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Carbon Footprint as Prominent Indicator of Agricultural Sustainability in Diverse Agro-climatic Zones of Northern India: A Critical Review

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A B S T R A C T

The human population on the planet is estimated to reach 9 billion by 2050; this requires significant increase of food production to meet the demands. Intensified farming systems have been identified as a viable means to increase grain production. Crop production inputs include carbon investment in the form of energy, for the manufacture and use of farm machinery, synthetic fertilizers, crop protection chemicals such as herbicides, insecticides and fungicides, groundwater irrigation and the direct use of fuel in farm operations. Such production technology operations in the agriculture sector contribute to Greenhouse Gas (GHG) emissions. On-farm cultivation operations also result in the loss of soil organic matter (SOM), hence another source of carbon (C) emission. Changes in cropland use and management practices influence direct and indirect energy consumption and emission of GHGs. The latest GHG inventory for India shows that the contribution of agriculture to country's total emissions is18 per cent, of which about 21per cent is related to nitrous oxide (N2O) emissions from agricultural soils and18 per cent to rice production. Green revolution technologies in diverse agro-climatic zones of Northern India have led to the overexploitation of the natural resources, especially groundwater. Moreover, GHG driven changing climate is adding to the environmental woes. Under such complex situations, firstly, it becomes very important to register the effect of each management activity on the overall C footprint of crop production. Secondly, as the areal distribution of crops, groundwater extraction and fertilizer consumption has changed invariably within different agro climatic zones of Northern India over time, thus, it is important to do spatio-temporal analysis of the change in C use efficiency, net C returns and C cost per unit of production in different crops. With increase in production level of crops, mainly sugarcane and cereal crops the amount of their residues, subjected to field burning, also grew from 15.9% in 2008-09 to 24% in 2016-17. Sustainability indices, based on inputs and outputs, helped identify crops with lower carbon footprint or more carbon efficient crops. Such spectacular gains in food grain production were mainly because of increased yields resulting from improved crop varieties combined with greater use of fertilizers, irrigation, plant protection chemicals, and other technologies associated with the 'Green Revolution'. However, these gains in food grain production have come at a cost to the environment. During the last 40 years (1970 to 2010), emission of greenhouse gases (GHGs) from the agriculture sector has increased by 35 percent, from 4.2 to 5.7 Gt CO eq yr^{-1} (Gt or Giga tonne = 10^{15}g; CO_2 = carbon dioxide). The increase has been greater during the decade 2000-2010, when agricultural emissions increased by 1.1 percent annually. Thus, there is a need for sustainable intensification of production systems for maintaining high yields without compromising the environmental integrity.

Introduction

Agriculture is an important sector of the economy in India, contributing about 20% of national gross domestic product, and providing a livelihood for nearly two-thirds of the population (ICAR, 2015) (1) (Fig. 1). Equally important is the contribution of agriculture to national food security. India achieved self-sufficiency in food production after the Green Revolution (GR), but retaining this success has been challenging due to the increasing scarcity of resources, including labour, water, energy, and rising costs of production (Saharawat *et al.*, 2010) (2). Increased use of production inputs, such as mineral fertiliser, has made Indian agriculture more greenhouse gas (GHG)-intensive. Agricultural production is a major emitter of GHGs, currently accounting for 18% of total GHG emissions in India (INCCA, 2010) (3). Recent estimates report that global food production must increase by 70% to meet the projected food demand of the estimated 9 billion global population by 2050 (CTA-CCAFS, 2011) (4). With a population of ~1.3 billion, it is evident that the food system in India will be central to the global challenge of providing sufficient nutritious food while minimising GHG emissions. However, given the increasing population and shifting dietary patterns, GHG emissions from agricultural production in India are expected to change.

In India, the majority of agricultural GHG emissions occur at the primary production stage (Pathak *et al.*, 2010) (5), and are generated through the production and use of agricultural inputs, farm machinery, soil disturbance, residue management and irrigation. These practices are used to increase yields and improve harvests. Due to its direct contribution to global GHG emissions, agriculture can also serve as an important climate change mitigation strategy (Smith *et al.*, 2013) (6), both by reducing GHG emissions to the atmosphere, and by sequestering atmospheric carbon into plant biomass and soil, though the role of some soil carbon sequestration practices for climate mitigation has been questioned (Powlson *et al.*, 2014) (7).

Agriculture sector contributes to GHG emissions through energy use in the production and use of farm machinery, synthetic fertilizers, and crop protection chemicals such as herbicides, insecticides and fungicides and by direct use of fuel in farm operations. Cultivation or ploughing of soil resulting in the loss of soil organic matter (SOM), is another source of carbon (C) emission. Changes in cropland use and management influence direct and indirect energy consumption and emission of GHGs.The latest GHG inventory for India shows that the contribution of agriculture to country's total emissions is 18 percent, of which about 21 percent is related to nitrous oxide (N_2O) emissions from agricultural soils and 18 percent to rice production (Government of India 2015) (8). Northern India, pioneer of India's Green Revolution, has sustained some negative effects of green revolution technologies in terms of overexploitation of the natural resources, especially groundwater. Therefore, to develop sustainable agricultural management strategies, it is important to enumerate the effect of each management activity on the overall C footprint of the crop production. Since the areal distribution of crops, groundwater extraction and fertilizer consumption has differentially changed within diverse zones of Northern India over time, thus, it is important to study the change in carbon use efficiency in terms of time and space as well. Such information will allow policy makers and extension experts to make appropriate decisions for efficient utilization of resources and prioritize areas for sustainable agriculture management.

Uttar Pradesh is the largest producer of food grains in India and accounted for about 17.83 per cent share in the country's total food grain output in 2016-17. Food grain production in the state in 2016-17 stood at 49,144.6 thousand tonnes. Pulses production in the state stood at 1,985.00 thousand tonnes in 2017-18*.Major food grains produced in the state include rice, wheat, maize, millet, gram, pea & lentil. With overall vegetable production of 28,226.19 thousand tonnes in 2017-18, the state remains largest producer of vegetables in India [Uttar Pradesh State Report – 2018 (10)] (Table 1–4).

GHG emissions

In the global context of addressing climate change, the key GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbon (CFC). The GHG emissions from agriculture and allied sectors are mainly CO_2, CH_4, and N_2O (Paustian 2016) (12). Further, only non-CO_2 sources are considered anthropogenic GHG emissions from agriculture. The CO_2 released from agriculture is considered neutral due to photosynthesis and fixation (IPCC 2007) (13). The high level of GHG emissions from agriculture is due to application of organic and inorganic inputs to the soil for crop production, decomposition of biomass and dead plant residues, crop production, plant respiration, livestock rearing, enteric fermentation in ruminants, manure handling, and burning of crop residues (IPCC 2007) (13) and savanna (Russell-Smith *et al.,* 2017) (14) (Fig. 2a). GHG emissions are caused not only by agriculture and food production but also by transportation, postharvest activities, and cooking of food (Kehlbacher *et al.,* 2016) (15). The agricultural sector is responsible for approximately 10–12 percent of total anthropogenic GHG emissions (FAO 2016). The emission trends sector by sector (Fig. 2b). Notably, all the sectors except AFOLU observed an annual growth rate of approximately 3 - 9%. It is also notable that while the emissions from the agriculture sector (excluding LULUCF) were increasing from 2005(335 Million tonnes CO_2e) to 2011 (352 Million tonnes CO2e), there was a decline in the year 2012 (348Million tonnes CO_2e) and emissions from AFOLU have declined thereafter mainly due to a stagnation in the growth of population of cattle and increase in removals from the forestry sector. The compounded annual declines in emissions from AFOLU in the reporting period were 1.9% (GHG Platform-India, 2017) (16).

Agriculture is the largest source of emissions of N_2O (Reay *et al.,* 2012) (18). N_2O is 298 times more effective than CO_2 at trapping heat in the atmosphere. In India, agriculture accounts for approximately 58percent of total emissions of N_2O, which are mostly, caused by application of fertilizers (FAO 2009) (19).The Ministry of Environment and Forests (MoEF 2010) (20) estimated that N_2O is responsible for approximately13 percent of Indian agricultural GHG emissions. Further, crop residues and the burning of crop fields/residues also contribute significantly to GHG emissions. Crop residues left on managed fields contain significant amounts of nitrogen and produce N_2O through the process of decomposition, while the burning of crop residues or vegetation usually releases CO_2; CH_4; N_2O; and other ozone precursors; and aerosols (including black carbon) into the atmosphere (IPCC, 2014) (21). Globally, the burning of savanna and crop residues accounts for approximately 6 percent of total emissions from agriculture, but for India the amount is less than 1 percent (FAO, 2016 (22)).

Chakrabarty (2018) (24) reported that from 2005 to 2013, India emitted 20.54 billion tons of carbon dioxide equivalents (CO_2e), with emissions growing annually by 5.57 percent. Emissions per capita grew, too, by 4.07 percent annually. In the year 2013, India emitted 2.8 gigatons CO_2e – less than the U.S. (6.2 gigatons CO_2e) or China (11 gigatons CO_2e).

Carbon equivalent emissions from inputs

Carbon equivalent (CE) emissions from inputs were based on- i) rates of fertilizer (N, P and K) and pesticides application to each crop, ii) irrigation water requirement of each crop and water management practices involving groundwater (tube well) or surface water (canal) irrigations, and iii) crop-specific farming practices (seed-bed preparation, tillage etc.) and farm power used for various operations (seeding, harvesting and threshing). In addition to aforementioned emissions, other sources of GHGs were methane emission from rice paddies, direct N_2O emissions from nitrogenous fertilizers and emissions from burning of crop residues. Input based CE emissions were computed individually for each crop grown in a district and summed for all crops to calculate total emissions in a district and eventually for the state. Total emissions for a given crop in the whole state were computed by adding emissions from that crop in different districts. The results were expressed in CE using appropriate conversion factors (Fig. 3).

Fertilizers

Data on seasonal (kharif and rabi) consumption of fertilizer N, P_2O_5 and K_2O in different districts of Uttar Pradesh, Punjab and India (Fertilizer Association of India 1981, 1991, 2001, 2011 and 2017) were converted to per ha seasonal consumption based on the cropped area during each season. The fertilizer consumption during each season was apportioned to various crops considering their nutrient requirement. Firstly, total NPK consumption by kharif/rabi pulses and oilseeds was computed based on the area under pulses and oilseeds.

Punjab Agricultural University recommended fertilizer application rates for pulses (15 kg N and 30 kg P_2O_5 ha^{-1}) and oilseeds (60 kg N and 30 kg K_2O ha^{-1}) were used to calculate fertilizer consumption by these crops. Consumption of potassium in legumes/pulses and oilseeds was assumed to be zero. Thereafter, NPK consumption was calculated for kharif/rabi cereals and other crops by subtracting the total amount consumed by kharif/rabi pulses and oilseeds from the total NPK consumed by all crops during a season. Based on per ha seasonal NPK consumption, per ha CE emissions were computed and were then used to compute total emissions from a given crop.

Though fertilizers per se do not emit CO_2 yet there are hidden C-costs associated with manufacturing, packaging, transportation and application of fertilizers. Estimates of hidden C-cost of fertilizers range between 0.9 and 1.8 kg C kg^{-1} N, 0.1 to 0.3 kg C kg^{-1} P_2O_5 and 0.1 to 0.2 kg C kg^{-1} K_2O (Lal 2004) (25). In this study, the C cost used for N, P_2O_5 and K_2O were 1.3, 0.20, and 0.15 kg C kg^{-1}, respectively.

Irrigation

Irrigation water requirement of a crop depends on seasonal evapotranspiration (ET), percolation and rainfall

Irrigation water = (ET + Percolation) – Rainfall

Evapotranspiration plus percolation for different crops in Punjab range between 320 and 2050 mm with highest for rice and the lowest for winter-sown oilseed crops (Table 5). Growing season rainfall for each crop in a district was computed as average (crop season) of 5 years (the study year and 4 preceding years). For instance, 1976-1980, 1986-1990, 1996-2000, 2006-2010 and 2012-2016 for the study years 1980-81, 1990-91,2000-01, 2010-11 and 2016-17, respectively. Seasonal rainfall for each crop in a district was computed from monthly rainfall data for the district.

Plant protection chemicals

Like fertilizers, there are hidden C-costs associated with manufacturing, packaging, transportation and application of pesticides. Each pesticide has different C-costs associated with its manufacture, transport and application. Because of lack of data on consumption of individual plant protection chemicals in different crops, consumption rate (g ha^{-1}) was calculated from the total plant protection chemicals consumed and the gross area sown. The consumption rate was used to calculate total CE emissions by multiplying the amount of chemical consumed with an emission factor of 4.93 kg C kg^{-1} of product.

Farm operations

Total energy consumed per ha to perform different farm operations for a given crop was multiplied with the total area under the crop to compute total CE emissions from field preparation, seeding, harvesting and threshing. Tillage for seedbed preparation, which involves disturbance of soil, is an important source of CO_2.

The tillage methods prevalent in the state include disk harrow and tine-cultivation. Crop-specific tillage operations were identified, and CE emissions were estimated based on the C emission factors for different types of machinery (Table 6). Emission factors were developed for agricultural machinery based on the technical specifications of locally-used machines and diesel consumed per ha for one operation. Carbon emissions from diesel consumption for an operation were calculated from the ratio of C emission to energy content of diesel (0.0732 kg C per kWh). Carbon cost associated with the manufacture and transport of machinery was not considered. Carbon emissions for a mechanized field operation were calculated for each crop as the product of number of operations, emission factor for the machinery and the area under the crop (Benbi, 2019) (27).

The total input-based CE emissions were computed by adding emissions from all the inputs viz fertilizers, plant protection chemicals, irrigation tillage and other farm operations.

Methane emission from rice fields

Methane (CH_4) emission occurs from rice fields due to prevalence of reduced conditions with submergence. The intensity of emissions depends on irrigation water management. Rice area in different districts was divided into three irrigation regimes viz. continuously flooded (CF), intermittently flooded with single aeration (IFSA) and intermittently flooded with multiple aerations (IF-MA). In different districts, 0 to 10 percent area fell into continuously flooded, 30 percent into intermittently flooded with single aeration and 60-70 percent under intermittently flooded with multiple aerations. Such irrigation regime values were arrived at based on expert opinion, soil type and water availability in a district. Methane emissions from rice fields under different hydrology were calculated using region-specific emission factors of 55.7, 34.5 and 23.3 kg CH_4 ha^{-1} for CF, IFSA and IF-MA, respectively (Khosa *et al.,* 2011). Methane emissions were converted to CE emissions using a Global Warming Potential of 28 (IPCC, 2013) (28).

Nitrous oxide emission

Direct Nitrous oxide (N_2O) emissions from applied fertilizer N were computed using emission factor of 0.0065 kg N_2O-N kg^{-1} fertilizer N (Garg *et al.*, 2012) (29). N_2O-N emissions for each district were calculated as per equation and converted to CE emissions using a100-years Global Warming Potential (GWP) of 265.

N_2O-N emissions = Fertilizer N * E_f

Where Fertilizer N is rate of synthetic fertilizer N applied to soil (kg N yr^{-1}), E_f is emission factor for N_2O-Nemissions from synthetic fertilizer N (kg N_2O-N kg^{-1} fertilizer N) (Fig. 4).

Emissions from crop residue burning

A district-wise inventory of CO_2, CO, CH_4 and N_2O emissions from burning of crop residues was prepared for different years using the IPCC (2006) guidelines. Rice, wheat and sugarcane stubble is mainly burnt to facilitate the sowing of the next crop in the rotation. Crop productivity/production values collected from Statistical Abstracts of Punjab for different years were used to compute residue produced per ha or total residue production.

Emission from open field burning of crop residue (FBCR) was calculated using equation below.

FBCR = Σcrops(P x Rf x DMf x Bf x Of x EF)

Where, P is the crop production, R_f is the residue to crop ratio, DMf is the dry matter fraction, Bf is the fraction burnt, Of is the fraction actually oxidized, EF is the emission factors for different GHGs. The amount of rice residue burnt during the years 1980-81 to 2000-01, was calculated as a field fraction (0.80) of the crop residue produced. Whereas for 2010-11 and 2016-17 it was calculated from the satellite observation data (PRSC 2015 & Pers. Comm. 2017) of rice area burnt in different districts. For wheat and sugarcane, the fraction of crop residue burnt was 0.15 and 0.10, respectively. The emission factors, which represent the amount of a pollutant released per unit of dry fuel consumed, were obtained from Andreae and Merlet (2001) (30). These were (g kg^{-1} dry matter burned) 1515, 92, 2.7, and 0.07 for CO_2, CO, CH_4, and N_2O respectively. The CO_2 emission factor for burning of rice residue was taken as 1460 g kg^{-1} dry matter burned (Gadde *et al.*, 2009) (31). These were converted to CE emissions using 100-years GWP of 265, 28 and 1.8, for N_2O, CH_4 and CO, respectively.

Carbon equivalent outputs

Carbon equivalent output comprised of aboveground crop biomass encompassing grain or economic Yield and straw yield, stubble and leaf litter and belowground root biomass. Information on crop production or productivity collated from Statistical Abstracts of Punjab was used to calculate the straw or residue produced using crop specific harvest indices (Table 7). Root biomass values were derived from aboveground biomass using shoot/root ratios for different crops. All the components were converted to CE using plant C content of 40 percent.

Components of carbon footprint

Carbon-based input

Fertilizer consumption, groundwater irrigation, consumption of plant protection chemicals, tillage for seed-bed preparation and other farm operations comprised total C based input for a crop.

The GHG emissions from Indian agriculture during 1970-2010 have increased by about 75%. Increase use of fertilizers and other agri-inputs and the rise in population of livestock are the major drivers for this increase in GHGs emissions (Fig. 5a). From 1970 to 2010, the emission of CH_4 from Indian rice fields has remained almost similar though the rice production increased from 115 Mt to 128 Mt. It is because of almost constant area under rice (43-44 M ha) and use of similar water and crop management practices by the farmers over the years. However, the emission of N_2Ohas increased considerably during this period because of the application of more fertilizers and manure in soil (Fig. 5b) (Pathak *et al.,* 2014 (32)).

Fertiliser based carbon equivalent emissions

Use of nitrogenous fertilizer accounts for approximately 17.4 percent of agricultural GHG emissions from different districts of Uttar Pradesh i.e., Basti, Faizabad, Farrukabad, Jyotiba Phule Nagar, Muzaffarnagar, and Varanasi including other parts of India (Patra and Babu, 2017 (34)). Sapkota *et al.,* (2019) (35) analysed the spatial distribution of the mitigation potential of efficient fertilizer use and rice-water management in order to identify mitigation hotspots at the scale at which policies are implemented in India. Our estimate shows that per-year GHG mitigation potential through reduced fertilizer consumption through precision nutrient management was highest in Uttar Pradesh (ca. 3.15 MtCO_2e) followed by Andhra Pradesh (2.04 Mt CO_2e), Maharasthra (1.72 MtCO_2e) and Punjab (1.5 MtCO_2e) Fig. 6a.

The production of Major Chemicals in 2018-19 is 11,578 thousand MT, compared to 11,068 thousand MT during the same period in 2017-18 implying a growth of 4.61%. The CAGR in production of total basic major Chemicals during the period 2014-15 to 2018-19 is 4.63%. The trend in the production of selected major chemicals is depicted in Fig. 6b (GOI, Annual report 2018-19).

UP is the largest producer of food grains among all states in India and accounted for about 17.83 per cent share in the country's total food grain output in 2016-17. Food grain production in the state in 2017-18 stood at 51,252.7 thousand tonnes and 18,416.3 thousand tonnes in 2018-19. Pulses production in the state stood at 2,208.0 thousand tonnes in 2017-18 (4^{th} Advance estimates) and 660.7 thousand tonnes under kharif season in 2018-19 (1^{st} Advance Estimates) (IBEF, 2019 (37)).

Tirado *et al.,* (2010) (38) reported that Fertiliser Association of India from 1960-61 to 2006-07 of production and consumption of the various forms of synthetic N fertilizers in India (Fig. 7a, FAI, 2007 (39)) and used best-available specific emission factors to estimate GHG emissions according to Intergovernmental Panel on Climate Change (IPCC) (Fig. 7b). The total emissions from synthetic N fertilizer reached 100 Mt of carbon dioxide equivalent (CO_2-e) in 2006-07 and half of these emissions resulted from the 11Mt of synthetic N produced in the country during that year (48Mt of CO_2-e) and the other half resulted from the 14Mt N applied in Indian farm soils the same year (51Mt of CO_2-e,ranging between 28 and 163 (up to 522)Mt ofCO_2-e, depending on the emission factor used (Fig. 7c).

Irrigation based carbon equivalent emissions

Mishra *et al.,* (2018) (40) reported that several factors affecting GHGs emission but water management in rice-wheat ecosystem plays crucial role in UP. It has been found that water regime in irrigated rice fields with large water percolation and scanting water supply; often lead to multiple aeration, which has a direct impact on CH_4 emission. In wheat crop does not have water flooding due to N_2O toxic environment. Irrigation-based CE emissions escalated 12.6-fold in rice; from 167 Gg in 1980-81 to 2112 Gg in 2016-17 (Fig. 8a). During the 37-years period, the emissions from irrigation increased at an average rate of 54 Gg CE yr^{-1} but the rate was higher (82 Gg CE yr^{-1}) during the decade 2000 to 2010. Increase in irrigation-based emissions was because of increased area under rice as well as higher per unit area emissions. Quantitatively, the area sown to rice increased 2.6-fold (from 1182 thousand ha in 1980-81 to 3046 thousand ha in 2016-17) and per unit area emissions increased 4.7-fold (from 143 to 667 kg CE ha^{-1}) during the 37-year period (Fig. 8b).

Mishra *et al.,* (2018) (40) reported that the CO_2 emissions due to bicarbonate (~0.72 $MTyr^{-1}$) are dominated by those due to groundwater pumping (31.29–131.02 $MTyr^{-1}$) in India. However, the total (pumping and bicarbonate) estimated annual CO_2 emission from groundwater is less than 2–7% of the total (annual) CO_2 emission from India. A few regions (western India and Indo-Gangetic Plain) have more than 90% of their area irrigated with ground water resources. The net irrigated area from different sources, mainly tube wells, has increased (except for tanks) between 1950 and 2010 (Fig. 8a).

Emissions from residue burning

Agricultural crop residue burning contribute towards the emission of greenhouse gases (CO_2, N_2O, CH_4), air pollutants (CO, NH_3, NO_2, SO_2, NMHC, volatile organic compounds), particulates matter and smoke thereby posing threat to human health. Crop residues and burning of crop residues account for 4.7 percent of total agricultural emissions and are identified as EV-C. Uttar Pradesh (72 districts) have a high EV-C, between greater than or equal to 0.0306 and less than0.0421 (Patra and Babu, 2017 (34)). Jain *et al.,* (2014) (41) observed that the generation of cereal crop residues was highest in the states of Uttar Pradesh (72 Mt) followed by Punjab (45.6 Mt), West Bengal (37.3 Mt), Andhra Pradesh (33 Mt) and Haryana (24.7Mt). Uttar Pradesh contributed maximum to the generation of residue of sugarcane (44.2 Mt) while residues from fibre crop was dominant in Gujarat (28.6 Mt) followed by West Bengal (24.4 Mt) and Maharashtra (19.5 Mt). Rajasthan and Gujarat generated about 9.26 and 5.1 Mt residues from oilseed crops (Fig.9a). Uttar Pradesh contributed maximum to the burning of sugarcane trash followed by Karnataka (Fig. 9b).

Emissions from rice fields

Ali *et al.,* (2019) (43) revealed that rice paddy fields act as a source of greenhouse gases such as methane (CH_4) and nitrous oxides (N_2O) depending on soil organic matter status, land use and cropping intensity, irrigation water and drainage management practices, soil microbial populations and their activities, soil properties, and climatic variables. The management practices such as tillage operations, levelling, plant residue incorporation, irrigation frequency and standing water levels, drainage system, and organic and inorganic soil amendments followed in rice farming influence the amount of CH_4 and N_2O emitted to the atmosphere. Generally, CH_4 gas is produced under flooded or anoxic soil conditions (Fig.10a), while N_2O gas is produced through nitrification and denitrification processes depending on soil aerobic (oxygenated) and anaerobic conditions (Fig. 10b).

Patra and Babu, (2017) (34) also found that the cultivation of rice, which emits CH_4, accounts for15.1 percent of agricultural GHG emissions from different districts of Uttar Pradesh ie., Basti, Faizabad, Farrukabad, Jyotiba Phulenagar, Muzaffarnagar, and Varanasi including other parts of India. Gupta *et al.,* (2009) (44) reported that using NATCOM EFs, the trend of national CH_4 emission inventory from paddy fields during 1979 to 2006 has indicated the emission estimates and the variability in the range of 3.62 ± 1 to4.09 ± 1.19 Tg y^{-1} (Fig. 11a), with an insignificant growth rate of 0.004 Tg y^{-1} (Fig.11a) and uncertainty ranges in theCH_4 emission estimates under different paddy water regimes for the period 1979–2006 are shown in Fig.11b. The states in India have been ranked according to their cumulative emissions in descending order (Fig. 11b).

Pathak *et al.,* (2005) (45) reported that continuous flooding of rice fields (42.25 million ha) resulted in annual net emissions of 1.07–1.10,0.038–0.048 and 21.16–60.96 Tg of CH_4-C, N_2O-N and CO_2-C, with accumulated global warming potential (GWP) of 130.93–272.83 Tg CO_2equivalent. Intermittent flooding of rice fields reduced annual net emissions to 0.12–0.13 Tg CH_4 –Cand 16.66–48.80 Tg $CO_2$15 –C. While N_2O emission increased to 0.056–0.060 Tg N_2O-N.The GWP, however, reduced to 91.73–211.80 Tg CO_2equivalents.

Since 1990, several estimates of CH_4 emission from Indian rice fields have been made and the emission estimate has been rationalized from the earlier estimate of 37.5 Mt to 3.3 Mt (Fig. 12a). However, the estimates of N_2O emission from agricultural soils have remained variable over the years (Pathak *et al.,* 2014 (32), Fig. 12b).

Emission from different crops

Kumar *et al.,* (2018) reported that western Uttar Pradesh, the production of maize has decreased drastically and NO_2 have shown an increasing trend. The linear correlation between NO_2 and maize production also seemed to be very low.Over the selected sites from north-west India, the production of rice and maize has reduced by ~40% and the increase in greenhouse gases (CO_2, NO_2 and CH_4) was almost 5% from 1998 to 2011 (Fig 13 a to c).

Sugarcane

Among the states within India, Uttar Pradesh produces the largest quantity of sugarcane at nearly 129 million tonnes (Mt) per year (DoES, 2016) (47). In Uttar Pradesh, sugarcane is cultivated in 2,162,400 hectares (ha) of land, with the total sugarcane production equalling 129 million tonne (Mt) on annual basis (Table 8 and Table 9). The gross annual bagasse production is 38.65 Mt. Considering that 70% of the total produced bagasse is available as surplus, net annual bagasse availability for co-generation in the state is 27.05 Mt. Bagasse production at the agro-climatic zone level varies from a minimum of 34.42kilo tonne (kt, 0.13% of state total) in the Vindhyan zone to a maximum of 9,178.20 kt (34%of state total) in the western plain zone, as shown in Table 8. The major sugarcane belt of Uttar Pradesh is situated in the western plain and mid-western plain zones, which collectively contribute nearly 50% of total sugarcane production in Uttar Pradesh (Hiloidhari *et al.,* 2018) (48).

Uttar Pradesh is divided into nine agro-climatic zones and seventy-two districts. The agro-climatic zones show a range of climatic conditions for the state, including dry conditions suited for Jatropha crops and rain-intensive conditions that are more conducive to sugarcane. Nearly 78% of the total population live in rural areas, with agriculture being the major source of livelihood (Hiloidhari *et al.,* 2018) (48).

Singh and Sharma (2016) (50) observed that carbon dioxide (CO_2) exchange between sugarcane plant and the atmosphere is one of the key processes that affect atmospheric CO_2 concentration and carbohydrate synthesis. His study was taken up during 2014-15, to assess the role of sugarcane cultivation in mitigating green house gases (GHGs), which is the main constituent of global warming, and to know the role of this crop in sequestering atmospheric CO_2 concentration in India, as well as in Uttar Pradesh, which is the major contributor state of sugarcane in India. Analysis revealed that CO_2 released by sugarcane crop in the field and during processing of the cane accounts for 20.65 million tons, however, the crop absorbed 228.89 million tons of CO_2 from the Indian atmosphere during its life cycle. This indicates that 208.24 million tons of extra equivalent CO_2 was absorbed from the atmosphere by the sugarcane crop planted in India (5.32 M ha) apart from CO_2 released during its own respiration. This extra build up of CO_2 in the air comes from different sources like other crops, soils, animals, burning, industries, etc. The extended study showed that out of 208.24 million tons of absorbed CO_2 from Indian environment, sugarcane grown in Uttar Pradesh (2.1 M ha) absorbed 84.58 million tons contributing 40.61 percent of the total CO_2 absorbed by the entire sugarcane crop grown in India which exhibited highest environmental cleaning over other states just like sugarcane production. The study stated that sugarcane crop plays an important role in purifying the air by acting as one of the potential CO_2 scavengers. As carbon dioxide is most abundant constituent of the GHGs thus their decreased level may ultimately mitigate the level of GHGs from the environment in sugarcane growing areas of Uttar Pradesh as well as in India and thus may contribute in combating global warming.

Sugarcane crop is one among those crops that is able to cope up with the increasing level of CO_2 due to four natural endowments it possesses (Fig. 14a). Very low carbon dioxide compensation point and unique property of sequestering carbon in form of phytolith or planstone is some of the important natural endowment with respect to the rising CO_2 concentration in atmosphere. Elevation in CO_2 concentration affects yield of several crops; however, sugarcane is the crop which has been bestowed with two important abilities, viz., low compensation point (ranging between 0-10 ppm) and carbon sequestering ability (181 kg C is sequestered/ha year) that helps in managing the effect of higher concentration of CO_2 on the crop. Moreover, sugarcane cultivation in the increasing scenario of CO_2 will also be beneficial for the higher productivity and yield of other crops as it will be able to lower the concentration ofCO_2 to some extent (Misra *et al.*, 2019) (51).

Sugarcane has been bestowed with four natural endowments, viz, higher optimal temperature for growth processes, compensatory ability, low carbon dioxide compensation point and carbon sequestration ability in respect to increasing CO_2 concentration that helps in showing better performance under highCO_2 concentrations in comparison to other crops (Misra *et al.*, 2019) (51).

For sugarcane, Tamil Nadu reports the highest level of land productivity (105.3 t/ha) as well as PWP (14.01 kg/m^3). As in the case of rice, one observes somewhat perverse relation between land productivity and IWP in sugarcane also. The tropical belts of Uttarkhand, Uttar Pradesh and Bihar report higher levels of IWP but lower levels of land productivity (Fig.15b). At the same time, the sub-tropical belts of Tamil Nadu, Karnataka, Maharashtra and Andhra Pradesh have high land productivity but lower levels of IWP values. This indicates the stated mismatch between sugarcane cropping pattern and water resource availability, which needs to be corrected by suitably adjusting the price of power and irrigation water, and by promoting more efficient technologies (such as drip) for irrigating sugarcane crop in these regions. The sugar licensing policy of preferring cooperatives sugar factories over private ones was one of the major reasons for the shift in the sugarcane growing belt from Bihar and eastern Uttar Pradesh towards the water stressed sub-tropical belts of Maharashtra, Karnataka and Tamil Nadu. But this is not in line with water resource endowment of the region (Sharma *et al.*, 2018) (53) (Table 9).

Contribution of different crops

Enumeration of the contribution of various crops towards total input based emissions showed that in 2016- 17, rice and wheat contributed 2971 and 1530 Gg CE, which respectively represented 63 and 33 per cent of the total emissions in croplands (Fig.15). The two crops together accounted for 81 and 96 per cent of emissions in 1980-81 and 2016-17, respectively. The input based emissions in rice and wheat have been growing since1980-81.The emissions in rice went up by4.4-fold between1980-81 and 2000-01and further increased ~2-fold during 2000-01 and 2016-17. The increase in emissions in wheat was relatively small. Despite starting with higher total emissions (590 Gg CE) compared to rice (329 Gg) in 1980, emissions in wheat were about half that of rice in 2016-17. The contribution of rice towards total emissions increased from 29 to 63 percent and that of wheat decreased from 52 to 33 percent over years. Maize contributed only 43 Gg CE in 2016-17 and its contribution towards total emissions declined from 5.5 to 0.9 percent. Cotton and sugarcane respectively contributed 76 and 60 Gg CE yr^{-1} in 2016-17. The contribution of cotton declined from 7 to 1.6 percent while that of sugarcane remained between 1 and 2 percent throughout. The contribution of oilseeds and pulses together declined from 4.3 to 0.24 percent.

Segregating the contribution of various input sources towards total emissions in different crops showed that groundwater irrigation and fertilizer use together accounted for 89 to 96 percent of the emissions in rice during 1980-81 to 2016-17 and rest of the emissions originated mainly from tillage and other farm operations (3.4-10.7%). Pumping of groundwater for irrigation was the most critical input source and its contribution towards total emissions in rice increased from about 51 percent in 1980-81 to 71 percent in 2016-17. Contribution of tillage and other farm operation based emissions declined from 10.7 percent in 1980-81 to 3.4 percent in 2016-17. Emissions from consumption of plant protection chemicals generally accounted for less than 1 percent of the total CE emissions. In sugarcane, irrigation accounted for 35 and 59 percent and fertilizer use accounted for 41 and 33 percent of the emissions in 1980-81 and 2016-17, respectively. In kharif and rabi pulses, the contribution of fertilizers decreased (~38 to 18%) over the years and that of irrigation increased (~18 to 59%). Similarly, in kharif oilseeds the contribution of irrigation increased (~7 to 57%) and that of fertilizers decreased (~76 to 35%).

Crop diversification

Diversification of cropping system can help in reducing the CFP of crops by 32 % to 315 %. Gan *et al.*, (2011) (54) reported that in durum wheat, diversification of cropping system with oilseeds and legumes lowered the carbon footprint. Durum wheat grown in a pulse–pulse–durum system had carbon footprint 0.27 kg CO_2eq kg^{-1} which is 34%lower than that of cereal–cereal–durum systems. Yan *et al.*, (2015) (55) showed that early rice had lower carbon footprint values (0.62 t CO_2-eqt^{-}

^{1}) than late rice (1.1 t CO_2- eqt^{-1}) system. Indica and japonica rice varieties were compared in Chinese rice fields and japonica varieties were found to have lower CFP (0.71t eqt^{-1}) than Indica rice varieties having 1.1t CO_2 eqt^{-1} (Pathak *et al.,* 2002) (56). Pathak *et al.,* (2010) (33) calculated the GWP of different crop production from the data generated from different field experiments conducted at Indian Agricultural Research Institute, New Delhi (Pathak *et al.,* 2003 & 2009) (57,58) and reported that CFP values of wheat, pulse, oilseed, cauliflower, brinjal, and potato are 0.12, 0.31, 0.42, 0.03, 0.03, and 0.02 kg CO_2 $eq.kg^{-1}$ produce respectively. Leaf colour chart (LCC) based N application lowered CFP from 0.13 kg CO_2eq kg^{-1} grain to 0.10 and 0.10 kg CO_2eq kg^{-1} grain in rice wheat cropping system in IARI, New Delhi.

Pathak *et al.,* (2003) (57) also found that the effect of both water as well as nitrogen management on GWP of rice-wheat cropping system at IARI, New Delhi. Lower CFP values were observed under intermittent wetting and drying conditions as compared to saturated rice cultivation. This is attributed to the fact that less CH_4 emission in IWD condition than saturated one lowered the CFP. Substitution of inorganic N with organic sources increased CH_4 emission resulting in higher CFP whereas application of nitrification inhibitor (NI) caused lower N_2O emission thereby reducing the CFP values.

Managing tillage practices to reduce carbon footprint

Tillage disturbance is the dominant factor reducing soil carbon stabilization within micro-aggregates in the clayey soil, whereas conservation practices increase soil organic carbon contents. In some cases, reduced tillage in combination with additional carbon input from cover crops significantly improved the soil organic carbon content (Pinheiro *et al.,* 2015) (59). Plant residue inputs from green manure and the incorporation into the soil by reduced tillage promoted the formation of new aggregates and activated the subsequent physical-chemical protection of organic carbon. Hu *et al.,* (2015) (60) reported that wheat-maize intercropping under reduced tillage with stubble retention increased crop yield by 8 % and reduced greenhouse gas emissions by 7 % compared with conventional tillage. However, soil organic carbon can be gained or lost depending on soil type and land use practices. Soil disturbance affects the quantity and quality of plant residues entering the soil, their seasonal and spatial distribution, and the ratio between above- and belowground inputs (Pinheiro *et al.,* 2015) (59). Data also showed that a linear relationship between carbon input and CO_2 output; an increase of 1 Tg CO_2 eq yr^{-1} of carbon input resulted in a corresponding increase in carbon output of 21 Tg CO_2 eq yr^{-1} (Maheswarappa *et al.,* 2011) (61). Tillage did not influence crop biomass and CO_2 flux nor on total soil carbon content (Sainju *et al.,* 2010) (62).

Cropping sequences in a rotation system have significant impacts on the carbon footprint (Gan *et al.,* 2011) (54). In a study of durum wheat had an average carbon footprint of 0.34 kg CO_2 eq kg^{-1} of grain when the crop was grown after mustard, which was 19 % lower than when grown after a cereal. Similarly, durum wheat grown after a chickpea, lentil, or dry pea lowered the carbon footprint of durum wheat by 28 % compared with when grown after a cereal. For a 3-year crop rotation, a pulse crop alternatively grown with an oilseed the previous 2 years lowered the carbon footprint of the 3rd-year durum wheat crop by an average 25 %. When pulse crops were grown continuously for the first 2 years of the 3-year rotation, the carbon footprint of the 3rd-year durum crop was lowered by 34 %. These results clearly demonstrate that the integration of various crop types into a well-designed rotation substantially lowers the carbon footprint of cereal crops.

Table.1 Production of Major Agricultural Crops in India (million tonnes) (Source: Directorate of Economics and Statistics, DAC&FW (11))

Crops	1950-51	1960-61	1970-71	1980-81	1990-91	2000-01	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17*
Food grains	**50.82**	**82.02**	**108.42**	**129.59**	**176.39**	**196.81**	**244.49**	**259.29**	**257.13**	**265.04**	**252.02**	**251.57**	**275.68**
Rice	20.58	34.58	42.22	53.63	74.29	84.98	95.98	105.30	105.23	106.65	105.48	104.41	110.15
Wheat	6.46	11.00	23.83	36.31	55.14	69.68	86.87	94.88	93.51	95.85	86.53	92.29	98.38
Maize	1.73	4.08	7.49	6.96	8.96	12.04	21.73	21.76	22.26	24.26	24.17	22.57	26.26
Nutri Cereals	15.38	23.74	30.55	29.02	32.70	31.08	43.40	42.01	40.04	43.29	42.86	38.52	44.19
Pulses	**8.41**	**12.79**	**11.82**	**10.63**	**14.26**	**11.08**	**18.24**	**17.09**	**18.34**	**19.25**	**17.15**	**16.35**	**22.95**
Gram	3.65	6.25	5.20	4.33	5.36	3.86	8.22	7.70	8.83	9.53	7.33	7.06	9.33
Tur or Arhar	1.72	2.07	1.88	1.96	2.41	2.25	2.86	2.65	3.02	3.17	2.81	2.56	4.78
Lentil (Massur)	--	--	0.37	0.47	0.85	0.92	0.94	1.06	1.13	1.02	1.04	0.98	--
Oilseeds	**5.16**	**6.98**	**9.63**	**9.37**	**18.61**	**18.44**	**32.48**	**29.50**	**30.94**	**32.75**	**27.51**	**25.25**	**32.10**
Groundnut	3.48	4.81	6.11	5.01	7.51	6.41	8.26	6.96	4.70	9.71	7.40	6.73	7.565
Rapeseed & Mustard	0.76	1.35	1.98	2.30	5.23	4.19	8.18	6.60	8.03	7.88	6.28	6.80	7.98
Soy Bean	--	--	0.01	0.44	2.60	5.28	12.74	12.21	14.67	11.86	10.37	8.57	13.79
Sunflower	--	--	0.08	0.07	0.87	0.65	0.65	0.52	0.54	0.50	0.43	0.30	0.24
Cotton #	3.04	5.60	4.76	7.01	9.84	9.52	33.00	35.20	34.22	35.90	34.80	30.01	33.09
Jute & Mesta @	3.31	5.26	6.19	8.16	9.23	10.56	10.62	11.40	10.93	11.68	11.13	10.52	10.60
Sugarcane	57.05	110.00	126.37	154.25	241.05	295.96	342.96	361.04	341.20	352.14	362.33	348.45	306.72
Tobacco	0.26	0.31	0.48	0.48	0.56	0.34	0.34	0.75	0.66	0.74	0.84	0.80	--

(Source: Directorate of Economics and Statistics, DAC&FW)

Table.2 All India crop-wise yield (quintal/ha)

Crops	1950-51	1990-91	2000-01	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17*
Rice	6.68	17.40	19.01	22.39	23.93	24.61	24.16	23.91	24.00	25.50
Jowar	3.53	8.14	7.64	9.49	9.57	8.50	9.57	8.85	6.97	8.89
Bajra	2.88	6.58	6.88	10.79	11.71	11.98	11.84	12.54	11.32	13.11
Maize	5.47	15.18	18.22	25.40	24.78	25.66	26.76	26.30	25.63	26.64
Wheat	6.63	22.81	27.08	29.88	31.77	31.17	31.45	27.50	30.34	32.16
Nutri Cereals	4.08	9.00	10.27	15.31	15.90	16.17	17.17	17.03	15.79	17.84
Gram	4.82	7.12	7.44	8.95	9.28	10.36	9.60	8.88	8.40	9.73
Tur or Arhar	7.88	6.73	6.18	6.55	6.62	7.76	8.13	7.30	6.46	8.85
Total Pulses	4.41	5.78	5.44	6.91	6.99	7.89	7.64	7.28	6.56	7.79
Total Foodgrains	**5.22**	**13.80**	**16.26**	**19.30**	**20.78**	**21.29**	**21.20**	**20.28**	**20.42**	**21.53**
Sugarcane	334.22	653.95	685.78	700.91	703.17	682.54	705.22	715.12	707.22	698.86
Groundnut	7.75	9.04	9.77	14.11	13.05	9.95	17.64	15.52	14.65	14.24
Mustard	3.68	9.04	9.36	11.85	11.45	12.62	11.85	10.83	11.83	13.24
Soy Bean	4.26	10.15	8.23	13.27	12.07	13.53	10.12	9.51	7.38	12.19
Sunflower	6.53	5.35	6.05	7.01	6.92	6.55	7.50	7.36	6.08	6.99
Total oilseeds	**4.81**	**7.71**	**8.10**	**11.93**	**11.35**	**11.68**	**11.68**	**10.75**	**9.68**	**12.25**
Cotton	0.88	2.25	1.90	4.99	4.91	4.86	5.10	4.62	4.15	5.19
Tobacco	7.31	13.53	13.18	16.37	16.13	15.42	16.12	18.42	17.81	NA

(Source: Directorate of Economics and Statistics, DAC&FW)

Table.3 World, Asian, and Indian trends in greenhouse gas emissions from various agricultural activities, as a percentage of the total (Source: FAO. 2016 (22))

Period	Enteric emissions			Manure left on pastures			Manure management			Manure applied		
	World	Asia	India	World	Asia	India	World	Asia	India	World	Asia	India
1980	45.4	35	50.8	15.6	10.9	10.8	8.3	6.6	5.0	4.4	3	2.5
1981-1990	41.1	33.9	50	14.2	10.5	10.8	7.5	6.4	4.9	4	3	2.5
1991-2000	40.3	33.7	47.8	14.9	10.9	10.5	7.1	6.6	4.8	3.8	3.3	2.4
2001-2005	40.1	34	47.4	15.3	11.4	10.6	6.8	6.9	4.8	3.6	3.5	2.5
2006-2010	40.3	34.3	46.2	16	11.6	10.5	6.8	7	4.6	3.7	3.6	2.5
2011	39.3	34.1	45	15.7	11.5	10.3	6.6	7	4.5	3.6	3.6	2.4
2012	39.4	34.1	45.4	15.9	11.7	10.4	6.6	7	4.5	3.6	3.7	2.4
2013	39.9	34.1	45.3	16.2	11.7	10.3	6.7	7	4.5	3.7	3.7	2.4
2014	39.7	34.3	45.2	16.1	11.8	10.3	6.7	7	4.5	3.7	3.7	2.4

Period	Rice cultivation			Synthetic fertilizer			Burning crop residue and savanna			Crop residue		
	World	Asia	India	World	Asia	India	World	Asia	India	World	Asia	India
1980	11.9	29.7	21.1	10.2	10.1	5.6	0.6	8	0.7	3.4	4	3.4
1981-1990	10.4	26	19.4	10.4	12	8	6.2	2.7	0.7	3.2	4	3.5
1991-2000	10.4	22.7	18	11.1	15	12	6.0	1.1	0.6	3.4	4	3.6
2001-2005	10.1	21.4	17	11.3	15.2	13.2	6.0	1	0.6	3.5	3.9	3.7
2006-2010	10.1	20.5	15.8	11.8	15.7	15.9	5.1	0.9	0.6	3.7	4	3.7
2011	10	20.4	15.4	12.2	16.1	17.7	6.1	0.8	0.6	3.8	4.2	3.9
2012	10	20.2	15.1	12.4	16	17.4	5.9	0.9	0.7	3.7	4.2	4
2013	10.1	20.4	15.5	12.5	15.9	17.2	4.5	0.7	0.6	4	4.2	4
2014	10	20	15.3	12.6	15.8	17.4	4.7	0.9	0.6	4	4.2	3.9

Table.4 Sector wise annual carbon emission and sequestration (Source: Ramachandra and Shwetmala, 2012)

Carbon sources	**CO_2 (Gg)**	**CO (Gg)**	**CH_4 (Gg)**	**Total CO_2 equivalent emission (Gg)**
Agriculture	85851.0	3459.2	15246.9	409495.88
Domestic	88378.5	14798.7	611.5	116018.91
Electricity	343344.5	1237.3	0.0	344581.81
Steel and cement industries	202190.0	0.0	0.0	202190.02
Transport	246232.4	3030.9	127.3	251936.79
Waste	0.0	0.0	995.72	21104.79
Total (Gg)	965996.5	22526.0	16990.8	1345328.2
Carbon sinks				**Carbon stored (Gg)**
Forest biomass				72916.77
Forest soil				20312.64
Agricultural soil				5600.49
Total (Gg)				98829.89
Net emission				1246498.3

Table.5 Seasonal evapotranspiration (ET) and percolation (mm) in principal field crops grown in Indian Punjab (Adapted from Arora *et al.*, 2008)

Crop	ET	Percolation	Total
Rice	650	1400	2050
Maize	480	270	750
Cotton	600	150	750
Wheat	380	80	460
Pulses	320	40	360
Oilseeds	280	40	320
Sugarcane	1350	200	1550

Table.6 Carbon equivalent cost of various field operations in different crops (Source: Benbi, 2019)

Crop	Field preparation		Seeding, harvesting and threshing	
	Operation	**CE kg ha^{-1}**	**Machinery**	**CE kg ha^{-1}**
Rice	Disking (1), cultivator (2), pulverization (1)	25.2	Combine harvester	7.1
Wheat	Disking (1), cultivator (2), planking (1)	16.9	Seed- cum fertilizer drill Thresher# or Straw combine	6.1 24.7 18.6
Maize	Disking (1), cultivator (2), planking (1)	23.0	Dehusking & shelling	18.2
Cotton	Disking(1), cultivator (2), planking (1)	23.0	Manual	0
Pulses	Cultivator (2), planking (1)	15.9	Manual	0
Groundnut	Cultivator (2), planking (1)	15.9	Mechanical	14.9
Oilseeds	Disking(1), cultivator (3), planking (3)	36.5	Manual	0
Sugarcane	Cultivation (5)	30.1	Planter	24.1

#in 1980-81 and 1990-91; * 2000-01 onwards

Table 7: Straw: economic yield and shoot: root ratio for different crops (Source: Benbi, 2019 (27))

Crop	Straw : economic yield ratio	Harvest index (HI)	Shoot/Root	Reference
Rice	1.88*	0.348	6.25	Author's unpublished
Wheat	1.5	0.40	7.14	Anonymous (1991)
Maize	2	0.333	6.67	Author's unpublished
Cotton	1.6	0.384	6.25	Pace *et al.*, 1999
Oilseeds	2	0.33	9.09	Arora *et al.*, (1993)
Sugarcane	0.35	0.74	5.88	Smith *et al.*, (2005)

*Includes conversion of paddy to rice (2/3 rd of paddy equals rice grain yield)

Table 8: Agro-climatic, zone-based bagasse potential for existing and future co-generation capacity in Uttar Pradesh, India.

Agro-climatic Zone	District	Sugar mills	Co-generation plants*	Surplus bagasse production, kt^b	Existing capacity, MW^c	Potential, MW^b	Scope of additional generation, MW^b	Remarks
Bhabar and Terai(ACZ1)	3	17	9	3.864	194	276	82.00 (718,320 MWh)	Largest existing and future potential of 141 and 202 MW in Bijnor district.
Bundelkhand (ACZ2)	7	3	0	825.09	0	5.89	5.89 (51,596.4 MWh)	Largest future potential of 1.86MW in Mahoba district.
Central (ACZ3)	16	11	6	2,131.35	90	152	62.00 (51,596.4 MWh)	Largest existing and future potential of 60 and 101 MW in Sitapur district.
Eastern plain (ACZ4)	11	9	4	1,186.92	67.95	85	17.05 (149,358 MWh)	Largest existing and future potential of 18 and 36 MW in Ayodhya district.
Midwestern plain(ACZ5)	5	19	5	3,751.19	141.5	268	126.50 (1,108.140 MWh)	Largest existing capacity in Mordabad (40 MW) and highest future potential in baireilly district (71 MW).
North eastern plain(ACZ6)	12	34	13	6545	215	467	252.00 (2,207.520 MWh)	Largest existing and future potential of 79 and 214 MW in Lakhimpur-Kheri district, respectively.
South western(ACZ7)	8	4	0	278.29	0	20	20.00 (175.200 MWh)	Largest future potential of 8 MW in Aligarh district.
Vindhyan (ACZ8)	3	1	0	34.42	0	2.46	2.46 (21.549.6 MWh)	Largest future potential of 1.41 MW in Mirzapur district.
Western plain (ACZ9)	7	35	16	9178.2	252.66	655	402.34 (3,524,498.4 MWh)	Largest existing and future potential of 140 and 232 MW in Muzaffarnagar district, respectively.
Uttar Pradesh	**72**	**133**	**53**	**27,794.46**	**961.11**	**1931.35**	**970.24 (8,499,302.4 MWh)**	

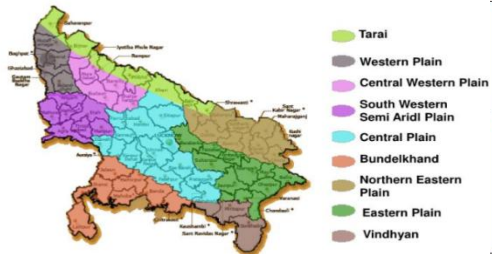
(Source: Indian Sugar Mills Association, 2016) (49).

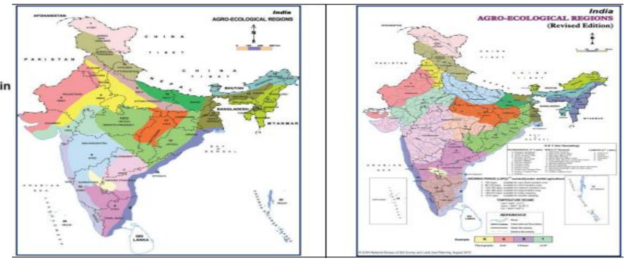
Table 9: Key statistics on sugarcane bagasse and bagasse-based bioelectricity potential for Uttar Pradesh, India

Parameter	State total	State average	Remarks
Total sugarcane area, ha	2,162,400	30,032	Largest in Boijnor district((233.300 ha)
Sugarcane production, kty^{-1}	128.819	1,790	Largest in Muzaffanagar district(15,465 kilo tonne)
Sugarcane productivity, $t\ ha^{-1}$	_	55.44	Largest in Bagpat district(67,68 $t\ ha^{-1}$)
Gross bagasse production, kty^{-1}	38,646	537	Largest gross and net bagasse
Net bagasse production, kty^{-1}	27,052	376	Production of 4,639.5 kt and 3,247.6 respectively
Bioelectricity generation potential, MW	1,931.35	26.81	Largest of 232 MW potential in Muzaffarnagar district
Per unit area bioelectricity potential, $KW\ km^2$	_	7.99	Largest of 57.81 kw km^{-2} in muzaffarnagar district.
Per capita bioelectricity potential, kWh per capita	_	76.00	Largest of 500.44 kwh per capita in bagpat district.

(Source: Geographical area, population data, sugarcane area, productivity data were collected from the Census of India, 2011 and DoES, 2016).

Fig.1(A) Agro-climatic zones of U.P
Fig.1(B) Agro-ecological Regions map of India (Source: ICAR-NBSS&LUP Technologies. 2016)





(a) 1992 **(b) 2015**

(A) **(B)**

Map showing (**a**) spatial distribution of long-term average annual accumulated growing degree days (AGDD); (**b**) temporal trends in annual accumulated growing degree days during the period 1900–2014 of U.P

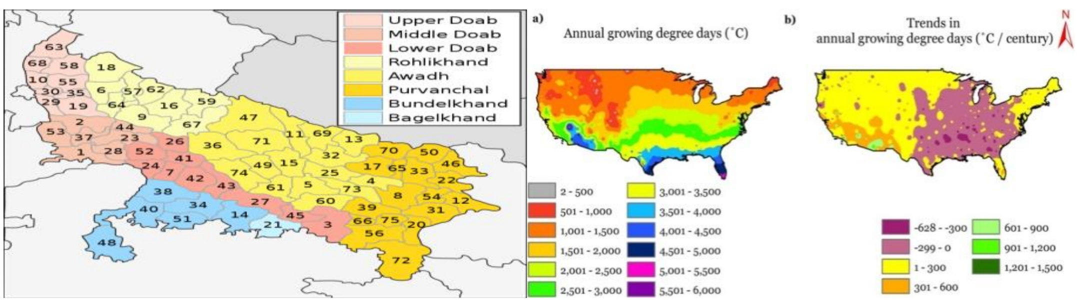
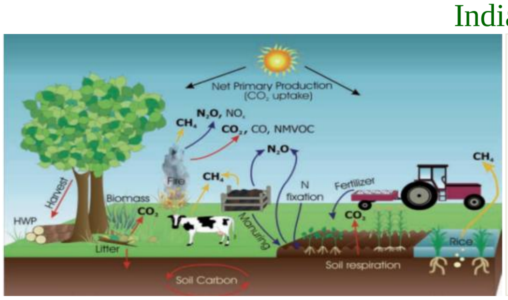
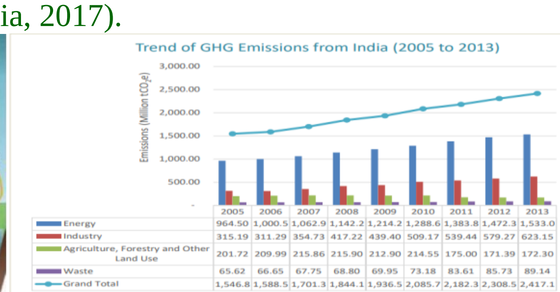


Fig.2 (a): GHG emission sources/removals and processes in managed ecosystems (Source: IPCC, 2006).
Fig.2 (b): Trend for economy wide emissions (2005 to 13) from India.(Source: GHG Platform-India, 2017).





	2005	2006	2007	2008	2009	2010	2011	2012	2013
Energy	964.50	1,000.5	1,062.9	1,142.2	1,214.2	1,288.6	1,383.8	1,472.3	1,533.0
Industry	315.19	311.29	354.73	417.22	439.40	509.17	539.44	579.27	623.15
Agriculture, Forestry and Other Land Use	201.72	209.99	215.86	215.90	212.90	214.55	175.00	171.39	172.30
Waste	65.62	66.65	67.75	68.80	69.95	73.18	83.61	85.73	89.14
Grand Total	1,546.8	1,588.5	1,701.3	1,844.1	1,936.5	2,085.7	2,182.3	2,308.5	2,417.1

(a) **(b)**

Fig.3 Sector wise contribution in total Carbon emission (CO_2 = 987.1 Tg/year, CO= 24.7 Tg/year, CH_4= 17.0 Tg/year) of India (Source: Ramachandra and Shwetmala, 2012).

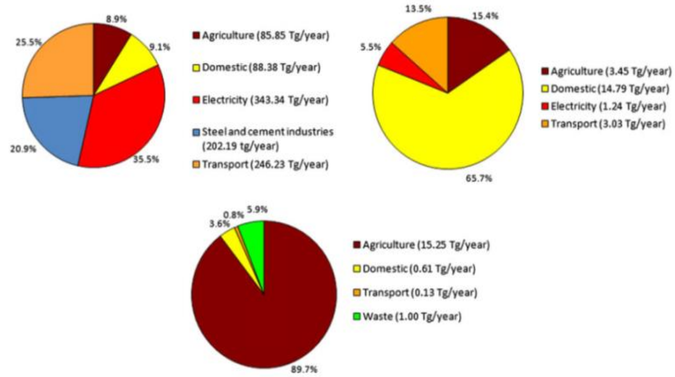
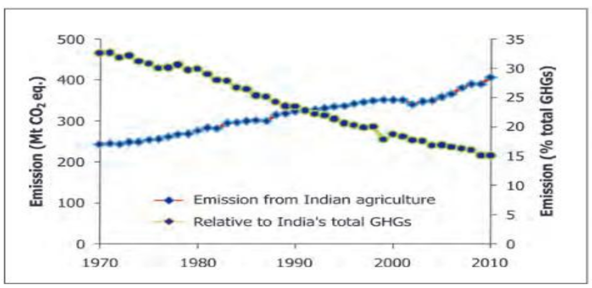
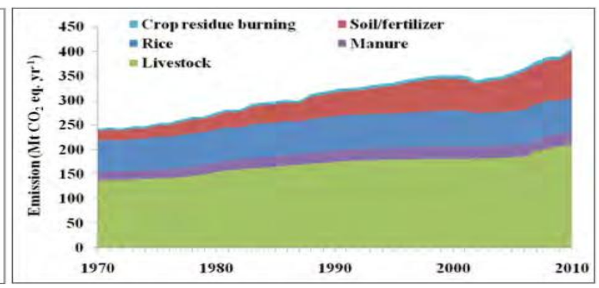


Fig.4 a) Trends in greenhouse gas emission from Indian agriculture and b) from different sources during 1970-2010 (Pathak *et al.*, 2010).

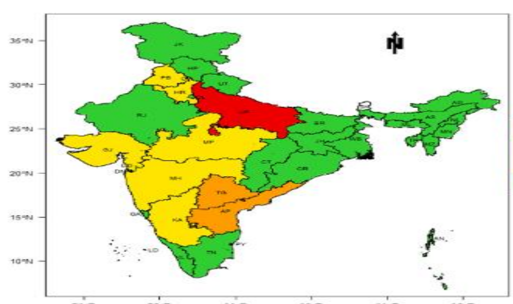




(a) (b)

Fig.5(a) Spatial distribution of GHG mitigation potential ($MtCO_2e$ per year) through improved fertilizer management in India (Source: Sapkota *et al.*, 2019).

Fig.5(b) Trends of production data in major chemicals (Source: Annual report 2018-2019 Govt. of India Ministry of Chemicals & Fertilizers).



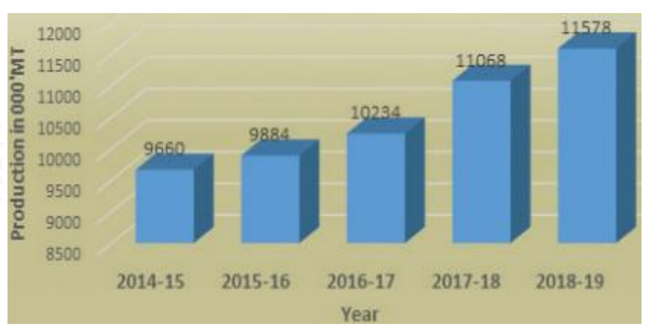
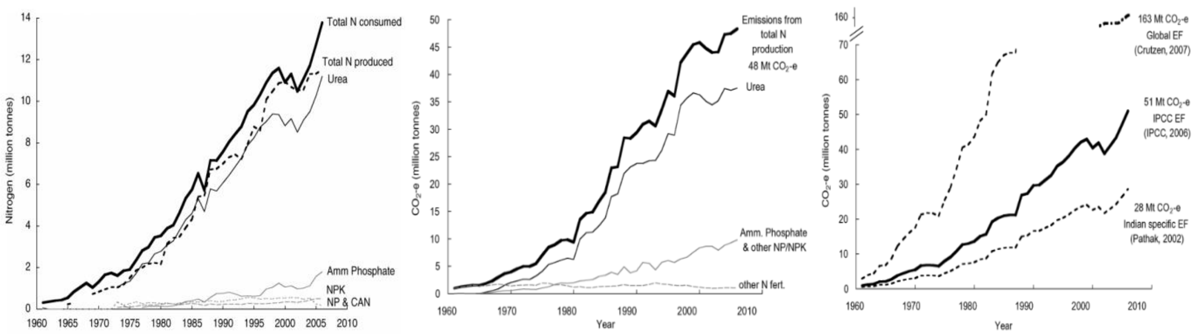


Fig.6 a) Consumption of N fertilizers **b)** GHG emissions from the manufacture of nationally produced synthetic N fertilizers and from **C)** synthetic N application to soils in India from 1960-61 to 2006-07 (Source: Fertiliser Association of India (FAI, 2007); Tirado *et al.,* 2010).



(a) (b) (c)

Fig.7 (a): Groundwater pumping in India change in the net irrigated area from different sources (Source: Mishra *et al.,* 2018)

Fig.7(b): Irrigation based CE emissions in different crops

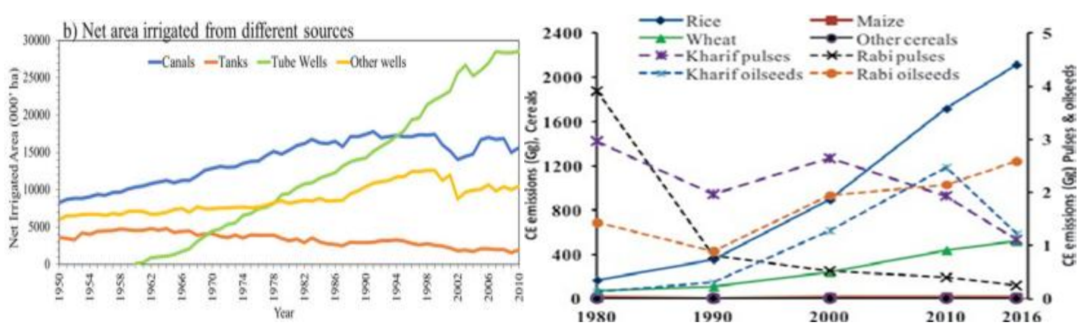


Fig.8 (a): The trend of crop residue generation in India. (Source: Ministry of Statistics and Program Implementation (MOSPI, 2013-14)

Fig.8 (b): The trend of crop residue generation in India. (Source: Ministry of Statistics and Program Implementation (MOSPI, 2013-14)

Fig.8 (c): State-wise distribution of crop residues burnt in India (Jain *et al.,* 2014)

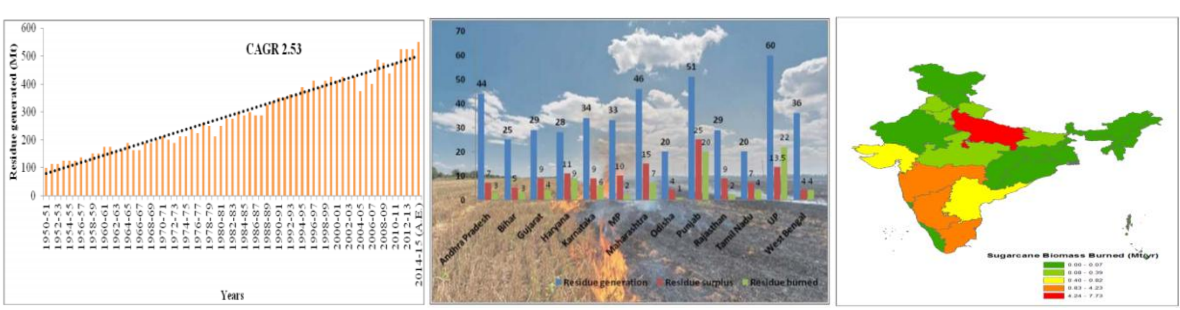
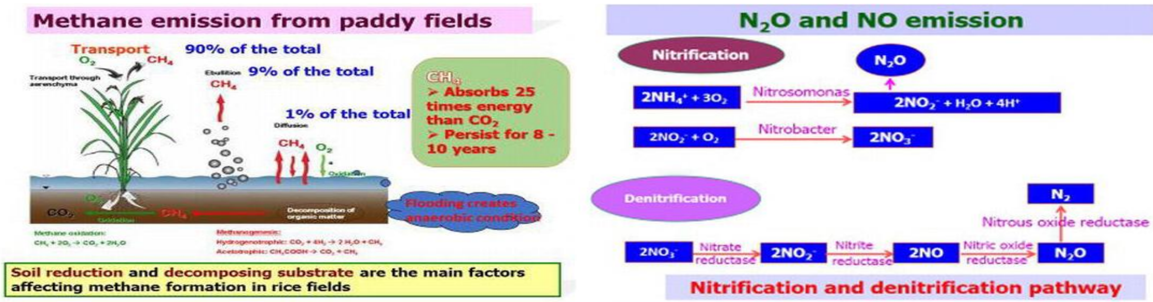


Fig.9: a) Methane production, oxidation, and emission from rice paddy field and **(b)** N_2O, NO, and N_2emissions from rice paddy field. (Source: Ali *et al.*, 2019)



(a) **(b)**

Fig.10 Methane emissions from Indian paddy fields from 1979 to 2006. (i) Variability in methane emissions, (ii) variability in cumulative methane emissions from Indian paddy water regimes. (iii) Variability in cumulative methane emissions from Indian states' paddy water regimes. (Source: Gupta *et al.*, 2009)

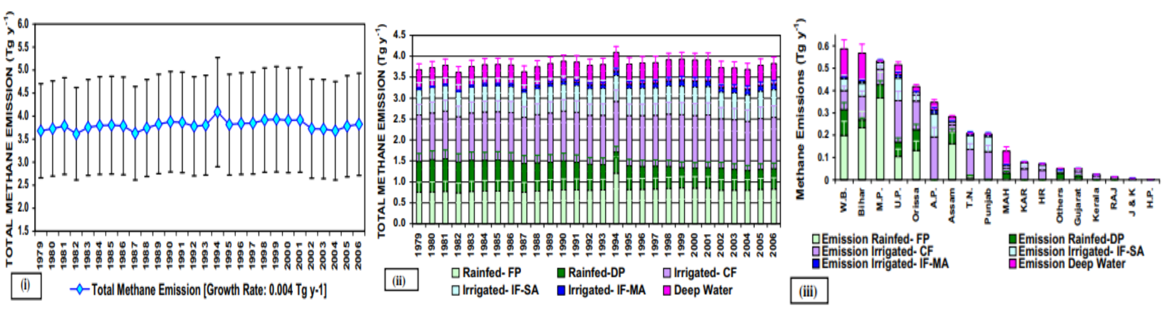
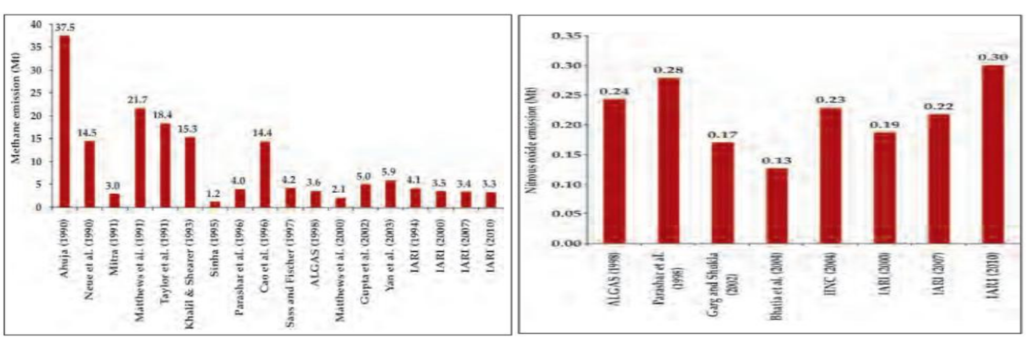


Fig.11(a): Estimates of methane emission from Indian rice fields over the years. IARI 1994, 2000, 2007 and 2010

Fig.11(b): Estimates of nitrous oxide emission from Indian agricultural soils. IARI 2000, 2007 and 2010 (Source: Pathak *et al.*, 2014)



(a) **(b)**

Fig.12 Time series of various variables e.g. maize production, rainfall and tropospheric NO_2over 5 sites (Saharanpur, Muzaffarnagar, Meerut, Ghaziabad, and Mathura) from Uttar Pradesh during summer (a) Maize production; (b) Rainfall anomalies;(c) Total tropospheric NO_2 (Source: Kumar *et al.*, 2018)

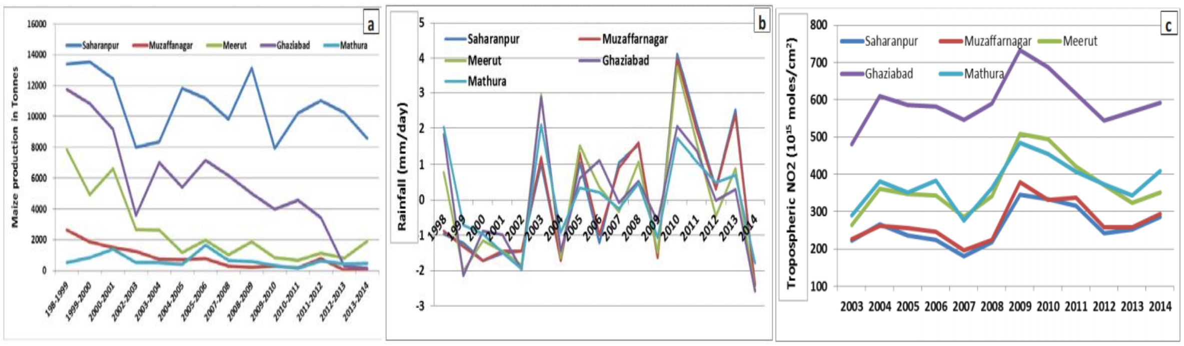
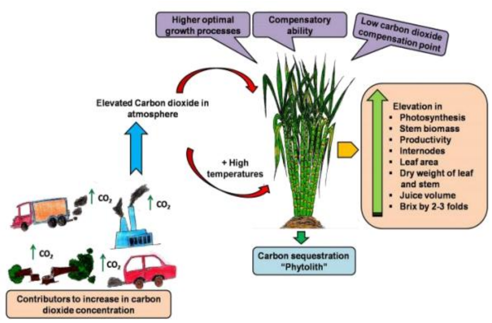


Fig.13 (a): Effect of elevated carbon dioxide concentration on sugarcane crop.
Fig.13(b): State-of-the-art of sugarcane production and per cent recovery in India and Uttar Pradesh (Source: Cooperative Sugar, 2014)



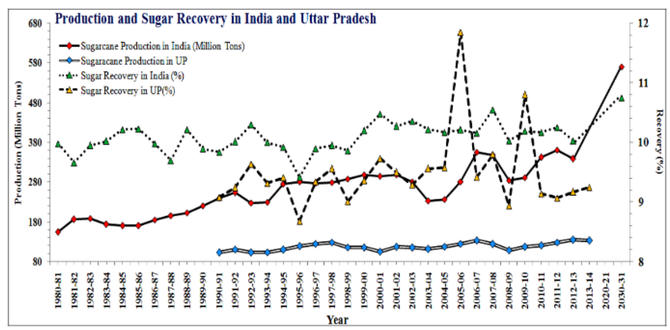
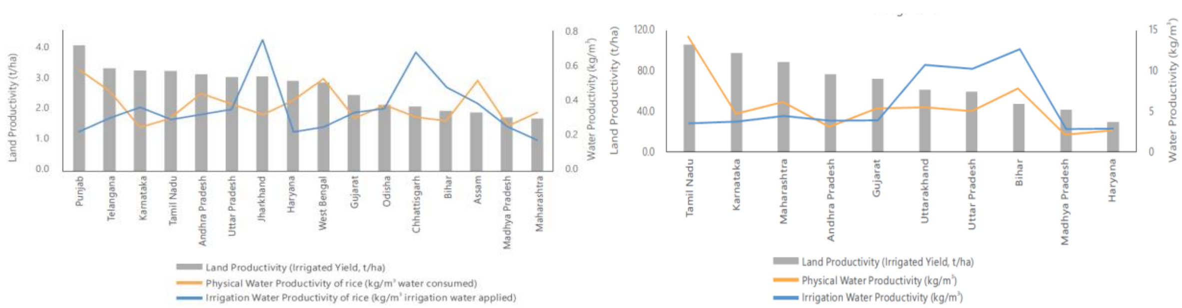
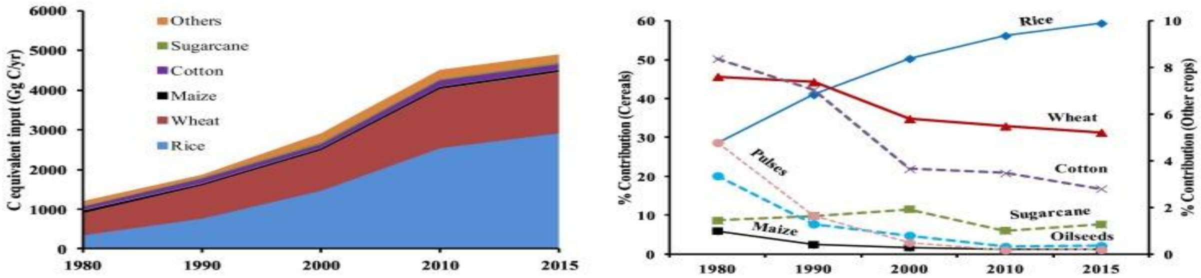


Fig.14 Comparison of land and water productivity of rice (a) and sugarcane (b) across major producing states (Source: Sharma *et al.*, 2018)



(a) **(b)**

Fig.15 Irrigation based EC emissions in different crops in U.P. during 1980-81 to 2015-16



Hence concluded that sustainable agricultural systems are needed to produce high-quality and affordable food in sufficient quantity to meet the growing population need for food, feed, and fuel, and, at the same time, farming systems must have a low impact on the environment. The challenge of meeting food demand while lowering the environmental footprints can be alleviated by adopting various improved agronomical practices. The key agronomical tactics include, but are not limited to diversification of cropping systems, improvement of N fertilizer use efficiency, adoption of intensified rotation with reduced summer fallow, enhancement of carbon conversion from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil, use of reduced tillage in combination with crop residue retention; integration of key cropping practices systematically, and inclusion of N_2-fixing pulses in crop rotations. This review signifies the importance of assessment of CFP of rice-wheat cropping system for reducing GHG emission while maintaining productivity of the system. In recent times adoption of certain conservation agricultural practices could help in reducing the CFP while maintaining productivity and better resource utilization.

Crop management practices like managing nitrogen application with crop demand, conservation tillage, residue incorporation, direct seeded rice, drip irrigation etc. improves resource use efficiency by decreasing losses of inputs to the surrounding environment Integration of these improved farming practices together enables to reduce the use of inorganic fertilizers, increase the system productivity, and lower the carbon footprint. Farmers are increasingly aware that crop production is no longer a yield-income business, and the way the crops are produced will have significant environmental consequences. Over 60 % of the total emissions in food products in grocery stores stem from farm gate raw material. Farmers play a key role in ensuring the provision of low-emission materials to the food chain. There are huge gaps between the development of new cropping technologies and the implementation of the technologies in farming operations. With relevant agro-environmental policies in place, along with the adoption of improved agronomical tactics, increasing food production with no cost to the environment can be achieved effectively, efficiently, and economically.

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