Nutr Cycl Agroecosyst (2010) 86:413–424
DOI 10.1007/s10705-009-9304-5

ORIGINAL ARTICLE

Trade-off between productivity enhancement and global warming potential of rice and wheat in India

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Received: 27 January 2009 / Accepted: 11 July 2009 / Published online: 1 August 2009

Abstract Increased use of irrigation and nitrogen (N) in rice and wheat would increase productivity. It would also enhance the emission of greenhouse gases from soil causing global warming and climate change. This study quantified the trade-offs between increased production with N fertilizer and irrigation application and the global warming potential (GWP) in the major rice and wheat growing regions of India. The InfoCrop model was used to simulate yield and GWP of rice and wheat for five regions in the country for two climatic scenarios i.e., current (1990–1999) and future (2050), two irrigation practices i.e., supply-driven irrigation (SDI) and demand-driven irrigation (DDI), and 10 levels of N and organic manure. Rice and wheat productivity of India can be increased from their current productivity of 3.26 and 2.73 Mg ha^{-1} to 5.66 and 6.15 Mg ha^{-1}, respectively with increased irrigation and N use. But this would increase the GWP by 27 and 40%, respectively. In spite of the increased GWP the carbon efficiency ratio (CER) would increase from the current values of 0.67 and 0.85 to 1.06 and 1.75 in rice and wheat, respectively. Thus there is a 'win-win' situation in terms of increased CER for increasing productivity. These situations need to be identified to harness the benefit with more rational management practices including efficient use of irrigation and N, the major drivers for yield and GWP.

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Keywords Food production · Global warming potential · Greenhouse gas · Rice · Wheat · Simulation modelling

Introduction

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) are the two most important cereals for food security of India. During the Green Revolution in the 1960s, production of both the crops increased tremendously due to increased area and productivity. Although India has achieved food self-sufficiency at national level, provision for food at sub-regional levels is still sub-optimal and remains a major challenge. The production of rice and wheat in India is also currently facing new challenges due to continued population growth, stagnation in farm level productivity, climate change and globalization (Pathak et al. 2003a). There is an urgent need to secure the past yield gains and further increase the yields of major staple food crops such as rice and wheat in different regions to meet the increasing demand. Demand for rice and wheat, contributing about 77% of the total food grain production in India (Economic Survey of India 2006–2007), is expected to increase to 225 Mt by

2020 (Paroda and Kumar 2000) against the current production of 161 Mt (MOA 2006). This increased production can be achieved through increased use of inputs, particularly irrigation and fertilizer. However, increased use of nitrogenous fertilizer and irrigation would increase the emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) causing global warming and climate change (IPCC 2007; Pathak and Wassmann 2007). There is a need to quantify the trade-offs between production and global warming potential (GWP) of rice and wheat so as to develop suitable technologies to increase food production and reduce GWP by increasing the carbon efficiency ratio (Bhatia et al. 2005). The objectives of the study were to: (1) evaluate the effect of increased irrigation and nitrogen use on GWP and carbon efficiency ratio (CER) of rice and wheat and (2) evaluate impact of different levels of N fertilizer application under the supply-driven vs. demand-driven irrigation on the yield and GWP of rice and wheat under current and 2050 climatic scenario.

Materials and methods

Study area

In India rice is generally grown during kharif season i.e., summer months (June–October) under monsoon climatic conditions and wheat is grown during the rabi season i.e., cooler and drier winter months (November–March) after rice harvest. In the east and south of the country, however, rice is grown during both kharif and rabi seasons. The country can be broadly divided into five major regions i.e., northern, southern, central, eastern and western regions in terms of seasonality and production of rice and wheat. In this study one or two representative locations were selected in each region to evaluate the trade-off between production and GWP (Fig. 1). At Ludhiana, Punjab in the northern region about 80% of the net cultivated area was under the rice-wheat system with more than 97% of area under irrigation. In Coimbatore, Tamil Nadu in the southern region, two rice crops were grown in an annual cycle with 90% area under irrigation. In the western region, Jodhpur in Rajasthan and Thane in Maharashtra were selected for wheat and rice, respectively. In central region Indore and Jabalpur in Madhya Pradesh for wheat and rice, respectively, and in the eastern region Patna in Bihar were selected as the representative locations for the study.

The regions varied in terms of climate and soil. There was more variation in the rabi temperature than the kharif temperature in the different regions. Maximum rabi rainfall took place in the southern region, whereas it was the least in the kharif season (Table 1). Properties of soils of different regions were compiled from published literature (NBSSLUP 1998; Velayutham and Bhattacharya 2000). The soil texture varied

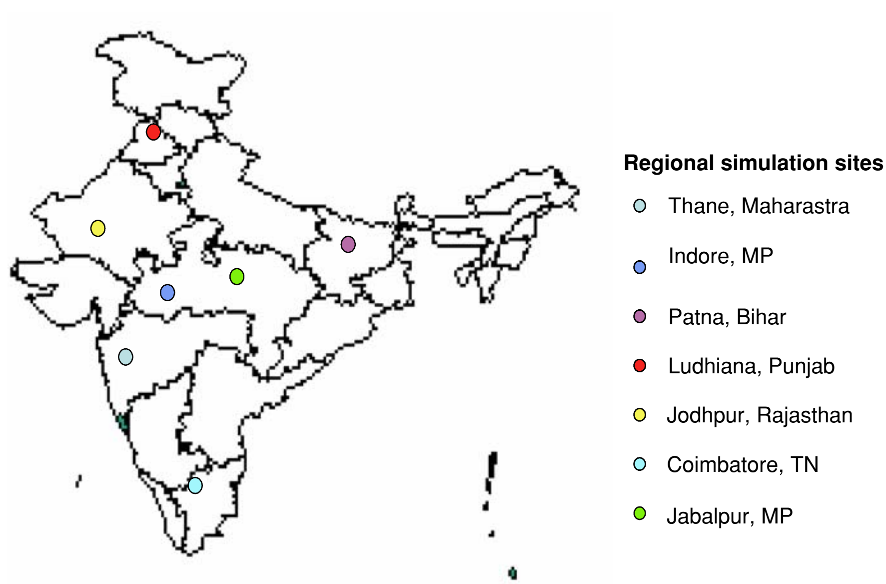

Fig. 1 The representative locations in various regions of India for simulation of yield and GWP of rice and wheat

Table 1 Weather parameters (mean of 10 years) during kharif and rabi seasons in the selected locations in the various regions of India

Site (Region)	Kharif (July–October)							Rabi (November–March)				
	Latitude (°N)	Longitude (°E)	Min. temp. (°C)	Max. temp. (°C)	Precipitation (mm)	Solar radiation (MJ m^{-2})	Irrigation	Min. temp. (°C)	Max. temp. (°C)	Precipitation (mm)	Solar radiation (MJ m^{-2})	Irrigation
Ludhiana (North)	30.91	75.9	24.5	34.1	528	23.0	Irrigated	8.8	22.3	96	14.5	Irrigated
Coimbatore (South)	11.00	77.00	23.1	32.8	234	18.1	Irrigated	19.3	30.0	393	17.4	Irrigated
Patna (East)	25.74	85.02	25.2	33.0	891	17.5	Rainfed	11.6	26.3	33	16.6	Partially irrigated
Jodhpur (West)	26.03	73.07	22.4	32.7	289	15.2	Rainfed	15.8	28.5	21	16.8	Partially irrigated
Thane (West)	19.20	73.03	25.6	32.9	1872	17.6	Rainfed	16.8	31.8	208	24.1	Partially irrigated
Jabalpur (Central)	23.17	79.98	24.6	32.4	1355	15.8	Rainfed	11.8	29.5	16	17.6	Partially irrigated
Indore (Central)	22.73	75.83	22.4	30.7	768	15.2	Rainfed	10.2	27.2	15	17.2	Partially irrigated

from clayey in the southern, loamy in the eastern, sandy loam in the northern to sandy soils in the western region. Organic carbon content of soils ranged from low to medium across the regions (Table 2). Irrigation availability varied considerably in the regions (MOA 2006). The eastern, western and central regions were rainfed, whereas southern and northern regions were fully irrigated for growing rice. For wheat the eastern, western and central regions are partially irrigated, northern region is fully irrigated and no wheat is grown in the southern region (Table 1).

Simulation of productivity and GWP

InfoCrop, a generic dynamic crop model designed to simulate the effects of weather, soils, agronomic management and major pests on crop growth and yield, and the environmental impacts like the emission of GHG (Aggarwal et al. 2006b), was used for simulation of productivity and GWP in rice and wheat. The model calculates CH_4 and CO_2 emissions from soil by simulating the processes of mineralization and immobilization of C. The model calculates fluxes of N_2O from soil by nitrification and denitrification pathways. The model computes the total GWP using the following equation.

$$GWP = CO_2 + CH_4 \times 25 + N_2O \times 298.$$

The carbon equivalent emission (CEE) was 27.3% of the GWP and CER was grain yield (in terms of C)/CEE.

The model has earlier been validated for rice and wheat dry matter production, grain yields and emissions of CO_2, CH_4 and N_2O and GWP in a variety of agro-environments in India (Aggarwal et al. 2006a; Bhatia et al. 2007; Ebrayi et al. 2007).

There are many off-farm (e.g. fertilizer and pesticide manufacture) and on-farm (tractor and machine use for tillage, irrigation, fertilizer and manure use) factors, which influence the emission of GHGs from agriculture. However, in this study only the emission of CH_4, N_2O and CO_2 from soil was simulated. Effect of various factors such as climate (temperature, rainfall), crop and irrigation, fertilizer and manure application on GHG emission from soil was included in the simulation. Emission of GHG due to various off-farm and on-farm activities was not considered because their contribution toward GHG emission is

Table 2 Soil properties in the selected locations in the various regions of India

Site (Region)	Organic C (%)	Clay (%)	Sand (%)	Bulk density (g m^{-3})	Moisture content at field capacity (%)	EC (dS m^{-1})	pH
Ludhiana (North)	0.4	20	42	1.35	20	0.3	7.5
Coimbatore (South)	0.8	45	38	1.38	30	0.3	7.5
Patna (East)	0.4	23	38	1.35	23	0.4	7.3
Jodhpur (West)	0.2	25	55	1.20	17	0.4	8.2
Thane (West)	0.7	52	28	1.45	35	0.2	6.5
Jabalpur (Central)	0.4	48	24	1.48	34	0.1	8.0
Indore (Central)	0.4	56	25	1.48	37	0.5	8.1

unlikely to change in the future climate change scenario.

Treatments for simulation

Yield and GWP of rice and wheat were simulated for each location for four treatments, which included two climatic scenarios i.e., current (1990–1999) and future (2050), two irrigation practices i.e., supply-driven irrigation (SDI) and demand-driven irrigation (DDI), and different levels of N (Table 3). Weather data for 1990–1999, obtained from the meteorological stations located at the sites, were used for the current climate (treatments A, B and D). The weather data from Hadley Centre Coupled Model version 3 (HADCM3) Special Report of Emissions Scenario (SRES) A2a for 2050 was used for future climate (treatment C). The monthly outputs of HadCM3 scenarios for specific grid pertaining to selected location were interpolated to obtain daily values. For this, the changed fields of maximum and minimum temperatures from baseline value were used in a function in the InfoCrop where these values are interpolated and added to the observed baseline (mean of 1960–1990) values. In case of rainfall, the percent deviation from baseline was used to get the scenario (2050) values. The SRES A2 emission scenario is commonly used for 'business as usual' impact studies and is characterized by self-reliant nations with continuously increasing population, regionally oriented economic development and slower and more fragmented technological changes and improvements to per capita income.

In case of SDI practice, followed in small-scale low-input farming, the days and amount of irrigation were given as inputs in the InfoCrop model. With this irrigation practice, rice was grown as rainfed crop in the eastern, western and central regions whereas in the northern and southern regions seven irrigations of 5 cm each were given up to 70 day after transplanting (DAT) at an interval of 10 days. In wheat two irrigations were given at crown root initiation (21 days after sowing, DAS) and at milky stage (84 DAS) in the eastern, western and central regions and 4 irrigations (21, 35, 65 and 84 DAS) in the northern region. The depth of irrigation was 6 cm in northern, 5 cm in western and eastern regions and 3 cm in the central region. In DDI practice, followed in commercial, high-input farming, the days and amount of irrigation were simulated by the InfoCrop model based on evapo-transpiration and soil water content in the root zone to have no water stress condition during the crop growing season.

In the treatments A, B and C; N fertilizer was applied as urea at 30–300 kg ha^{-1} in increments of

Table 3 Treatments used for simulation of productivity and global warming potential of rice and wheat in the various regions in India

Treatment	Climate (year)	Irrigation	N (kg ha^{-1})
A	Current (1990–1999)	Supply driven (SDI)	30–300
B	Current (1990–1999)	Demand driven (DDI)	30–300
C	Future (2050)	Demand driven (DDI)	30–300
D	Current (1990–1999)	Demand driven (DDI)	30–240 (along with 10–30% of N through FYM)

30 kg ha^{-1} (Table 3). In treatment D, 10–30% of inorganic N was applied through farmyard manure (FYM) containing 1% N on dry weight basis with a C:N ratio of 30 at the start of simulation.

Rice was transplanted on July 10 for the northern, central and eastern regions and June 1 and November 17 for the southern region. Wheat was sown on December 10 in the northern, eastern and western regions and December 1 in the central region.

Trade-off curves

This study quantified the trade-offs between the rice and wheat production and environmental sustainability of agriculture in terms of GWP. The trade-off curves were generated using the % increase in simulated yield versus the % increase in simulated GWP for different N levels under the two irrigation practices and two climate scenarios. The trade-off curves thus represented the simulated pattern of yield and GWP with progressive movement from low to high levels of N application under different irrigation practices and climate change scenarios. For comparison of simulated yields and GWP in various regions, published data (CMIE 2000) on yield and N fertilizer use for the year 2000 was taken as baseline.

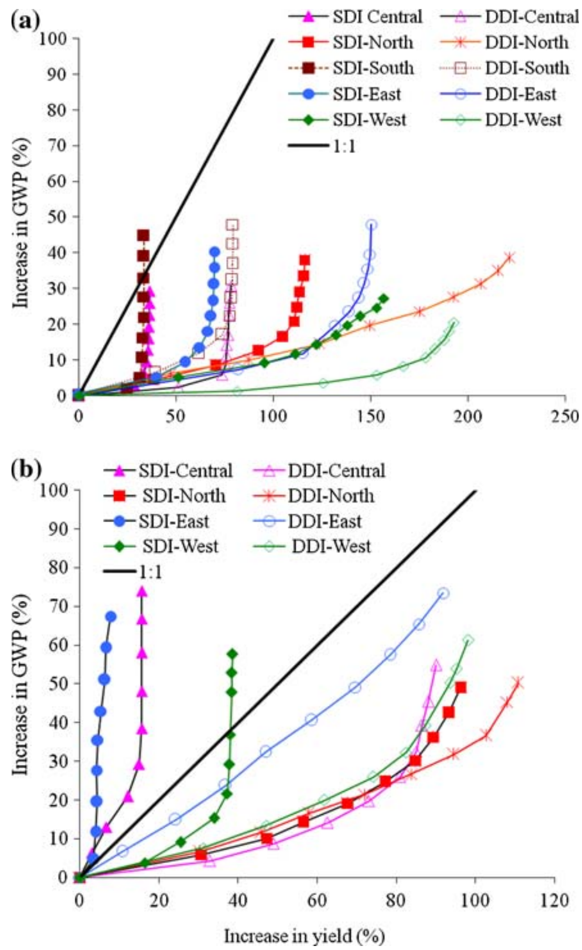

Fig. 2 Trade-off between GWP and yields of rice (**a**) and wheat (**b**) under supply-driven and demand-driven irrigation practices with application of 30–300 kg N ha^{-1} in various regions of India (Increase in yield and GWP as compared to year 2000)

Results and discussion

Effect of irrigation, nitrogen and climate on yield and GWP in rice

Irrigation

In the SDI practice in the eastern region, rice responded positively up to 150 kg N ha^{-1} application with 66 and 19% increase in yield and GWP, respectively (Fig. 2a). Further increase in N level had no effect on yield but enhanced the GWP. In northern region with seven irrigations given in the SDI practice, rice responded up to 180 kg N ha^{-1} with increase of 110% in yield and 21% in GWP over the baseline yield at 90 kg N ha^{-1} and GWP, respectively. Higher amount of N application resulted in higher amount of N_2O emission with more GWP (Izaurralde et al. 2004). With SDI practice in the southern region rice yield was higher in rabi than in kharif season because of more sunshine hour and longer crop duration (Table 1). However, GWP was higher in kharif due to higher temperature leading to more emissions of GHGs. In the western region the crop responded up to 90 kg N ha^{-1} with 95% increase in yield and 8% increase in GWP compared to the base line. The simulated CH_4 and N_2O emissions were similar to that reported earlier by Jain et al. (2000), Pathak et al. (2002), (2003b) and Malla et al. (2005) for the northern region and Adhya et al. (2000) for eastern region.

In the DDI practice, rice crop responded to N application upto 150–270 kg N ha^{-1} depending on the region. The GWP also enhanced with higher N application across the regions (Fig. 2a). There was

Table 4 Impact of different N treatments, irrigation and climate scenarios on yield and GWP of rice and wheat in the various regions of India

Treatments	North		Central		South[d]		East		West	
	Yield (Mg ha^{-1})	GWP (Mg CO_2 ha^{-1})	Yield (Mg ha^{-1})	GWP (Mg CO_2 ha^{-1})	Yield (Mg ha^{-1})	GWP (Mg CO_2 ha^{-1})	Yield (Mg ha^{-1})	GWP (Mg CO_2 ha^{-1})	Yield (Mg ha^{-1})	GWP (Mg CO_2 ha^{-1})
Rice										
N level (kg N ha^{-1})										
0	2.45	1.75	1.45	1.69	2.23	1.65	1.82	1.81	1.85	1.55
120	6.02	2.56	3.6	2.41	5.83	2.28	5.23	2.58	5.41	2.35
180[a]	7.22	2.72	3.72	2.49	6.05	2.59	5.35	2.61	6.08	2.47
135 + 20% N (FYM)[b]	6.07	4.27	3.91	3.72	5.57	4.26	5.61	4.29	5.31	6.07
Irrigation										
Supply-driven (2000)[c]	5.27	2.26	2.65	2.09	3.52	1.72	4.88	2.39	4.52	2.03
Demand-driven (2000)[c]	6.52	2.70	3.47	2.39	5.52	1.99	5.36	2.83	5.28	2.21
Demand-driven (2050)[c]	6.21	2.82	2.94	2.31	5.01	2.17	5.31	2.90	5.11	2.42
Wheat										
N level (kg N ha^{-1})										
0	1.95	1.05	1.44	0.98			1.29	1.01	1.52	1.07
120	6.11	1.66	4.64	1.52			4.45	1.38	4.51	1.33
180	7.12	1.81	5.60	1.63			5.16	1.57	5.20	1.47
135 + 20% N (FYM)[b]	6.74	2.74	5.01	2.56			5.09	2.52	4.74	2.36
Irrigation										
Supply-driven (2000)[c]	6.32	1.68	2.69	1.32			3.20	1.35	3.35	1.25
Demand-driven (2000)[c]	6.61	1.78	5.12	1.66			4.89	1.53	4.86	1.45
Demand-driven (2050)[c]	4.54	1.52	3.35	1.85			4.01	1.43	3.55	1.50

[a] 180 kg N ha^{-1} for north and 150 kg N ha^{-1} in rest of the regions in rice

[b] Average of N treatments from 30 to 240 kg N ha^{-1}

[c] Average of N treatments from 30 to 300 kg N ha^{-1}

[d] No wheat is grown in South region

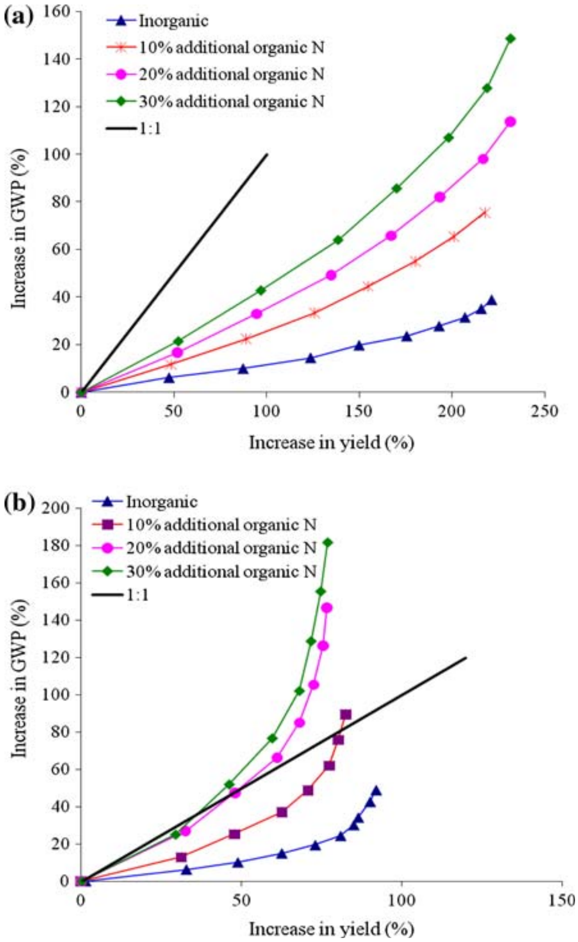

Fig. 3 Trade-off between GWP and yields of rice in the northern region (**a**) and wheat in the central region (**b**) on application of 30–240 kg N ha^{-1} with FYM (10–30% N) (Increase in yield and GWP as compared to year 2000)

higher emission of GHGs under the DDI practice compared to the SDI practice leading to higher GWP (Table 4). As water availability was not a constraint in DDI practice, there was more availability of C and N substrates leading to higher production of GHGs (Smith and Conen 2004). In the DDI practice in the southern region, yield of rice increased by 40% whereas GWP decreased by 7% in rabi as compared to kharif season.

Nitrogen

Application of N fertilizer had a positive relationship with GWP but response in terms of yield was obtained only up to certain level (240 kg N ha^{-1}; Fig. 2a). In the eastern region, for example, application of 120 kg N ha^{-1} increased rice yield by 111% and GWP by 14% (Table 4). On applying further amount of N yield remained unchanged but the GWP increased.

The N applied in excess of plant requirement was either leached or lost through volatilization and denitrification, which contributed towards N_2O emission. Application of N did not influence CH_4 emission and enhanced GWP was mostly because of higher N_2O emission. CH_4 emission is more impacted by temperature and organic matter content of soil, and crop growth stages (Huang et al. 1998) and water regime (Halvorson et al. 2005; Pathak et al. 2005).

The GWP increased by 15, 25 and 31% on addition of 10, 20 and 30% of N through FYM along

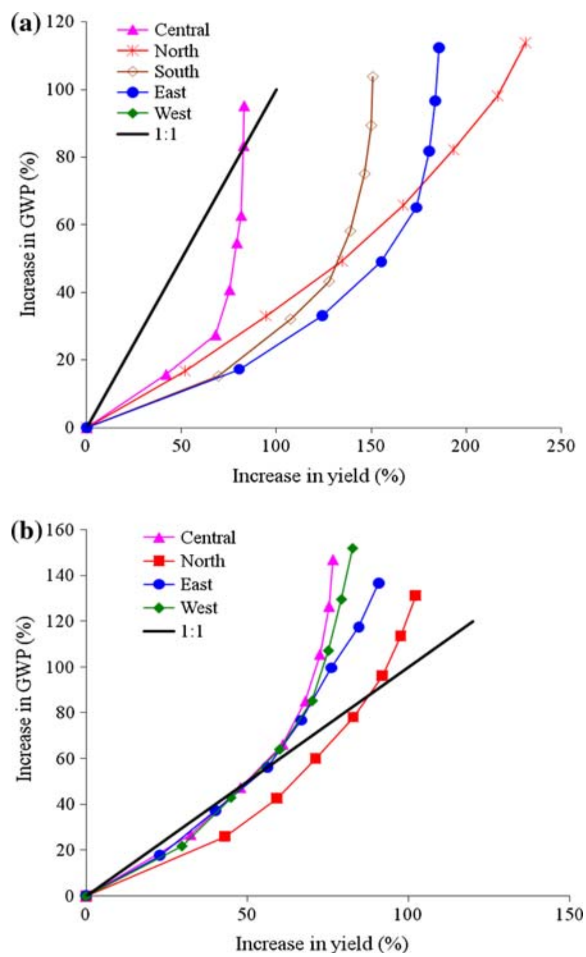

Fig. 4 Trade-off between GWP and yields of rice (**a**) and wheat (**b**) on application of 30–240 kg N ha^{-1} with FYM (20% N) in various regions of India (Increase in yield and GWP as compared to year 2000)

with the current N fertilizer application level (90 kg N ha^{-1}) in the northern region (Fig. 3a). There was, however, no significant yield advantage with addition of 10% organic N but with 20% N through FYM yield increased by 10–25% at the different N levels in the northern region. The response to FYM application on GWP and yield in the other regions, however, were different (Fig. 4a). Rice yields in these regions increased marginally with increasing FYM but the corresponding increase in GWP was much higher (Table 4). The reason for much higher GWP in the other regions was not very clear but there were more CH_4 and CO_2 emissions in these regions. In addition to supplying decomposable carbon, application of organic matter hastens the drop in redox potential resulting in higher CH_4 production (Neue 1993).

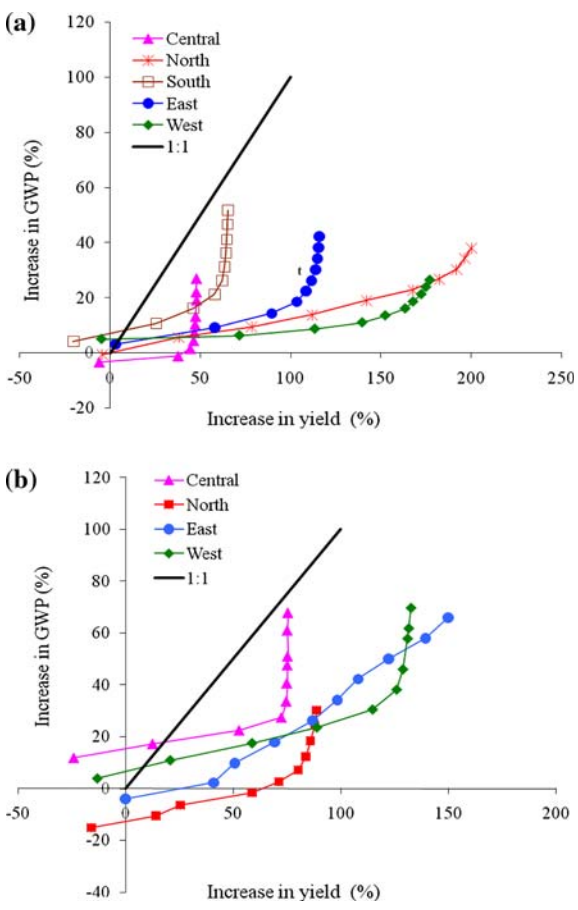

Fig. 5 Trade-off between GWP and yields of rice (**a**) and wheat (**b**) on application of 30–300 kg N ha^{-1} under 2050 climate scenario in various regions of India (Increase in yield and GWP as compared to year 2000)

Climate change

There was no impact of climate scenario of 2050 on rice yields in the eastern region, whereas the rice yield reduced by 4–20% as compared to the current yield in the other regions (Fig. 5a). Decreasing rice yield with increasing temperature with climate change has been reported earlier (Pathak et al. 2003a; Peng et al. 2004; IPCC 2007). However, in terms of GWP, climate scenario of 2050 had no impact in the northern region, 3–5% increase in the eastern and southern regions and 5% reduction in the central region over the current levels. It is expected that decreased productivity of rice in future climate would decrease root biomass production resulting in lower carbon input in soil and lower CO_2 and CH_4 emissions. On the other hand increased temperature would enhance decomposition of organic matter and increase root biomass and root exudation thereby promoting CO_2 and CH_4 emissions (Schrope et al. 1999). The net impact of climate change on GWP of rice would, therefore, be site-specific depending upon production level and extent of temperature increase.

Effect of irrigation, nitrogen and climate on yield and GWP of wheat

Irrigation

Under the SDI practice wheat crop responded positively only up to application of 60 kg N ha^{-1} but GWP continued to increase up to 300 kg N ha^{-1} in the eastern, western and central regions (Fig. 2b). In the northern region wheat yield increased by 90% over the current yield on application of 240 kg N ha^{-1} with corresponding GWP increase by 32%. The increased availability of mineral–N on applying higher doses of fertilizer and lower plant N uptake resulted in higher N_2O emission and higher GWP.

Under the DDI practice yield increased by more than 90% across the regions on application up to 300 kg N ha^{-1} (Fig. 2b). In the northern region yield increased by 110% and GWP by 50% primarily due to increased N_2O and CO_2 emissions. Irrigation in DDI practice increased CO_2 flux compared to the SDI due to higher soil water content (Sainju et al. 2008) and thus the GWP was higher under DDI irrigation (Table 4). Soil water directly and indirectly influenced the emissions of the GHGs from soil by providing suitable conditions for microbial growth, releasing of available C and N from soil organic matter and providing a diffusion medium through which substrates and products are moved to and away from soil microorganisms (Pathak 1999).

Nitrogen

With an increase in N fertilizer application, significant increase in wheat yields and GWP was observed in all the regions (Fig. 2b). There were more volatilization losses (data not shown). Accelerated nitrification/denitrification associated with more root biomass and exudation (Mikan et al. 2000) at higher N levels led to increased N_2O emission. CO_2 emission also enhanced with larger N input because of enhanced soil respiration (Hungate et al. 1997). The GWP increased by 46–73% on application of 300 kg N ha^{-1} in various regions. With increase in N fertilizer application, the maximum impact was observed on the emission of N_2O which varied across the regions with more emission in the sandy soils of northern and western regions than in the clayey soils in central and southern regions. Van Groenigen et al. (2004) reported that N_2O emission varied with N application rate and soil type. The variation in GWP across the regions might be due to difference in weather conditions and soil types especially texture and soil organic carbon which played a key role in the green house gases emissions (McTaggart et al. 2002; Izaurralde et al. 2004).

The addition of organic fertilizer along with inorganic fertilizer led to significant increase in GWP over the inorganic N application alone, though there was no significant increase in yields (Fig. 3b). Addition of 20 and 30% N through FYM along with the inorganic N increased the GWP by 52 and 77% mostly because of more CO_2 emission with higher organic C availability for oxidation. Regional differences in GWP (Fig. 4b) due to varied N_2O and CO_2 emissions in response to identical organic amendments could be attributed to a combination of soil and climate related factors (Wassmann et al. 2000).

Climate change

On application of current level of N fertilizer, there was 14–24% decline in wheat yield over the base year 2000 in all but the eastern region under the 2050 scenario (Fig. 5b). Kalra et al. (2008) predicted similar yield losses in wheat for northern India using the WTGROWS model. In the eastern region the 2050 climate scenario increased wheat yield due to the increased precipitation in this rainfed region. However, with application of more N, wheat yield could be improved under the climate 2050 scenario.

Table 5 Trade-off between productivity, global warming potential (GWP) and carbon efficiency ratio (CER) of rice and wheat in the various regions of India

Region	Current				Potential			
	N level (kg ha^{-1})	Yield (kg ha^{-1})	GWP (kg CO_2 equiv. ha^{-1})	CER	N level (kg ha^{-1})	Yield (kg ha^{-1})	GWP (kg CO_2 equiv. ha^{-1})	CER
Rice								
North	90	3,291	2,460	0.65	240	7,500	2,910	1.26
East	30	2,457	2,235	0.54	120	5,200	2,580	0.98
South	60	3,785	1,865	0.99	150	6,000	2,590	1.13
Central	30	1,785	1,950	0.45	120	3,600	2,405	0.73
West	30	2,451	1,680	0.71	150	6,000	2,470	1.18
Wheat								
North	90	2,881	1,400	1.00	270	8,000	2,010	1.94
East	40	1,788	1,070	0.81	240	5,800	1,705	1.66
Central	50	1,823	1,285	0.69	180	5,600	1,628	1.68
West	30	2,008	1,110	0.88	180	5,200	1,472	1.72

In the central region yield increased up to 19% on application of 120 kg N ha^{-1}. However, subsequent increase of N input up to 300 kg N ha^{-1}only enhanced GWP by 67% without any impact on yield. The higher GWP values in 2050 may be due to the higher increase in the maximum temperature in the rabi season in the eastern and central regions (2.24–2.9°C) leading to greater decomposition of soil organic matter and increased microbial activity resulting in enhanced CO_2 and N_2O emissions.

Trade-off analysis

Rice

Maximum response to increased N level was observed in the northern region (up to 240 kg N ha^{-1}) with an achievable yield of 7.50 Mg ha^{-1} (Table 5). This was followed by the southern region and western regions (up to 150 kg N ha^{-1}) with an achievable yield of 6.00 Mg ha^{-1}. Eastern and central regions responded only up to 120 kg N ha^{-1} with achievable yield of 5.20 and 3.60 Mg ha^{-1} respectively. This increase in yield resulted in increased GWP. Simulated results thus showed that the country can increase average yield up to 5.66 Mg ha^{-1} from the current 3.26 Mg ha^{-1} with improved management of N and water (Table 5). However, this would simultaneously increase GWP by 27% over the current value. In spite of the increased GWP, the CER would increase from current value of 0.67–1.06 across all the regions. This would require increased use of irrigation water especially in the central and eastern regions.

Wheat

Maximum response to higher N application was observed in the northern region (up to 270 kg N ha^{-1}) followed by the eastern region (up to 240 kg N ha^{-1}) with yields of 8.00 and 5.80 Mg ha^{-1}, respectively. The central and western regions responded only up to 180 kg N ha^{-1} with achievable yield of 5.60 and 5.20 Mg ha^{-1}, respectively. The study thus showed that wheat productivity in India can be increased from 2.73 to 6.15 Mg ha^{-1} with better management of N and water (Table 5). As current yields are already high in the northern region and low in the eastern and central regions, the potential to increase wheat productivity is large in the latter. As a trade-off, however, this increase in yield would result in increased GWP by 40% over the current GWP but the CER would increase from the current value of 0.85–1.75 across the regions. As water requirement in wheat is low compared to rice, it would be more feasible to achieve the enhanced CER in wheat or other crops requiring low water in the eastern, western and central regions in years to come.

Conclusions

The simulation study evaluated the yield response and GWP of rice and wheat due to increased N and water use in current and future climatic scenarios. The current yields of rice and wheat were limited by water and N availability. The productivity can be increased substantially with increased use and better management of N and water. However, this would lead to an increased GWP. Supplementing organic manure with inorganic N is beneficial for soil health, but its use would enhance GWP without much increase in yield. Moreover, with the 2050 climatic scenario, rice and wheat yields in India may be impacted and could lead to a positive feedback on global warming. Therefore, gain in one area (increased yield) would cause loss in the other (increased GWP). But in some cases a ‘win-win’ outcome (increased CER) can be achieved. Options that reduce GHG emissions and increase yield and CER are clearly the most desirable. There is a greater need today for more rational management practices including efficient use of inputs particularly irrigation and N.

Acknowledgments The authors are thankful for the financial support provided by the ICAR Climate Network project in this study. We also thank Ms. Swaroopa, Division of Environmental Sciences, Indian Agricultural Research Institute, New Delhi for her help in the simulation studies.

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