7.2 ton ha^{-1} in rice and from 3.6 to 5.5 ton ha^{-1} in wheat. The results indicated that the model was generally able to explain the differences in biomass, grain yield, emissions of carbon dioxide, methane and nitrous oxides, and long-term trends in soil organic carbon, in diverse agro-environments. The losses in dry matter and grain yield due to different pests and their populations were also explained

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satisfactorily. There were some discrepancies in the simulated emission of these gases during first few days after sowing/transplanting possibly because of the absence of tillage effects in the model. The sensitivity of the model to change in ambient temperature, crop duration and pest incidence was similar to the available field knowledge. The application of the model to quantify multiple pests damage through iso-loss curves is demonstrated. Another application illustrated is the use of InfoCrop for analyzing the trade-offs between increasing crop production, agronomic management strategies, and their global warming potential.

Keywords: Infocrop; Simulation; Crop model; Validation; Climate change; GHG emissions; Soil carbon; Pest modelling

1. Introduction

Agriculture in tropical countries of Asia is today facing challenges due to stagnation in farm level productivity in intensive farming areas, trade uncertainties, competition for land and water by industry and urban settlements, and increasing environmental degradation (Sinha et al., 1998; FAO, 1999; Duxbury et al., 2000; Ladha et al., 2003; Aggarwal et al., 2004). At the same time, continued population growth is resulting in increasing food demand. The rising temperatures and carbon dioxide, and uncertainties in rainfall associated with global climatic change may further impact the food production (IPCC, 2001; Aggarwal, 2003). Agriculture, especially rice paddies, emits methane and nitrous oxide, which contribute to the enhanced greenhouse effect (IPCC, 2001). Since food production needs to be increased to meet the rising population driven demand, strategies need to be developed that can lead to higher food production while ensuring minimal greenhouse gas (GHG) emissions and maintaining soil fertility.

Simulation models can assist in examining the effect of different scenarios of future development on trade-offs between food production and its environmental impact. However, most of the currently available models are not able to fully meet the expanding requirement of integrated information on global change impacts, GHG emissions and soil carbon and nitrogen dynamics while simulating crop productivity. In addition, these models generally do not consider growth and yield loss due to insects and diseases, common in tropical and sub-tropical environments. In the companion paper (Aggarwal et al., 2005), we have described InfoCrop – a generic crop model developed to meet these specific requirements. The model simulates the effects of weather, soils, agronomic management (including planting, nitrogen, residues and irrigation) and major pests on crop growth, yield, soil carbon, water and nitrogen, and the associated environmental impacts. InfoCrop can be used for a variety of applications at field, farm and regional levels. The objective of this paper is to demonstrate the performance of the model, in terms of its validation for rice and wheat, including sensitivity to some major inputs. This is followed by demonstration of two typical applications of the model. The first application describes iso-loss curves for the simultaneous pest damage in wheat by rust and termites. Such curves are difficult to generate purely from field experiments but are required for pest monitoring and quantifying the damage potential of the population present on the crop at a given growth stage. These curves can further help in deciding the need for control measures when linked to the economic value of different loss levels. The second application explores the trade-offs between water and nitrogen management, yield, and GHG emissions in a futuristic scenario of increasing demand for rice production in tropics. This application has been demonstrated for eastern India, where yield gaps are large and the crop suffers from partial water and nutrient stresses (Aggarwal et al., 2000).

2. Materials and methods

2.1. Model

InfoCrop considers following processes of crop growth and development, soil water, nitrogen and carbon, and crop–pest interactions. Each process is described by a set of equations, in which the parameters vary depending upon the crop/cultivar.

- *Crop growth and development*: phenology, photosynthesis, partitioning, leaf area growth, storage organ numbers, source: sink balance, transpiration, and uptake, allocation and redistribution of nitrogen.
- Effects of water, nitrogen, temperature, flooding and frost stresses on crop growth and development.
- *Crop–pest interactions*: damage mechanisms of insects and diseases.
- *Soil water balance*: root water uptake, inter-layer movement, drainage, evaporation, runoff, ponding.
- *Soil nitrogen balance*: mineralisation, uptake, nitrification, volatilization, inter-layer movement, denitrification, leaching.
- *Soil organic carbon dynamics*: mineralisation and immobilization.
- *Emissions of green house gases*: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O).

The basic model is written in Fortran Simulation Translator programming language (FST/FSE; Graduate School of Production Ecology, Wageningen, The Netherlands; van Kraalingan, 1995), also recommended by the International Consortium for Agricultural Systems Applications (ICASA) as a standard languages for systems simulation (Jones et al., 2001). Another version of the model has been developed to facilitate its greater applications in agricultural research and development by the individuals interested in using simulation but not familiar with programming. The user-interface of this software has been written using Microsoft.Net framework while the back-end has FSE models and databases in MS-Access. More details of the model are provided in the companion paper (Aggarwal et al., 2005).

2.2. Field experiments for evaluation of model performance

Eleven independent field experiments dealing with crop–pest interactions, soil carbon dynamics, and emission of GHG in rice and wheat crops were used for the performance evaluation of the model. Except for Experiment 6 conducted at Cuttack (20°80′N and 85°93′E, 36 m asl) in eastern India (Reddy et al., 1993), and Experiment 11 conducted at Ludhiana (30°55′N and 75°54′E, 242 m asl), all experiments were done at the experimental farm of the Indian Agricultural Research Institute, New Delhi, India (28°40′N and 77°12′E, 216 m asl). The latter is sub-tropical, semi-arid, with annual rainfall of 750 mm. The mean maximum and minimum temperatures from July to October (rice season) are 35 and 18 °C and 22.6 and 6.7 °C from November to April (wheat season). The alluvial soil of experimental site was sandy loam in texture and has 0.45% organic carbon and 0.03% total N. Brief details of different experiments are as follows:

Experiment 1: Thirty days old rice seedlings (variety Pusa 44) were transplanted in 20 × 15 cm spacing on July 15, 1999 in a puddled field. The replicated experiment was fertilized with 120 kg N ha^{-1} added as surface broadcast of urea in three splits. Phosphorus and potassium were incorporated into the soil at the time of transplanting in all plots. Soil was maintained at saturation/flooded most of the times by applying frequent irrigations. Pests and diseases were controlled throughout the growth cycle of the crop. Emissions of CH_4, CO_2 and N_2O were measured frequently from the plots following the standard methodologies (Pathak et al., 2002, 2003).

Experiment 2: The rice Experiment 1 of 1999 was repeated in 2000 crop season. Emissions of only CH_4 and N_2O were measured frequently from the plots.

Experiment 3: The above experiment was again repeated in 2003 as well. Emissions of CH_4, CO_2 and N_2O were measured frequently from the plots.

Experiment 4: This experiment was also conducted at the same site in 2000 with rice variety Pusa-834 with an objective to understand pest–crop damage relationships. One-month-old seedlings were transplanted on 20 July. Recommended management of irrigation and fertilizers was followed. Tillers were removed surgically in several treatments to simulate the damage mechanism of stem borers. The following replicated treatments were imposed in this experiment:

1. Crop completely protected from diseases and pests.
2. Only insects present.
3. Protection from insects 40 days after transplanting (DAT).
4. Protection from insects from 60 DAT.
5. Protection from insects from 80 DAT.
6. Tiller removal @ 25% before flowering (50 DAT).
7. Tiller removal @ 50% before flowering (50 DAT).
8. Tiller removal @ 20% after flowering (70 DAT).
9. Tiller removal @ 40% after flowering (70 DAT).
10. Tiller removal @ 60% after flowering (70 DAT).

Data on insect pests incidence were recorded at weekly interval in various treatments following random sampling. The leaf folder (*Cnaphalocrosis medinalis)* incidence was recorded on 6 hills in each treatment by selecting one hill from each of the 6 centre rows of the plot. The number of total leaves and infested leaves due to leaf folder was recorded on each hill and percent leaf folder incidence determined. The treatments, which were to be protected against insect pests, were sprayed with profenofos insecticide. In the de-tillering treatments, tillers were artificially removed before flowering as well as after flowering depending upon the treatment. Data on dry matter and grain yield was recorded at maturity from a representative area of the plot.

Experiment 5: Experiment 4 with rice was repeated in 2001. The treatments in this experiment were modified slightly based on experience of the first experiment. The artificial tiller removal treatments to mimic stem borer damage were increased during second year. The treatments in this experiment were as follows:

1. Crop completely protected from diseases and pests.
2. Only insects present.
3. Insects and diseases present throughout.
4. Protection from insects from 50 DAT.
5. Protection from insects from 70 DAT.
6. Tiller removal @ 25% before flowering (40 DAT).
7. Tiller removal @ 50% before flowering (40 DAT).
8. Tiller removal @ 75% before flowering (40 DAT).
9. Tiller removal @ 25% before flowering (50 DAT).
10. Tiller removal @ 50% before flowering (50 DAT).
11. Tiller removal @ 75% before flowering (50 DAT).
12. Tiller removal @ 25% after flowering (70 DAT).
13. Tiller removal @ 50% after flowering (70 DAT).

Experiment 6: Since there was no leaf area measurements over time in the above experiments, a published experiment conducted earlier for bacterial leaf blight (BLB) disease effects on rice during 1993 at Cuttack, India (Reddy et al., 1993) was also used for validation of the model. The crop was transplanted in a well-puddled field on May 29 using 30-day old seedlings. The disease incidence was 'initiated' at three different crop development stages: at early tillering (70 days after sowing (DAS)), at late tillering (85 DAS), and at flag leaf appearance (95 DAS). The clipping method was used to inoculate the rice plants with BLB pathogen (Kauffman et al., 1973). Crop and disease characteristics were observed periodically on 5 plants in 3 adjacent rows.

Experiment 7: Wheat (variety HD 2329, 100 kg seed ha^{-1}) was sown on November 27, 1999 in rows. The replicated experiment was fertilized with 120 kg N ha^{-1} added as urea in 4 equal splits. The field was irrigated 5 times at recommended growth stages. Pests and diseases were controlled throughout the growth cycle. Emissions of CO_2 and N_2O were measured frequently from the plots following the standard methodologies (Pathak et al., 2002, 2003).

Experiment 8: The Experiment 7 with wheat was repeated in 2000–2001 season as well.

Experiment 9: This wheat experiment was also conducted at the same site in 2000–2001 with an objective to understand pest–crop damage relationships. Recommended doses of fertilizer and irrigation were applied at the desired stages. The treatments were as follows:

1. Crop completely free (insects and diseases completely protected).
2. Only insects allowed to infest.
3. Only diseases allowed to develop.
4. Insects and diseases allowed to infest till flowering.
5. Insects and diseases allowed to infest till maturity.
6. Tiller removal @ 10% before flowering to mimic stem borer damage.
7. Tiller removal @ 20% before flowering to mimic higher stem borer damage.

Experiment 10: Experiment 9 was repeated in 2001–2002 with wheat variety HD 2285. To ensure disease development, leaf rust *Puccinia recondita* was inoculated on the wheat crop by: (i) spraying spores of the fungus on the foliage; (ii) placing infected plants between the rows of the crop; (iii) by injecting spores of the fungus into the plant stems by a hypodermic syringe. The incidence of leaf rust was recorded on leaves of randomly selected eight tillers in each plot and Peterson's scale was used to calculate average incidence. The rust was controlled by spraying fungicide, henzee in treatments, which were to be kept free from disease.

The aphid population was recorded on randomly selected 30 tillers in each plot. The treatments, which were to be kept free of aphid incidence, were sprayed with insecticide, *Quinalphos*. The effect of stem borer, *Sesamia inferens* was imitated by artificial tiller removal before flowering as well as after flowering as per the treatments.

Experiment 11: Long-term data for evaluating model's performance in respect of changes in soil organic carbon is not easily available in the tropics. Published data of a long-term rice–wheat cropping system (Bhandari et al., 2002) conducted at Ludhiana in the Indo-Gangetic plains for 13 years (1985–1997) was used for this purpose although complete details of the agronomic management needed for simulation were not documented in the paper. The publication reported occasional measurements of soil organic carbon for the surface soil layer in few years. The soil of this experimental site was Typic Ustochrept with pH 8.15 and 0.38% organic carbon. The following four contrasting treatments were selected for the evaluation:

1. 100% recommended NPK applied as inorganic fertilizer.
2. 50% NPK + farmyard manure applied in rice and 100% NPK in wheat.
3. 50% NPK + green manure applied in rice and 100% NPK in wheat.
4. Control (no fertilizer addition).

2.3. Calibration

Crop coefficients used earlier in WTGROWS (Aggarwal et al., 1994) for wheat and ORYZA1 for rice (Aggarwal et al., 1997), earlier versions of InfoCrop are used in the present model. For calibration of damage coefficients related to pests, treatment 10 of Experiment 4 (rice) and treatment 4 of Experiment 10 (wheat) were used. Several coefficients are involved in the computation of soil carbon, water, and nitrogen, and emission of GHG (Aggarwal et al., 2005). Their values were largely based on the literature survey. Further calibration of these coefficients was done using Experiment 1 for rice and Experiment 8 for wheat by repeated iterations until a close match between simulated and observed values was obtained. These coefficients were used in the subsequent validation and application.

2.4. Validation

The basic phenology, crop growth, dry matter and yield of the parent models of InfoCrop (SUCROS, WTGROWS, ORYZA, and MACROS) have been extensively validated earlier (Aggarwal et al., 1994, 1997; Berge et al., 1997; Bouman et al., 2001; Sankaran et al., 2000; Mall and Aggarwal, 2002). These processes are generally the same in InfoCrop, therefore, relatively less attention has been paid now to their further validation.

The data of all experiments/treatments not used for calibration was used for the validation. Management practices relating to dates of seeding and transplanting, plant population, spacing, and applications of N and irrigation as measured in the different treatments were used in the simulation.

In case of simulation of long-term changes in soil carbon, some of the required inputs were not available. It was, therefore, assumed that the same varieties of rice and wheat were used every year, and the sowing dates/transplanting dates and irrigation management was typical of the standard for the region. InfoCrop does not yet have the capability to automatically simulate cropping systems in a multi-year time horizon. Therefore, for this evaluation, the first rice crop and soil (in 1985 crop season) were initialized with the standard parameters. The soil parameters at the harvest of rice were physically noted and used as the initial conditions for the following wheat crop. Similarly the soil parameters noted at the end of wheat season were used for the following rice crop. This sequence was followed every year.

2.5. Sensitivity analysis

The sensitivity of the model can be analyzed for a large number of input parameters. However, to keep the analysis to a manageable level, the model's response to changes in only three key inputs has only been studied. These were ambient temperature, thermal time required for vegetative crop duration, and pest damage due to rust and termite infestation. These studies were done using weather and soils data of New Delhi, a typical representative of sub-tropical environments. In all cases, optimal sowing dates and recommended fertilizer management was used. Simulation was done using 10 years of weather data, however, only the mean results are shown.

The effect of change in temperature was studied in irrigated rice and wheat for every 1 °C change in maximum as well as minimum temperatures during the entire life cycle. The range of such evaluation was from −6 to +6 °C. Crop duration has significant effect on the performance of both rice and wheat in the semi-tropical environments such as those of New Delhi. The sensitivity of the model to crop duration was evaluated by studying the impact of change in thermal time required from seedling emergence to flowering (TTVG). The sensitivity of the model to pest damage was analyzed by imposing different degrees of rust severity or termite infestation on a 60 days old wheat crop. It was assumed that the infestation continued for 20 days after which this was completely checked by application of pesticides.

2.6. Application of the model

2.6.1. Quantification of multiple pests damage (iso-loss curves)

Different scenarios were formulated by enforcing simultaneous incidence of rust disease on leaves and termite infestation at various growth stages of wheat crop. The simulated crop was sown at the recommended time with optimal level of fertilizers and irrigation. The simulations were done for 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% leaf rust infection and termite infestation. The effects of these incidences were assessed assuming a 10-day period of infestation at 40, 50, 60, 70, 80 and 90 days after sowing the crop. The results on yield loss were then used to plot iso-loss curves.

2.6.2. Trade-off between global warming potential and food production

To understand the magnitude of improvement in food production, and its linkage with the input management and its consequence on emissions of GHG and associated global warming potential, a simulation experiment was done for the lowland rice at Faizabad in Eastern India. The control crop was provided with 80 kg N ha^{-1} fertilizer, intermittent irrigation and no organic matter to mimic the current agronomic environment. Eight other treatments were also simulated where additional 80 kg N ha^{-1} was applied as either inorganic or as organic (farmyard manure) source. Interaction of these nutrient applications with two irrigation treatments (a) continuous flooding and (b) irrigation applied to maintain soil moisture at field capacity, were also simulated. In all there were 9 treatments as listed in Table 1. Simulations were done using 10 years of weather data of New Delhi. The mean simulated grain yield, irrigation applied, and cumulative emission of all GHGs and their global warming potential were calculated from the results.

3. Results and discussion

3.1. Model evaluation

3.1.1. Leaf area index

The performance of the model was evaluated for three treatments of rice of Expe-riment 5 where leaf area changes were measured and the incidence of disease was at different stages (Fig. 1). The results showed that InfoCrop was in general

Table 1
Simulated grain yields, irrigation water used, and global warming potential of different treatments of rice contrasting in inorganic/organic fertilizer management and irrigation

Inorganic N (kg ha^{-1})	Organic matter (kg ha^{-1})	Irrigation	Grain yield (kg ha^{-1})	Irrigation (mm)	Global warming potential (kg CO_2 ha^{-1})	Carbon efficiency (g CO_2 kg^{-1} grain)	Water use efficiency (kg ha^{-1} grain mm^{-1}) water used
80	0	Intermittent	3335	256	1239	371	13.04
80	0	Based on soil moisture	4212	729	1608	382	5.78
80	0	Continuous flooding	4475	1676	1882	421	2.67
160	0	Intermittent	4241	269	1384	326	15.79
160	0	Based on soil moisture	4913	754	1746	355	6.51
160	0	Continuous flooding	4966	1684	2014	406	2.95
80	80	Intermittent	4145	264	3235	780	15.68
80	80	Based on soil moisture	4937	754	4800	972	6.54
80	80	Continuous flooding	5139	1689	5679	1105	3.04

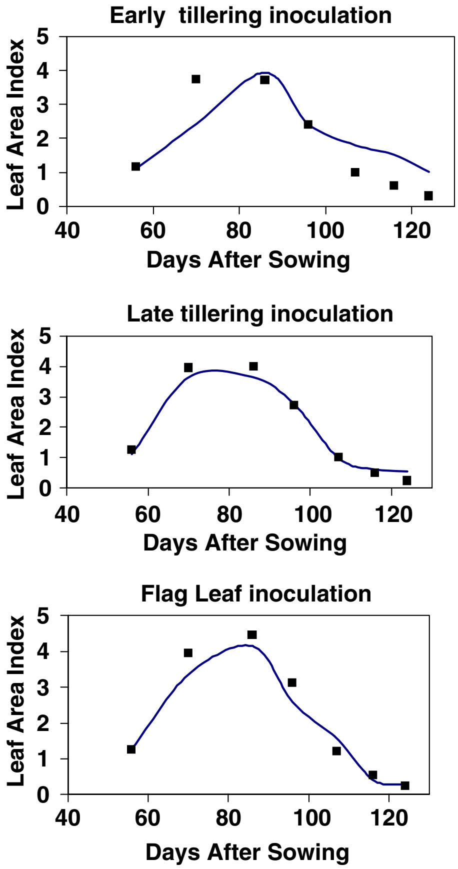

Fig. 1. Observed and InfoCrop simulated changes in LAI in three treatments, where pest damage was at different stages in rice.

able to simulate the temporal changes in leaf area index in all treatments satisfactorily except when incidence of disease was high in the beginning of the crop development.

3.1.2. Dry matter

Rice: The measured dry matter varied from 7.00 to 15.5 ton ha^{-1} in different treatments of Experiments 4 and 5 (Fig. 2). The grain yields in these experiments also showed a large variation of 2.8–7.3 ton ha^{-1}. In both experiments, the simulated dry matter was very close to the measured values. The RMSE was 0.81 ton ha^{-1} as compared to the mean value of 11.7 ton ha^{-1} indicating relatively small error. Similar response was also noticed for these experiments in terms of grain yield (Fig. 2). The RMSE of this was 0.44 ton ha^{-1} against the mean value of 5.3 ton ha^{-1} indicating the satisfactory performance of InfoCrop in terms of rice grain yield.

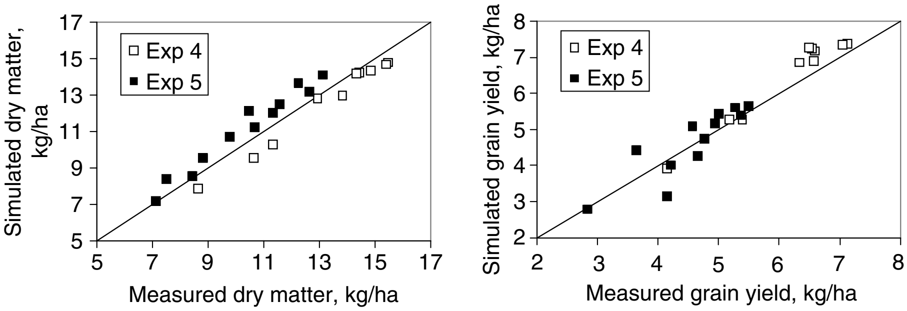

Fig. 2. Measured and simulated dry matter and grain yields in different experiments of rice. For details of the experiments, refer to Section 2.

Wheat: InfoCrop simulated dry matter and grain yield of all treatments of Experiments 9 and 10 satisfactorily (Fig. 3). The measured dry matter varied from 7.0 to 11.5 ton ha^{-1} and the grain yield varied from 3.5 to 5.7 ton ha^{-1}. The RMSE of dry matter was 0.55 ton ha^{-1} against the mean value of 9.9 ton ha^{-1}. Similarly RMSE for grain yield was 0.21 ton ha^{-1} against the mean value of 4.7 ton ha^{-1}.

3.1.3. Loss in dry matter due to pests

Rice: The loss in measured dry matter and grain yield due to pests across Experiments 4 and 5 varied from 0% to 48% (Fig. 4). Simulation model was able to explain the loss in dry matter very satisfactorily as is evident from a small RMSE of 2.8% only. Although the model was able to explain the trend in yield losses also adequately, the simulation was not as good as that of dry matter loss. This resulted in slightly higher RMSE (6.7%) for grain yield. This deviation was largely due to inadequate simulation of treatments 8 and 13 of Experiment 4 where the simulated stem borer damage was high.

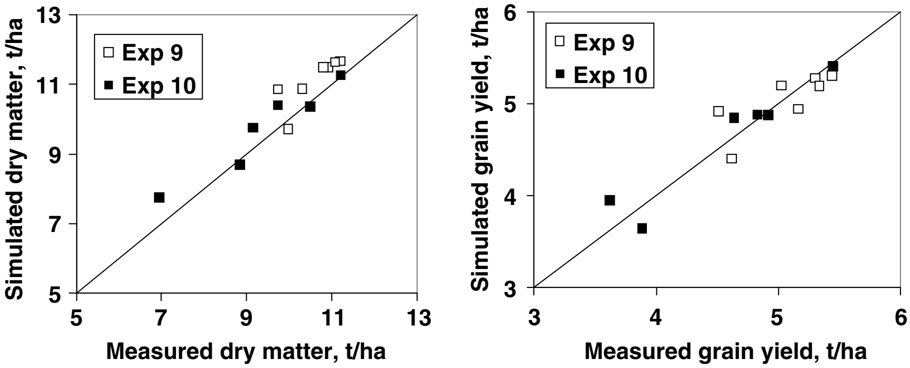

Fig. 3. Measured and simulated dry matter and grain yields in different experiments of wheat. For details of the experiments, refer to Section 2.

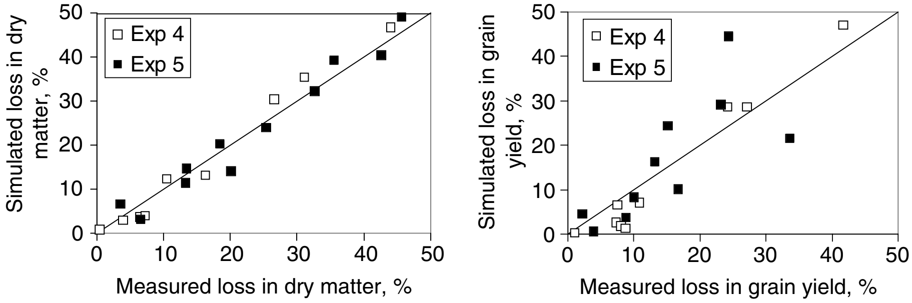

Fig. 4. Measured and simulated loss in dry matter and grain yields in different experiments of rice. For details of the experiments, refer to Section 2.

Wheat: The measured loss in dry matter varied from 0% to 40% in different treatments of Experiments 9 and 10 (Fig. 5). This loss in grain yield varied from 2% to 35% in case of grain yield. As in the case of rice, InfoCrop was able to explain these variations in dry matter as well as in grain yield very satisfactorily. The RMSE for dry matter loss was 3.7% and for grain yield was 4.7%.

3.1.4. Soil organic carbon

The control treatment in Experiment 11 showed that the soil organic carbon was maintained at around 0.4% in all years (Fig. 6). This gradually increased to 0.5% when the recommended dose of NPK was added. The build-up of organic carbon was further enhanced over time by the addition of organic matter especially farm yard manure. Similar trends in soil organic carbon are known for several places in the Indo-Gangetic plains (Katyal et al., 1998).

The simulated soil organic carbon was always very close to the observed carbon in the control treatment (Fig. 6). However, when NPK alone was applied the sim-

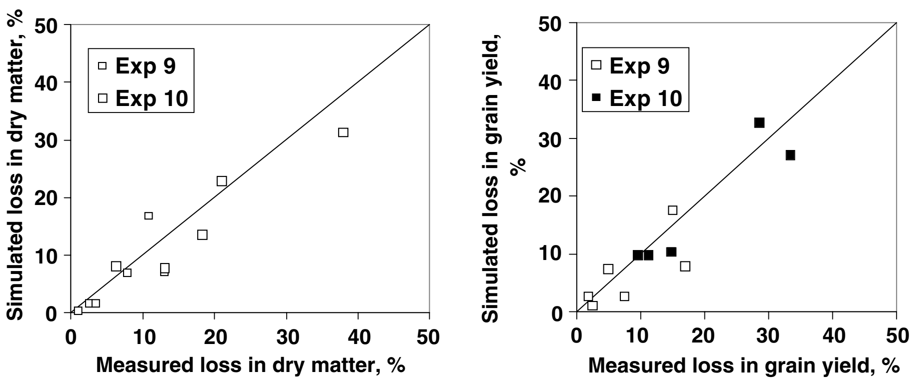

Fig. 5. Measured and simulated loss in dry matter and grain yields in different experiments of wheat. For details of the experiments, refer to Section 2.

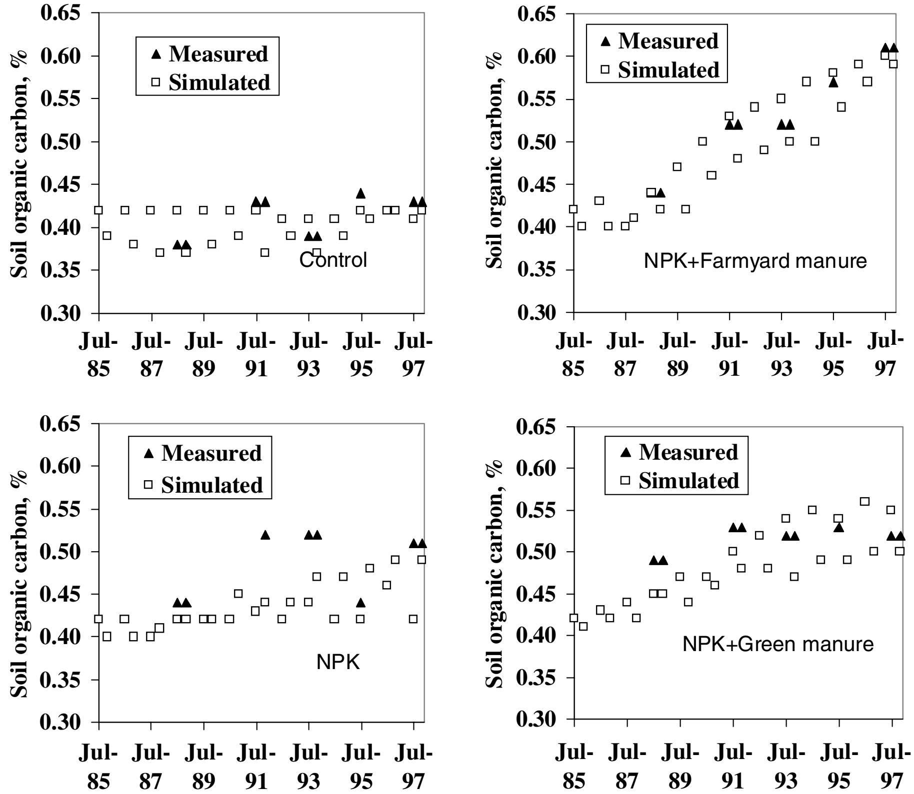

Fig. 6. Observed and simulated changes in soil organic carbon with time in a rice–wheat system at Ludhiana in north-western India for treatments contrasting in nutrient management. NPK refers to an application of 100% recommended dose of the ferilizers.

ulated organic carbon was considerably lower than the observed values between 1991 and 1994 crop season. The reason for this is not clear; possibly the inadequate calibration of the model and limited availability of input parameters from the experiment could be responsible for this. Nevertheless, at the end of the 13 years of the experiment, measured soil organic carbon was 0.51% and the simulated value was only marginally lower (0.49%). When green manure or farmyard manure was added the model again simulated satisfactorily the trend of change in soil organic carbon. In 50% NPK + green manure treatment, simulated values of organic carbon increased from 0.42% to 0.55% over the years, while in 50% NPK + FYM treatment it increased from 0.42% to 0.6%. In the first few years, the observed organic carbon was higher by upto 10% than the simulated values when green manure was added. Nevertheless, considering that there was only very limited calibration of the model, it can be concluded that despite these discrepancies, the model simulated the trend of change in organic carbon in all four treatments reasonably well.

3.1.5. Emission of GHG

Rice: The temporal variation in measured methane emission in 2000 and 2003 crop seasons varied from almost nil to 1.5 kg ha^{-1} day^{-1} (Figs. 7 and 8). This was due to changes in soil carbon and water management. The simulation model was in general able to explain these variations throughout the crop season satisfactorily. However, two major deviations were noticed. The model showed no significant methane emission immediately after transplanting for the first few days whereas there were measurements to the extent of 0.5 kg ha^{-1} day^{-1}. This could have been due to inadequate characterization of initial soil organic carbon in the field and the possibility of unsatisfactory simulation of surface ponding of water by the model. The later is the result of a large number of interactions between soil physical properties and water fluxes. Accurate simulation of water fluxes require very small time steps, whereas we have used a time step of one day keeping in view that the inputs should be simple and easily measurable, the overall goal of this model's development. The model showed a peak emission of 2.97 kg ha^{-1} day^{-1} on 51st day in 2000 (Fig. 7). A similar peak was observed on 35th day in 2003 (Fig. 8). Unfortunately, there were no measurements of methane emission on these specific days. It is, therefore, not clear if such peaks were correctly simulated.

The measured emission of N_2O varied from 1.0 to 18 g ha^{-1} day^{-1} in two years of sampling (Figs. 7 and 8). There were three/four peaks in the measurements coincid-

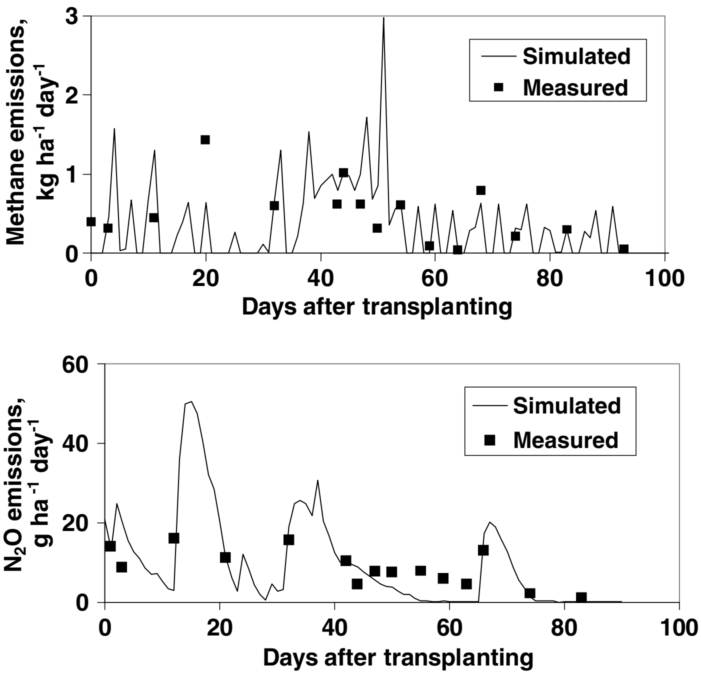

Fig. 7. Measured and simulated emissions of methane and nitrous oxide from rice crop of 2000.

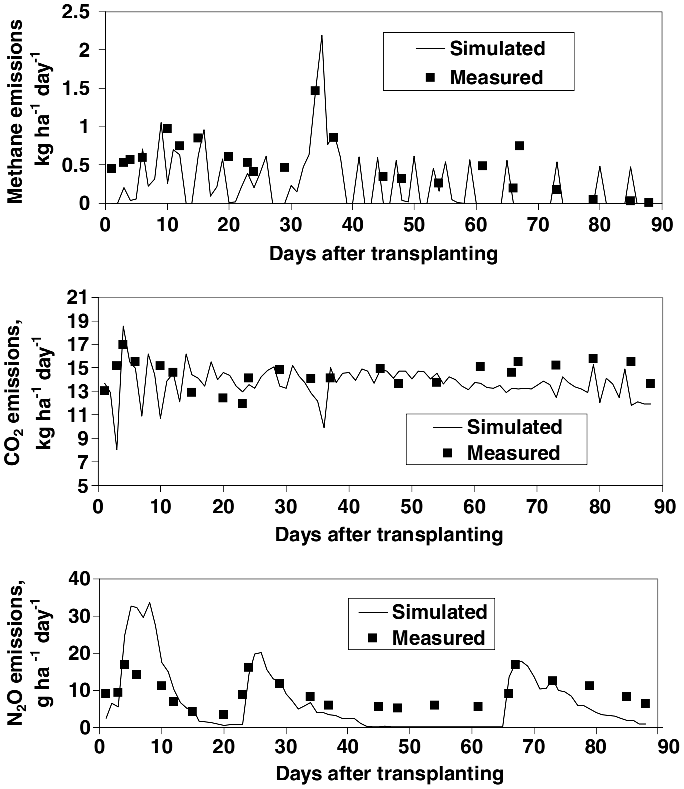

Fig. 8. Measured and simulated emissions of methane, carbon dioxide, and nitrous oxide from rice crop of 2003.

ing with fertilizer application. InfoCrop also simulated these peaks at the right time and in right quantities except when the first dose of fertilizer was applied after transplanting. At this time, the simulated peak of emission was almost double of the measurement in 2003. The reasons for this deviation are not very clear at this stage. A possible reason could be that the puddling of soil creates a microenvironment that is conducive for higher N_2O emissions, which were not picked up by the model. This aspect needs to be examined in more detail in future. There was also some underestimation of emissions sometimes between two fertilizer application dates in both years. However, since the overall emission during these periods was low, it is not expected to cause any significant error.

The measured emission of CO_2 varied from 12 to 17 kg ha^{-1} day^{-1} (Fig. 8). The model also showed similar variation in CO_2 emission at all times except towards maturity where when there were small dips in emission. Since there were no measurements of CO_2 emission on those specific days, it is not clear if these were a problem with the simulation model. Evaluating the performance of the model where continuous measurements are available is desirable.

Wheat: The measured CO_2 emission varied from 10 to 22 kg ha^{-1} day^{-1} (Fig. 9). The average emission was 15 kg ha^{-1} day^{-1}. InfoCrop was in general able to simulate much of this variation across times except on the first day after sowing when the model underestimated emission of CO_2. This could be possibly due to lack of consideration of the tillage effects in the model, which could promote higher emission in the short term.

The N_2O emission showed four peaks in the measurements, which varied from 2 to 13 g ha^{-1} day^{-1}. InfoCrop was able to simulate these patterns reasonably well except during the first 15 days (Fig. 9). The model missed high N_2O emission on day one and then over-estimated emission relative to measurements. Again, the impact of tillage on soil physical and chemical environment in the soil, which is not yet simulated by the model, could have resulted in this discrepancy.

3.2. Sensitivity analysis

There was no effect of change in temperature from −2 to +1 °C in grain yield of wheat. This response was as expected in a normal planted crop with optimal temperatures throughout the growth period. Further increase in temperatures resulted in a gradual decrease in yield of wheat reaching 30% at +5 °C (Fig. 10). This was due to reduction in crop duration, especially during the grain-filling phase. A decrease in temperature beyond −2 °C resulted in a linear decrease of almost 1500 kg °C^{-1}. The decrease was due to partial frost effect on growth and development at low temperatures during December–January when the minimum temperatures are already low.

In case of rice, a decrease in temperature resulted in slight increase in yield associated with a small increase in crop duration. An 1 °C increase in temperature

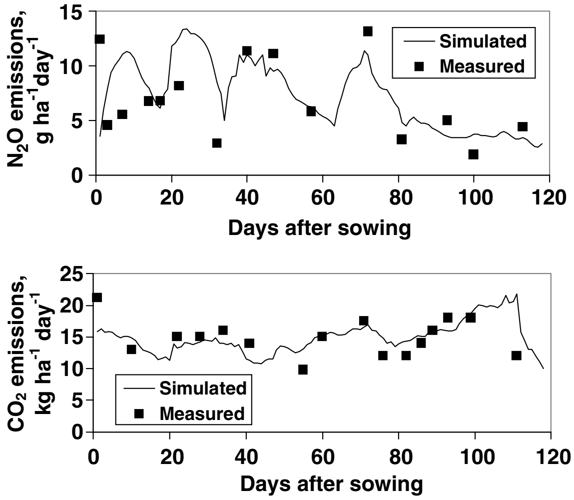

Fig. 9. Measured and simulated emissions of carbon dioxide and nitrous oxide from the wheat field.

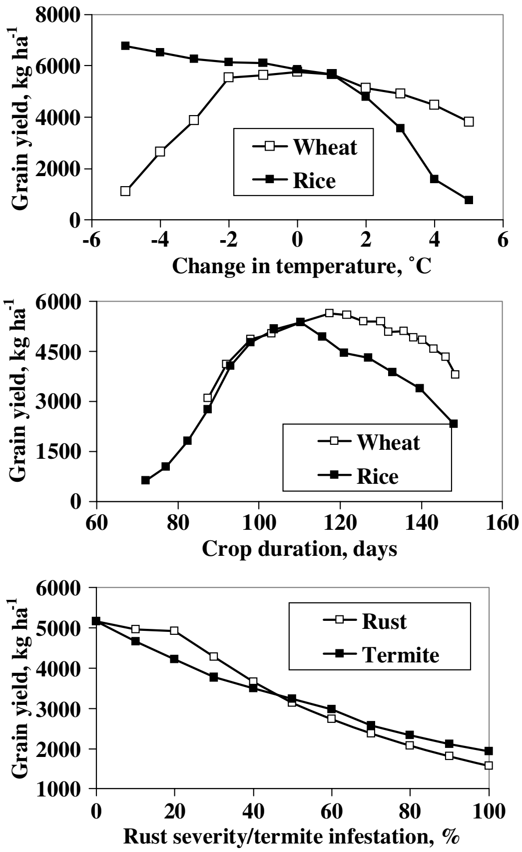

Fig. 10. Sensitivity of grain yields to: (a) changes in ambient temperatures; (b) crop duration; (c) infestation of termites and leaf rust. Effect of pests was evaluated only for wheat whereas temperatures and crop duration effects were studied for wheat as well as rice.

resulted in only a small decrease in grain yield; subsequent increase in temperature caused considerable reduction in yield (Fig. 10). This decrease was related with a reduction in leaf area index and the grain numbers with increasing temperatures.

Increase in thermal time for vegetative phase resulted in increased crop duration in rice as well as in wheat. The maximum yields were obtained when the crop duration was between 118 and 125 days in wheat and 108 and 112 days in rice (Fig. 10). Any change in crop duration from this optimal period resulted in a decrease in grain yield in both crops. A decrease in crop duration resulted in lower grain yields in both crops; the rate of decrease was about 200 kg ha^{-1} day^{-1} reduction in crop duration. If the crop duration increased beyond the optimal period, grain yields declined, especially in rice. This was because increased crop duration in rice exposes the crop to cool temperature injury during grain setting and grain-filling stages as well as reduces photosynthesis. In case of wheat, longer vegetative duration results in a relatively higher grain number but the grain-filling phase is shifted to higher temperature period resulting in its reduced duration and consequently yields.

The model showed a linear decrease in grain yield as the infestation of termites increased. However, in case of leaf rust the crop was able to generally compensate reduction in photosynthesis area if the severity was less than 20%. At higher severity the losses were very significant (Fig. 10). This was because in case of termites infestation all plant organs including grains were lost, and these could not recover later even when the pest was controlled. By comparison, mild rust incidence reduced photosynthetic area but the number of grains was not affected and they were to a large extent filled up by the remaining green area.

These results on sensitivity analysis of the model generally follow the observed trends of change in yields of irrigated rice and wheat in field conditions in the sub-tropical environments of north India. Even the magnitude of change in yield to changes in input parameters was also similar to the response in field conditions providing overall confidence in the model structure and function.

3.3. Applications of the model

3.3.1. Multiple pests damage

The curves relating yield loss to simultaneous rust infection and termite infestation in wheat showed higher loss as the crop became older (Fig. 11). This was simply due to the limited capacity of the determinate plants such as wheat to compensate for the lost tillers/leaf area as the crop aged. A loss of 35% occurred, if the infestation was 70% of both pests at 40 days after sowing (DAS). The magnitude of loss was the same with 60% pest infestation if the pests occurred at 60 DAS. Once the crop approached flowering stage (85 DAS), 35% yield was lost with only 45% pest infestation. The results also showed that the yield losses were negligible at all crop stages

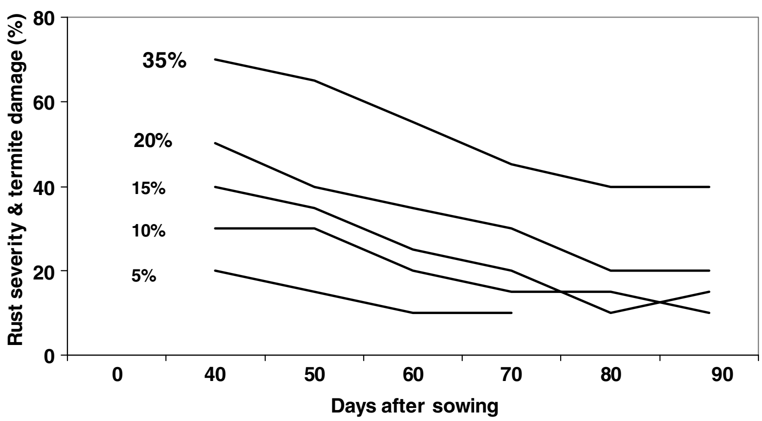

Fig. 11. Iso-loss curves of yield for different degrees of simultaneous infestation of leaf rust and termite on wheat at different stages.

if the infestation was less than 20%. The losses were intermediate at all other pest infestation levels during different crop stages (Fig. 11).

A comparison of the above results of multiple pests damage with the sensitivity of yields to individual pests (Fig. 10(c)) indicated that the yield loss was governed only by the dominant pest infestation. Presence of two or more pests at the same time did not cause significant additional losses.

3.3.2. Trade-off between food production and green house gases emissions

The control crop, with intermittent irrigation and modest inorganic fertilizer application, yielded 3335 kg ha^{-1}. Each kg of this production required 13.04 mm of water and resulted in a global warming potential equivalent to 0.37 kg of CO_2. Continuous flooding although increased grain yields by 33% but resulted in a substantial decrease in the water use efficiency and a large (50%) increase in global warming potential (Table 1). However, if the fields were maintained only at field capacity similar yields were obtained with substantial saving in irrigation water and only a very modest increase in the global warming potential.

Grain yields also increased when additional inorganic fertilizer was added even at the intermittent irrigation level indicating that yields were limited by both water and nutrient availability. As a consequence, the water use efficiency was slightly improved and the global warming potential marginally increased at all irrigation levels. When organic matter was added to increase nutrient availability the grain yields increased as much as that by inorganic fertilizer alone. This did not require any significant additional water and hence the water use efficiency of the two treatments was similar. However, there was almost a 2–3 times increase in the emissions of GHG and hence the global warming potential at all irrigation levels. Thus, it is clear that to meet the future rice demand from Eastern India scientific irrigation practices are needed and, if global warming potential of agriculture remains an issue, caution is needed in organic matter additions.

4. Discussion and conclusions

The results have provided evidence that InfoCrop is generally able to simulate crop growth and yield, yield losses due to different pests, long-term changes in soil organic carbon and emissions of different GHG in rice and wheat crops grown under diverse agro-environments. That the model response to change in critical inputs is similar to the available field knowledge provides further confidence in InfoCrop. The paper also demonstrates that increasing crop production in developing countries in future, needed to meet the growing food demands, would have significant environmental consequences. Similarly, the trade-off between building soil fertility through organic manures and the emissions of GHG has also been illustrated.

The simulations, especially of GHGs emissions, can further improve if the tillage effects at sowing/transplanting time are also included in the model. An additional weakness of the model is its inability to simulate nitrous oxide emissions when soil fertility is low such as periods between two consecutive fertilizer applications. Since the emissions during such periods are generally expected to be small in low fertility soils such as those in south Asia, this constraint of the model many not be very important in using this for applications.

Results on the performance of model in terms of crop yields and other attributes are now also available for pearl millet, maize, potato, cotton, and mustard, and these will be published in due course. InfoCrop thus provides a platform for the integrated assessment of crop production opportunities and associated environmental impacts in tropical environments. It is currently being used for estimating potential yields and yield gaps of major food crops in different agro ecological regions, assessing impacts of climatic variability and climatic change, forecasting crop yields, developing national level inventories for GHG emissions from agriculture, assessing trade-offs among organic farming, food production, and GHG emissions, and quantifying yield loss due to multiple pests. Other potential uses of the model are quantification of strategies required to minimize emission of GHG and ensuring build-up of soil fertility while increasing food production in future, developing water and nitrogen management schedules for different regions, understanding and exploiting genotype × environment × management interactions, developing pest management strategies through iso-loss curves, and long-term impact assessment of current and potential agronomic management strategies on yields, soil carbon, water, and nitrogen cycles. The availability of a simple, user-friendly menu driven interface (Aggarwal et al., 2005), and the in-built data on most of the inputs required for simulation in this version is now accelerating the use of crop models in agricultural research and development in India.

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