Low Carbon Technologies for Agriculture:
A Study on Rice and Wheat Systems in the Indo-Gangetic Plains

Editors

H Pathak and PK Aggarwal

भाकृअनुप
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The Indian Agricultural Research Institute (IARI) is the premier national institute of the Indian Council of Agricultural Research for research, education and extension in agriculture. Established in 1905, IARI is based in the capital city of New Delhi and is engaged in climate change research for the past 20 years. The focus of IARI's climate change research has been on the quantification of the sensitivities of current food production systems to different scenarios of climatic change, development of the inventory of greenhouse gas emissions from Indian agriculture and determination of the mitigation options for climatic changes, evaluation of the available management and genetic adaptation strategies for climatic change and climatic variability, and suggesting policy options for implementing mitigation and adaptation options and providing policy support for international negotiations on the global climatic changes.

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Foreword

Several of the human activities are substantially increasing concentration of greenhouse gases (GHGs) in the atmosphere. It is resulting in unnatural warming of the Earth's surface and a rise in temperature of the atmosphere, posing a threat to the natural ecosystems and humankind. The rising demand for food commodities is also causing increasing pressure on agriculture and consequently, on the climate system. Climate change is likely to intensify this pressure on agriculture. Therefore, continuous efforts are required for mitigation of GHGs emission to reduce the vulnerability of Indian agriculture to the impacts of climate change.

While all the countries, especially the developing countries, need access to resources required to achieve sustainable social and economic development, there is a need to achieve greater energy efficiency for controlling emissions of GHGs. The application of novel low energy-intensive technologies, viz. low carbon technologies, which make the agricultural operations economically and socially beneficial, and help protect the climate system for the present and future generations, is urgently required.

Agriculture has the potential to mitigate emission of GHGs by adopting low carbon technologies. Comprehensive estimates of GHGs emission from different agricultural operations including production, processing, post-harvest management and marketing are required for evaluating the economic potential of different low carbon technologies in Indian agriculture.

This book has presented the status of GHGs emission research in India and quantified the potential and cost of low carbon technologies in Indian agriculture by studying the rice and wheat production systems of the Indo-Gangetic Plains. It has also highlighted opportunities, constraints and interventions required for promoting low carbon technologies in Indian agriculture.

I appreciate the efforts made by the authors in carrying out the studies and the editors in bringing out this book. I do hope that this book will be useful for students, researchers and policy-makers of agriculture.

H.S. Gupta
Director
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Preface

Global warming is a prominent environmental issue of the twenty-first century. Agriculture contributes to the global warming primarily through the emission and consumption of greenhouse gases (GHGs), viz. methane, nitrous oxide and carbon dioxide. The major sources of emission of GHGs in the agriculture sector are enteric fermentation, rice cultivation, agricultural soils, manure management and on-field burning of crop residue. There are some indirect sources also like manufacturing of fertilizers, pesticides, herbicides, etc. Therefore, it is highly pertinent to develop such technologies that help in reducing GHGs emission from agriculture. It will not only mitigate climate change but also reduce consumption of costly inputs by enhancing their use-efficiency causing an increase in farmers' income.

This book has presented the potential of some low carbon technologies for reducing the emission of GHGs from agriculture by studying the production system of two major crops, viz. rice and wheat in the Indo-Gangetic Plains (IGP). Various constraints and interventions required to promote the mitigation strategies have also been outlined.

I congratulate the authors and the editors in bringing out its book. I am sure that the book will be a valuable reference source for researchers as well as policy makers in promoting low carbon technologies for agriculture in different regions of the country.

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List of Abbreviations

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalent
DSR	Direct-seeded rice
DVR	Crop diversification
GHG	Greenhouse gas
GM	Green manure
GWP	Global warming potential
IGP	Indo-Gangetic Plains
INM	Integrated nutrient management
IPCC	Inter-Governmental Panel on Climate Change
J	Joule
LCC	Leaf colour chart
Mha	Million hectares
Mt	Million tons
N	Nitrogen
N_2O	Nitrous oxide
NI	Nitrification inhibitor
PGM	Phosphogypsum
SHGs	Self help groups
SPR	Sprinkler irrigation
SRI	System of rice intensification
SSNM	Site-specific nutrient management
USG	Urea super granules
YMX	Yield maximization

Executive Summary

Today, global warming is the most prominent environmental issue across the world. It is caused by the increased concentration of greenhouse gases (GHGs) in the atmosphere and leads to a phenomenon widely known as 'greenhouse effect'. Amongst various sources of GHGs, agriculture is considered a major contributor primarily through the emission of methane and nitrous oxide.

According to a report of Indian Network for Climate Change Assessment, the net emission of GHGs from India was 1728 million tons (Mt) of CO_2 eq. in the year 2007. The main sectors contributing to this emission are energy, industry, agriculture and waste. With a total emission of 334 Mt CO_2 eq., the major sources in the agricultural sector are enteric fermentation (63.4%), rice cultivation (20.9%), agricultural soils (13.0%), manure management (2.4%) and on-field burning of crop residues (2.0%). The crop production sector (rice cultivation, soil and field burning of crop residues), thus contributes 35.9% to the total emissions from agriculture. It is therefore, pertinent to develop technologies to reduce emission of GHGs from agriculture. This will not only mitigate climate change but also reduce consumption of costly inputs by enhancing their use efficiency and increase farmers' income by producing more with less of inputs.

A two year on-farm study in three villages in Jalandhar district of Punjab showed that direct-seeded rice (DSR) is a feasible alternative to conventional puddled transplanted rice (TPR) for mitigating methane emission, besides saving water and labour. Simulation studies showed that total global warming potential (GWP) in transplanted rice in various districts of Punjab ranged from 2.0 to 4.6 t CO_2 eq. ha^{-1} and in the DSR it ranged from 1.3 to 2.9 t CO_2 eq. ha^{-1}. The DSR crop saved 3-4 irrigations compared to transplanted rice without any yield penalty. Human labour use also reduced to 45% and tractor use to 58% in the DSR compared to the TPR.

Twenty technologies have been analysed for their potential to mitigate GHGs emission in rice in the upper and lower Indo-Gangetic Plains (IGP) and their economic feasibilities have been assessed. During crop production under conventional management practices, GWP of rice cultivation was 3957 kg CO_2 ha^{-1}

in the upper-IGP and 2934 kg CO_2 ha^{-1} in the lower-IGP. Compared to the current practices of farmers, 15 technologies in the upper-IGP and 14 technologies in the lower-IGP have the potential to reduce the GWP. In the upper-IGP, only seven technologies, viz. sprinkler irrigation, direct seeded rice, use of nitrification inhibitor, use of urea super granules, use of leaf colour chart, site-specific nutrient management and crop diversification have depicted ability to reduce GWP without any additional cost. In the lower-IGP, use of nitrification inhibitor, use of leaf colour chart, site-specific nutrient management and crop diversification have shown reduction in GWP with no additional cost.

Ten technologies have been assessed in wheat for GHGs mitigation potential and economics. The GWP in the upper-IGP is 1808 kg CO_2 ha^{-1}, whereas in the lower-IGP it is 1280 kg CO_2 ha^{-1}. Among the various technologies zero tillage, integrated nutrient management, organic farming, use of nitrification inhibitor and site-specific nutrient management have proved to be beneficial in terms of GWP reduction and profit enhancement in the upper-IGP. In the lower-IGP, zero tillage, integrated nutrient management, use of nitrification inhibitor and site-specific nutrient management technologies have been found both GHG-friendly and economically feasible. Integrated nutrient management has caused 10% increase in income and 109% reduction in GWP in the upper-IGP. In the lower-IGP, zero tillage could cause 9% increase in net return and 105% reduction in GWP as compared to the conventional practices of farmers.

Regional impact of GHGs mitigation was assessed for the state of Punjab considering farmers' conventional practices and one mitigation technology, viz., mid-season drainage. The GWP with continuous flooding of rice in the state is found to be 8.3 Mt CO_2 eq. If the entire area under continuous flooding in the state is converted to mid-season drainage, the GWP will be reduced by 33%. At a carbon (C) trading price of US$ 10 Mg^{-1} of CO_2 eq., it would bring US$ 28.0 million to the rice farmers of the state. However, the methodology for monitoring and transaction cost for processing the C trading have to be worked out. Policies and incentives should be developed that would encourage farmers to adopt mitigation options to harness benefits of C trading.

The GHGs emissions in the life-cycles of rice and wheat have been calculated for the upper-IGP and lower-IGP. In the life-cycle of rice, total GWP of emissions in the lower-IGP is relatively higher than of emissions in the upper-IGP. This is due to parboiling of rice in the lower-IGP. The GHGs emissions during production have revealed maximum GWP in both the IGP regions which is followed by GWP of emissions during marketing. In the life-cycle of wheat, GWP of emissions in the upper-IGP is higher than in the lower-IGP. Emissions during production contributes maximum to the total GWP in both the IGP regions, followed by GWP of emissions in marketing. A comparison of total GWP of emissions during life-cycle of rice and wheat has shown higher GWP of rice production than of wheat production in the upper-IGP and lower-IGP regions. This is mainly due to contribution of methane emission to total GHGs emissions in rice production.

The major benefits of low carbon agricultural technologies are savings in irrigation water, labour and energy; reduction in GHGs emission; better water- and nutrient-use efficiency; provision of tolerance to moisture and heat stresses; improvement in soil health; and increase in income. There are some constraints also; these include high initial cost, infrastructure for installation and maintenance, knowledge-intensiveness and technical capability, high production cost, risk in rainfed areas, weed problem, yield loss, inadequate market facility, lack of awareness and limited post-harvest facilities.

The policy interventions required to overcome the constraints are development of irrigation facilities, incentives for saving of water, carbon credits for mitigation, subsidy and incentive for installation of resource conserving infrastructure, trainings to farmers for skill development, public awareness generation, development of effective, low-cost, environment-friendly herbicides, accurate weather forecasting, development of post-harvest facilities and refining of technologies to make them simple, cheap and effective.

The study has shown that several options are available for mitigating GHGs emission in agriculture. Policies and incentives would have to be developed to encourage farmers for adopting these mitigation options to harness benefits of improved soil health and better water- and energy-use efficiencies.

Greenhouse Gas Emissions from Indian Agriculture

A Bhatia, N Jain and H Pathak

Introduction

Today, global warming is the most prominent environmental issue before the humanity. It is caused by the increase in concentration of greenhouse gases (GHGs) in the atmosphere. The GHGs, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), trap the outgoing infrared radiations from the earth's surface and thus raise the temperature. The accumulation of GHGs in atmosphere and the consequent rise in earth's temperature is termed as 'greenhouse effect'. According to a world agency, Inter-Governmental Panel on Climate Change (IPCC), due to greenhouse effect the global mean annual temperature was recorded higher by 0.40-0.76 °C at the end of the 20th century than was at the end of the 19th century (IPCC, 2007). This agency has projected a rise of 1.1 to 6.4 °C in temperature by the end of the 21st century. The global warming is leading to several other regional and global changes such as rainfall, soil moisture and sea level.

Among different sources, agricultural soil is the major contributor to greenhouse effect. Globally, agriculture accounts for 54% of anthropogenic methane and 58% of nitrous oxide emissions. In soils, methane is produced during microbial decomposition of organic matter under anaerobic conditions. Rice fields submerged with water, therefore, are the potential source of methane. Continuous submergence, higher organic C content and use of organic manure in puddled soils enhance methane emission. Burning of crop residues also contributes to the global methane budget. Enteric fermentation in ruminants is another major source of methane.

Nitrogenous fertilizers are the source of N_2O in fertilized soils, whereas the indigenous N contributes to its release in unfertilized soil. Soil water content and the availability of carbon enhance the production of N_2O, provided a suitable nitrate source is available. Generally, increase in N_2O emission is observed following irrigation and precipitation. Burning of crop residues also contributes to the global N_2O budget.

Agriculture is a source of carbon dioxide also. Soil management practices such as tillage trigger carbon dioxide emission through biological decomposition of soil organic matter. Tillage breaks the soil aggregates, increases oxygen supply and exposes surface area of organic material promoting the decomposition of organic matter. Fuel-use for various agricultural operations and burning of crop residues are the other sources of carbon dioxide emissions. An off-site source of CO_2 is the manufacturing of fertilizers and pesticides. These emissions of GHGs also occur during production and consumption of food commodities. Comprehensive estimates of GHGs emission from food systems (including production, processing, marketing, etc.) in India are required for evaluating the economic potential of different mitigation strategies.

As per Indian Network for Climate Change Assessment (INCCA) Report (2010), the net GHGs emissions were 1727.7 million tons (Mt) of CO_2 eq. from India in 2007. The main source was the energy sector, contributing 57.8% to the total GHGs, followed by industrial (21.7%), agricultural (17.6%) and waste (3.0%) sectors. In the agricultural sector with a total emission of 334.4 Mt CO_2 eq., the major sources are enteric fermentation (63.4%), rice cultivation (20.9%), agricultural soils (13.0%), manure management (2.4%) and on-field burning of crop residues (2.0%). Thus, the crop production sector (rice cultivation, soils, and field burning of crop residues) contributes 35.9% of the total emissions from agriculture (INCCA, 2010).

Status of GHGs emission research in India

Methane

In India, field and laboratory experiments are being conducted since early-1990s in several institutes including Indian Agricultural Research Institute (IARI), New Delhi; National Physical Laboratory (NPL), New Delhi; Central Rice Research Institute (CRRI), Cuttack, Orissa, to (a) measure methane emission from rice ecosystems, (b) evaluate the effect of irrigation and fertilizer management on methane emission, (c) assess the influence of organic amendment on methane emission, (d) measure the methane emission potential of different soils of India, and (e) develop an inventory of methane emission from Indian agriculture using indigenous, site-specific emission coefficients. These studies helped in rationalizing the methane emission estimates from Indian rice fields. Results of the methane emissions from agricultural soils based on actual field measurements are summarized in Table 1.

Table 1. Seasonal methane emission from rice fields at different locations in India

Location	Methane (kg ha^{-1})	No. of observations	Average (kg ha^{-1})
Nadia, West Bengal	108-290	3	158
Purulia, West Bengal	110	1	110
Barrackpore, West Bengal	18-630	3	222
Jorhat, Assam	97-460	5	175
Tezpur, Assam	10-14	2	11.7
North 24 Parganas, West Bengal	145-462	2	305
Cuttack, Orissa	7-303	44	91
Bhubaneshwar, Orissa	140-186	2	163
New Delhi	10-221	68	39
Allahabad, Uttar Pradesh	5	1	5
Kumarganj, Uttar Pradesh	20	1	20
Maruteru, Andhra Pradesh	150	1	150
Madras, Tamil Nadu	110-182	2	149
Trichur, Kerala	37	1	37
Trivandrum, Kerala	90	1	90
Kasindra, Gujarat	120	1	120
Pant Nagar, Uttarakhand	54-114	4	79
Karnal, Haryana	64-100	2	81
Varanasi, Uttar Pradesh	0.1-261	15	117
Raipur, Madhya Pradesh	4-109	6	34
Ludhiana, Punjab	452-1650	5	875

Source: Pathak et al. (2010)

Nitrous oxide

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic nitrogen (N) in the soil. This methodology, therefore, estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge), or of mineralization of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils (e.g., forest land/grassland/ settlements converted to crop land).

During the past one decade several experiments have been conducted in India to (a) measure nitrous oxide emission from soil, (b) evaluate the effect of crop management on nitrous oxide emission, (c) develop an inventory of nitrous oxide emission from agricultural soils of India, (d) evaluate the mitigation strategies, and (e) develop a simulation model for estimation of nitrous oxide emission. Nitrous oxide emission was measured using the closed-chamber technique and analyzed by gas chromatograph using an electron capture detector (ECD). Results of the N_2O emissions from agricultural soils based on actual field measurements are summarized in Table 2.

Table 2. Emissions of N_2O from agricultural fields in India

Crop	Fertilizer[a]	N dose (kg ha^{-1})	Irrigation[b] (No.)	Duration (day)	N_2O emission (kg N ha^{-1})
Rice	Urea	140	CF	70	0.06
Rice	Urea	140	IF	90	0.16
Rice	AS	140	IF	90	0.23
Rice	Urea	120	SS	105	0.17
Rice	AS	120	SS	105	0.15
Rice	PN	120	SS	105	0.19
Rice	Urea	120	SS	90	0.74
Rice	Urea	120	IF	90	0.93
Wheat	Urea	140	3	125	0.71
Wheat	Urea	120	5	125	0.77
Wheat	Urea	120	5	95	0.55
Green gram	-	0	2	72	0.01
Horsegram	-	0	2	105	0.01
Black gram	-	0	2	93	0.02
Sorghum	Urea	80	1	113	0.52
Pearl millet	Urea	80	1	110	0.47
Soybean	Urea	60	2	114	0.49
Groundnut	Urea	60	2	116	0.46
Pigeon pea	Urea	40	3	118	0.37
Maize	Urea	120	4	105	0.64
Green gram	Urea	60	2	100	0.48
Mustard	Urea	80	3	116	0.56
Chick pea	Urea	40	2	138	0.49

[a]AS, Ammonium sulphate; PN, potassium nitrate

[b]CF, continuously flooded; IF, intermittently flooded; SS, saturated soil

Source: Pathak et al. (2010)

Carbon dioxide

Since agricultural soils act both as a source and a sink for carbon dioxide, the net flux is very small.

Inventory of GHGs emission from Indian agriculture

The research on GHGs emission from Indian agriculture started in 1990s when, based on very limited measurements done elsewhere, it was reported that Indian rice fields emit 37.5 Mt methane per year. With sustained and systematic indigenous research the methane emission estimates have been rationalized (Fig. 1). The current

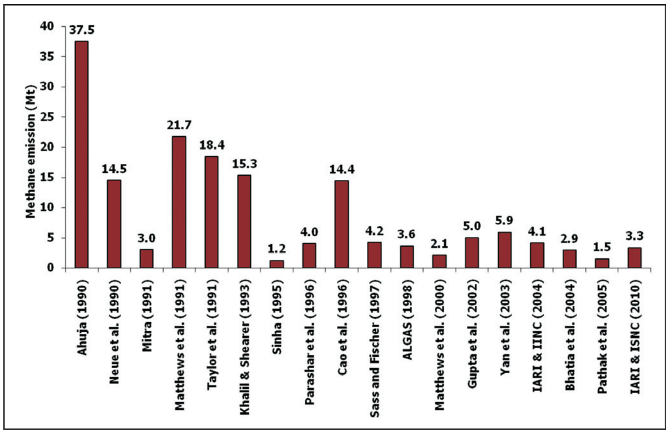

Fig. 1. Estimates of methane emission from Indian rice fields by various researchers over the years
Source: Pathak et al. (2010)

estimates show that Indian rice fields covering an area of 43.86 million ha (Mha) emit 3.37 Mt of methane. The nitrous oxide emission from Indian agricultural soils is 0.14 Mt. Several attempts have been made to estimate CH_4 emission from Indian rice fields (Mitra, 1991; Parashar et al., 1991; 1996; Matthews et al., 2000; Yan et al., 2003; Bhatia et al., 2004). However, only a few studies (Cao et al., 1996; Matthews et al., 2000, Bhatia et al., 2007) have attempted to calculate detailed regional CH_4 emissions using simulation modeling. The emission estimates vary widely with the methodology adopted and assumptions made on the importance of different factors affecting CH_4 emission (Table 3). Ahuja (1990) gave an estimate of 37.8 Mt yr^{-1} CH_4 emission from Indian paddies, which was based on emission data of European and American paddy fields and extrapolated to the Indian region. Later on, a value of 3.0 Mt yr^{-1} was estimated on the basis of measurements done up to 1990 at various rice-growing regions in the country (Mitra, 1991; Parashar et al.,

Table 3. Greenhouse gas emissions from Indian agriculture during 2007

Source	CH_4	N_2O	CO_2 eq.
		Million ton	
Enteric fermentation	10.10	-	212.09
Manure management	0.12	-	2.44
Rice cultivation	3.37	-	84.24
Agricultural soil	-	0.22	64.7
Crop residue burning	0.25	0.01	8.21
Total	**13.84**	**0.23**	**371.68**

Source: INCCA (2010)

1991). Parashar et al. (1996) further revised the budget to be 4.0 Mt yr^{-1} with a range between 2.7 and 5.4 Mt yr^{-1}. Matthews et al. (2000) used the MERES model to simulate CH_4 emission from rice paddies in India and estimated a value of 2.1 Mt CH_4 yr^{-1}. Gupta et al. (2002) using average emission factors for all paddy water regimes, which included harvested areas having soils with high organic carbon and organic amendments, estimated a budget of 5.0 Mt yr^{-1}. Yan et al. (2003) using region specific emission factors estimated India's CH_4 emission to be 5.9 Mt yr^{-1}.

Several attempts have been made to estimate N_2O emissions from Indian soils. Parashar et al. (1998) had estimated emissions of N_2O to be 199-279 thousand tons yr^{-1} from agricultural soils in India (Fig. 1). In another study, N_2O emission from Indian agricultural soils was estimated to be 240 thousand tons yr^{-1} (ALGAS, 1998). Garg et al. (2001) using the IPCC methodology and emission coefficients (IPCC, 1996) have given an estimate of 170 thousand tons yr^{-1} N_2O emission from Indian soils. The estimate included emissions from biological N fixation, N fertilizer and indirect emissions from soils. These estimates varied largely as adequate coverage of all sources of N_2O emissions was not made and there were too many assumptions without the actual measurement data. Bhatia et al. (2004) have estimated N_2O emissions to be 126 thousand tons for the base year 1994-95 from Indian agricultural soils using some measured emission coefficients. However, using the IPCC default emission coefficients, the emission has been found to be 228 thousand tons N_2O yr^{-1}.

Recently, an inventory of GHG emissions from Indian agriculture for the year 2007 has been prepared (INCCA, 2010). The emission sources accounted for are enteric fermentation in livestock, manure management, rice cultivation, agricultural soils and burning of crop residues.

According to INCCA, the agricultural sector emitted 371.7 Mt of CO_2 eq. comprising 13.84 Mt of CH_4 and 0.227 Mt of N_2O. Enteric fermentation constituted 61% of the total CO_2 eq. emissions from this sector and 20% of the emissions were from rice cultivation. Agricultural soils emitted 16% of the total CO_2 eq. emission from agriculture (INCCA, 2010). The remaining 3% of the emissions are attributed to livestock manure management and burning of crop residues in field.

Indian rice fields covering an area of 43.86 Mha (MoA, 2008) emitted 3.37 Mt of CH_4 in 2007. Of the total rice area, 55% was irrigated (MoA, 2008), 12% was rainfed upland (Huke and Huke, 1997), 3% was under deepwater and the remaining 30% was rainfed lowland. The irrigated rice area was further sub-divided into (i) continuously flooded (26.9%), (ii) single aeration (35.7%), and (iii) multiple aerations (37.4%) based on Gupta et al. (2009). The rainfed area was also sub-divided into flood-prone (27.1%) and drought-prone (72.9%) based on Huke and Huke (1997).

The CH_4 emission has been found to vary with different rice ecosystems. The highest emission has been from irrigated continuously-flooded rice (34%), followed by rainfed flood-prone rice (21%). The rainfed drought-prone, single aeration, deep water and irrigated multiple-aeration rice ecosystems have depicted contributions of 17%, 16%, 8% and 4% of CH_4, respectively. Emission of methane from Indian rice fields has remained almost similar during the period 1995 to 2007 though the rice production has increased from 115 Mt to 128 Mt. It is because of area under rice remaining almost constant (43-44 Mha) and following of similar water and crop management practices by the farmers over the years.

The total N_2O–N emission from India was estimated to be 0.14 Mt in 2007. The direct and indirect N_2O emissions from Indian agricultural soils were estimated to be 186.4 thousand tons (55.3 Mt CO_2 equivalent) and 30.61 thousand tons (5.8 Mt CO_2 equivalent), respectively. In spite of an increase in N-fertilizer consumption, N_2O emissions from agricultural soils reduced in 2007 with respect to 1994. This is mainly due to the use of India specific emission factors that are lower by almost 38% than the IPCC default values. The revised emission factor is 0.62 kg N_2O-N kg^{-1} N applied for direct emission (Majumdar et al., 2002; Pathak et al., 2002; 2004; Bhatia et al., 2005, Malla et al., 2005, NATCOM, 2004) and 0.50 kg N_2O-N kg^{-1} N applied for indirect emission. Application of N-fertilizer is the major source of N_2O-N emission contributing 70%, followed by crop residues and mineralization of organic-N in soil.

Unlike emission of methane which has remained constant over the years, emission of N_2O has increased from 169 to 217 thousand tons during 1995 to 2007 because of increased N-fertilizer use by the farmers.

Emission of GHGs from agriculture in different states has shown that Punjab, Haryana, Uttar Pradesh and Andhra Pradesh emit higher amount of N_2O-N because of higher amount of N-fertilizer use. On the other hand, West Bengal, Andhra Pradesh, Orissa, Bihar, Jharkhand and North-Eastern states emit higher amount of methane per ha of rice cultivation.

Because of increasing emission of nitrous oxide, the total global warming potential (GWP) (methane × 25 + nitrous oxide × 298) of Indian agriculture per unit area (kg CO_2 eq. ha^{-1}) is increasing. However, GWP per unit of produce (kg CO_2 eq. t^{-1}) is decreasing (Fig. 2). Similarly, GHGs intensity per unit agricultural gross domestic product (Ag-GDP) has also declined over the years. This decline has been

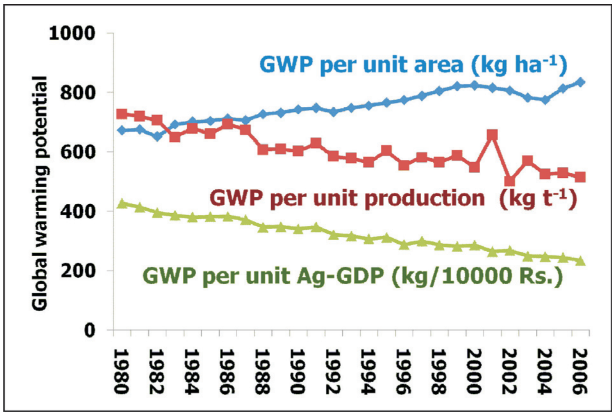

Fig. 2. Trend in intensity of greenhouse gas emission from Indian agriculture GWP, Global warming potential; Ag-GDP, Agricultural gross domestic product

Source: Pathak et al. (2011, unpublished)

due to increase in agricultural production of the country through adoption of high-yielding crop varieties and better crop management practices without increase in area under agriculture. Though application of N-fertilizer has increased the agricultural GWP, the increase in yield, and thereby agricultural GDP (because of higher N-use) has been greater. The analysis has shown that there is enough scope of improving agricultural production in the country without off-setting the GHGs emission. Moreover, agriculture has the potential to mitigate GHGs cost-effectively through changes in agricultural technologies and management practices. Mitigation of GHGs emission from agriculture can be achieved by sequestering C in soil and reducing methane and nitrous oxide emissions from soil through change in land-use management. Changes in the management of irrigation, fertilizer use, and soils can reduce emission of both nitrous oxide and methane. Such options are not only important for global warming mitigation but also for improving soil fertility and sustainable agriculture.

Emission of greenhouse gases due to burning of crop residues

Generally, residues from nine crops (rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed-mustard and groundnut) are burnt in the field. Total crop residues generated by these nine major crops are about 566 Mt of which about 93 Mt are subjected to burning in the fields. Burning of crop residues in fields emitted 0.25 Mt of CH_4 and 0.007 Mt of N_2O in 2007. The burning of rice straw contributed the maximum (39%) to this GHGs emission. Large-scale burning of rice residues in Punjab, Haryana and western Uttar Pradesh is a matter of serious concern not only for GHGs emission but also for problems of pollution, health hazards and loss of nutrients (Pathak et al., 2006). Emission of GHGs due to burning of crop residues in field has, however, remained almost similar over the years.

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2

Potential and Cost of Low Carbon Technologies in Rice and Wheat Systems: A Case Study of the Indo-Gangetic Plains

H Pathak, B Chakrabarti, A Bhatia, N Jain and PK Aggarwal

Introduction

Agricultural soils contribute to the greenhouse effect primarily through the emission and consumption of GHGs such as methane, nitrous oxide and carbon dioxide. Methane is produced in soil during microbial decomposition of organic matter under anaerobic conditions. Rice fields submerged with water, are the potential source of methane. Nitrogenous fertilizer is a source of N_2O in fertilized soils, whereas the indigenous N contributes to the release of this GHGs in unfertilized soil. Burning of crop residues also contributes to the N_2O emission. Agricultural soils may also act as a sink or source for carbon dioxide (CO_2), but the net flux is small. Fuel use for various agricultural operations and burning of crop residues is a source of carbon dioxide emission. An off-site source is the production of carbon dioxide for manufacturing fertilizers and pesticides.

Scientific agriculture can help in mitigating GHGs emission. The following strategies have been recommended for mitigating methane emission from rice cultivation.

- altering water management, particularly promoting intermittent irrigation and mid-season drainage;
- improving organic matter management by promoting aerobic degradation through composting or incorporating it into soil during off-season drained period;
- use of rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index; and
- application of fermented manure such as biogas slurry in place of unfermented farmyard manure (Pathak et al., 2010). A single mid-season drainage may reduce seasonal methane emission. This emission could be reduced further by intermittent irrigation, yielding a 30% reduction as compared to mid-season drainage (Lu et al., 2000).

Emission of N_2O can be reduced by following management practices that improve N-use efficiency including using slow or controlled release of fertilizer or nitrification inhibitors which retard the microbial processes leading to N_2O formation (Robertson, 2004). The most efficient management practices to reduce nitrous oxide emission are:

- site-specific nutrient management, and
- use of nitrification inhibitors such as nitrapyrin and dicyandiamide.

There are some plant-derived organics such as neem oil, neem cake and karanja seed extract which can also act as nitrification inhibitors. Nitrification inhibitors reduce N_2O emission directly by reducing nitrification, and indirectly by reducing the availability of NO_3 for denitrification (McTaggart et al., 1997; Castaldi and Smith, 1998). Zu et al. (2002) have observed lowering of emissions of both N_2O and CH_4 during rice growth using a combination of dicyandiamide (DCD) and hydroquinone. Demand-driven N-use using a leaf colour chart (LCC) could reduce nitrous oxide emission and GWP by about 11% (Bhatia et al., 2010). This chapter assesses the potential of various technologies to mitigate GHGs emission in rice and wheat at site as well as at regional scales in the Indo-Gangetic Plains (IGP) and evaluates the economic viability of various mitigation strategies in agriculture.

Materials and methods

Study sites

The study was conducted in two regions broadly classified as upper-IGP and lower-IGP (Fig. 1). The upper-IGP comprises Punjab, Haryana and Uttar Pradesh (western part), while Uttar Pradesh (eastern part), Bihar and West Bengal come under the lower-IGP. Technical coefficients, i.e., coefficients describing relationships between various inputs and outputs were generated for the major land-use systems in the upper-IGP and lower-IGP using the target-oriented-approach based on the physical environment and the production technique (Pathak and Wassmann, 2007; Pathak et al., 2011). With this an optimal combination of inputs was identified to realize a

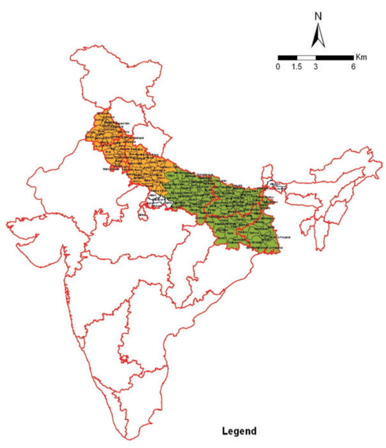


Fig. 1. Study sites in the Indo-Gangetic plains of India
Source: NBSSLUP (2010, unpublished)

particular yield (output) level, based on the knowledge of crop growth conditions. The outputs, i.e., GHGs emissions were then calculated based on the amount of input used and the related output. Input and output relationships were expressed per hectare and were scale independent. In this approach, inputs and outputs for a given land-use system were determined by the physical environment and the production technique. The compilation of GHGs emissions was done at district-level using (district-specific) information on soil and climate.

Model description

The InfoRCT (Information on Use of Resource-Conserving Technologies) simulation model (Pathak et al., 2011) was used to calculate GHGs emission through machine and fertilizer use to calculate total GWP of conventional and other different technologies. This model integrates biophysical, agronomic, and socioeconomic data to establish input-output relationships related to water, fertilizer, labor, and biocide uses; GHGs emissions in the rice-wheat system. The inputs and outputs are calculated on a season basis using the target-oriented approach (Ponsioen et al., 2006; Pathak and Wassmann, 2007). With this, an optimal combination of inputs was identified to realize a target yield based on the biophysical environment and production techniques such as RCTs. Outputs such as GHGs emissions were then calculated based on the amount of input used and the related soil-plant-atmospheric processes.

The InfoRCT was programed in Microsoft Excel containing various parameters organized in different worksheets. The data in the worksheets 'Site', 'Crop', 'Price', 'Labor', and 'Biocide' were region-specific, reflecting natural conditions as well as the current practice of farmers. The worksheets 'Technologies' and 'Resource Balances' contained generic information. The worksheets can be amended easily if other technologies are to be assessed or more technical coefficients need be computed.

The model requires input data pertaining to the conventional practices of farmers. From these inputs, the model calculates the required amounts of fertilizer, irrigation water, biocides, human and machine labor, and seeds as well as N budget, biocide residue, and GHGs emissions in rice, wheat, and the rice-wheat system when conventional farm practices and various other technologies are followed. To make the model user-friendly, a front-end has been developed with all the input data required to be provided by the user.

Calculation of emission of greenhouse gases using InfoRCT model

In soil, methane is formed from organic C present in soil and C added through organic residues, dead roots, and root exudates. Indigenous CH_4 emission (CH_4_em_ind, kg C ha^{-1} d^{-1}) was calculated as a function of available C substrate, that is, dissolved organic C, which in turn is related to soil organic carbon (SOC) (%), bulk density (g cm^{-3}), soil depth (cm), crop duration (days), and the rate of decomposition (0.000085 per day) of SOC (Pathak and Wassmann, 2007):

$$CH_4\_em\_ind = SOC \times 1000 \times bulk\_density \times soil\_depth \times 0.000085 \times crop\_duration \times 0.27 \times 0.55$$

Actual CH_4 emission (CH_4_em_ac, kg C ha^{-1} d^{-1}) was then calculated as

$$CH_4\_em\_ac = (CH_4\_em\_ind \times Tech\_CH_4 + (root\_input + manure\_input \times 0.5) \times 0.27 \times 0.55 \times 0.4) \times 2^{**}(Temp - 25)/10$$

where, Tech_CH_4 is a technology-dependent factor for CH_4 emission; root_input and manure_input correspond to the respective organic input (kg); 0.5 represents the fraction of manure mineralized during the growing season (assuming that 50% of the manure will be decomposed during the fallow period); 0.27 is the ratio of the molecular weights of methane and carbohydrate; 0.55 is the initial fraction of produced methane that is emitted; 0.4 is the C content of the root and manure inputs; 2**(Temp - 25)/10 is the temperature correction factor, where Temp is the seasonal average temperature (°C). Although manure inputs are documented for all technologies, root inputs (composed of exudates and dead roots) were derived from above-ground biomass using the equations derived by Pathak and Wassmann (2007).

Nitrous oxide emission (N_2O_em_ac, kg N ha^{-1}) was related to the mineralization of organic N (from soil, residues, and manure) into an inorganic pool (NH_4^+), which was in turn related to the mineralization of C, addition of inorganic fertilizer as either NH_4^+ or urea forms, and rates of nitrification and denitrification (0.0024 kg kg^{-1}). A similar approach has been used in the denitrification and decomposition (DNDC) model for estimating N_2O emission from soil by Li (2000):

$$N_2O\_em\_ac = [(CO_2\_em\_ac + CH_4\_em\_ac)/10 + Fertilizer\ N] \times 0.0024 \times Tech\_N_2O$$

where, CO_2_em_ac is emission of CO_2 (kg C ha^{-1}) (see below) and Tech_N_2O is the N_2O emission coefficient at different technology levels.

In InfoRCT, emission of CO_2 has been related to (i) fossil fuel consumption from farm operations and off-farm production of inputs, (ii) changes in SOC, and (iii) C-sequestration and fuel savings in some selected technologies. The computations of fossil fuel consumption and savings are based on simple algorithms and published data (Grace et al., 2003). The computation of soil-borne (net) CO_2 emissions is primarily based on soil factors and a technology-specific index. Emission of CO_2 (CO_2_em_ac, kg C ha^{-1}), that is, change in SOC, has been related to SOC (%) of soil, bulk density (g cm^{-3}), soil depth (cm), crop duration (days), rate of decomposition (0.000085 per day) of SOC, temperature correction factor, and technology-specific index (Tech_SOC_CO_2):

$$CO_2\_em\_ac = SOC \times 1000 \times bulk\_density \times soil\_depth \times 0.000085 \times crop\_duration \times 2^{**}((Temp - 25)/10) \times Tech\_SOC\_CO_2$$

Emissions of CO_2 from farm operations and for the production of various farm inputs were calculated using the values given by Pathak and Wassmann (2007).

Global warming potential (GWP) is an index used to compare the effectiveness of each greenhouse gas in trapping heat in the atmosphere relative to a standard gas, by convention, CO_2. The GWP for CH_4 (based on a 100-year time horizon) is 25, while that for N_2O is 298 when the GWP value for CO_2 is taken as 1. Global warming potential (kg CO_2 equivalent ha^{-1}) of a system was calculated (IPCC, 2007) as:

$$GWP = CH_4\_em\_ac \times 16/12 \times 25 + N_2O\_em\_ac \times 44/28 \times 298 + (CO_2\_em\_ac + CO_2\_em\_op + CO_2\_em\_in) \times 44/12$$

Earlier the model was validated using data from field measurements from other experiments in the rice-wheat system conducted within the IGP (Majumdar et al., 2002; Pathak et al., 2003b; Malla et al., 2005).

Data inputs

The first step in a target-oriented approach of input-output estimation is to decide the yield target. In the present study, the current yields in different districts of the Punjab state were obtained from FAI (2009) and were taken as the yields for the conventional farmers' practice. Yields in the other technologies were determined using the technology-dependent yield indices. The requirements of N, P, and K for rice and wheat were calculated using the values given by Witt et al. (1999) and Pathak et al. (2003a), respectively.

A survey, conducted, provided information related to manure use, and human and machine labour use in different states. For mitigation technologies, machine labour and human labour were adjusted using those indices.

Resource inventory

The study regions have different climatic conditions. The annual rainfall in the upper-IGP is around 550 mm, while lower-IGP receives 1200 mm rainfall (Table 1). Temperature during the *kharif* season is higher in upper-IGP, while during *rabi* the temperatures are much lower. Organic carbon content of soils is more (0.8%) in the lower-IGP than the upper-IGP (0.6%) (Table 1). Clay contents vary from 20% (upper-IGP) to 35% (lower-IGP), while pH varies from 7.7 to 6.5, respectively. Rice and wheat are the two important crops grown in both the regions. Therefore, for the

Table 1. Characterization of sites in the Indo-Gangetic Plains selected for the current study

Site[a]	Upper-IGP	Lower-IGP
Annual rainfall (mm)	550	1200
Temperature *kharif* (°C)	29	24
Temperature *rabi* (°C)	14	19
Soil depth (cm)	150	150
Soil organic C (%)	0.60	0.80
Clay (%)	20	35
pH	7.7	6.5
Bulk density (Mg m^{-3})	1.44	1.42
N application rate rice (kg ha^{-1})	180	116
N application rate wheat (kg ha^{-1})	192	135
Rice yield (Mg ha^{-1})	6.00	4.50
Wheat yield (Mg ha^{-1})	4.50	3.50

[a]Average values across the region

present study this cropping system was selected. Consumption of nitrogenous fertilizer in rice and wheat is 180 kg ha^{-1} and 192 kg ha^{-1} in upper-IGP while it is much lower at 116 kg ha^{-1} and 135 kg ha^{-1} in lower-IGP, respectively. The average yield of rice and wheat crops is more in the upper parts of the IGP.

Mitigation technologies

Emissions of CH_4 and N_2O are affected mainly by water regime and N supply, while CO_2 is emitted in large amounts on burning of rice straw. So different technologies were selected with four different identifiers in rice and three identifiers in wheat, suitable for mitigating emission of GHGs for the current study. Twenty such technologies were selected for rice crop in both the regions, while for wheat crop, ten technologies were selected. In rice, the technologies varied in terms of their irrigation pattern, N supply, straw management and additives and new management practices. In the upper-IGP, rice straw is burnt in all the technologies except in one (technology 16), where rice straw was used as the cattle feed (Table 2). In the lower-IGP, the scenario is just the reverse with rice straw being fed to cattle in all technologies, except one (technology 16), where it was burnt (Table 2). In wheat, the technologies varied in terms of N supply, straw management and additives and new management and these technologies were similar for both the upper-IGP as well as lower-IGP (Table 3).

Economic evaluation

The cost of cultivation was calculated by taking into account costs of seed, fertilizers, biocide, human labor, machines hiring for land preparation, irrigation, fertilizer application, plant protection, harvesting, and threshing, and the time required per ha to complete an individual field operation. The cost of irrigation was calculated by multiplying the time (h) required to pump the calculated amount of irrigation water, consumption of diesel by a pump ($L\ h^{-1}$), and the cost of diesel. The cost of human labour, machine labour and diesel were their current prices in northern India collected by a market survey. Technologies also involve some extra recurring and non-recurring expenditures. A technology cost, i.e., price of the machine (₹) divided by area (ha) planted or sown in its average life-span, was used when new machinery such as a zero-till drill were required. Gross income was derived using the minimum support price offered by the Government of India for rice and wheat. Net income of the farmers was calculated as the difference between gross income and total costs of inputs and labor. The economic feasibility of various technologies vis-à-vis the conventional farmers' practice was compared considering net income and GWP.

Simulation of GHGs emission and mitigation at a regional scale

Emission of GHGs and potential of its mitigation were simulated for the Punjab state at district level. Only two technologies, viz. conventional continuous flooding and mid-season drainage, were considered for this simulation. A resource inventory of soil, climate and fertilizer-use was prepared for every district of Punjab using

Table 2. Characterization of rice management technologies for low carbon in the upper and lower Indo-Gangetic Plains

Technology	Irrigation pattern	Type of N-supply	[a]Straw management (upper IGP/ lower IGP)	Additives and new management, Remarks
1. Transplanted rice	Continuous flooding	Urea	Burnt/cattle feed	Conventional puddled transplanted rice
2. Mid-season drainage	Mid-season drainage	Urea	Burnt/cattle feed	Mid-season drainage (less methane)
3. Aerobic rice	Aerobic (no flooding)	Urea	Burnt/cattle feed	Aerobic rice (less methane)
4. System of rice intensification (SRI)	Aerobic (no flooding)	Urea + FYM	Burnt/cattle feed	System of rice intensification (less methane)
5. Direct-seeded rice (DSR)	Aerobic (no flooding)	Urea	Burnt/cattle feed	Dry direct seeded rice (less methane)
6. Sprinkler irrigation (SPR)	Aerobic (no flooding)	Urea	Burnt/cattle feed	Irrigation through sprinkler (less methane)
7. Zero tillage (ZT)	Aerobic (no flooding)	Urea	Soil incorporation	Zero till direct seeded (less methane, C-sequestration)
8. Integrated nutrient management (INM)	Continuous flooding	Urea + FYM	Burnt/cattle feed	Integrated nutrient management
9. Organic rice	Continuous flooding	FYM	Burnt/cattle feed	Organic farming (price: 1.5× regular)
10. Phosphogypsum (PGM)	Continuous flooding	Urea	Burnt/cattle feed	Phosphogypsum (less CH_4)
11. Nitrification inhibitor (NI)	Continuous flooding	Urea	Burnt/cattle feed	Nitrification inhibitor (less N_2O)
12. Urea super granule (USG)	Continuous flooding	Urea	Burnt/cattle feed	N through urea super granule
13. Leaf colour chart (LCC)	Continuous flooding	Urea	Burnt/cattle feed	Leaf colour chart-based N use (less N_2O)

Technology	Irrigation pattern	Type of N-supply	[a]Straw management (upper IGP/ lower IGP)	Additives and new management, Remarks
14. Site-specific nutrient management (SSNM)	Continuous flooding	Urea	Burnt/cattle feed	Site-specific nutrient management (less N_2O)
15. Green manuring (GM)	Continuous flooding	Urea + GM	Burnt/cattle feed	Green manure (more methane)
16. Straw fed to cattle	Continuous flooding	Urea	Cattle feed/burnt	Straw fed to cattle
17. C sequestration	Continuous flooding	Urea	C sequestered	Straw used as construction material
18. New cultivar	Continuous flooding	Urea	Burnt/cattle feed	New cultivar: less GHG, 2× seed price
19. Yield maximization (YMX)	Continuous flooding	Urea	Burnt/cattle feed	Yield maximization with more inputs
20. Diversification (DVR)	Aerobic (no flooding)	Urea	Burnt/cattle feed	Crop diversification, maize replaces rice

[a]Straw is burnt in upper-IGP and straw is used as cattle feed in lower-IGP

Table 3. Characterization of wheat management technologies for low carbon in the upper- and lower-Indo-Gangetic Plains

S.No.	Technology	Type of N-supply	Straw management	Additives and new management, Remarks
1.	Conventional tillage	Urea	Used as cattle feed	Conventional tilled wheat
2.	Sprinkler irrigation (SPR) methane)	Urea	Used as cattle feed	Irrigation through sprinkler (less
3.	Zero tillage (ZT) C-sequestration)	Urea	Soil incorporation	Zero till direct seeded (less methane,
4.	Integrated nutrient management (INM)	Urea + FYM	Used as cattle feed	Integrated nutrient management
5.	Organic wheat	FYM	Used as cattle feed	Organic farming (price: 1.5× regular)
6.	Nitrification inhibitor (NI)	Urea	Used as cattle feed	Nitrification inhibitor (less N_2O)
7.	Site-specific nutrient management (SSNM) management (less N_2O)	Urea	Used as cattle feed	Site-specific nutrient
8.	Straw fed to cattle	Urea	Burnt	Straw fed to cattle
9.	New cultivar	Urea	Used as cattle feed	New cultivar: less GHG, 2× seed price
10.	Yield maximization (YMX)	Urea	Used as cattle feed	Yield maximization with more inputs

primary surveys, Government Statistics and published literature (Table 4). The state has a net sown area of 4.17 Mha and rice is cultivated as a *kharif* crop under puddled transplanted condition in 2.73 Mha (Statistical Hand Book, Govt. of Punjab, 2009). Annual rainfall varies from 93 mm to 957 mm. Punjab soils contain organic carbon ranging from 0.22% to 1.12% with pH varying from 7.5 to 8.1 (Table 4). Similarly, GHGs emission can be simulated for other states also at the district level and suitable mitigation technologies can be developed.

Table 4. Area, rainfall, yield and soil properties in different districts of Punjab

District	Net sown area ('000 ha)	Area under rice ('000 ha)	Annual rainfall (mm yr^{-1})	Soil organic C (%)	Soil pH	Rice yield Mg ha^{-1}
Amritsar	218	183	265.4	0.61	7.9	4.36
Barnala	125	102	417.0	0.66	8.1	7.14
Bathinda	297	97	336.7	0.15	7.8	6.60
Faridkot	128	95	520.6	0.75	7.9	6.54
Fatehgarh Sahib	102	85	751.5	0.54	7.5	6.41
Ferozepur	475	260	224.1	0.50	8.0	6.06
Gurdaspur	287	201	808.4	0.42	6.7	4.95
Hoshiarpur	201	60	885.6	0.50	7.6	5.22
Jalandhar	237	155	673.8	0.73	7.8	5.70
Kapurthala	134	114	644.0	0.45	7.5	5.63
Ludhiana	306	254	775.9	0.22	7.5	6.71
Mansa	190	71	139.3	0.15	7.8	6.25
Moga	198	174	428.8	0.64	8.0	6.90
Muktsar	224	95	379.6	1.12	7.9	6.35
Nawan Shahar	95	52	517.8	0.67	7.7	6.15
Patiala	271	238	950.9	0.40	7.5	6.36
Ropar	79	36	957.3	0.84	7.6	5.78
Sangroor	311	267	355.5	0.66	8.1	6.93
SAS Nagar	75	27	459.0	0.84	7.6	4.89
Taran Taaran	218	169	93.3	0.60	7.9	4.66

Results and Discussion

Emission of greenhouse gases in rice cultivation

Emissions of GHGs from soil, burning of rice straw, manure management, farm operations and production of various agricultural inputs were estimated in the study. Burning of rice straw contributed to the emissions of CH_4 and N_2O. Nitrous oxide is also emitted from soils, fertilizer application and manure management. The study has shown that soil is the major contributor of CH_4. In conventional practices, fluxes of CH_4 from soil in rice were 48 kg ha^{-1} in the upper-IGP, and 88 kg ha^{-1} in the lower-IGP (Tables 5 & 7). Emission of N_2O-N due to fertilizer application varied from 0.87 kg ha^{-1} in the upper-IGP to 0.56 kg ha^{-1} in lower-IGP. Burning of rice straw emitted 19 kg CH_4 ha^{-1} and 0.6 kg N_2O-N ha^{-1} in the upper-IGP. In the lower-IGP since straw is fed to the cattle and therefore there is no problem of its burning. CO_2 is emitted from on-farm and off-farm operations like use of machines, production of fertilizers and pesticides. Farm operations and off-farm practices such as production of fertilizers and biocides contributed 394 kg CO_2-C ha^{-1} and 187 kg CO_2-C ha^{-1} in the upper-IGP and lower-IGP, respectively. Contribution of soil to CO_2 emission was taken as zero in the present study. This is based upon the observation in several long-term fertility experiments in rice-wheat cropping systems in northwest India, showing a more or less static organic C status for the past 25-30 years (Ladha et al., 2003). In soils under rice-rice cropping systems of South Asia also, organic C status is reported to remain stable. Under conventional management practices, there is no C sequestration in upper-IGP, while in lower-IGP 97 kg CO_2-C ha^{-1} can be sequestered even with current management practices. Total global warming potential (GWP) of rice cultivation is 3957 kg CO_2 ha^{-1} and 2934 kg CO_2 ha^{-1} in the upper-IGP and lower-IGP, respectively (Tables 6 & 8). The net return obtained from rice cultivation is also more in the upper-IGP.

Wheat is grown under aerobic condition; therefore, soil emission of CH_4 is zero. As wheat straw is used for cattle feed in both the regions, it is not burnt *in situ* and does not contribute to GHGs emission. In wheat the contribution to GHGs emissions is from soil (N_2O), cattle and manure management (CH_4) and farm operations and off-farm production of agricultural inputs (CO_2). Emission of N_2O-N from soils due to fertilizer application ranged from 0.92 to 0.65 kg ha^{-1} in the upper-IGP and lower-IGP, respectively (Tables 9 and 11). Farm operations and off-farm practices contributed 363 kg CO_2-C ha^{-1} in the upper-IGP, while in the lower-IGP, it was 254 kg CO_2-C ha^{-1}. Under the current management practices, carbon is not sequestered

Table 5. Emission of greenhouse gases in rice with different technological options in the upper Indo-Gangetic Plains

Technology[a]	CH_4 burning (kg ha^{-1})	N_2O-N burning (kg ha^{-1})	CH_4 soil (kg ha^{-1})	N_2O-N soil & manure (kg ha^{-1})	N_2O-N fertilizer (kg ha^{-1})	CO_2 on-farm & off-farm (kg ha^{-1})	CO_2-C sequestration (kg ha^{-1})	Total (kg CO_2 ha^{-1}) GWP
Transplanted rice	19	0.6	48	0.27	0.87	394	0	3957
Mid-season drainage	19	0.6	34	0.29	1.01	381	0	3625
Aerobic rice	18	0.6	19	0.31	1.09	345	0	3141
System of rice intensification	19	0.6	17	0.31	0.76	260	300	1542
Direct-seeded rice	18	0.6	5	0.30	0.98	318	0	2623
Sprinkler irrigation	19	0.6	0	0.30	0.95	309	0	2494
Zero till	0	0.0	11	0.31	1.01	363	432	637
Integrated nutrient management	21	0.7	166	0.33	0.70	362	300	5707
Organic rice	17	0.6	283	0.31	0.00	111	600	6129
Phosphogypsum	19	0.6	34	0.27	0.87	394	0	3593
Nitrification inhibitor	21	0.7	43	0.14	0.40	407	0	3684
Urea super granule	21	0.7	48	0.16	0.49	409	0	3864
Leaf colour chart	21	0.7	48	0.16	0.49	407	0	3856
Site-specific nutrient management	21	0.7	48	0.22	0.65	404	0	3949
Green manuring	21	0.7	166	0.33	0.70	360	300	5699
Straw fed to cattle	0	0.0	48	0.27	0.87	399	130	2725
C sequestration	0	0.0	48	0.33	1.04	399	2016	-4085
New cultivar	19	0.6	43	0.24	0.71	372	0	3669
Yield maximization	29	1.0	49	0.29	1.62	729	0	5954
Diversification	17	0.6	0	0.25	0.68	269	0	2118

[a]Details of the Technologies are given in Table 2

Table 6. Global warming potential (GWP) of rice cultivation and cost-benefit analysis of different technologies in the upper Indo-Gangetic Plains

Technology[a]	Total GWP (kg CO_2 ha^{-1})	Net return (‘ ha^{-1})	Difference in net return (‘ ha^{-1})[b]	Difference in GWP (kg CO_2 ha^{-1})	Cost of mitigation (‘ kg^{-1} CO_2)
Transplanted rice	3957	27301	0	0	
Mid-season drainage	3625	25992	-1310	-332	3.94
Aerobic rice	3141	25970	-1332	-817	1.63
System of rice intensification	1542	23886	-3416	-2415	1.41
Direct-seeded rice	2623	27788	486	-1334	-0.36
Sprinkler irrigation	2494	28422	1121	-1463	-0.77
Zero till	637	24154	-3148	-3320	0.95
Integrated nutrient management	5707	28262	960	1750	
Organic rice	6129	35306	8004	2172	
Phosphogypsum	3593	24587	-2714	-365	7.45
Nitrification inhibitor	3684	27310	8	-273	-0.03
Urea super granule	3864	28271	969	-93	-10.44
Leaf colour chart	3856	28903	1602	-101	-15.84
Site-specific nutrient management	3949	28732	1431	-9	-167.43
Green manuring	5699	28507	1206	1742	
Straw fed to cattle	2725	25821	-1481	-1233	1.20
C sequestration	-4085	24721	-2581	-8043	0.32
New cultivar	3669	26399	-903	-288	3.13
Yield maximization	5954	37641	10340	1997	
Diversification	2118	33764	6463	-1839	-3.51

[a]Details of the Technologies are given in Table 2

[b]Difference compared to the conventional puddled transplanted rice.

Table 7. Emission of greenhouse gases in rice with different technological options in the lower Indo-Gangetic Plains

Technology[a]	CH_4 burning	N_2O-N burning	CH_4 soil	N_2O-N soil & manure	N_2O-N fertilizer	CO_2 on-farm & off-farm	CO_2-C sequestration	Total GWP (kg CO_2 ha^{-1})
	(kg ha^{-1})							
Transplanted rice	0	0	88	0.29	0.56	187	97	2934
Mid-season drainage	0	0	62	0.31	0.64	197	97	2357
Aerobic rice	0	0	35	0.32	0.69	198	92	1741
System of rice intensification	0	0	25	0.32	0.38	117	97	1034
Direct-seeded rice	0	0	9	0.31	0.62	181	92	979
Sprinkler irrigation	0	0	0	0.30	0.61	182	97	735
Zero till	0	0	13	0.31	0.70	198	324	346
Integrated nutrient management	0	0	255	0.37	0.38	128	300	6089
Organic rice	0	0	421	0.36	0.00	23	600	8569
Phosphogypsum	0	0	62	0.28	0.56	187	97	2266
Nitrification inhibitor	0	0	80	0.14	0.27	183	107	2461
Urea super granule	0	0	88	0.18	0.32	184	107	2725
Leaf colour chart	0	0	88	0.18	0.32	183	107	2722
Site-specific nutrient management	0	0	88	0.23	0.42	182	107	2794
Green manuring	0	0	255	0.37	0.38	128	300	6086
Straw fed to cattle	14	0.5	88	0.29	0.56	189	0	3877
C sequestration	0	0	88	0.35	0.67	189	1512	-2168
New cultivar	0	0	79	0.26	0.46	173	97	2599
Yield maximization	0	0	89	0.31	1.12	347	146	3634
Diversification	0	0	0	0.25	0.41	147	87	529

[a]Details of the Technologies are given in Table 2

Table 8. Global warming potential of rice cultivation and cost-benefit analysis of different technologies in the lower Indo-Gangetic Plains

Technology[a]	Total GWP (kg CO_2 ha^{-1})	Net return (₹ ha^{-1})	Difference in net return (₹ ha^{-1})[b]	Difference in GWP (kg CO_2 ha^{-1})	Cost of mitigation (₹ kg^{-1} CO_2)
Transplanted rice	2934	17465	0	0	
Mid-season drainage	2357	15290	-2175	-576	3.77
Aerobic rice	1741	14069	-3396	-1192	2.85
System of rice intensification	1034	9214	-8251	-1899	4.34
Direct-seeded rice	979	16006	-1459	-1955	0.75
Sprinkler irrigation	735	14050	-3414	-2199	1.55
Zero till	346	15945	-1520	-2588	0.59
Integrated nutrient management	6089	17119	-345	3156	
Organic rice	8569	20913	3448	5635	
Phosphogypsum	2266	15429	-2036	-668	3.05
Nitrification inhibitor	2461	17531	66	-472	-0.14
Urea super granule	2725	17459	-6	-208	0.03
Leaf colour chart	2722	17695	231	-212	-1.09
Site-specific nutrient management	2794	17468	3	-139	-0.02
Green manuring	6086	17288	-176	3152	
Straw fed to cattle	3877	15886	-1579	944	
C sequestration	-2168	14786	-2679	-5101	0.53
New cultivar	2599	16500	-964	-335	2.88
Yield maximization	3634	24539	7075	700	
Diversification	529	20777	3313	-2405	-1.38

[a]Details of the Technologies are given in Table 2

[b]Difference compared to the conventional puddled transplanted rice.

Table 9. Emission of greenhouse gases in wheat with different technological options in the upper Indo-Gangetic Plains

Technology[a]	N_2O-N soil & manure (kg ha^{-1})	N_2O-N fertilizer (kg ha^{-1})	CO_2 on-farm & off-farm (kg ha^{-1})	CO_2-C sequestration (kg ha^{-1})	Total GWP (kg CO_2 ha^{-1})
Conventional tillage	0.10	0.92	363	0	1808
Sprinkler irrigation	0.10	0.77	304	0	1519
Zero tillage	0.11	0.84	276	368	111
Integrated nutrient management	0.10	0.36	195	300	-171
Organic wheat	0.09	0.00	76	600	-1880
Nitrification inhibitor	0.08	0.68	356	0	1663
Site-specific nutrient management	0.09	0.77	353	0	1696
Straw fed to cattle	0.10	0.92	368	0	1824
New cultivar	0.10	1.03	417	0	2056
Yield maximization	0.10	1.77	614	0	3128

[a]Details of the Technologies are given in Table 2

Table 10. Global warming potential of wheat cultivation and cost-benefit analysis of different technologies in the upper Indo-Gangetic Plains

Technology [a]	Total GWP (kg CO_2 ha^{-1})	Net return (₹ ha^{-1})	Diff. in net return (₹ ha^{-1})[b]	Diff in GWP (kg CO_2 ha^{-1})	Cost of mitigation (₹ kg^{-1} CO_2)
Conventional tillage	1808	28361	0	0	-
Sprinkler irrigation	1519	28057	-304	-290	1.05
Zero tillage	111	29231	870	-1697	-0.51
Integrated nutrient management	-171	31137	2776	-1979	-1.40
Organic wheat	-1880	29631	1270	-3688	-0.34
Nitrification inhibitor	1663	32385	4024	-146	-27.65
Site-specific nutrient management	1696	30691	2330	-112	-20.75
Straw fed to cattle	1824	26580	-1781	16	
New cultivar	2056	34746	6385	248	
Yield maximization	3128	43564	15203	1320	

[a]Details of the Technologies are given in Table 3

[b]Difference compared to the conventional tilled wheat.

Table 11. Emission of greenhouse gases in wheat with different technological options in the lower Indo-Gangetic Plains

Technology [a]	N_2O-N soil & manure (kg ha^{-1})	N_2O-N fertilizer (kg ha^{-1})	CO_2 on-farm & off-farm (kg ha^{-1})	CO_2-C sequestration (kg ha^{-1})	Total GWP (kg CO_2 ha^{-1})
Conventional tillage	0.10	0.65	254	0	1280
Sprinkler irrigation	0.10	0.54	215	0	1085
Zero tillage	0.11	0.56	183	286	-61
Integrated nutrient management	0.10	0.36	174	300	-250
Organic wheat	0.09	0.00	57	600	-1952
Nitrification inhibitor	0.08	0.49	253	0	1190
Site-specific nutrient management	0.09	0.55	251	0	1216
Straw fed to cattle	0.10	0.65	259	0	1296
New cultivar	0.10	0.74	300	0	1488
Yield maximization	0.10	1.29	451	0	2305

[a]Details of the Technologies are given in Table 3

Table 12. Global warming potential of wheat cultivation and cost-benefit analysis of different technologies in the lower Indo-Gangetic Plains

Technology [a]	Total GWP (kg CO_2 ha^{-1})	Net return fertilizer (₹ ha^{-1})	Diff. in net return (₹ ha^{-1})[b]	Diff. in GWP (kg CO_2 ha^{-1})	Cost of mitigation (₹ kg^{-1}CO_2)
Conventional tillage	1280	17669	0	0	-
Sprinkler irrigation	1085	16851	-818	-195	4.19
Zero tillage	-61	19345	1676	-1341	-1.25
Integrated nutrient management	-250	18001	333	-1530	-0.22
Organic wheat	-1952	17033	-636	-3233	0.20
Nitrification inhibitor	1190	20430	2762	-90	-30.68
Site-specific nutrient management	1216	18678	1010	-64	-15.72
Straw fed to cattle	1296	15594	-2075	16	-
New cultivar	1488	21682	4013	207	-
Yield maximization	2305	27197	9528	1025	-

[a]Details of the Technologies are given in Table 3
[b]Difference compared to the conventional tilled wheat

in any region. Total GWP in upper-IGP is 1808 kg CO_2 equivalent ha^{-1} (Table 10). In the lower-IGP, the total GWP is 1280 kg CO_2 equivalent ha^{-1} (Table 12).

Mitigation technologies varied in irrigation pattern, N supply, straw management and additives or new management. In both upper-IGP and lower-IGP, the maximum (283 and 421 kg ha^{-1}) CH_4 was emitted in the organic technology which is the continuously flooded organic treatment (Tables 5 and 7). Continuous flooding and application of organic matter resulted in standing water in rice field, and availability of C-substrate for the methanogemic bacteria, which led to high CH_4 emission in this treatment. Methane emission was zero in the SPR and DVR technologies. In the SPR technology, sprinkler irrigation method was followed, which resulted in no standing water in rice field, thereby no CH_4 emission. Technology DVR is crop diversification, where rice was replaced with upland crop maize with less water requirement and no CH_4 emission. In aerobic and direct seeded rice application of less irrigation water led to very less CH_4 emission in both the regions.

In the YMX technology, very high dose of N was applied through fertilizer in order to increase yield. This resulted in highest N_2O emission (1.62 kg ha^{-1} in the upper-IGP & 1.12 kg ha^{-1} in the lower-IGP) from this technology in both the regions (Tables 5 & 7). Although organic matter application led to maximum methane emission in rice, the N_2O emission was zero in this technology. Application rate of nitrogenous fertilizer is less in maize than in rice. This has resulted in less N_2O emission (0.68 kg ha^{-1} in the upper-IGP and 0.41 kg ha^{-1} in the lower-IGP) in the crop diversification technology. Use of nitrification inhibitor lowered the nitrification rate and substantially reduced the N_2O emission in both the locations.

Carbon dioxide emission due to on-farm and off-farm activities was lowest (111 kg ha^{-1} in upper-IGP and 23 kg ha^{-1} in lower-IGP) in organic treatment and highest (729 kg ha^{-1} and 347 kg ha^{-1}) in the YMX technology, where input-use was maximum for maximization of yield (Tables 5 and 7).

The C-sequestration technology has the maximum potential (2016 and 1512 kg CO_2-C ha^{-1}) to sequester C because in this technology rice straw was used for making construction material instead of burning. Hence, global warming potential of this technology was negative. In an organic treatment, 600 kg CO_2-C ha^{-1} was sequestered in the upper-IGP (Table 5). Carbon was sequestered in all the technologies in the lower-IGP except in technology where rice straw was burnt. Global warming potential was lowest (637 kg CO_2 ha^{-1} in the upper-IGP and 346 kg CO_2 ha^{-1} in the

Table 13. Emission of greenhouse gases under conventional continuously flooded and mid-season drainage in rice in different districts of Punjab

District	Conventional continuously flooded				Mid-season drainage			
	Methane	Nitrous oxide	Carbon dioxide	Total GHGs	Methane	Nitrous oxide	Carbon dioxide	Total GHGs
	Mg CO_2 eq. ha^{-1}							
Amritsar	1.2	0.4	1.3	2.9	0.1	0.6	1.2	1.9
Barnala	1.0	0.4	2.1	3.5	0.2	0.6	1.8	2.5
Bathinda	0.6	0.3	1.2	2.2	0.1	0.5	1.2	1.8
Faridkot	1.3	0.5	0.9	2.7	0.2	0.6	0.9	1.7
Fatehgarh Sahib	1.3	0.5	1.5	3.3	0.2	0.6	1.2	2.1
Ferozepur	1.4	0.5	1.6	3.5	0.2	0.6	1.4	2.3
Gurdaspur	1.0	0.4	0.9	2.2	0.2	0.5	0.7	1.4
Hoshiarpur	0.8	0.3	0.8	2.0	0.1	0.5	0.7	1.3
Jalandhar	1.3	0.4	1.2	2.9	0.2	0.6	1.1	1.8
Kapurthala	0.8	0.3	1.3	2.5	0.1	0.5	1.1	1.7
Ludhiana	1.2	0.5	1.7	3.3	0.2	0.6	1.4	2.3
Mansa	0.9	0.4	1.2	2.5	0.2	0.5	1.1	1.8
Moga	1.0	0.4	1.7	3.2	0.2	0.6	1.5	2.3
Muktsar	0.8	0.3	0.8	2.0	0.1	0.5	0.8	1.4
Nawan Shahar	0.8	0.3	1.6	2.7	0.1	0.5	1.4	1.9
Patiala	1.0	0.4	1.3	2.8	0.2	0.6	1.1	1.9
Ropar	1.7	0.5	0.9	3.2	0.2	0.7	0.8	1.7
Sangroor	1.9	0.6	2.1	4.6	0.3	0.8	1.8	2.9
SAS Nagar	1.7	0.5	1.2	3.5	0.2	0.7	1.1	2.0
Taran Taaran	1.2	0.4	1.4	3.0	0.1	0.6	1.3	2.0
Average	**1.1**	**0.4**	**1.3**	**2.9**	**0.2**	**0.6**	**1.2**	**1.9**
Standard deviation	**0.4**	**0.1**	**0.4**	**0.6**	**0.1**	**0.1**	**0.3**	**0.4**

Table 14. Total global warming potential of rice growing areas of Punjab and possible reduction with mid-season drainage in rice

District	GWP with 100% continuously flooded (Mt)	GWP with 100% mid-season drainage(Mt)	GWP with 50% continuously flooded and 50% mid-season drainage(Mt)
Amritsar	0.5	0.3	0.4
Barnala	0.4	0.3	0.3
Bathinda	0.2	0.2	0.2
Faridkot	0.3	0.2	0.2
Fatehgarh Sahib	0.3	0.2	0.2
Ferozepur	0.9	0.6	0.7
Gurdaspur	0.4	0.3	0.4
Hoshiarpur	0.1	0.1	0.1
Jalandhar	0.5	0.3	0.4
Kapurthala	0.3	0.2	0.2
Ludhiana	0.8	0.6	0.7
Mansa	0.2	0.1	0.2
Moga	0.6	0.4	0.5
Muktsar	0.2	0.1	0.2
Nawan Shahar	0.1	0.1	0.1
Patiala	0.7	0.4	0.6
Ropar	0.1	0.1	0.1
Sangroor	1.2	0.8	1.0
SAS Nagar	0.1	0.1	0.1
Taran Taaran	0.5	0.3	0.4
Total	8.3	5.6	6.9
Mitigation (Mt)		2.8	1.4
Mitigation (%)		33.4	16.7
Carbon price in million US $ (@ 10 $/Mg CO_2)		27.9	13.9

lower IGP) in the Zero till technology, with direct seeded rice and residue incorporation in both the regions (Tables 6 and 8). This technology was also able to sequester C in both the regions.

Emission of greenhouse gases in wheat cultivation

In the wheat crop there was no N_2O emission from fertilizer application in the organic technology, which is the organic treatment (Tables 9 and 11). Since no inorganic fertilizer was added, the N_2O emission was zero in both the regions. Technology YMX caused maximum N_2O emission (1.77 kg ha^{-1} in upper-IGP and 1.29 kg ha^{-1} in lower-IGP) (Tables 9 and 11) in wheat crop. Integrated nutrient management (INM) led to reduction in N_2O emission as compared to conventional practices in both the regions.

The CO_2 emission due to on-farm and off-farm activities was lowest (76 kg CO_2 ha^{-1} in the upper-IGP and 57 kg CO_2 ha^{-1} in the lower-IGP) in the organic technology. This technology was also able to sequester C in wheat crop in both upper-IGP and lower-IGP. The lowest GHGs emission and maximum C sequestration led to a negative GWP in the organic technology in wheat crop. Zero tillage and integrated nutrient management resulted in C-sequestration in wheat crop in both the regions. In the zero tillage technology, GWP was lower (111 kg CO_2 ha^{-1}) in the upper-IGP, and negative (-61 kg CO_2 ha^{-1}) in the lower-IGP (Tables 10 & 12). Although the YMX technology (yield maximization) showed maximum net return in both the regions, the GWP was also very high with this technology. Integrated nutrient management (INM) resulted in a negative GWP in wheat. In the lower-IGP, zero tillage was a promising technology with negative GWP and good economic return.

Comparison of GHGs emission from lower-IGP and upper-IGP

In the case of rice crop, the technologies studied in both the regions varied in terms of their straw management. In the upper-IGP in all the technologies, except in Zero till, straw management and C sequestration rice straw is burnt, while in the lower-IGP, except in straw management technology, in all others rice straw is fed to the cattle. The hypothesis behind selection of these technologies is that rice straw is generally burnt in the upper-IGP, while it is used as a cattle feed in the lower-IGP. Irrespective of the technologies adopted, methane emission is more in lower-IGP than in upper-IGP. This is attributed to the difference in climate and soil of both the regions. High rainfall and more soil organic matter in lower IGP might have attributed to increased activity of the methanogens resulting in more CH_4 emission in this region. N_2O emission from fertilizer application and carbon dioxide emission from on-farm and off-farm activities are more in the upper-IGP than in the lower IGP. This is due to the fact that use of inputs in terms of fertilizers, biocides and irrigation is more in the former. In the upper-IGP, emission of CH_4 and N_2O occurred due to burning of rice straw in most of the technologies, while in the lower-IGP CH_4 and N_2O emissions due to burning were zero in all the technologies except in the straw management. In the lower-IGP, carbon was sequestered in all the technologies except in straw management, where rice straw was burnt. In the upper-IGP, C-sequestration occurred only in 7 technologies. Both GWP and net return of different technologies in rice were more in upper-IGP than lower-IGP. A negative GWP was observed for C sequestration technology in both the regions. Although GWP of many technologies was less than conventional management in both the regions, all of them were not feasible in terms of their economic return. In the upper-IGP cost of mitigation of 7 technologies, viz. use of sprinkler irrigation, direct seeded rice, use of nitrification inhibitor, use of urea super granules, use of leaf colour chart, site-specific nutrient management and crop diversification was negative, making them suitable for adoption. On the other hand, in the lower-IGP, 4 technologies were economically feasible in terms of their cost of mitigation. Direct seeded rice, use of sprinkler irrigation and use of urea super granules can reduce GWP with no extra cost involved in upper-IGP. But in the lower-IGP, implementation of these 3 technologies will involve some extra cost.

Unlike rice, there is no CH_4 emission in wheat crop, since it is grown in upland condition. The N_2O is emitted from soil and fertilizer application in wheat crop. Similar to rice, N_2O emission from wheat is more in the upper-IGP than in the lower-IGP, due to high dose of nitrogenous fertilizers. The CO_2 emission due to on-farm and off-farm activities was also more in the upper-IGP. C sequestration in wheat crop occurred in the technology Zero till, INM and organic in both the regions. GWP of different technologies and net returns were more in upper-IGP than in lower-IGP. In the lower-IGP, zero tillage in wheat resulted in the negative GWP, which is not the case in upper-IGP. Integrated nutrient management and organic farming resulted in negative GWP in both the regions. Zero tillage, integrated nutrient management, use of nitrification inhibitor and site-specific nutrient management will reduce GWP than conventional management in wheat with no extra cost involved in both the regions.

Economic implications of different mitigation strategies

Compared to the current practices of farmers, 15 technologies in upper-IGP and 14 technologies in lower-IGP have the potential to reduce the GWP. In the upper-IGP, net return in rice with various technologies ranged from ₹ 24154 ha^{-1} with zero till direct seeded rice with residue incorporation to ₹ 37641 ha^{-1} with yield maximization technology (Table 6). On the other hand, in lower-IGP net return in rice crop ranged from ₹ 9214 ha^{-1} in SRI to ₹ 24539 ha^{-1} in yield maximization technology (Table 8). However, crop diversification was able to decrease GWP in both the regions, by 46% in upper-IGP and by 82% in lower-IGP. At the same time, it increased the net return by 24% in upper-IGP and 19% in lower-IGP. In the upper-IGP, direct seeded rice and use of sprinkler irrigation reduced GWP by 34% and 37% with marginal increase (2% & 4%) in net return. Use of nitrification inhibitor also reduced GWP and increased net return in both the regions. Therefore, from economic consideration, these technologies have the potential to be adopted by the farmers of these states. Although many technologies are able to reduce GHGs emission, the adoption of some technologies involve some extra cost which make them not feasible for adoption by farmers. The following seven technologies were able to reduce GWP without any extra cost in the upper IGP (Fig. 2a): (1) sprinkler irrigation (SPR), (2) direct seeded rice (DSR), (3) use of nitrification inhibitor (NI), (4) use of urea super granules (USG), (5) use of leaf colour chart (LCC), (6) site-specific nutrient management (SSNM), and (7) crop diversification (DVR). On the other hand, in the lower-IGP (i) use of nitrification inhibitor (NI), (ii) use of LCC, (iii) site-specific nutrient management (SSNM), and (iv) crop diversification (DVR) reduced GWP with no additional cost (Fig. 2b).

(a) Upper-IGP **(b) Lower-IGP**

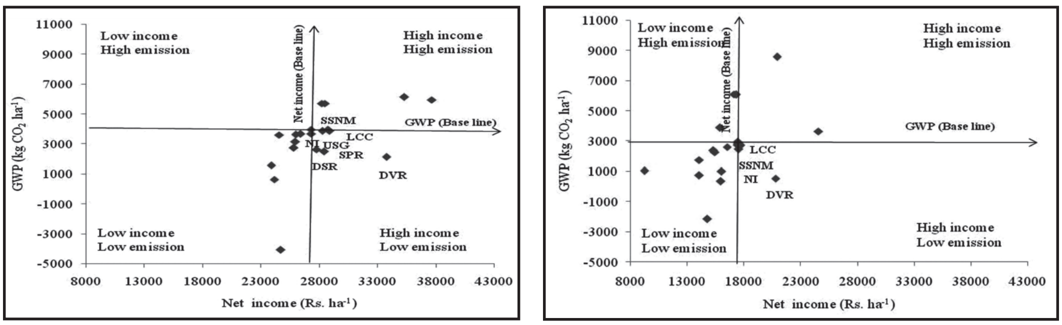


Fig. 2. Marginal abatement cost for reducing global warming potential from the baseline technology of continuously flooded and farmers' practice in rice in (a) upper and (b) lower Indo-Gangetic Plains

Refer to Table 2 for description of the technologies. DVR, Diversification; LCC, GWP, Global warming potential; Leaf colour chart; NI, Nitrification inhibitor; SPR, Sprinkler; SSNM, Site-specific nutrient management; USG, Urea super granule

(a) Upper-IGP (b) Lower-IGP

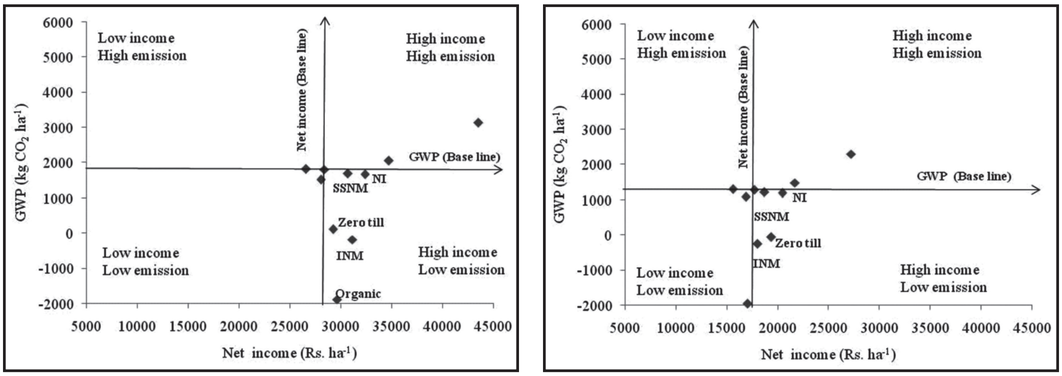


Fig. 3. Marginal abatement cost for reducing global warming potential from the baseline technology of farmers' practice in wheat in (a) upper and (b) lower Indo-Gangetic Plains

Refer to Table 2 for description of the technologies. GWP, Global warming potential; INM, Integrated nutrient management; NI, Nitrification inhibitor

In wheat crop under conventional management practices, net returns were ₹ 28361 ha^{-1} and ₹ 17669 ha^{-1} in upper-IGP and lower-IGP, respectively (Tables 10 & 12). Among the various technologies studied in wheat (1) zero tillage, (2) integrated nutrient management (INM), (3) organic farming, (4) use of NI, and (5) site-specific nutrient management (SSNM) technologies proved to be beneficial in terms of GWP reduction and profit enhancement in the upper-IGP (Fig. 3a). In the lower-IGP (1) zero tillage, (2) integrated nutrient management (INM), (3) use of NI, and (4) site-specific nutrient management (SSNM) technologies were both environmentally beneficial and economically feasible (Fig. 3b). Integrated nutrient management caused 10% increase in income and 109% reduction in GWP in the upper-IGP. Net returns with this technology were ₹ 31137 ha^{-1} in the upper-IGP (Table 10). In the lower-IGP, zero tillage caused 9% increase in net returns (₹19345 ha^{-1}), while sequestering C, thereby reduced GWP by 105% as compared to the conventional practice of farmers (Table 12). Organic farming was able to reduce GWP in both the regions in wheat crop; but it was not economically profitable, especially in the lower-IGP.

Mitigation of GHGs at regional scale

The study showed that under transplanted rice maximum global warming was because of CO_2, followed by methane and nitrous oxide (Fig. 4). Use of diesel for tractor and pumping groundwater were the major sources of CO_2. Flooded soil was the major contributor of CH_4. The average GWP due to all the three GHGs

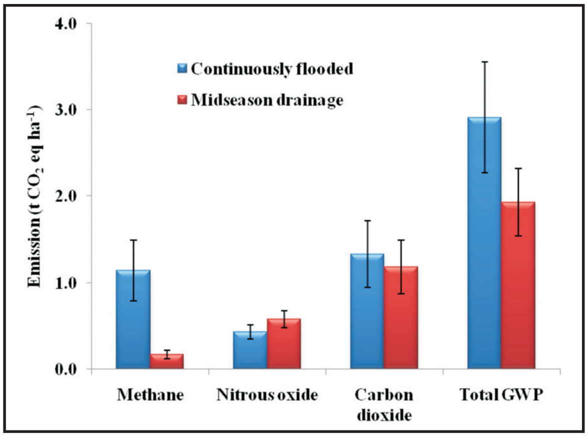
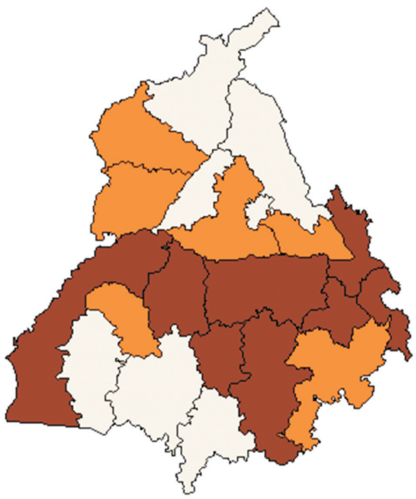
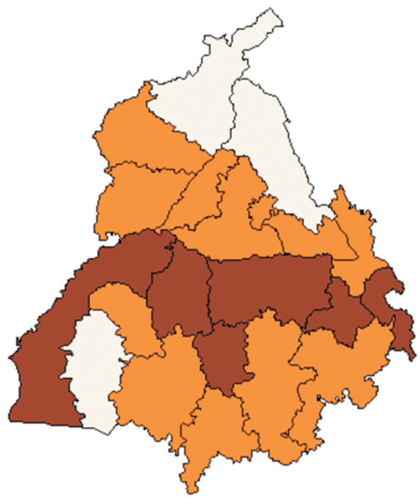


Fig. 4. Global warming potential of conventional continuously flooded and mid-season drainage technologies in rice



Continuously flooded (CF)



Mid-season drainage (MD)

Colour Legends	GWP with continuous flooding(t CO_2 ha^{-1})	GWP with mid-season drainage (t CO_2 ha^{-1})
	2.0-2.5	1.3-1.5
	2.5-3.0	1.5-2.0
	3.0-4.5	**2.0-3.0**

Fig. 5. Global warming potential in conventional continuously flooded and mid-season drainage technologies in rice in different districts of Punjab

(CO_2, CH_4 and N_2O) in continuously flooded rice was 2.91 Mg ha^{-1}. Emission of CH_4 from soil in rice ranged from 0.6 to 1.9 Mg CO_2 eq. ha^{-1} in different districts of Punjab (Table 13). Emission of N_2O varied from 0.3 to 0.6 Mg CO_2 eq. ha^{-1}, whereas CO_2 emission was in the range of 0.8 to 2.1 Mg CO_2 eq. ha^{-1}. The total GWP in rice in different districts ranged from 2.0 to 4.7 Mg CO_2 eq. ha^{-1}. The spatial distribution of GWP with conventional transplanted rice in different districts of Punjab is shown in Fig. 5.

The average GWP of all the three GHGs with mid-season drainage was 1.9 Mg ha^{-1} and maximum global warming was because of CO_2, followed by nitrous oxide and methane (Fig. 4). Emission of CH_4 from soil with mid-season drainage was only 0.1 to 0.3 Mg CO_2 eq. ha^{-1} in different districts of Punjab (Table 13). Emission of N_2O varied from 0.5 to 0.8 Mg CO_2 eq. ha^{-1}, whereas CO_2 emission was in the range of 0.8 to 1.8 Mg CO_2 eq. ha^{-1}. The total GWP with continuously flooded and mid-season drainage in different districts ranged from 2.0-4.6 Mg CO_2 eq. ha^{-1} and 1.3-3.0 Mg CO_2 eq. ha^{-1}, respectively. The spatial distribution of GWP with mid-season drainage in different districts of Punjab is shown in Fig. 5.

Global warming potential in rice cultivated under continuously flooded in different districts ranged from 0.1 to 1.2 Mt CO_2 eq. (Table 14). The variations depend upon area under rice, which varied between 27 thousand ha and 267 thousand ha, soil organic C, fertilizer application and biocide use, and on-farm and off-farm operations. The Sangrur district had the highest GWP in rice, followed by Ferozepur, Ludhiana and Patiala districts. The total GWP with continuously flooded rice in the state is 8.3 Mt CO_2 eq. (Table 14). If the entire area under continuously flooded rice in the state is converted to mid-season drainage, the GWP will be reduced to 5.6 Mt CO_2 eq. and if 50% area is converted to mid-season drainage, the GWP will be 7.0 Mt CO_2 eq. These two scenarios would mitigate GWP by 33% and 16.7%, respectively. At a C trading price of 10 US$ Mg^{-1} of CO_2 eq., this would bring US$ 28.0 million and US$ 14.0 million, respectively to the rice farmers of the state. However, the methodology for monitoring and transaction cost for processing the C trading have to be worked out.

For India's agricultural production systems to be viable in future, there is a need to identify crop management systems that are climate-change compatible, where soil organic C is enhanced or at least maintained and GHGs emission is reduced. Different mitigation technologies had pronounced effects on the GWP of the rice crop. Modifications of water, nutrient and rice straw management could reduce the GWP. However, the technologies may involve extra expenditure and reduce the net income of farmers. Eventually, the cost/benefit ratio of each technology will largely determine its adoptability by the farmers. Policies and incentives should be evolved that would encourage farmers to adopt mitigation options and thus improve soil health and use water and energy more efficiently. There are uncertainties in upscaling the estimation of GWP at the state level because of its diverse soil and climatic conditions and socio-economic status of the farmers. More accurate GWP can only be estimated using mechanistic simulation models using exhaustive quality data at the farm or village level. Such exercise will improve estimates of GWP and provide a baseline for evaluation of various mitigation strategies.

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3

Low Carbon Technologies in Agriculture: On-farm and Simulation Studies on Direct-seeded Rice

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R Tomar, N Jain and A Bhatia

Introduction

Rice (*Oryza sativa*) is one of the most important staple food crops in the world. Currently, it is the staple food of almost 3 billion people, that is, about 50% of the world population. Globally rice fields cover around 158 million hectares with an annual production of 685 million tons (FAO, 2009). More than 90% of this is produced and consumed in Asia with two countries, China and India, growing more than half the total crop, providing 50% of the total calorie intake of Asia's population. Conventionally rice is grown by puddling the soil and transplanting rice seedlings in the puddled soil. However, this practice requires large quantity of water (3000 to 5000 L of water to produce 1 kg rice) and human labour, which are becoming costly and scarce day by day.

Conventional puddled transplanted rice (TPR) contributes substantially to the emission of greenhouse gases (GHGs), particularly methane (CH_4). It is also likely to face more risks because of climate change. Dry direct-seeded rice (DSR), which does not need puddling of soil and transplanting as the seeds are directly sown in tilled or no-tilled soil, is a feasible alternative to save water and labour. It also has good potential to adapt to climate change, which is expected to increase the variability of monsoon rainfall and the risks of early or late-season drought. Growing DSR could have substantial impact on methane emission as DSR fields are not continuously submerged with water. However, no studies have been carried out to evaluate the impacts on DSR on GHG emission. The present study was conducted to quantify methane and nitrous oxide emissions from DSR compared to TPR and to quantify GHG mitigation potential of DSR in a regional scale.

Materials and Methods

Field experimentation

Field experiments were carried out in nine farmers' fields during kharif season (June to October) of 2009 and 2010 in three villages in Jalandhar district of Punjab, India for estimating GHG emission from DSR and TPR crops. Soil samples from each field were collected and analyzed for organic C, pH and EC (Table 1). Organic C content of soil in Rozri site was 0.59-0.68%, whereas it was higher at Talwandi Abdar (0.78-0.89%) (Table 1). Soil pH of the sites was neutral to slightly alkaline (7.4-7.9). The electrical conductivity of soil ranged from 0.34 to 0.391 d S m^{-1}.

Table 1. Properties of soil of different experimental fields in Jalandhar, Punjab

Location	Crop establishment[a]	pH	EC (d Sm^{-1})	Organic C (%)
Rozri 1	DSR	7.4	0.34	0.68
Rozri 2	TPR	7.5	0.34	0.61
Rozri 3	DSR	7.6	0.35	0.68
Rozri 4	TPR	7.6	0.37	0.59
Talwandi Abdar 1	DSR	7.6	0.34	0.83
Talwandi Abdar 2	DSR	7.7	0.34	0.88
Talwandi Abdar 3	DSR	7.9	0.39	0.89
Talwandi Abdar 4	DSR	7.8	0.36	0.78
Pachranga	TPR	7.5	0.34	0.50

[a]DSR, Direct-seeded rice; TPR, transplanted rice

Both crops were grown following recommended package of practices and data on crop management (date of sowing, germination, irrigation, fertilizer application, doses of NPK, amount of irrigation, weeding, pesticide application, date of harvesting, etc.) were collected (Table 2). The DSR crop was sown between last week of May and 1st week of June in 2009 and between 1st and 3rd week of June in 2010. The TPR was transplanted after 4 weeks of sowing in DSR. Two tillage operations were done for DSR whereas 3 tillage operations were done for transplanted rice before planting. In both the cases 15 kg ha^{-1} seed was used. Similarly in all the fields herbicide cartap hydrochloride 4% G at 0.8 kg ha^{-1} was used. Additionally, pesticide imidacloprid 17.8% SL at 17.8 ml ha^{-1} was used in the DSR. Application of N varied from 97 to 113 kg ha^{-1} while P and K applications were 36-60 kg ha^{-1} and 0 to 38 kg ha^{-1}. During 2009, 21-22 irrigations were given in the TPR but in DSR it was reduced to 14-16. During 2010, 15-16 irrigations were given in the TPR and 12-13 irrigations in the DSR.

Collection and analysis of gas samples

Gas samples were collected using the closed-chamber technique (Pathak et al., 2002). Chambers of 50 cm × 30 cm × 100 cm size made of 6 mm acrylic sheets were used for

Table 2. Crop management practices and input use in different fields in Jalandhar, Punjab during 2009

Management/Input use	Rozri 1	Rozri 2	Rozri 3	Talwandi Abdar 1	Talwandi Abdar 2	Panchranga
Crop establishment[a]	DSR	TPR	DSR	DSR	DSR	TPR
Variety	26 P 26 hybrid	26 P 26 hybrid	Pusa Basmati 1121	Pusa Basmati 1121	V 6129	Pusa Basmati 1121
No. of tillage	2	3	2	2	2	3
Date of planting	05/06/2009	18/06/2009	10/06/2009	10/06/2009	27/05/2009	24/06/2009
Date of harvesting	09/10/09	05/10/09	20/10/09	05/10/09	01/11/09	23/10/09
Crop duration (day)	125	110	132	117	156	119
Seed rate (kg ha^{-1})	15	15	15	15	15	15
Pesticide: Cartap Hydro. 4% G (kg ha^{-1})	0.8	0.8	0.8	0.8	0.8	0.8
Pesticide: Imidacloprid 17.8% SL (ml ha^{-1})	17.8	17.8	17.8	Nil	Nil	Nil
N through urea (kg ha^{-1}) (Splits)	87 (29, 29, 29)	64 (35, 29)	81(35, 23, 23)	81(35, 23, 23)	87 (29, 29, 29)	95 (46, 29)
N through DAP (kg ha^{-1})	14	23	16	16	16	18
Total N (kg ha^{-1})	101	87	97	97	103	113
P through DAP (kg ha^{-1})	36	60	42	42	42	48
K through MoP (kg ha^{-1})	0	30	30	30	0	38
No. of Irrigation	14	22	16	16	14	21
Human labour (days)	16	39	15	13	17	28
Tractor labour (hours)	16	29	14	14	18	24

[a]DSR, Direct-seeded rice; TPR, transplanted rice

sampling. An aluminum channel was placed in the field and is used with each acrylic chamber. The aluminum channel was inserted 10 cm inside the soil and the channels filled with water to make the system air- tight. One rubber septum was fitted at the top of chamber to collect gas samples. The chamber was thoroughly flushed several times with a 50 ml syringe to homogenize the inside air thoroughly. Gas samples were drawn with 20ml syringe with the help of hypodermic needle (24 gauge). After drawing sample, syringes were made air-tight with three way stop cock. Head space volume inside the box was recorded, which will be used to calculate flux of nitrous oxide and methane. Gas samples at 0, 1/2 and 1 hrs were collected from the chamber.

Methane and nitrous oxide (N_2O) concentrations in the gas samples were analysed by Gas Chromatograph (Schimadzu 8A) fitted with a flame ionization detector (FID) and electron capture detector (ECD), respectively. Estimation of total CH_4 and N_2O emissions during the crop season was done by successive linear interpolation of average emission on the sampling days assuming that emission followed a linear trend during the periods when no sample was taken (Pathak et al., 2003).

Simulating GHG emission from rice fields

The InfoRCT (Information on Use of Resource-Conserving Technologies) simulation model (Pathak et al., 2011) was used to calculate GHG emission including carbon dioxide (CO_2), CH_4 and N_2O from farm operations, use of inputs and off-farm production of inputs for DSR compared to transplanted rice. The model integrates biophysical, agronomic, and socioeconomic data to establish input-output relationships related to water, fertilizer, labour, and biocide uses; GHG emissions; biocide residue in soil; and N fluxes in the rice-wheat system. The inputs and outputs such as GHG emissions were calculated on a season basis using the target-oriented approach (Ponsioen et al., 2006; Pathak and Wassmann, 2007; Pathak et al., 2010). The global warming potential (GWP) was calculated using the following equation (IPCC, 2007).

$$\text{GWP (kg ha}^{-1}\ CO_2\text{ eq.)} = CH_4\text{ (kg ha}^{-1}) * 25 + N_2O\text{ (kg ha}^{-1}) * 298 + CO_2\text{ (kg ha}^{-1})$$

Field measurements conducted during 2009 and 2010 were used for validation of the model. Earlier simulated emission of N_2O-N was validated with measured data from the same experiment (Mohanty, 2008; unpublished). Predicted methane emission and N loss were validated using published data from other experiments in the rice-wheat system conducted within the Indo-Gangetic Plains (Majumdar et al., 2002; Pathak et al., 2003; Malla et al., 2005).

Upscaling of GHG emission in a regional scale

A resource inventory of soil, climate and fertilizer use was prepared for the district level for Punjab state of India using primary surveys, Government Statistics and published literature (Table 3). The state has 20 administrative districts with a net sown area of 4.17 Mha and rice is cultivated as a kharif crop under puddled transplanted condition in 2.73 Mha area (Statistical Hand Book, Govt. of Punjab, 2009). Annual rainfall varies from 93 to 957 mm. Punjab soils contain organic carbon

Table 3. Area, rainfall, yield and soil properties in different districts of Punjab

District	Net sown area	Area under rice	Area under DSR[a]	Annual rainfall	Soil organic C	Soil pH	Paddy yield
	(000 ha)	(000 ha)	(ha)	(mm yr^{-1})	(%)		Mg ha^{-1}
Amritsar	218	183	17	265.4	0.61	7.9	4.36
Barnala	125	102	144	417.0	0.66	8.1	7.14
Bathinda	297	97	243	336.7	0.15	7.8	6.60
Faridkot	128	95	233	520.6	0.75	7.9	6.54
Fatehgarh Sahib	102	85	-	751.5	0.54	7.5	6.41
Ferozepur	475	260	1082	224.1	0.50	8.0	6.06
Gurdaspur	287	201	13	808.4	0.42	6.7	4.95
Hoshiarpur	201	60	21	885.6	0.50	7.6	5.22
Jalandhar	237	155	69	673.8	0.73	7.8	5.70
Kapurthala	134	114	-	644.0	0.45	7.5	5.63
Ludhiana	306	254	91	775.9	0.22	7.5	6.71
Mansa	190	71	82	139.3	0.15	7.8	6.25
Moga	198	174	49	428.8	0.64	8.0	6.90
Muktsar	224	95	197	379.6	1.12	7.9	6.35
N Shahar	95	52	-	517.8	0.67	7.7	6.15
Patiala	271	238	-	950.9	0.40	7.5	6.36
Ropar	79	36	22	957.3	0.84	7.6	5.78
Sangroor	311	267	397	355.5	0.66	8.1	6.93
SAS Nagar	75	27	22	459.0	0.84	7.6	4.89
Taran Taaran	218	169	397	93.3	0.60	7.9	4.66

[a]-, data not available

ranging from 0.22 to 1.12% with pH 7.5 to 8.1 (Table 3). Currently DSR is grown in about 3000 ha of land in Punjab.

Results and Discussion

Measured emissions of methane and nitrous oxide

The trends of methane and nitrous oxide emission were similar in both the years. Therefore, the data of only year 2010 have been given (Figs. 1 and 2). There was very small methane emission ranging from 0 to 0.1 kg ha^{-1} d^{-1} in the DSR fields in different sites (Fig. 1). In transplanted rice, methane emission ranged from 0.2 to 0.8 kg ha^{-1} d^{-1} (Fig. 1). Cumulative methane emission was 0.6 to 1.5 kg ha^{-1} in the DSR and 42.4 to 57.8 kg ha^{-1} in TPR during 2009 (Table 4). During 2010 methane emission in the DSR and TPR ranged from 4.2 to 4.9 kg ha^{-1} and 56.0 to 56.5 kg ha^{-1}, respectively (Table 4). The biogenic methane results from the metabolic activities of a small but highly specific bacterial group called methanogens. Their activity increases in anaerobic condition. The standing water on soil surface in conventional rice fields limits the transport of oxygen into the soil and the microbial activities render the water-saturated soil practically devoid of oxygen, thus creating anaerobic condition. Thus in conventional transplanted rice fields where standing water on soil surface is maintained throughout the crop growing season, methane emission was high. As the DSR fields were not continuously submerged with water, there was no anerobic condition created. As a result methane emission was very small.

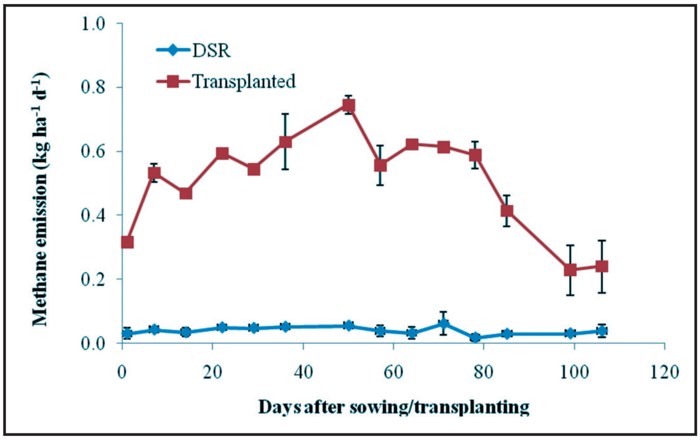

Fig. 1. Emission of methane in transplanted and direct seeded rice in Jalandhar, Punjab, India during 2010.

Table 4. Methane and nitrous oxide emission in direct-seeded and transplanted rice in Jalandhar, Punjab during 2009 and 2010

Location	Crop establishment[a]	Methane (kg ha^{-1})		Nitrous oxide (kg ha^{-1})	
		Mean	SD[b]	Mean	SD[b]
2009					
Rozri 1	DSR	0.6	0.1	1.2	0.2
Rozri 2	TPR	42.4	1.5	1.1	0.3
Rozri 3	DSR	0.5	0.1	1.2	0.1
Talwandi 1	DSR	1.5	0.4	1.1	0.0
Talwandi 2	DSR	1.3	0.6	0.9	0.1
Pachranga	TPR	57.8	9.8	0.8	0.2
2010					
Rozri 1	DSR	4.1	0.4	2.2	0.1
Rozri 2	TPR	56.5	0.6	1.6	0.2
Rozri 3	DSR	4.2	0.4	2.0	0.1
Rozri 4	TPR	56.0	1.1	1.8	0.1
Talwandi 3	DSR	4.7	0.1	2.1	0.1
Talwandi 4	DSR	4.9	0.8	2.0	0.1

[a]DSR, Direct-seeded rice; TPR, transplanted rice

[b]SD, Standard deviation

Emission of nitrous oxide was more or less similar in the DSR and TPR fields and ranged from 9.7 g ha^{-1} d^{-1} to 25.9 g ha^{-1} d^{-1} in different sites (Fig. 2). Mean emission

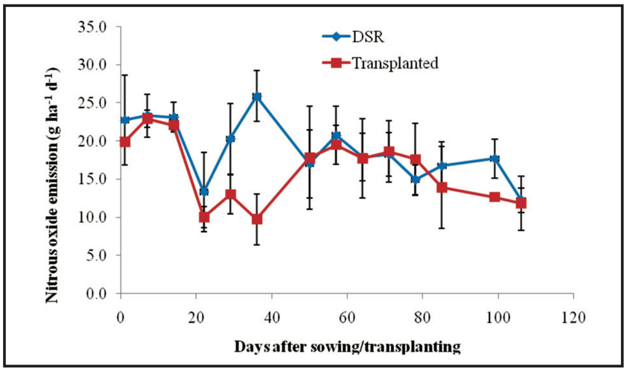

Fig. 2. Emission of nitrous oxide in transplanted and direct seeded rice in Jalandhar, Punjab, India during 2010.

ranged from 12.3 to 25.9 g ha^{-1} d^{-1} in DSR and 9.7 to 22.9 g ha^{-1} d^{-1} in transplanted rice fields. Cumulative emission of nitrous oxide during the entire crop duration was 0.9 to 1.2 kg ha^{-1} in the DSR in 2009 and 0.8 to 1.1 kg ha^{-1} in the TPR fields (Table 4). During 2010 N_2O emission was 2.0-2.2 kg ha^{-1} in the DSR and 1.6-1.8 kg ha^{-1} in the TPR. The biological processes of denitrification and nitrification are the major mechanisms of nitrous oxide emission from agricultural soils. Denitrification takes place under anaerobic soil condition, whereas nitrification occurs in the aerobic condition (Pathak 1999). Denitrification was the major mechanism for N_2O emission in TPR because of the prevailing anaerobic condition. In DSR the main mechanism for N_2O emission was nitrification, which takes place under aerobic condition (Pathak et al., 2011).

Simulated emission of GHGs

Simulated emission of CO_2, which resulted due to various on-farm and off-farm operations was 1.34 t CO_2 ha^{-1} in the TPR and 1.19 t CO_2 ha^{-1} in the DSR in different districts of Punjab (Fig. 3). Under the TPR maximum global warming was because of CO_2 followed by methane and nitrous oxide (Fig. 3). Use of diesel for tractor and pumping ground water are the major sources of CO_2. As No. of irrigation and use of tractor was more in TPR compared to DSR (Table 2), emission of CO_2 was more in TPR. Flooded soil was the major contributor of CH_4. The average GWP due to all the three GHGs (CO_2, CH_4 and N_2O) in transplanted rice was 2.91 t ha^{-1}. Emission of CH_4 from soil in rice ranged from 0.8 to 1.9 t CO_2 eq. ha^{-1} in the various districts of

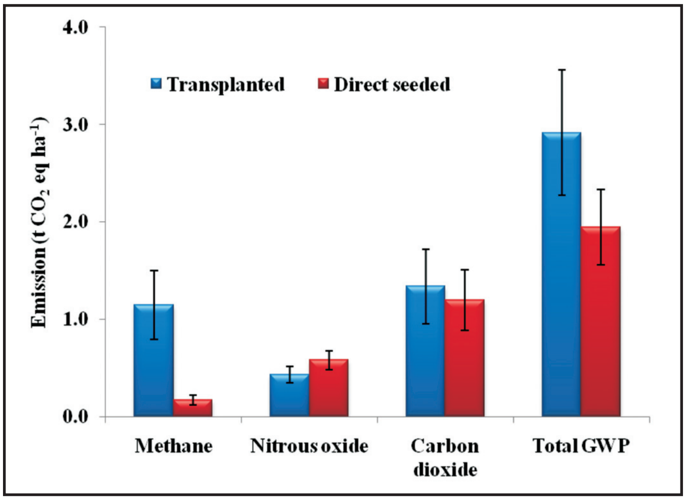

Fig. 3. Global warming potential of transplanted and direct-seeded rice.

Punjab (Table 5). The emission of N_2O varied from 0.3 to 0.6 t CO_2 eq. ha^{-1} whereas CO_2 emission was in the range of 0.8 to 2.1 t CO_2 eq. ha^{-1}.

The average GWP of all the three GHGs in the DSR was 1.94 t ha^{-1} and maximum global warming was because of CO_2 followed by nitrous oxide and methane (Fig. 3). Emission of CH_4 from soil in DSR was only 0.1 to 0.3 t CO_2 eq. ha^{-1} in the various districts of Punjab (Table 5). The emission of N_2O varied from 0.5 to 0.8 Mg CO_2 eq. ha^{-1} whereas CO_2 emission was in the range of 0.8 to 1.8 Mg CO_2 eq. ha^{-1}. The total GWP in transplanted rice and DSR in various districts ranged from 2.0-4.6 and 1.3 to 3.0 Mg CO_2 eq. ha^{-1} respectively.

Upscaling of GHGs emissions to various districts of Punjab

Global warming potential in rice cultivated under current farmers' practice in different districts ranged from 0.1 to 1.2 Mt CO_2 eq. (Table 6). The variations depend upon area under rice, which varied between 27 and 267 thousand ha, soil organic C, fertilizer and biocide use, and on- and off-farm operations. Sangrur district had the highest GWP in rice followed by Ferozepur, Ludhiana and Patiala. Total GWP of conventional transplanted rice in the state is 8.3 Mt CO_2 eq. If the entire area under conventional transplanted rice in the state is converted to DSR the GWP will be reduced to 5.6 Mt CO_2 eq. and if 50% area is converted to DSR the GWP will be 7.0 Mt CO_2 eq. These two scenarios would mitigate GWP by 33% and 16.6%, respectively. At a C trading price of 10 US$ Mg^{-1} of CO_2 eq. this would bring 28.0 and 14.0 million US$, respectively to the rice farmers' of the state. However, the methodology for monitoring and transaction cost for processing the C trading have to be worked out.

Yield and yield attributes of rice

Yield of rice was highest in 26P26 variety (7.7 t ha^{-1}) at Rozri 1 in DSR in 2009 (Table 7) and in Arize 6129 (6.67 t ha^{-1}) at Rozri 3 in 2010. In PB 1121 the yield ranged from 4.1 to 4.3 t ha^{-1}. Transplanted rice at Rozri 2 recorded lower yield (7.4 and 6.45 t ha^{-1}) in 2009 and 2010 (Table 7), respectively. At Talwandi Abdar sites yields were lower (4.08-4.15 t ha^{-1}).

In general DSR and transplanted rice gave similar yields. Data on yield attributes i.e., No. of panicle per unit area, panicle length, No. of grain per panicle and 1000-grain weight also showed that DSR was comparable to transplanted rice (Table 7). The DSR used 68% water and saved 32% water compared to transplanted rice

Table 5. Emission of greenhouse gases under conventional and direct seeded rice in different districts of Punjab

District	Conventional puddled transplanted rice (TPR)				Dry direct-seeded rice (DSR)			
	Methane	Nitrous oxide	Carbon dioxide	Total GHG	Methane	Nitrous oxide	Carbon dioxide	Total GHG
	t CO_2 eq. ha^{-1}							
Amritsar	1.2	0.4	1.3	2.9	0.1	0.6	1.2	1.9
Barnala	1.0	0.4	2.1	3.5	0.2	0.6	1.8	2.5
Bathinda	0.6	0.3	1.2	2.2	0.1	0.5	1.2	1.8
Faridkot	1.3	0.5	0.9	2.7	0.2	0.6	0.9	1.7
Fatehgarh Sahib	1.3	0.5	1.5	3.3	0.2	0.6	1.3	2.1
Ferozepur	1.4	0.5	1.6	3.5	0.2	0.6	1.4	2.3
Gurdaspur	1.0	0.4	0.9	2.2	0.2	0.5	0.8	1.4
Hoshiarpur	0.8	0.3	0.8	2.0	0.1	0.5	0.8	1.3
Jalandhar	1.3	0.4	1.2	2.9	0.2	0.6	1.1	1.8
Kapurthala	0.8	0.3	1.3	2.5	0.1	0.5	1.1	1.7
Ludhiana	1.2	0.5	1.7	3.3	0.2	0.6	1.4	2.3
Mansa	0.9	0.4	1.2	2.5	0.2	0.5	1.1	1.8
Moga	1.0	0.4	1.7	3.2	0.2	0.6	1.5	2.3
Muktsar	0.8	0.3	0.8	2.0	0.1	0.5	0.9	1.4
N Shahar	0.8	0.3	1.6	2.7	0.1	0.5	1.4	1.9
Patiala	1.0	0.4	1.3	2.8	0.2	0.6	1.1	1.9
Ropar	1.7	0.5	0.9	3.2	0.2	0.7	0.8	1.7
Sangroor	1.9	0.6	2.1	4.6	0.3	0.8	1.8	2.9
SAS Nagar	1.7	0.5	1.2	3.5	0.2	0.7	1.1	2.0
Taran Taaran	1.2	0.4	1.4	3.0	0.1	0.6	1.3	2.0
Average	**1.1**	**0.4**	**1.3**	**2.9**	**0.2**	**0.6**	**1.2**	**1.9**

Table 6. Total global warming potential of rice growing areas of Punjab and possible reduction with dry direct-seeded rice

District	GWP with 100% TPR[a]	GWP with 100% DSR	GWP with 50% DSR and 50% TPR
	Mt CO_2 eq. ha^{-1}		
Amritsar	0.5	0.4	0.4
Barnala	0.4	0.3	0.3
Bathinda	0.2	0.2	0.2
Faridkot	0.3	0.2	0.2
Fatehgarh Sahib	0.3	0.2	0.2
Ferozepur	0.9	0.6	0.8
Gurdaspur	0.4	0.3	0.4
Hoshiarpur	0.1	0.1	0.1
Jalandhar	0.5	0.3	0.4
Kapurthala	0.3	0.2	0.2
Ludhiana	0.8	0.6	0.7
Mansa	0.2	0.1	0.2
Moga	0.6	0.4	0.5
Muktsar	0.2	0.1	0.2
N Shahar	0.1	0.1	0.1
Patiala	0.7	0.4	0.6
Ropar	0.1	0.1	0.1
Sangroor	1.2	0.8	1.0
SAS Nagar	0.1	0.1	0.1
Taran Taaran	0.5	0.3	0.4
Total	8.3	5.6	7.0
Mitigation (Mt)		2.8	1.4
Mitigation (%)		33.1	16.6
Carbon price in million US \$ (@ 10 \$ t^{-1} CO_2)		28.0	14.0

[a]DSR, Direct-seeded rice; TPR, transplanted rice; GWP, Global warming potential

without any yield penalty. In DSR human labour use reduced to 45-52% and tractor use to 46-58% compared to transplanted rice in the two years of the study.

Conclusions

Water shortage, labour shortage and climate change are going to pose serious challenges for agricultural production and food security of developing countries.

Table 7. Yield and yield attributes of rice in direct-seeded and transplanted condition in Jalandhar, Punjab during 2009 and 2010

Location	Establishment[a]	Variety	Panicle m^{-2}	Panicle length (cm)	No. of grain/ panicle	1000 grain weight (g)	Grain yield ($t\ ha^{-1}$)
2009							
Rozri 1	DSR	26P26	338	27.6	134.9	37	7.7
Rozri 2	TPR	26P26	330	27.9	129.8	34	7.4
Rozri 3	DSR	PB 1121	395	29.1	133.4	35	4.3
Talwandi 1	DSR	V 6129	-[b]	-	-	-	5.5
Talwandi 2	DSR	PB 1121	-	-	-	-	4.1
Pachranga	TPR	PB 1121	384	28.7	103.3	30	4.0
2010							
Rozri 1	DSR	Arize 6129	321	27.6	210	25.7	6.2
Rozri 2	TPR	Arize 6129	317	25.9	205	26.0	6.4
Rozri 3	DSR	Arize 6129	319	27.2	205	26.0	6.7
Rozri 4	TPR	Arize 6129	319	27.9	206	26.4	6.4
Talwandi 3	DSR	PB 1121	136	29.1	136	36.0	4.1
Talwandi 4	DSR	PB 1121	129	28.4	129	36.4	4.1

[a]DSR, Direct-seeded rice; TPR, transplanted rice
[b]-, data not available

Field experiments at Jalandhar, Punjab showed that the DSR reduces GHG emission and saves irrigation water, human labour and machine labour without any yield penalty compared to conventional puddled transplanted rice. Thus, the DSR seems to be a feasible alternative to conventional puddled transplanted rice for mitigating and adapting to climate change, saving water and labour and increasing farmers' income.

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4

Greenhouse Gas Emission from Rice and Wheat Systems: A Life-Cycle Assessment

H Pathak, T Agarwal and N Jain

Introduction

Food consumption in relation to environmental impact has received attention at different levels in recent years. Research on the environmental effects of food consumption usually focuses on energy-use and waste production and has rarely evaluated emission of greenhouse gases (GHGs). From food consumption, carbon dioxide (CO_2) is the most important GHG, followed by methane (CH_4) and nitrous oxide (N_2O). Fuel combustion activities are the main sources of CO_2 emission, whereas animal husbandry and rice cultivation are the main sources of CH_4 emission, and the emission of N_2O is mainly from turnover of nitrogen in soil, application of N fertilizer and various industrial processes.

Food production systems as a group are highly heterogeneous, the range of products is wide and production systems vary within product groups as well. However, there are some common traits. To start with, for production of food crops (cereals, pulses and oilseeds), emissions of fossil CO_2 are less important than for most other industrial products, instead emissions of biogenic GHGs are more important for crop production. Products of animal origin, such as meat and dairy, have on an average higher emission per kilogram than vegetable products have though there are some exceptions also (Pathak et al., 2010b). Transportation of food commodities plays an important role in GHGs emission. Food wastes ending up in landfills also make a significant contribution to GHG emissions, methane is generated when food is degraded under anaerobic conditions in landfills. Packaging can be of significance, but it is a trade-off between functionality of the packaging as protecting the food and emissions of the packaging material.

Rice and wheat are the two most important staple foods in India. The objective of the present study was to quantify emission of GHGs (CO_2, CH_4 and N_2O) during life cycle, i.e., production, transportation, processing, marketing and preparation, of rice and wheat in India.

Methodology

Study sites

The study was conducted for the upper-IGP and lower-IGP (*see* chapter 2), the two predominantly wheat-consuming and rice-consuming regions of the country, respectively. The upper-IGP comprises Punjab, Haryana and western Uttar Pradesh, while eastern Uttar Pradesh, Bihar and West Bengal come under the lower-IGP. Emission of GHGs during the life-cycle of rice as well as of wheat in these two regions was calculated.

Life-cycles of rice and wheat

In the analysis, various components and stages of the life-cycle as well as their related tiers (direct and indirect) that are associated with GHG emissions were

Stages	Process	Equipment	Input	GHG
Production	Tillage	Tractor/Power tiller	Diesel	CO_2
		Bullock	-	CH_4
	Sowing	Seed drill	Diesel	CO_2
		Manual	-	-
	Transplanting	Manual	-	-
	Irrigation	Pump	Diesel/electricity	CO_2
	Fertilizer production	Factory	Electricity	CO_2
	Fertilizer application	Fertilizer drill	Diesel	CO_2
		Manual	-	-
	Biocide production	Factory	Electricity	CO_2
	Biocide application	Sprayer	-	-
	Soil microbial processes	-	-	$CH_4/N_2O/CO_2$
	Harvesting	Combine	Diesel	CO_2
		Manual	-	-
Processing	Drying	Sun drying	-	
		Machine dryer	Electricity	CO_2
	Milling (parboiling)	Stove	Biomass	$CO_2/N_2O/CH_4$
		Rice mill	Electricity	CO_2
Marketing	Packaging	Bag	Electricity	CO_2
	Transporting	Truck/Rail	Diesel/electricity	CO_2
	Storing	Warehouse	Electricity	CO_2
Consumption	Cooking	Oven	Gas/electricity	CO_2

Fig. 1. A schematic diagram of different stages, processes, inputs, equipment and greenhouse gas emission in the life-cycle of rice production system

Stages	Process	Equipment	Input	GHG
Production	Tillage	Tractor/Power tiller	Diesel	CO_2
		Bullock	-	CH_4
	Sowing	Seed drill	Diesel	CO_2
		Manual	-	-
	Irrigation	Pump	Diesel/electricity	CO_2
	Fertilizer production	Factory	Electricity	CO_2
	Fertilizer application	Fertilizer drill	Diesel	CO_2
		Manual	-	-
	Biocide production	Factory	Electricity	CO_2
	Biocide application	Sprayer	-	-
	Harvesting	Combine	Diesel	CO_2
		Manual	-	-
Processing	Drying	Sun drying	-	
	Milling	Mill	Electricity	CO_2
Marketing	Packaging	Bag	Electricity	CO_2
	Transporting	Truck/Rail	Diesel/electricity	CO_2
	Storing	Warehouse	Electricity	CO_2
Consumption	Cooking	Bakery	Electricity	CO_2
		Chapati	Gas	CO_2

Fig. 2. A schematic diagram of different stages, processes, inputs, equipment and greenhouse gas emission in the life-cycle of wheat production system

included (Figs. 1 and 2). All stages of production including tillage, inter-culture and harvesting and activities related to post-harvest storage and processing prior to its entry into the trading system for sales to final consumers were identified. In addition, the indirect contribution to GHGs emission during manufacturing of fertilizer and pesticide was also included.

Various stages in the life-cycle of rice are depicted in Fig. 1 and of wheat in Fig. 2. The fields are typically ploughed before seeding of rice/wheat, the plough being drawn by a diesel-powered tractor or bullocks. Direct seeding is done in the case of wheat, while in the rice fields it is done either by direct seeding or manual seedling transplantation. After seeding, irrigation is done using a diesel-powered pump. For rice crop, the field is flooded with water which leads to anaerobic conditions, consequently methane gas is produced. Fertilizer is applied to the wheat/rice fields after irrigation. Nitrogenous fertilizers lead to the emission of nitrous oxide from the soils. After maturity, the crop is harvested by combine harvesters and threshers. Combine harvester is operated by 60-75 kW engines. Pedal and power operated are the two main types of paddy threshers. These threshers are operated by 5-10 HP electric motor or diesel engine and tractor. Work capacity of pedal threshers is 40-50 kg/hr, while power-operated threshers' capacity varies from 200 to 1300 kg/hr. The paddy threshed by manual beating or by pedal-operated paddy thresher is cleaned by using hand/power-operated winnowing fans. Cleaned paddy (on an average) yields 72% rice, 22% husk and 6% bran. After harvesting, paddy is dried to reduce its moisture content to 14% (Fig. 1). Drying is done either under shade or by means of mechanical drier in which heated or unheated air is passed through the paddy in a bin. Remaining impurities like pieces of stones, dust, lumps of mud, etc. are removed by winnowing. After cleaning, parboiling is done by soaking paddy in water for a short time, followed by heating once or twice in steam and drying before milling. Milling is done to remove the husk and retain a specified percentage of bran from the seeds. Rice milling includes hand pounding which involves pounding of paddy with hand stone or poles, whereas raw milling and parboiled rice milling is performed through huller, sheller or rubber roller mills. Rice husk is the largest by-product of rice milling industry which amounts to 22-24% of the total paddy. The heating value of husk has been reported to be 13 MJ kg^{-1} (3000-3500 kcal kg^{-1}). Husk is used for generating steam for parboiling paddy and as heat source for mechanical dryers (Nayak, 1996). Paddy/rice is transported from field to the market and from market to the consumers by bullock cart, tractor trolley, trucks, railway wagons, rickshaw and bicycle (http://agmarknet.nic.in/rice-paddy-profile_copy.pdf). The average transport distance was assumed to be 1000 km and 100 km in the upper-IGP and lower-IGP regions, respectively using a diesel-powered vehicle.

Wheat does not undergo as many steps of processing as rice after harvesting (Fig. 2). It is marketed after drying as raw wheat from the farms and then milled for flour or non-flour products. Of the total wheat production, 80% is milled into two broad product categories, viz. ~90% into whole-wheat flour (*atta*) and remaining into non-atta products, such as refined wheat flour (*maida*), semolina (*suji*) and bran (http://ceodifference.org/mgi/reports/pdfs/india/Wheatmilling.pdf). Most of the wheat flour is consumed directly by households to prepare unleavened Indian bread (*chapattis*). Wheat flour is milled in two formats: nearly 98% is milled in simple, electrically operated grinder called *chakkis* and the remaining is milled in modern industrial mills. A third format, manual grinding at home, is now almost obsolete. Marketing of wheat also involves transportation by bullock cart, tractor trolley, trucks, railway wagons, rickshaw and bicycle at different stages (http://agmarknet.nic.in/profile_wheat.pdf). The average transportation distance for wheat was considered 250 km and 1000 km in the upper-IGP and lower-IGP regions, respectively using a diesel-powered vehicle.

The post-harvest losses in rice and wheat were estimated to the tune of 8-10% of total production. Packaging of food is the vital step in ensuring longer shelf-life and preservation of quality and provision of protection against deterioration and damage during transportation and storage. The Government of India has made it obligatory to pack entire food grains in jute bags only. In the distribution of rice and wheat, the means and cost of transportation play an important role. The jute bags are transported in bulk from field to market by means of bullock carts, tractor trolley, truck and railways wagons.

Emission of GHGs during life-cycles of rice and wheat

The InfoRCT simulation model (Pathak et al., 2011) was used to calculate GHGs emission during production of rice and wheat. The model requires input data pertaining to amounts of fertilizer, irrigation water, biocides and machine labor, which is prsented in Table 1. The GHGs emission during post-harvest processing (drying, milling), transportation, packaging and marketing of wheat and rice was calculated using energy consumption at each step. A conversion factor of 0.022 kgC GJ^{-1} and 0.025 kgC GJ^{-1} was used for carbon emission from fossil fuel burning and coal burning, respectively (Manaloor and Sen, 2009).

Results and discussion

Emission of greenhouse gases

Production of rice and wheat

Emission of greenhouse gases during production of rice and wheat in the upper- and lower-IGP regions is given in Table 2. Methane emission from soils cropped with rice was 88 kg ha^{-1} in the lower-IGP, which was nearly two-times higher than the emission (48 kg ha^{-1}) in the upper-IGP region. Residue burning contributed 19 kg ha^{-1} of methane only in the upper-IGP, as no residue burning was done in the

Table 1. Farm activities related to greenhouse gas emission in production of rice and wheat in the upper and lower Indo-Gangetic Plains

Region	Irrigation (mm)	Biocide ($g\ ha^{-1}$)	N fertilizer ($kg\ ha^{-1}$)	P fertilizer ($kg\ ha^{-1}$)	K fertilizer ($kg\ ha^{-1}$)	Machine labour (hour)	Diesel-tractor ($L\ ha^{-1}$)	Diesel-pump ($L\ ha^{-1}$)	Yield ($t\ ha^{-1}$)	Residue ($t\ ha^{-1}$)
Rice										
Upper-IGP	800	500	140	40	5	20	32.0	146.0	6.0	7.2
Lower-IGP	60	500	65	33	25	8	12.8	11.0	4.5	5.4
Wheat										
Upper-IGP	350	300	140	40	5	20	32.0	64.0	4.0	5.4
Lower-IGP	250	300	65	33	25	18	28.8	46.0	3.0	4.1

Table 2. Emission of greenhouse gases in production of rice and wheat in the upper and lower Indo-Gangetic Plains

Region	CH_4 burning	N_2O-N burning	CH_4 soil	N_2O-N soil and manure	N_2O-N fertilizer	CO_2-C on-farm and off-farm	Total GWP (CO_2 eq.)
				$kg\ ha^{-1}$			
Rice							
Upper-IGP	19	0.6	48	0.27	0.67	328	3623
Lower-IGP	0	0	88	0.29	0.31	120	2935
Wheat							
Upper-IGP	0	0	0	0.10	0.67	268	1342
Lower-IGP	0	0	0	0.10	0.31	155	758

lower-IGP, where the residue was fed to cattle. Similarly, the emission of N_2O-N from crop residue burning took place only in the upper-IGP. Rate of fertilizer application was assumed to be same in both rice as well as wheat crops in the upper-IGP and lower-IGP regions. Thus, the N_2O-N emission from fertilizer application was the same in both rice and wheat crops in the upper-IGP (0.67 kg ha^{-1}) as rice is predominantly grown under alternately wetting and drying conditions of soil due to the highly percolating nature of soil in this region. The emission of N_2O was nearly half (0.31 kg ha^{-1}) in the lower-IGP due to rate of fertilizer application being only one-fifth to that of upper-IGP region. The CO_2-C emissions were higher in the upper-IGP during production of both rice and wheat because of higher consumption of diesel in the on-farm operations of irrigation. Due to higher rainfall in the lower-IGP, less irrigation (therefore less diesel consumption) was required in rice, which led to lower emission of CO_2. However, more diesel tractors are required for different tillage operations in wheat than rice, leading to higher CO_2 emission from wheat in the lower-IGP. Soil cropped with wheat did not contribute to methane emissions as many times aerobic soil serves as a sink of methane (Pathak et al., 2003).

Post-harvest processing of rice and wheat

During any post-harvest process the major GHG emitted is carbon dioxide. Different post-harvest processes for rice and wheat, energy consumption in each process, corresponding carbon emissions and their prevalence in the upper-IGP and lower-IGP are given Tables 3 and 4, respectively. In the case of rice, parboiling which is more prevalent in the lower-IGP, is the most energy-intensive process consuming 2164 MJ t^{-1} of energy in soaking and steaming. This is followed by the drying process which consumes 976 MJ t^{-1} (Goyal et al., 2010). About 60% of the total production of paddy is parboiled in India. The people living in eastern India and coastal belts generally prefer to consume the parboiled rice. Both the processes, soaking and steaming, utilize thermal energy generated mainly by using rice husk. Parboiling and drying contribute 54 kg C t^{-1} and 24.39 kg C t^{-1} CO_2-C emissions, respectively. Rice milling is relatively a less energy-intensive process and consumes mainly electrical energy. There are about 15 million rice processing mills in India. Hullers and modern mechanized mills are the two main types of rice processing mills in India. Hullers are prevalent in the lower-IGP, while modern mechanized mills are seen in the upper-IGP. Rice milling consumes more energy in the lower-IGP than in upper-IGP. Overall, post-harvest processing of rice emits significantly higher, viz.

Table 3. Emission of greenhouse gases in post-harvest processing of rice in the upper and lower Indo-Gangetic Plains

Post-harvest process	Upper-IGP			Lower-IGP			GHGs emission	GHGs emission per unit produce	
	Electrical (MJ t^{-1})	Thermal (MJ t^{-1})	Total (MJ t^{-1})	Electrical (MJ t^{-1})	Thermal (MJ t^{-1})	Total (MJ t^{-1})	Per unit energy (kg C MJ^{-1})	Upper -IGP (kg C t^{-1})	Lower-IGP
Cleaning	14	-	14	4	-	4	0.025	0.34	0.1
Parboiling									
Soaking	-	-	-	4	1890	1894	0.025	-	47.35
Steaming	-	-	-	-	270	270	0.025	-	6.75
Drying	-	-	-	31	945	976	0.025	-	24.39
Milling	92	-	92	130	-	130	0.025	2.3	3.25
Packaging	2	-	2	2	-	2	0.025	0.05	0.05
Others	-	-	-	26	-	26	0.025	-	0.65
Total	107		107	197	3105	3302		2.68	82.54

Table 4. Emission of greenhouse gases during post-harvest processing of wheat in the upper and lower Indo-Gangetic Plains

Post-harvest process	Energy source	GHGs emission	Prevalent in the region	
	Electrical ($MJ\ t^{-1}$)	Per unit energy ($kg\ C\ MJ^{-1}$)	per unit produce ($kg\ C\ t^{-1}$)	
Drying	976	0.025	24.40	Lower-IGP
Traditional milling	68.5	0.025	1.71	Lower-IGP
Modern milling	105.3	0.025	2.63	Upper-IGP

82.54 kg C t^{-1} CO_2-C in the lower-IGP as compared to 2.68 kg C t^{-1} CO_2-C in the upper-IGP.

The post-harvest processing of wheat, which includes mainly drying and milling, is less energy-intensive as compared to processing of rice. The CO_2-C emission was 2.6 kg t^{-1} from modern/mechanized mills as compared to the primary mills with 1.7 kg C t^{-1} emission. There were 2.6 million small flour mills and 820 large flour mills in the year 1999. Wheat milling per unit produce requires more energy in the upper-IGP in contrast with the rice milling. Therefore, more CO_2-C is emitted from wheat milling in the upper-IGP than in lower-IGP.

Transportation and packaging

Transportation is required at various stages before the product reaches the consumers. In the case of rice, average transportation distance from field to market is more in the upper-IGP region than in lower-IGP. This is because lower-IGP is mainly a rice-growing region. Consequently, transportation of rice emits 13.6 kg C t^{-1} in the upper-IGP and only 1.4 kg C t^{-1} in the lower-IGP region. Average distance for transporting the harvested wheat to the market was taken higher (1000 km) in the lower-IGP than in upper-IGP (250 km). This mainly relates to the fact that upper-IGP is mainly a wheat-growing region. This corresponds with 3.4 kg C t^{-1} and 13.6 kg C t^{-1} CO_2-C emissions in the upper-IGP and lower-IGP regions, respectively.

Energy consumption in the packaging and marketing of rice and wheat was assumed to be the same due to the lack of data for individual crops. Packaging in jute/plastic bags consumes 687 MJ t^{-1} energy, which corresponds to 15.3 kg C t^{-1} CO_2-C emissions. Marketing mainly involves transportation of wheat flour and rice from market to the consumers mainly by diesel-driven vehicles and contributes

58.2 kg CO_2-C t^{-1} (http://www.icpeenvis.nic.in/icpefoodnpackaging/pdfs/10_cereals.pdf).

Global warming potential (GWP) of rice and wheat system

The GHG emissions and corresponding total global warming potential (GWP) of different processes in the life-cycle of rice and wheat are given in Tables 5 and 6, respectively. Total GWP of rice crop was relatively higher in the lower-IGP (1224

Table 5. Emission of greenhouse gases in the life-cycle of rice in the upper and lower Indo-Gangetic Plains

Activity	Energy use MJ t^{-1}	CO_2-C kg t^{-1}	CH_4	N_2O-N	GWP
Upper-IGP					
Production[a]	-	54.7	11.2	0.26	602.3
Milling	92	2.3	-	-	8.4
Transportation (1000 km)	-	13.6	-	-	50.0
Packaging	687	15.3	-	-	56.1
Marketing	2613	58.2	-	-	213.6
Total					930.5
Lower-IGP					
Production	-	26.7	19.6	0.13	649.2
Drying	976	24.4	-	-	89.5
Parboiling	2164	54.1	-	-	198.4
Steel huller milling	130	3.3	-	-	11.9
Transportation (100 km)	-	1.4	-	-	5.0
Packaging	687	15.3	-	-	56.1
Marketing	2613	58.2	-	-	213.6
Total					1223.7

[a]GHG emissions during all the processes of production were calculated using InfoRCT model (Pathak et al., 2011)

CO_2 eq.) than in the upper-IGP (931 CO_2 eq.). This was due to higher GWP of the rice production system; drying and parboiling post-production processes in the lower-IGP. Emissions during the production contributed more than 50 % to the total GWP, followed by marketing (17 - 23%) in both the IGP regions. Among all

Table 6. Emission of greenhouse gases in the life-cycle of wheat in the upper and lower Indo-Gangetic Plains

Activity	Energy use MJ t^{-1}	CO_2-C kg t^{-1}	CH_4	N_2O-N	GWP
Upper-IGP					
Production[a]	-	54.7	11.2	0.26	602.3
Production[a]	-	67	-	0.19	335.8
Drying	976	24.4	-	-	89.5
Flour milling	105.3	2.6	-	-	9.7
Transportation	-	3.4	-	-	12.5
Packaging	687	15.3	-	-	56.1
Marketing	2613	58.2	-	-	213.6
Total					717.1
Lower-IGP					
Production	-	51.67	-	0.14	253.4
Drying	976	24.4	-	-	89.5
Flour milling	68.5	1.7	-	-	6.3
Transportation	-	13.6	-	-	50.0
Packaging	687	15.3	-	-	56.1
Marketing	2613	58.2	-	-	213.6
Total					668.9

[a]GHG emissions during all the processes of production were calculated using InfoRCT model (Pathak et al., 2011)

post-production processes, parboiling of rice in the lower-IGP was the most energy-intensive process having GWP of 198.4 CO_2 eq.

In the life-cycle of wheat, GWP of emissions was higher in the upper-IGP than in the lower-IGP. Emissions during production contribute maximum (38-47%) to the total GWP in both the IGP regions, followed by GWP of emissions in marketing (30 – 32%). Kasmaprapruet et al. (2009) have reported that during life-cycle of rice, maximum (95%) global warming is contributed by the cultivation process, followed by harvesting process (2%) and seeding and milling processes (2%). A comparison of total GWP of emissions during life-cycle of rice and wheat shows higher GWP of rice production than of wheat in both the IGP regions. It is mainly due to contribution of methane emission to the total GHG emissions in rice production.

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5

Promotion of Low Carbon Technologies in Indian Agriculture: Opportunities and Constraints

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Introduction

To make Indian agriculture viable in future, we shall have to identify crop management systems that are climate resilient and less carbon-intensive, so that soil organic C could be enhanced or at least maintained and emission of greenhouse gases (GHGs) is reduced. Modifications in the management of water, nutrients and residues would help in reducing the GHG emissions. As discussed in the earlier section, different mitigation technologies have pronounced effects on the global warming potential (GWP) of the rice and wheat crops and some of them have the capacity to reduce the GWP vis-à-vis to farmers' current practices. However, these technologies may involve some additional expenditure and reduce the net income of farmers. Therefore, it is the cost/benefit ratio of a technology that will largely determine its acceptability by the farmers. Some of the technologies have even economic advantage while mitigating GHGs emission. These technologies help the farmers and governments achieve the dual objectives of providing food security and reducing GHGs emissions.

Today, it is important for Indian agriculture to identify agro-technologies that have proven potential to mitigate GHGs emission; increase yield and income; and provide developmental co-benefits. A major challenge before Indian agriculture is to mainstream low carbon pathways as a tool in increasing yield and translating them into activities at field levels. Due to urgent need and nature of climate change impacts, India and other nations must make all efforts (policy and financial) to identify and adopt the economically beneficial mitigation technologies. Every new technology must be examined in the context of current systems, infrastructure, values and practices, and capacities for future development. This chapter analyzes the constraints in adoption of low carbon technologies in agriculture and suggests measures to promote their wider acceptance of the farming community.

Low carbon technologies

It has been discussed in the earlier chapters that there are at least 14 technologies for rice crop and 6 technologies for wheat crop which have the potential to reduce global warming potential (GWP) in upper and lower Indo-Gangetic Plains (IGP). But some of these technologies are not considered economically profitable for the farmers. Therefore, these technologies have been analyzed to find their economic feasibility as well as potential in GHGs mitigation or C credit generation.

In rice crop grown in the upper-IGP, the new technologies have the capacity to reduce GWP in the range from 0.2% to 203.2% (Table 1). Maximum reduction in GWP has been observed in C sequestration technology where rice straw was used as a construction material. Zero tillage also has a high GWP reduction strength of 83.9%. The calculation of benefit-cost ratio has revealed that in the upper-IGP out of the 14 new technologies, 5 have higher values of benefit-cost ratio than of the conventional practice. Crop diversification has depicted the maximum benefit:cost ratio of 2.52 vis-à-vis of 1.92 in the present practices. In the lower-IGP, reduction in GWP ranged from 4.77% to 173.89% over the conventional management (Table 2). Similar to the upper-IGP, C sequestration technology has shown maximum reduction in GWP in this region. Six technologies, namely mid-season drainage, aerobic rice, direct seeded rice, sprinkler (SPR), zero till and crop diversification (DVR) have shown higher values of benefit:cost ratio than of conventional practice in this region with returns from C trading.

In the lower-IGP, the conventional management has a benefit:cost ratio of 1.69. The zero-till technology has shown a B:C ratio of 1.80 with reduction of GWP by 88.2% in this region. In fact, three technologies, namely, direct seeded rice (DSR), zero till and crop diversification from rice to maize (DVR) have depicted higher values of benefit:cost ratio than of conventional management. The crop diversification has shown the maximum benefit:cost ratio (1.98) in the lower-IGP also. If this reduction in GWP could be traded as C credit with economic returns of US $ 15 t^{-1} CO_2, then farmers could get some additional income also by adoption of these technologies. Inclusion of price for C reduction has increased the benefit:cost ratio of these technologies. In the lower-IGP, the benefit:cost ratio of DVR increases to 2.07 when cost of C trading is included.

The magnitude of GHGs mitigation per ha by any of the new technologies, however, is quite small compared to the conventional practices (Tables 1 and 2).

Table 1. Potential low carbon agricultural technologies for rice production in the upper-IGP

	Technology[a]	GWP (CO_2 eq. ha^{-1})	Change in GWP over conventional practices (%)	Benefit: cost ratio	Benefit: cost ratio with carbon credit	Area required for 1000 t CO_2 mitigation (ha)	Minimum No. of farmers needed for practical C trading
1.	Conventional rice	3957		1.92			
2.	Mid-season drainage	3625	-8.39	1.92	1.93	3012.1	662
3.	Aerobic rice	3141	-20.62	2.01	2.04	1225.5	269
4.	System of rice intensification	1542	-61.03	1.79	1.85	414.1	91
5.	Direct-seeded rice	2623	-33.71	2.17	2.21	749.6	165
6.	Sprinkler irrigation	2494	-36.97	1.99	2.03	683.5	150
7.	Zero tillage	637	-83.90	2.02	2.12	301.2	66
8.	Phosphogypsum	3593	-9.20	1.83	1.84	2747.3	604
9.	Nitrification inhibitor	3684	-6.90	1.84	1.85	3663.0	805
10.	Urea super granule	3864	-2.35	1.82	1.82	10752.7	2363
11.	Leaf colour chart	3856	-2.55	1.86	1.86	9901.0	2176
12.	Site-specific nutrient management	3949	-0.20	1.85	1.85	125000.0	27473
13.	C sequestration	-4085	-203.23	1.74	1.92	124.4	27
14.	New cultivar	3669	-7.28	1.86	1.87	3472.2	763
15.	Crop diversification	2118	-46.47	2.52	2.58	543.8	120

[a]Detailed description of the technologies and assessment of GWP and economics are given in chapter 2.

Table 2. Potential low carbon agricultural technologies for rice production in the lower-IGP

	Technology[a]	GWP (CO_2 eq. ha^{-1})	Change in GWP over conventional practices (%)	Benefit: cost ratio	Benefit: cost ratio with carbon credit	Area required for 1000 t CO_2 mitigation (ha)	Minimum No. of farmers needed for practical C trading
1.	Conventional rice	2934		1.69			
2.	Mid-season drainage	2357	-19.67	1.60	1.62	1733.1	1787
3.	Aerobic rice	1741	-40.66	1.57	1.61	838.2	864
4.	System of rice intensification	1034	-64.76	1.29	1.34	526.3	543
5.	Direct-seeded rice	979	-66.63	1.71	1.77	511.5	527
6.	Sprinkler irrigation	735	-74.95	1.49	1.55	454.8	469
7.	Zero tillage	346	-88.21	1.80	1.89	386.4	398
8.	Phosphogypsum	2266	-22.77	1.61	1.63	1497.0	1543
9.	Nitrification inhibitor	2461	-16.12	1.64	1.66	2114.2	2180
10.	Urea super granule	2725	-7.12	1.59	1.60	4784.7	4933
11.	Leaf colour chart	2722	-7.23	1.60	1.61	4717.0	4863
12.	Site-specific nutrient management	2794	-4.77	1.59	1.59	7142.9	7364
13.	C sequestration	-2168	-173.89	1.51	1.65	196.0	202
14.	New cultivar	2599	-11.42	1.63	1.64	2985.1	3077
15.	Crop diversification	529	-81.97	1.98	2.07	415.8	429

[a]Detailed description of the technologies and assessment of GWP and economics are given in chapter 2.

Moreover, a large transaction cost is involved in reaching to the stage of C trading. To make it profitable a considerable size of C mitigation should be generated, for which these technologies need be adopted on a large scale. Since the average size of landholding by the farmers is small in India, a large number of farmers would have to adopt these technologies to avail the benefit of C trading. It may be achieved by forming cooperatives, self help groups (SHGs), under collaborative efforts of government or even large private companies. The area required for 1000 ton of CO_2 mitigation due to adoption of each of these technologies has been calculated considering GHGs mitigation per ha and average landholding size in both the regions (Tables 1 and 2). For adoption of C sequestration technology, only 124 ha and 196 ha area would be required in the lower-IGP and upper-IGP, respectively to sequester 1000 ton CO_2 (Tables 1 & 2). This is attributed to the fact that CO_2 mitigation potential is highest in this technology.

Adoption of crop diversification technology (DVR) which has shown highest benefit in terms of economic return, will require 543 ha and 415 ha land in the upper-IGP and lower-IGP, respectively to sequester 1000 ton CO_2. Among the other technologies which have shown promising economic returns is the zero till; it can sequester 1000 ton CO_2 with minimum land area of 301 ha and 386 ha in the upper-IGP and lower-IGP, respectively. With per capita landholding of 4.55 ha in the upper-IGP and of 0.97 ha in the lower-IGP, the number of farmers needed to have advantage of adoption of this technology for CO_2 mitigation is 66 in the upper-IGP and 398 in the lower-IGP. For the DVR technology, 120 and 429 farmers are required for 1000 ton CO_2 mitigation in these regions, respectively. On the other hand, maximum area will be required with site-specific nutrient management (SSNM) technology in both the locations for CO_2 mitigation.

In the case of wheat crop, GWP reduction strength of the technologies ranged from 6% to 204% in the upper-IGP (Table 3) and 5% to 252% in the lower-IGP (Table 4). The GWP reduction was maximum with organic management and minimum with SSNM in wheat crop. But, the benefit:cost ratio of organic management was less than of conventional management in both the regions. Zero till and nitrification inhibitor (NI) technologies have shown higher values of benefit: cost ratio than of conventional practice in the wheat crop. Therefore, these technologies are useful in terms of GWP reduction as well as economically profitable for the farmers. Since zero-till technology has a high GWP reduction potential in wheat, therefore inclusion of returns for C credit could further increase the benefit:cost ratio to 2.26 in the upper-IGP and 1.91 in

Table 3. Potential low carbon agricultural technologies for wheat production in the upper-IGP

Technology[a]	GWP (CO_2 eq. ha^{-1})	Change in GWP over conventional practices (%)	Benefit: cost ratio	Benefit: cost ratio with carbon credit	Area required for 1000 t CO_2 mitigation (ha)	Minimum No. of farmers needed for practical C trading
1. Conventional	1808					
2. Sprinkle irrigation	1519	-15.98	1.93	1.92	3460.2	760
3. Zero tillage	111	-93.86	1.92	2.26	589.3	130
4. Integrated nutrient management	-171	-109.46	2.20	1.98	505.3	111
5. Organic	-1880	-203.98	1.93	2.01	271.2	60
6. Nitrification inhibitor	1663	-8.02	1.92	2.01	6896.6	1516
7. Site-specific nutrient management	1696	-6.19	2.01	1.91	8928.6	1962

[a]Detailed description of the technologies and assessment of GWP and economics are given in chapter 2.

Table 4. Potential low carbon agricultural technologies for wheat production in the lower-IGP

Technology[a]	GWP (CO_2 eq. ha^{-1})	Change in GWP over conventional practices (%)	Benefit: cost ratio	Benefit: cost ratio with carbon credit	Area required for 1000 t CO_2 mitigation (ha)	Minimum No. of farmers needed for practical C trading
1. Conventional	1280		1.63			
2. Sprinkle irrigation	1085	-15.23	1.59	1.59	5128.2	5287
3. Zero tillage	-61	-104.77	1.87	1.91	745.7	769
4. Integrated nutrient management	-250	-119.53	1.56	1.59	653.6	674
5. Organic	-1952	-252.50	1.55	1.63	309.4	319
6. Nitrification inhibitor	1190	-7.03	1.69	1.69	11111.1	11455
7. Site-specific nutrient management	1216	-5.00	1.59	1.59	15625.0	16108

[a]Detailed description of the technologies and assessment of GWP and economics are given in chapter 2.

the lower-IGP (Tables 3 and 4). In the upper-IGP, the benefit:cost ratio of the integrated nutrient management (INM) technology increased to 1.98, which is more than of conventional practice (1.93), when credit was given for CO_2 mitigation. With zero-till technology, 589 ha and 745 ha wheat area will be required to mitigate 1000 ton CO_2 in the upper-IGP and lower-IGP, respectively. It will require involvement of 130 and 769 farmers for adoption of this technology in the upper-IGP and lower-IGP, respectively. The INM technology would be able to sequester 1000 ton CO_2 in 505 ha and 653 ha of land with involvement of 111 and 674 farmers in the upper-IGP and lower-IGP, respectively. In organic management although CO_2 could be sequestered in smaller area with less number of farmers in both the regions, it is not likely to be acceptable by the farmers since it is not cost-effective.

Benefits, constraints and required interventions for promoting low C technologies

Major benefits and constraints in each of the low C technologies were identified and are presented in Table 5. The major benefits include savings in irrigation water, labour and energy; reduction in GHGs emission, higher water- and nutrient-use efficiencies, provision of tolerance to moisture and heat stresses, improvement in soil health and increase income. Major constraints include high initial cost, infrastructure for installation and maintenance, knowledge intensiveness and technical soundness, high production cost, risks in the rainfed areas, weed problem, yield loss, inadequate market facility, lack of awareness and limited post-harvest facilities. The interventions required to overcome the constraints are creation of irrigation facility, provision of incentives for saving of water, carbon credits for mitigation, subsidy and other incentives for installation of resource conserving infrastructure, trainings for skill development, public awareness generation, development of low-cost, environment-friendly herbicides, accurate weather forecasting, development of post-harvest facilities and refining of technologies for making them simple, cheap and effective.

While there exist numerous options for low carbon agriculture, success of these innovations can be enhanced by targeting technologies to the specific socio-economic and environmental conditions. While it has been pointed out that mitigation technologies are being promoted, it is also important to know that the current level of commitment in-terms of both policy and implementation is far short of achieving any significant mitigation target. The major barriers to adoption and expansion of

Table 5. Benefits, challenges and required interventions for promoting low-carbon and cost-effective mitigation technologies in rice and wheat in the Indo-Gangetic Plains

Technology	Major benefits[a]	Key challenges	Required interventions
		Rice	
Alternate wetting and drying/Mid-season drainage	• Saving in irrigation water (25-30%)· • Saving in labor (10-15%) and energy • Reduction in methane emission (70-75%)	• Weed problem • Yield loss (5-10%)· • Difficulties and risk in rainfed areas • Increase in N_2O emission (5-10%)	• Development of effective, low cost, environment friendly herbicides • Accurate weather forecasting • Development of Irrigation facilities • Provision of incentives for saving water • Introduction of carbon credit for mitigation
Drip and sprinkler irrigation	• Saving in irrigation water (25-30%) • Saving in energy • Higher water- and nutrient-use efficiencies	• High initial cost • Need of infrastructure for installation and maintenance • Highly technical	• Introduction of subsidy for installation • Organization of trainings for skill development • Generation of public awareness • Introduction of carbon credit for mitigation
Nitrification inhibitor/urea super granules	• Reduction in losses and increase in N-use efficiency	• High production cost • Technical application process • Non-availability in the market	• Motivation of industries to manufacture these products • Provision of incentives to farmers • Generation of public awareness • Introduction of carbon credit for mitigation
Site-specific N management/ use of LCC	• Reduction in losses and increase in N-use efficiency	• Lack of awareness • Soil testing facility inadequate	• Establishment of more soil testing laboratories • Provision of incentives to farmers

Technology	Major benefits[a]	Key challenges	Required interventions
			• Generation of public awareness • Introduction of carbon credit for mitigation
Direct seeding of rice	• Saving in irrigation water (25-30%) • Saving in labor (10-15%) and energy • Reduction in methane emission (70-75%) • Increase in stress tolerance	• Knowledge intensive • Weed problem • Yield loss (5-10%) • Increase in N_2O emission (5-10%)	• Development of effective, low cost, environment-friendly herbicides • Training to farmers • Provision of incentive for saving of water • Introduction of carbon credit for mitigation
Crop diversification (rice to maize)	• Saving in irrigation water (50-60%) • Saving in labor (20-25%) and energy • Reduction in methane emission (90-100%)	• Minimum support price not available • Inadequate market • Lack of awareness • Limited post-harvest facilities	• Provision of minimum support price • Development of market infra structure • Awareness generation • Development of post-harvest facilities
		Wheat	
Zero tillage	• Saving in fuel (70-90 L diesel ha^{-1}) • Saving in water	• Knowledge intensive • Non-availability and maintenance of quality zero-till drill • Lack of awareness	• Refinement of technology • Skill development for operation and maintenance of drill • Awareness generation
Integrated nutrient management/ organic farming	• Improvement in soil health • Increase in N-use efficiency • Reduction in GWP • Increase in income	• Non-availability of manure • Poor quality of manure • High transportation cost	• Promotion of agri-wastes for compost • Promotion of biogas for energy and manure • Introduction of carbon credit for biogas

Technology	Major benefits[a]	Key challenges	Required interventions
Nitrification inhibitor/Site-specific N management	• Reduction in losses and increase in N-use efficiency	• High production cost • Technical application process • Non-availability in the market	• Motivation of industries to manufacture these products • Provision of incentives to farmers • Generation of public awareness • Introduction of carbon credit for mitigation

[a]Figures within the parenthesis are compared to conventional practices

low carbon technologies in the Indian agriculture have been the lack of proper incentives (financial and market-driven) for adoption, scaling-up of technologies and capacity building of farmers. While pilot efforts have seen successful, Indian farming community is not forthcoming to adopt these innovations. The agricultural experts argue for introduction of carbon credits and exploration of domestic carbon markets in India. Such benefits would definitely encourage other farmers also to take up low carbon technology options. The low carbon processes in agriculture have to be developed and disseminated keeping in mind the socio-cultural and environmental domain of the targeted area.

Agriculture offers promising opportunities for mitigating GHGs emissions through carbon sequestration, appropriate soil and land-use management, and biomass production. Many agricultural activities, carried out by the farming community to increase the sustainability of production systems, may qualify for the Kyoto Mechanisms and earn carbon credits. This would increase farmer's income or attract investment benefiting sustainable development of Indian agriculture. Therefore, policy should be formulated to encourage farmers for adopting the mitigation technologies with compromising production and income. Three avenues, viz. investments, incentives and information should be pursued to promote mitigation technologies (IFPRI, 2009). There is a general lack of awareness and information among smallholder farmers regarding the causes and risks of climate change, let alone mitigation strategies. Some of the policy options for promoting GHGs mitigation in Indian agriculture are suggested below.

- Innovative payment mechanisms and support systems may be evolved for novel institutions of agricultural mitigation. Agriculture differs from other sources of GHGs in that the sources are individually small, geographically dispersed, and are often served by inadequate physical and institutional infrastructure. Cost-effective payment mechanisms to encourage agricultural mitigation must reflect these differences (IFPRI, 2009).
- To help mitigation of climate change, appropriate extension system should be developed. It may include linkages to new markets (especially carbon), acess to information on new regulatory structures, and new government priorities and policies.
- The initial step to encourage the use of low carbon farming technologies is information dissemination and capacity-building of farmers. It can be achieved through organization of workshops and seminars where academics,

development agencies and government departments could provide information on climate change, and on concepts such as reduced emissions.

- Identification of progressive farmers in each region and motivating then to adoption of new crop technologies. These farmers could subsequently disseminate low carbon technologies among other farmers for wider adoption.
- Higher resource allocations to research on predictions of interactions between climate change and agriculture. Measures that recognize the linkages between pro-poor development policies for sustainable growth and sound climate change policies be accorded resource support.
- Resources be allocated for infrastructural and institutional innovations in water and nutrient management.
- Development of rural infrastructure, both physical and institutional be included in resource allocations to enhance the resilience of agriculture in the face of the uncertainties of climate change.

References

IFPRI (2009) Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen. The International Food Policy Research Institute (IFPRI).2020 Vision for Food, Agriculture, and the Environment, 29 p.