*Review Article***Greenhouse Gas Emission from Indian Agriculture: Trends, Drivers and Mitigation Strategies**

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Climate change, caused by the increase in concentrations of greenhouse gases (GHGs) in the atmosphere, has emerged as the most prominent environmental issue all over the world. It will have a considerable impact on agriculture including crops, livestock and fisheries. Agriculture, crucial for ensuring food, nutritional and livelihood security of India, is exposed to the stresses arising from climatic variability and climate change. Agriculture sector is also a major contributor to the enhanced greenhouse effect with the emissions of carbon dioxide, methane and nitrous oxide. Indian agricultural sector emitted about 420 Mt of CO₂ eq. during 2010. Enteric fermentation contributed 56% of the emission followed by agricultural soil (23%) and rice fields (18%). On-farm burning of crop residues and manure management contributed 2% and 1% of the emission, respectively. During 1970-2010, the GHGs emission from Indian agriculture has increased by about 75%. The increasing use of fertilizers and other agri-inputs and the rising population of livestock are the major drivers for this increase in GHGs emission. The relative contribution of Indian agriculture to the total GHGs emission from all the sectors of the country, however, has decreased from 33% in 1970 to 18% in 2010. Mitigation of GHGs emission from agriculture can be achieved by sequestering C and reducing the emissions of methane and nitrous oxide through changes in land-use management and enhancing input-use efficiency. A win-win solution would be to develop such mitigation strategies that help in climate change adaptation and promote sustainable agricultural development.

Keywords: Adaptation; Carbon Sequestration; Climate Change; Global Warming Potential; Greenhouse Gas; Methane; Mitigation; Nitrous Oxide

Introduction

Agricultural lands occupy about 40% of the earth's land surface (FAO, 2015). About 70% of the agricultural lands are used for pasture, 27% are arable lands, mainly devoted to annual crops and only 3% for permanent crops. Global harvested area for all crops has increased from 1.06 billion hectares (Bha) in 1961 to 1.38 Bha in 2011, a 30% increase (FAO, 2015). Global population during the same period has increased from 3.08 to 7.24 billion, a 135% increase. The ratio of farm land to people therefore, declined from 0.344 ha in 1961 to 0.191 ha in 2011, a 45% decrease. Productivity of crop, however, has increased considerably. For example, cereal production

has tripled from 0.87 billion ton (Bt) to 2.59 Bt during the period (FAO, 2015). Growing demand and technological improvements have led to widespread changes in livestock production systems from small holder mixed systems to large-scale commodity-specific systems, from roughages to concentrate feeds, and from dispersed to concentrated production systems.

Agriculture is crucial for ensuring food, nutritional and livelihood security of India. It engages almost two-thirds of the workforce in gainful employment and accounts for a 13.8% share in India's gross domestic product. The country is well-endowed with natural resources including land, water,

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vegetation and climate. Out of 328 million ha (Mha) geographical area of the country, agriculture occupies about 141 Mha (Table 1). However, land holdings of Indian farmers are small. More than 85% of Indian farmers are marginal (cultivating up to 1 hectare) and small (cultivating between 1 hectare and 2 hectares). The farms are diverse, heterogeneous and unorganized. Moreover, almost 60% of country's net cultivated area is rainfed and exposed to abiotic and biotic stresses. Providing food and nutritional security to the increasing population is a major challenge for Indian agriculture. Population of the country may reach around 1.6 billion in the year 2050 requiring annually 450 million tons (Mt) of food grain against the current production of about 260 Mt (MoA, 2014). Besides the need of food grain, there is a need of feed and fodder for livestock and poultry. These demands are to be met from an almost stagnant net sown area of 141 Mha in the country. In the global context, India with 2.4% of the world's total land area and only 4.0% of the total replenishable fresh water has to cater to 17% of the world's population. Therefore, the sustainable management of land and water is crucial for food and nutritional security of the country, particularly with global climate change scenario.

Global warming, caused by the increase in concentrations of GHGs in the atmosphere, has

Table 1: Land use in India

Land use	Area (Million ha)
1. Geographical area	328.73
2. Reporting area	305.82
3. Area not available for cultivation	
a) Forests	69.70
b) Area put to non-agricultural uses	24.48
c) Barren and unculturable land	17.73
4. Other uncultivated area	
1. Permanent pastures and other grazing lands	10.45
2. Area under tree crops & groves	3.37
3. Culturable waste land	13.17
5. Fallow land	26.04
6. Area under agriculture	140.88

Source: ICAR-NAAS (2010)

emerged as the most prominent environmental issue all over the world. These GHGs viz., carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) trap the outgoing infrared radiations from the earth's surface and thus raise the atmospheric temperature. The Inter-Governmental Panel on Climate Change (IPCC), in its Fifth Assessment Report, has reiterated that warming of the climatic system is unequivocal. The anthropogenic influence on the climatic system is evident from the increasing concentrations of GHGs in the atmosphere and the positive radiative forcing. As a result, the temperature of atmosphere and ocean is going up, snow and ice are melting fast and sea level is rising. This global climate change will have considerable impact on the crops, soil, livestock, fisheries and pests.

The agricultural sector is believed to contribute to the greenhouse effect and the ensuing climate change is likely to have adverse impact on this sector. Various agricultural activities such as land clearing, cultivation of crops, irrigation, animal husbandry, fisheries and aquaculture have a significant impact on the emission of GHGs (IPCC, 2014). An in-depth understanding of trends in emission of GHGs, their drivers, and the relation between the two, is essential for comprehending the need for mitigation and adaptation. The objectives of this paper are to evaluate the emission of GHGs from Indian agriculture, analyze the drivers and trends of GHGs emission and assess the potential of various mitigation options.

Drivers of Agricultural Change and Greenhouse Gas Emission

Agriculture is a complex sector involving different driving parameters (economic, social and environmental). Major drivers for agricultural change include population increase, food and energy security, globalization and liberalization, increase in per capita income, change in food consumption and dietary trend, water and labour shortage, technological development, climate change, price of carbon in the market and co-benefits of GHGs mitigation and synergy with sustainable development (Table 2). A few more drivers, particularly in the social and cultural fronts, may play significant role in future changes in

agriculture. The drivers work at global, national and local levels.

Global population is expected to be about 9.1 billion by 2050 i.e., about 3 billion more people than in 2010 and the per capita land availability will be only 0.152 ha. The global demand for food will increase as 2.3 billion more people with 2.9 times income, consuming twice as much, will be added by 2050 (Clay, 2010). Food production is expected to double in the next 30 years in order to feed the planet's growing human population (UNFCCC, 2008). Global annual cereal production is expected to increase from current 2100 Mt to 3000 Mt and meat production may reach from 200 Mt to 470 Mt by 2050 (FAO, 2015). Moreover, by 2050, more people will live in cities. Extrapolating urban residents' demands of today, they will depend on others for their food. All these changes will put tremendous pressure on agriculture resulting in considerable changes in emission of GHGs. Agricultural production has grown much faster than the population in recent decades, leading to a steady increase in per capita agricultural output and a steady decline in world prices for most agricultural commodities, particularly since the 1960s (Hazell and Wood, 2008). Agriculture expansion is the most important and immediate driver for deforestation (Gibbs *et al.*, 2010). Water, labour and nutrient availability will be the major supply-side drivers which would also include efficiency gains associated with vertical integration in food supply chains. The food supply generated by our industrial food and agriculture complex has changed what and how people eat. The dietary trends for many people have led to today's excessive calories, salt, and high glycemic carbohydrates with too few fruits, vegetables, whole grains, nuts, seeds and legumes (Harvie *et al.*, 2011).

For Indian agriculture, increasing population and intensification of agriculture with more and more use of irrigation water, fertilizer and pesticide and increased mechanization have been the major drivers of GHGs emission. Though, the net agricultural area of the country has remained more or less stagnant at about 141 Mha during the last 3 decades, the production has doubled, mainly because of use of high yielding varieties and intensive use of agri-inputs.

During recent years, the per capita income has increased leading to change in food consumption and dietary trend. Increased urbanization, labour shortage for farm operations, technological development, shifts in public policy including subsidies and trade, finance and investments and supply-chain initiatives have also led to diversification of agriculture and have influenced GHGs emissions in the sector.

Emission of Greenhouse Gases from Indian Agriculture

In 2010, the global emission of GHGs was about 50 Bt CO₂ eq. in which contribution of India was of about 2.34 Bt CO₂ eq. i.e., about 5% of the total emission. Agriculture contributed globally over 11% of the total GHGs emission. The share of Indian agriculture was about 7% of global emission from agriculture. The energy sector in India contributes the highest amount GHGs (65%) followed by agriculture (18%) and industry (16%) (Fig. 1). Indian agricultural sector, including crop and animal husbandry, emitted 418 Mt of CO₂ eq. (Table 3). Enteric fermentation i.e., emission from ruminant animals contributed the highest (56%) amount of the emission from this sector, followed by agricultural soil (23%) and rice fields (18%) (Fig. 1). Burning of crop residues in field contributed 2% and manure management contributed 1% of the emission.

Over the years, several estimates of methane emission from Indian rice fields have been made (Fig. 2). In recent years, Indian Agricultural Research Institute, New Delhi, in collaboration with other ICAR

Fig. 1: Emission of greenhouse gases from A: various sectors of Indian economy and B: sub-sectors of agriculture in 2010

Fig. 2: Estimates of methane emission from Indian rice fields over the years. IARI 1994, 2000, 2007 and 2010 are the values estimated by Indian Agricultural Research Institute, New Delhi for the respective years. Adapted from Pathak *et al.* (2014)

Table 2: Major global, country and local scale drivers of agricultural change

Drivers	Trend*
Global-scale drivers	
World prices for agricultural products	--/0
International trade and globalization of markets	+ /++
Energy prices	+ /++
Country-scale drivers	
Per capita income growth	- /+
Urbanization	+ /++
Shifts in public policy	+
Security: financial/business and conflict/crisis	- /+
Water scarcity	++
Local-scale drivers	
Poverty	- /+
Population pressure and demographic structure	- /++
Capacity of natural resources	- - /+
Infrastructure and market access	+ /++
Non-farm opportunities and labour scarcity	0 /+

*Trend: --, strongly declining/negative; -, declining/negative; 0, stable; +, increasing/ positive; ++, strongly increasing/positive; '/' indicates a range. Source: Modified from Hazel and Wood (2008)

and CSIR Institutes, has rationalized the earlier estimate of 37.5 Mt to 3.3 Mt (Pathak *et al.*, 2014). Among the various rice ecosystems, the highest emission was from the irrigated continuously flooded rice (34%), followed by rainfed flood-prone rice and irrigated single aeration (18%) (Bhatia *et al.*, 2012; 2013). Rainfed drought-prone, deep water and irrigated multiple aerations rice ecosystems contributed 16%, 8% and 6% of methane, respectively (Pathak *et al.*, 2014). Fertilizer was the largest source contributing 77% to the total nitrous oxide emission (Fig. 3). Emission of CH_4 and N_2O and global warming potential (GWP) varies spatially at the national and state levels (Pathak *et al.*, 2014). Emission of methane ranges from 4 to 190 kg ha^{-1} in different states of India. Higher methane emission values, observed in some of the states in southern and eastern India, are due to the continuous submergence of the fields under water and a higher soil organic C content. Emission of N_2O from the various states of India ranges from 0.18 to 9.11 kg ha^{-1} . Emissions of N_2O were higher from southern (Andhra Pradesh, Karnataka, Pondicherry) and northern (Punjab, Haryana) states of the country. The high emission of N_2O was due to large area under rice, and more use of N fertilizers. In northern India, rice is generally grown under

Fig. 3: Contribution of different sources to nitrous oxide emission from Indian agricultural soils in 2010. Adapted from Pathak *et al.* (2014)

intermittent drying and wetting conditions and considerable amounts of nitrous oxide emission could occur because of alternate wetting and drying of rice fields resulting in repetition of alternate nitrification and denitrification processes. The eastern and southern parts of the country have shown a higher GWP, mainly because of higher emissions of CH_4 and N_2O due to large area under rice cultivation. The highest GWP was observed in the states lying in the Indo-Gangetic Plains (IGP) as this is the major rice-wheat growing belt of the country with higher consumption of nitrogenous fertilizer and large area under rice cultivation.

Trends in Greenhouse Gases Emission

Globally, emission of GHGs in the agriculture sector increased by 35%, from 4.2 Gt CO_2 eq. yr^{-1} to 5.7 Gt CO_2 eq. yr^{-1} during 1970 to 2010 (IPCC, 2014). Enteric fermentation was the largest contributor to methane emission followed by rice cultivation and manure management (IPCC, 2014). Soil, application of fertilizer and manure were the major contributors. Between 1970 and 2010, emission of methane increased by 18% whereas emission of nitrous oxide increased by 73%. Though total global emission increased but per capita emission went down from 2.5 ton in 1970 to 1.6 ton in 2010 because of growth in population. Per capita emission decreased in Latin

America (LAM), Middle East and Africa (MAF) and Economies and Transition (REF) countries whereas in Asia and Organization for Economic Co-operation and Development (OECD90) countries it remained almost unchanged.

During 1970 to 2010, the GHGs emissions from Indian agriculture have increased by about 75% (Fig. 4). The increased use of fertilizers and other agri-inputs and the rise in population of livestock are the major drivers for this increase in GHGs emissions. The relative contribution of Indian agriculture to the total GHGs emission from all the sectors of the country, however, has decreased from 33% in 1970 to 15% in 2010 (Pathak *et al.*, 2014). A faster growth and consequently higher emissions from the energy, industry and transport sectors *vis-a-vis* agricultural sector are responsible for the decrease in the relative contribution to GHGs from agriculture.

Fig. 4: Greenhouse gas emission intensity in Indian agriculture during 1970 to 2010. Adapted from Pathak *et al.* (2014)

Table 3: Greenhouse gas emissions from Indian agriculture in 2010

Source	Methane	Nitrous oxide	GWP (CO ₂ eq.)
Enteric fermentation	10.90	-	228.9
Manure management	0.13	0.08	27.5
Rice cultivation	3.4	-	85.0
Agricultural soil	-	0.26	77.8
Crop residue burning	0.30	0.01	9.6
Total	14.73	0.35	417.8

Pathak *et al.* (2014)

From 1970 to 2010, the emission of CH₄ from Indian rice fields has remained almost similar, though the rice production increased from 115 to 128 Mt. It is because of almost constant area under rice cultivation (43-44 Mha) and use of similar water and crop management practices by the farmers over the years. However, the emission of N₂O has increased considerably during this period because of the application of more fertilizers and manure in soil.

During 1970 and 2010, the GHGs emission per ha of land under food grains increased by about 90%. However, the GHGs emission intensity per ton of food grains production decreased by 15% (Fig. 4). This decline was due to the increase in agricultural production of the country because of adoption of high-yielding varieties of crops and animal breeds, as well as better crop and animal management practices without appreciable increase in ruminant population and area under rice, both of which are the major sources of methane. Though the application of N fertilizer increased the agricultural GWP, the increase in yield was greater. The analysis has shown enough scope for improving agricultural production in the country without off-setting the GHGs emission.

In general, GHGs emissions are expected to continue to increase due to increased demand for food as populations grow, and shifts in diets as societies in developing countries become wealthier and meat consumption increases. By 2030, GHGs emissions from agriculture are expected to be almost 60% higher than in 1990 (Table 4). The largest increases will be in N₂O emissions from soils (75%), as fertilizer use increases rapidly. Emission of CH₄ from other agricultural sources (predominantly biomass burning) will also increase greatly (70%), but these emissions will still account for only 5% of the total agricultural emissions. Emissions from manure management will still be significant and may increase on the order of 31% for N₂O and 47% for CH₄ from this source.

The area of rice grown globally is forecast to increase only by 4.5% by 2030 (FAO, 2003), so methane emissions from rice production would not be expected to increase substantially. There may even be reductions if less rice is grown under continuous flooding (causing anaerobic soil conditions) as a result

Table 4: Top 10 emitters of non-CO₂ GHGs from agriculture (Mt CO₂eq.)

Country	1990	Country	2005	Country	2030
China	903	China	1,101	China	1,459
India	575	India	740	India	988
USA	440	Brazil	515	Brazil	731
Brazil	388	USA	486	USA	529
Russian Fed.	168	Pakistan	150	Argentina	211
Pakistan	110	Russian Fed.	135	Russian Fed.	205
Mexico	106	Argentina	130	Pakistan	193
Argentina	106	Indonesia	125	Nigeria	189
France	102	Mexico	115	Mexico	170
Australia	94	Nigeria	112	Indonesia	163
Global total	5343		6291		8493

USEPA (2006)

of scarcity of water, or if new rice cultivars that emit less methane are adopted. However, USEPA (2006) projects a 16% increase in CH₄ emissions from rice crops between 2005 and 2020, mostly due to a sustained increase in the area of irrigated rice (IPCC, 2007).

Agricultural N₂O emissions are projected to increase by 35-60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production. Similarly, it is estimated that N₂O emissions will increase by about 50% by 2020 (relative to 1990). If demands for food increase, and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced, and perhaps also a reduction in emissions per capita food consumption (IPCC, 2007).

The projected trends of GHGs emission from Indian agriculture have indicated that under the business-as-usual scenario, the emission will increase by 17% by 2030 compared to that in 2010 (Pathak *et al.*, 2014).

Mitigating Greenhouse Gases Emission from Agriculture

Agriculture is unique as it offers opportunities for mitigation from supply-side and also from demand-side. The supply-side opportunities include (1) sustainable intensification, (2) improving N fertilizer production and management, (3) reducing emissions from enteric fermentation, (4) reducing methane emissions from rice cultivation and (5) improving manure management. The demand-side opportunities are (1) sequestering carbon in agricultural systems, (2) reducing food waste and (3) shifting dietary trends. The IPCC (2014) has identified the following mitigation options in agriculture: (1) Plant management: improved variety, rotation, cropping system; (2) Nutrient management: Type of fertilizer, urease/nitrification inhibitor; (3) Tillage/residue management: Reduced tillage, residue retention; (4) Water management: Improved water application, drainage; (5) Land use change: Agro-forestry, bio-energy crops and (6) Biochar application. Some of the mitigation options relevant for Indian agriculture are discussed below.

Mitigation of Methane Emission from Rice Fields

Methane is produced in soil during microbial decomposition of organic matter under anaerobic conditions. Rice fields submerged under water are the potential source of CH₄ production. Continuous submergence, higher organic C content and use of organic manure in puddled soil enhance methane emission. The strategies for mitigating methane emission from rice cultivation could be altering water management, particularly promoting alternate wetting and drying (AWD); adopting direct-seeding of rice (DSR) and system of rice intensification (SRI); improving organic matter management by promoting aerobic degradation through composting or incorporating it into soil during off-season drained period; using rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index; and application of fermented manure like biogas slurry in place of unfermented farmyard manure (Pathak *et al.*, 2015).

The AWD practice involves flooding a farm field

and then allowing the field to dry until the upper soil layer starts to dry out, then reflooding and draining in cycles throughout the season. Because it so frequently sets back the generation of methane-producing bacteria, AWD achieves even larger reductions in methane than only one drawdown. AWD should not be seen as a rigid prescription but more as an ideal, with intermediate options involving less frequent drainage, although the level of methane reductions will depend on how stringently it is practiced. Bhatia *et al.* (2012) have shown that by shifting water management from the current practice to intermittent flooding in all the irrigated rice area of the country, the national CH₄ flux from irrigated rice fields could be reduced by 40%. However, under the intermittent flooding scenario, the N₂O-N fluxes could increase by 6%.

Improved water management such as AWD and shifting from flooded to merely moist soils is the most attractive mitigation because of water and energy saving incentives to farmers. However, despite the water savings and potential yield benefits of water management, many farmers face important technical and practical constraints. The most obvious and immediate challenge for any mid-season drainage is that farmers should be able to manage their water reliably. To practice AWD, farmers should be able first to allow their fields to dry, and then, they must have a reliable source of water to rewet their fields as soon as needed. Most rice-growing regions have distinct wet and dry seasons. In the wet season, farmers may not be able to drain their fields adequately. In the dry season, studies indicate that only some irrigation systems have the physical or logistical systems in place to provide sufficiently reliable water to encourage farmers to practice this kind of water management (Pathak *et al.*, 2015).

Despite these limitations, there are several opportunities to reduce GHGs emission. Large parts of India irrigate by pumping from groundwater, which means they are able to control their irrigation. Yet even where water level management is not capable of providing full-scale AWD, farmers might have enough control to practice dry-seeding, or to perform at least one drawdown during the production season. But

some water management control is still necessary. For example, with dry-seeding, farmers still need to be able to keep soils moist from the period after seeds are grown to when the rice plant emerges. Overall, analysis suggests that improvements in water management will be necessary to allow many of the world's farms to practice AWD, at least in some seasons, and that the farmers already have a greater capacity to practice AWD than they are now practicing (Pathak *et al.*, 2015). Unfortunately, none of the farmers have any direct incentive to adopt water-saving practices for the specific purpose of reducing GHGs emissions, and only in limited contexts are farmers encouraged to engage in these practices because of water supply issues. Even though water limitations are serious in many rice-growing regions, farmers often receive water through gravity-driven irrigation and rarely financially benefit from reducing their water use because they do not pay for the quantity of water they use. In groundwater systems, the incentives are more pronounced as farmers can benefit from reduced pumping costs. However, even under those circumstances the incentives may not always be applicable, e.g. in India, those energy costs are heavily subsidized.

The DSR and SRI crops do not require continuous soil submergence, and therefore reduce

or totally eliminate methane emission when rice is grown as an aerobic crop. The DSR and SRI have potential to reduce the GWP by about 35-75% compared to the conventional puddled transplanted rice (Table 5). A package of practices for mitigation of GHGs emission from conventional puddled transplanted rice could include intermittent flooding, which reduces GWP by 25-30% over continuous flooding, growing of shorter duration rice such as Pusa Basmati 1509, which reduces GWP by 15-20% compared to Pusa Basmati 1121 and use of neem oil coated urea, which decreases GWP by 10-15% compared to common prilled urea (Fig. 5).

Besides, improved rice straw management through off-season application under dry soil

Fig. 5: Global warming potential (GWP) in rice with different varieties (Pusa Basmati 1121 and Pusa Basmati 1509), fertilizer and water management practices

Table 5: Potential and constraints of greenhouse gas mitigation options in Indian agriculture

Technology	Mitigation (%)*	Yield (%)*	Requirements
Methane from rice field			
Intermittent drying	25-30	90-100	Assured irrigation
Direct-seeded rice	30-50	90-100	Sowing machine, herbicide
System of rice intensification	25-30	95-110	More labour, assured irrigation
Short duration variety	15-20	95-115	-
Nitrous oxide from soil			
Demand-driven N use	10-15	105-110	Knowledge intensive, tool needed
Nitrification inhibitor	10-15	105-110	Additional cost
Carbon sequestration in soil			
Conservation agriculture	5-10	95-110	Knowledge intensive, tool needed
Integrated nutrient management	5-10	95-110	Manure availability, additional cost

*Compared to the conventional practices. Adapted from Pathak *et al.* (2014)

conditions, composting, turning rice straw into biochar and better nutrient management are other options for GHGs mitigation in rice. There are substantial co-benefits of the above options including increased productivity and resilience, cost saving and water saving.

Mitigation of Nitrous Oxide Emission

Nitrous oxide is produced 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 N in soil through additions of synthetic or organic fertilizers, manure, crop residues, sewage sludge or mineralization of N in soil organic matter following drainage/management of organic soils and cultivation/land-use change on mineral soils. Options for reducing N_2O emission from soil includes enhancing N use efficiency and reducing loss of applied N in soil, plant breeding and genetic modifications to increase the N uptake, use of manure or integrated use of manure and fertilizer to reduce reliance on chemical fertilizer, application of N based on soil-test and use of technologically advanced fertilizers such as slow-release fertilizers or nitrification inhibitors. These options, besides reducing emission, have co-benefits such as cost savings, increased yields, improved health and pollution abatement.

Enhancing the efficiency of fertilizer N with the use of right kind of fertilizer applied with right method at appropriate rate, time, and place, however, is the key to reduce emission of nitrous oxide from soil. The demand-driven N use using a leaf colour chart (LCC) could reduce the nitrous oxide emission and GWP by about 11-14% (Bhatia *et al.*, 2012; Jain *et al.*, 2013). Use of nitrification inhibitors such as coated calcium carbide and dicyandiamide can reduce emission by 10-15% (Table 5). There are some plant-derived

organics such as neem oil, neem cake and karanja seed extract which can also act as nitrification inhibitors. Pathak *et al.* (2011b) analyzed 16 technologies, which differed in terms of water regime, method of N application, forms of N and tools of fertilizer recommendation for their GHGs mitigation potential and economic return in Haryana, a rice growing region in India. In the current farmers' practice, recovery efficiency of N was 33%, which increased to 35-41% with various technologies except in mid-season drainage and alternate flooding technologies where it decreased to 29-31%. The technologies also reduced GWP by 1 to 9%. Resource conserving technology was the most cost-effective strategy to reduce N loss and GHGs emission whereas integrated N management cost high for mitigating GHGs emission (Fig. 6). However, the technologies except no tillage, mid-season drying and alternate flooding reduced the net income of the farmers. When the environmental cost (cost of N loss and GWP) was included, net income with various technologies was either at par or more than the farmers' practice.

Fig. 6: Marginal abatement cost for reducing global warming potential (GWP) from the baseline technology of continuous flooding and farmers' practice (cf_fp) in Haryana. With resource conserving technology (cf_ct), mid-season drainage (md_fm) and alternate flooding (af_fm) technologies GWP is reduced without any extra cost involved. With integrated nutrient management (cf_in) technology GWP is increased

Sequestration of Carbon in Agricultural Soils

The main source of carbon dioxide in agriculture is the soil management practices such as tillage which

triggers emission of this gas through biological decomposition of soil organic matter. Tillage breaks the soil aggregates, increases the oxygen supply and exposes the surface area of organic material promoting the decomposition of organic matter. Use of fuel for various agricultural operations and burning of crop residues are the other sources of carbon dioxide emission. An off-site source is the manufacturing of farm implements, fertilizers and pesticides. The mitigation of CO₂ emission from agriculture could also be achieved by increasing C sequestration in soil (Lal, 2004; Pathak *et al.*, 2011a). Carbon sequestration is the capture and storage of carbon (in soil, water, vegetation, and engineering structure) that would otherwise be emitted to the atmosphere. For C sequestration the following considerations are important: (1) the storage of C should be for a longer term (30 yrs. or more), (2) all the GHGs (methane, N₂O) and all forms of C (organic and inorganic C) should be included for quantifying C sequestration, (3) whole soil profile, rather than surface soil needs to be considered for assessing C stock, (4) assessment should be at regional scale rather than site or field scales and (5) all the components of the agro-ecosystems and their life cycle should be assessed.

Management of soil for C sequestration should include the following approaches. Firstly, protection of existing carbon in soil by reducing rate of decomposition of organic matter with reduced tillage or no tillage and prevention of soil erosion with terracing, contour strips and cover crops. Secondly, increasing the amount of carbon in the system by retaining crop residues on soil, growing perennial crops, which have larger root systems, applying slow degradable C sources such as biochar and integrated and balanced use of plant nutrients. Pathak *et al.* (2011a) analyzed 26 long-term experiments (LTEs) running for 8 to 32 years in 14 out of total 15 agro-climatic zones (ACZs) of India to assess the potential of C sequestration. Compared to the control (no fertilizer) treatment, the recommended doses N, P and K+ farm yard manure (FYM) treatment sequestered 0.33 Mg C ha⁻¹ yr⁻¹ whereas, the recommended doses N, P and K treatment sequestered 0.16 Mg C ha⁻¹ yr⁻¹. The C sequestration

potential in different nutrient management scenarios ranged from 2.1 Mg C ha⁻¹ to 4.8 Mg C ha⁻¹ of the LTEs. Total C sequestration potential in the agricultural soils of the country was 300 to 620 Mt. The analysis showed that a judicious nutrient management is crucial to soil organic C (SOC) sequestration in tropical soils. An adequate supply of nutrients to soil can enhance biomass production and SOC content. The use of organic manure and compost enhances the SOC pool more than the application of same amount of nutrients as inorganic fertilizers. The long-term manure application increases the SOC pool, and the effects may persist for a century. The increased SOC not only mitigates CO₂ emission but also enhances soil productivity. It is, however, argued that SOC sequestration is a big challenge in soils of the tropics and the sub-tropics, where climate is harsh and the resource-poor farmers cannot afford the input of organic manure and crop residues. The rate of C mineralization is high in the tropics because of high temperature. Whether in soil, perennial crops or trees, carbon makes agriculture more sustainable. The other options of C sequestration include agro-forestry and improved carbon storage in grazing lands through improved pasture management practices.

As discussed above, agriculture-based carbon sequestration has advantages and disadvantages. Advantages include low cost, relatively simple implementation, and easy scalability. However, an important disadvantage is that agriculture-based carbon sequestration is easily reversible, the dynamic process is asymmetric; accumulation proceeds slowly and at different rates for different cropping practices and locations.

Reducing Emission from Ruminants and Manure Management

Changes in animal agriculture that would reduce GHGs emissions include raising fewer ruminants and shifting from ruminants to poultry, improving feeding and manure management practices and increasing efficiency in feed and livestock production. Other mitigation options include increased feeding efficiency through improved forages as well as dietary additives that suppress methanogenesis (IPCC, 2007; Smith *et*

al., 2008). Improved diets for livestock is one the most promising methods of GHGs emission because they tend to be low-tech, low-cost, low-risk, and provide productivity gains. Inclusion of supplements and additives in animal feed, however, is suitable for organized livestock sector. In the unorganized, free grazing systems of livestock management, supplements and additives are difficult to deliver and may not be very effective. Moreover, this kind of interventions, though have shown potential, are still largely in the research phase. Herd management interventions such as disease prevention and providing shelter for the animals, as well as high-end genetics hold significant opportunities for India. Improving the quality of forages, processing feeds to improve digestibility and adding grain-based concentrates to livestock diets are the other options for mitigation of GHGs emission from livestock.

Efficient management of manure and its use in soil reduce the need for synthetic fertilizers, displace fossil fuels, create profitable products, and increase the productivity of croplands and pastures and thereby reduce intensity of GHGs emission. Anaerobic fermentation of manure in biogas digesters can produce methane, which can be used as fuel or converted into electricity. Better storage and handling practices like reducing storage time, covering the manure pit, avoiding straw/hay bedding, changing the diet of livestock by including balancing dietary proteins, tannin supplements, and other feed additives to affect the volume and composition of manure, and shift to diversified farming systems integrating crops and livestock are effective means of reducing GHGs emission.

Genetic Enhancement of Crops and Animals

A large increase in food production has been achieved through development of new varieties and hybrids, genetic selection, adoption of improved breeding techniques, and recently, genetic engineering and modification technology. We now have the ability to identify traits within a genome to increase productivity, as well as drought and pest resistance. Scientific advances will also allow us to identify and improve other traits such as increased efficiency of input

uptake or even producing inputs within the plant and enhancement of beneficial nutrients in soils. These programs could improve the overall product quality, flavour profiles, nutritional benefits, shelf-life, and carbon sequestration, while reducing input demands, water content, embedded carbon and water, and losses from waste throughout the value chain. New genetic engineering technologies would also allow work to be done on perennials in a time frame shorter than ever before. This would include important perennials and tree crops such as cocoa, coffee, palm oil, oranges, bananas, plantations, fruits, and nuts. These crops could sequester carbon and help in GHGs mitigation. Another area that could result in a net increase in the available calories is animal breeding and genetics. Most work to date has focused on reducing anti-nutritionals in feed and increasing the palatability of feed and feed conversion ratios (FCRs) rather than on changing the animals themselves. A considerable work is being undertaken to reduce the amount of methane produced by the livestock in order to reduce their contribution to GHGs emissions.

Enhancing Input-use Efficiency and Conservation Agriculture

Agricultural inputs such as water, nutrients, pesticides and labour are the critical factors of agricultural production. However, the efficiency of these inputs in Indian agriculture is low, causing large amounts of losses and GHGs emission. Increasing use of resource conserving technologies such as water-, labour- and nutrient-saving technologies and increased mechanization in agriculture can save inputs, increase profits, reduce waste and alter GHGs emission. Farmers can make money by adopting some of these technologies through carbon sequestration and GHGs mitigation. Coupled with technological gains, farmers need to follow better management practices (BMPs) to increase production, reduce costs, reduce waste or impacts, and increase profits. In addition, the GHGs emissions can be reduced by the substitution of fossil fuels for energy production by the agricultural feedstocks (e.g. crop residues, dung, and dedicated energy crops). Policies and incentives will have to be developed to encourage farmers for adopting these mitigation options to harness the benefits of improved

Table 6: Interventions for promoting GHGs mitigation technologies in rice and wheat crops in the Indo-Gangetic Plains

Technology	Major benefits	Key challenges	Required interventions
Rice			
Alternate wetting and drying/mid-season drainage	<ul style="list-style-type: none"> • Saving in irrigation water (25-30%)^a • Saving in labor (10-15%) and energy • Reduction in methane emission (30-35%) 	<ul style="list-style-type: none"> • Weed problem • Yield loss (5-10%) • Difficulties and risk in rainfed areas • Increase in N₂O emission (25-30%) 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Saving in irrigation water (25-30%) • Saving in energy • Higher water- and nutrient-use efficiencies 	<ul style="list-style-type: none"> • High initial cost • Need of infrastructure for installation and maintenance • Technical skill required 	<ul style="list-style-type: none"> • Introduction of subsidy for installation • Organization of trainings for skill development • Generation of public awareness • Introduction of carbon credits for mitigation
Nitrification inhibitor/urea super-granules	<ul style="list-style-type: none"> • Reduction in N-losses and increase in N-use efficiency 	<ul style="list-style-type: none"> • High production cost • Technical application process • Non-availability in the market 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Reduction in N-losses and increase in N-use efficiency 	<ul style="list-style-type: none"> • Lack of awareness • Inadequate soil testing facilities 	<ul style="list-style-type: none"> • Establishment of more soil testing laboratories • Provision of incentives to farmers • Generation of public awareness • Introduction of carbon credits for mitigation
Direct seeding of rice	<ul style="list-style-type: none"> • Saving in irrigation water (25-30%) • Saving in labor (10-15%) and energy • Reduction in methane emission (70-75%) • Increase in stress tolerance 	<ul style="list-style-type: none"> • Knowledge intensive • Weed problems • Yield loss (5-10%) • Increase in N₂O emission (45-50%) 	<ul style="list-style-type: none"> • Development of effective, low cost, environment-friendly herbicides • Organization of training for farmers • Provision of incentives for saving of water • Introduction of carbon credits for mitigation
Crop diversification (rice to maize)	<ul style="list-style-type: none"> • Saving in irrigation water (50-60%) • Saving in labor (20-25%) and energy • Reduction in methane emission (90-100%) 	<ul style="list-style-type: none"> • Govt. has no Minimum Support Price • Inadequate market • Lack of awareness • Limited post-harvest facilities • Increase in N₂O emission (45-50%) 	<ul style="list-style-type: none"> • Provision of minimum support price • Development of market infrastructure • Awareness generation • Development of post-harvest facilities
Wheat			
Zero tillage	<ul style="list-style-type: none"> • Saving in fuel (70-90 L diesel ha⁻¹) • Saving in water 	<ul style="list-style-type: none"> • Knowledge-intensive • Non-availability and maintenance of quality zero-till drill • Lack of awareness 	<ul style="list-style-type: none"> • Refinement of technology • Skill development for operation and maintenance of drill • Awareness generation
Integrated nutrient management/ organic farming	<ul style="list-style-type: none"> • Improvement in soil health • Increase in N-use efficiency • Reduction in GWP • Increase in income 	<ul style="list-style-type: none"> • Non-availability of manure • Poor quality of manure • High transportation cost 	<ul style="list-style-type: none"> • Promotion of agri-wastes for compost making • Promotion of biogas for energy and manure use • Introduction of carbon credits for biogas
Nitrification inhibitor/site-specific N management	<ul style="list-style-type: none"> • Reduction in N- losses and increase in N-use efficiency 	<ul style="list-style-type: none"> • High production cost • Application process highly technical • Non-availability in the market 	<ul style="list-style-type: none"> • Motivation to industries for manufacture these products • Provision of incentives to farmers • Generation of public awareness • Introduction of carbon credits for mitigation

^aFigures within the parenthesis are in comparison to conventional practices. Adapted from Pathak *et al.* (2014)

soil health and better water- and energy-use efficiencies. The benefits, challenges and required interventions for promoting low-carbon and cost-effective GHGs mitigation technologies for rice and wheat crops in the IGP are given in Table 6.

Greenhouse Gas Emission and Food Consumption

With increasing income and urbanization, meat consumption in the world has grown considerably. Earlier this trend was limited to the developed world. But with rapid increase in purchasing power in recent decades in developing countries, animal protein consumption has gone up substantially. This trend will not only cause a major setback to global food security but also add to mounting emission of GHGs. As far as emissions related to food consumption are concerned, carbon dioxide (CO_2) is the most important GHGs, followed by methane (CH_4) and nitrous oxide (N_2O) (Krammer *et al.*, 1999). Carbon emission occurs during various stages of life cycle of food products. Food chains around the world are responsible for a large share of total emission of GHGs. Steinfeldt *et al.* (2006) reported that 18% of global GHGs emission could be attributed to animal products alone. For the European Union, about 29% of GHGs emissions are related to food consumption (EIPRO, 2006). The IPCC, in its Fifth Assessment Report pointed out that lifestyle changes and behavior patterns can contribute to climate change mitigation across all sectors. In this context, it is argued that reducing animal protein consumption can bring down GHGs emission.

Pathak *et al.* (2010) evaluated GHGs emission from 24 Indian food items and observed that animal food products and rice cultivation mostly contributed to methane emission, food products from crops contributed to emission of nitrous oxide while farm operations, production of farm inputs, transport, processing and preparation of food contributed to the emission of carbon dioxide. They showed that animal products such as meat and milk have higher emission than crop products such as chapatti and vegetables. A non-vegetarian meal with mutton had the highest GHGs emission, 1.8 times a vegetarian meal, 1.5 times

a non-vegetarian meal with chicken and an ovo-vegetarian meal and 1.4 times a lacto-vegetarian meal (Fig. 7). The study indicated that change in dietary pattern offers possibility for GHGs mitigation. At the national level, 87% emission came from food production followed by preparation (10%), processing (2%) and transportation (1%). As Indians mostly consume fresh foods produced locally, the contribution of food production to GHGs emission was very high. However, because of increased urbanization and preference for processed food, the contribution of food preparation, processing and transportation may increase in years to come. More information, therefore, is needed about the life cycle impacts of food products on GHGs emission to work out a climate-smart, nutritive and healthy diet.

Climate Change Adaptation Options and their Mitigation Co-benefits

Mitigation and adaptation are often viewed as separate activities. However, in agriculture, the adaptation measures can also generate significant mitigation effects, making them a highly worthwhile investment. It is unequivocal that concerted efforts are required for mitigation and adaptation to reduce the vulnerability of Indian agriculture to the adverse impacts of climate change and making it more resilient. However, mitigation options take a longer time to affect the

Fig. 7: Global warming potential (GWP) of various vegetarian and non-vegetarian meals in India. Source: Pathak *et al.* (2010)

climate change, whereas adaptation options are required almost immediately. The adaptive capacity of the poor farmers is often limited because of their subsistence agriculture and low formal education. Therefore, simple, economically-viable and culturally-acceptable adaptation strategies have to be developed and implemented. Fortunately, the adaptation strategies have several mitigation co-benefits (Pathak *et al.*, 2010). The co-mitigation benefits of such strategies, however, may be highly location-specific.

Economic Implications of GHGs Mitigation

Pathak and Wassmann (2007) analyzed 20 technologies of rice production for their GWP and associated cost. These technologies differed in terms of water regime, residue management/utilization, soil management and additives, which represented different mitigation options for GHGs emissions. Compared to the farmers' current practice of rice production, 13 of these 20 technologies were found to have the potential to reduce the GWP by 8% to 51%. Modification of water management from continuous flooding to alternate flooding or application of urea alone instead of urea plus FYM would reduce the GWP by 15% and 29%, respectively, while feeding of rice straw to cattle and supplying of N through urea will reduce it by 41% compared to the current practice of burning rice straw and using FYM. However, they also reduced the net income of farmers. For the baseline technology of inorganic N (urea) fertilization, amendment with phosphogypsum and nitrification inhibitors were the most promising mitigation options resulting in shadow prices of <10 US\$ per ton of carbon dioxide equivalent (Pathak and Wassmann, 2007). Assuming a mix of urea and FYM for the baseline, mid-season drainage had a better cost-benefit ratio than alternate flooding, but was less profitable than husk utilization. Biogas technology was, in most cases, the preferable option. In another study, Pathak (2010) evaluated 16 technologies, generally recommended for increasing N-use efficiency, for their GHGs mitigation potential and economic returns. The technologies reduced GWP by 1 to 9%. With resource-conserving technologies, mid-season drainage and alternate flooding technologies, the GWP is reduced without extra cost. The GWP increases

with integrated nutrient management because of higher inputs of organic C through manure, which promotes methane emission in the submerged soil in rice.

The GHGs mitigation potential of the most promising technologies and their constraints are summarized in Table 5. Some technologies such as intermittent drying, site-specific N management, etc. can be easily adopted by the farmers without extra investment, whereas the other technologies need economic incentives and policy support.

Trade-offs between Crop Production and GHGs Emission

The demand for rice and wheat, contributing about 77% to the total food grains production in India, is expected to increase. This increased production can be achieved through higher use of farm inputs, particularly irrigation and fertilizer. However, the increased use of nitrogenous fertilizer and irrigation would enhance the emission of GHGs. There is a need to quantify the trade-offs between production and GWP of rice and wheat crops so as to develop suitable technologies to increase food production and reduce GWP by increasing the carbon efficiency ratio. Bhatia *et al.* (2010) have used the InfoCrop model to simulate yield and GWP of soils in rice and wheat crop for five regions of the country for two climatic scenarios, viz. current (1990-1999) and future (2050), two irrigation practices i.e., supply-driven irrigation (SDI) and demand-driven irrigation (DDI), and 10 levels of N and organic manure. The simulation study has evaluated the yield response and GWP of rice and wheat crops due to increased N and water use in current and future climatic scenarios. The current yields of rice and wheat are limited by water and N availability. The productivity can be increased substantially with increased use and better management of N and water. The rice and wheat productivity of India can be increased from their current productivity of 3.26 Mg ha⁻¹ and 2.73 Mg ha⁻¹ to 5.66 Mg ha⁻¹ and 6.15 Mg ha⁻¹, respectively, with increased irrigation and N-use. But, this would increase the GWP by 27% and 40%, respectively. In spite of the increased GWP, the carbon efficiency ratio (CER) would increase from the current values of 0.67 and 0.85 to 1.06 and 1.75 in rice and wheat,

respectively. Supplementation of organic manure with inorganic N is beneficial for soil health, but its use would enhance GHGs emission without much increase in yield. Moreover, under the 2050 climatic scenario, the rice and wheat yields in India may be affected and could lead to a positive feedback on global warming. Therefore, gain in one area (increased yield) would cause loss in the other (increased GWP). But in some cases, a 'win-win' situation can be achieved. Options that reduce GHGs emissions and increase yield and CER, are clearly the most desirable ones. There is a greater need today for more rational management practices including efficient use of inputs, particularly irrigation and N.

Carbon Trading Options in Indian Agriculture

The countries with commitments under the Kyoto Protocol to limit or reduce their GHGs emissions must meet their targets primarily through the national measures. As an additional means of meeting these targets, the Kyoto Protocol introduced three market-based mechanisms, thereby creating what is now known as the "carbon trading". The three Kyoto mechanisms include Joint Implementation (JI), Clean Development Mechanism (CDM) and International Emission Trading (IET). The JI allows the developed countries to sell emission reduction units earned from their GHGs mitigation units to other developed countries. The CDM is designed to enable industrialized countries to finance emission reduction projects, bringing about sustainable development in developing countries and receiving credit for this. The JI and CDM are the two project-based mechanisms which feed the carbon market. The JI enables the industrialized countries to carry out joint implementation projects with other developed countries, while the CDM involves investment in sustainable development projects that reduce emissions in the developing countries. The international emission trading (IET) involves trading in emissions reduction credits. A country which has less entitlement to emit than its actual emissions could purchase credits to overcome its shortfall. Many agricultural activities, carried out by the farming community to increase the sustainability of production

systems, may potentially qualify for the Kyoto Mechanisms and can earn carbon credits. This would increase the farmers' income or attract investments benefiting sustainable development and the population at large. However, currently the carbon market is very weak with price of carbon being less than 1 US\$ per ton of CO₂. It is assumed that the price may pick up after UNFCCC Agreement in 2015 on GHGs mitigation.

Conclusions

Agricultural practices are the major sources of GHGs emission. But, agriculture can also mitigate GHGs emissions through the reduction in N₂O and CH₄ emissions, as well as through carbon sequestration. Measuring and monitoring GHGs emissions is fundamental for managing emissions effectively. A robust understanding of how much carbon can be sequestered, or how much GHGs emissions can be reduced by different practices, is central to making informed decisions about the most appropriate mitigation strategies. However, measuring procedures are complex and uncertain. Therefore, there is need for user-friendly, cost-effective methods for GHGs quantification that work across scales, regions and systems. Though, there are significant opportunities for GHGs mitigation in agriculture, but numerous barriers need to be overcome. Gap between technical potential and realized GHGs mitigation is due to barriers to implementation, including climate and non-climate policies, as well as institutional, social, educational, and economic constraints. Capturing the potential of agricultural mitigation and its co-benefits will require new and additional resources, multiple funding streams, innovative and flexible forms of financing, and the unequivocal eligibility of agriculture, including soil carbon sequestration, in existing and any new financing mechanisms. Adapting the technologies to local conditions is necessary, and involving local farmers, extension agents and research institutions in technology design and dissemination is critical. It would also require increased Research and Development efforts on mitigation and adaptation, capacity building, development activities and changes in land-use management.

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