Working Paper

Options for Mitigating GHG Emissions in Agriculture (with Special Context to Fertilizer Use), with Associated Analysis of the Technical, and Socio-Economic Barriers and Opportunities

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Creating Innovative Solutions for a Sustainable Future

INTRODUCTION

India is the third-largest contributor to global greenhouse gas (GHG) emissions. Indian agriculture is vulnerable to climate change mainly due to the rise in temperature, deterioration of soil organic carbon (SOC), and unpredictability of monsoon rainfall. The country's pledge to curb the 'emissions' by 33–35% of its national economy by 2030 as compared to 2005 levels demands proactive mitigation measures at the ground level. Identification of the key factors that influence GHG emissions and carbon sequestration potential, along with cost-effective and scalable mitigation strategies can help in formulating a national roadmap. Strategic emission reduction efforts for achieving National Biodiversity Targets (NBTs) and Sustainable Development Goals (SDGs) without conceding on livelihood, food and nutritional security of communities, and national economic aspirations are unique and a crucial challenge for India in contrast to other developed nations. To achieve this goal, minimizing the influence of climate change to a 1.5°C upsurge in temperature requires a drastic restructuring of the farm sector management – from how we produce, to how we consume, reduce post-harvest losses, and manage potential carbon sinks of the farm sector. Although, accomplishing these calibrated changes could be a more difficult task for Indian agriculture compare to other sectors due to the absence of widely adopted cutting-edge technologies. However, agro-technologies have always delivered on national missions, whether it was for providing food security since the 1960s or meeting the current nutritional security demand. Therefore, though it is a difficult task to accomplish the GHG emissions reduction targets, it may not be an impossible proposition for stakeholders of the agricultural sector.

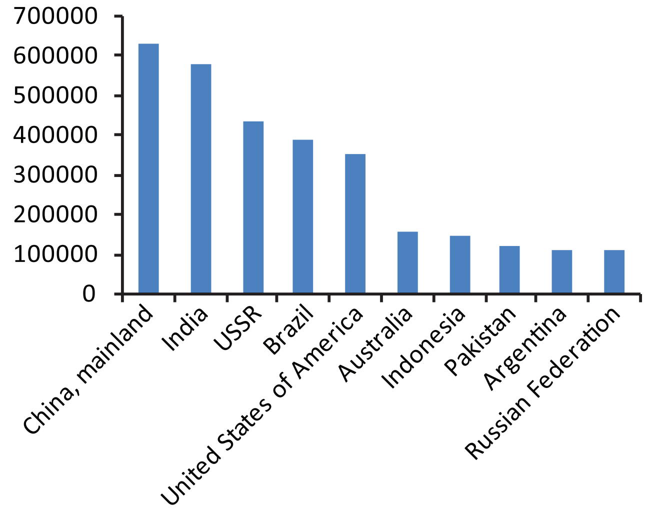

Figure 1 (a) Top 10 Global Emitters of GHG from Agriculture (Average 2005-2017)

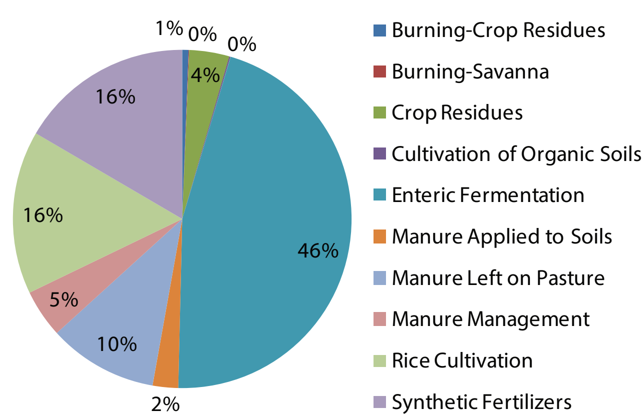

Figure 1 (b) Major contributing source of GHG for agriculture (Average 2005–2017)

Background

Indian agriculture is the second-highest contributor of GHGs in the world, also shown in Figure 1A. Agriculture predominantly contributes to the emission of high global warming potential (GWP) gases which are rich in methane (CH_4) and nitrous oxide (N_2O) – mainly coming from enteric fermentation, synthetic fertilizer usage, and rice cultivation, as shown in Figure 1B.

The disproportionate emission of powerful GHGs such as N_2O and CH_4 from intensive agriculture is a major concern for realizing sustainable GHG emission targets. On the other hand, CH_4 has a short half-life (12 years) in the atmosphere in comparison to N_2O and other major GWP contributors. Thus, it makes CH_4 an ideal target molecule for rapidly balancing out the carbon footprint from Indian agriculture. However, the increase in population and food habit changes (preference for animal protein) due to enhanced purchasing power will be the major accelerators of offsetting the environmental footprint of the agricultural sector in India. It is estimated that consumption of affluent diets by the entire population could lead to a 19–36% growth in environmental footprints across the indices (Aleksandrowicz, Green, Joy, *et al.* 2019). Thus, to have a sustainable GHG emission efficiency at the national scale, implementation of climate regenerative technologies for increasing the efficiency of food production and policies to reduce food waste will be imperative despite the major impediment of small farm holdings by Indian farmers, burgeoning middle-class population, and urbanization.

This report highlights the current estimates of emission from India's agriculture since 2005 (considering Nationally Determined Contributions [NDC] targets; in comparison to 2005 emissions), contributed by seven different agricultural emissions sub-domains (burning crop residues, crop residues, cultivation of organic soils, cropland, manure applied to soils, manure management, rice cultivation, and synthetic fertilizers). Emission projections were calculated for both 2030 and 2050 based on a baseline defined as the 2005–2007 average of the equivalent FAOSTAT activity data (Alexandratos and Bruinsma 2012). Data for the 'cultivation of organic soils' were obtained as per the FAOSTAT. The CO_2e of GHG is currently calculated using GWP-CH_4 = 21 and GWP-N_2O = 310. Additionally, emissions from land use for 'cropland' were also presented. GHG emissions from this sub-domain of 'land use' are presently restricted to CO_2 emissions from cropland organic soils. These values were estimated based on the carbon losses from drained histosols under cropland and expressed as net emissions/removal Gg CO_2e (gigagram carbon dioxide equivalent).

This analysis provided a clear insight into GHG emission status and sequestration potential of India's agricultural cropland. It will provide a better outlook for formulating emissions and sequestration sub-domains-specific policy framework, their implementation, technological interventions, and future research and development (R&D) priorities for climate regenerative agriculture towards accomplishing nationally set targets.

The report also assesses the technical mitigation potential of agriculture. A detailed case study is presented in this report w.r.t. GHG mitigation options from fertilizers' use.

Status

Agricultural Emissions

i) Burning crop residues

Emissions from burning crop residues comprise GHG gases formed by the combustion of a percentage of crop residues burnt on-field. The biomass available for burning was estimated considering the portions removed before burning due to animal consumption, decay in the field, and use in other sectors (e.g., biofuel, domestic livestock feed, building materials). The average emission (2005–2017) of CO_2e from burning crop residues of agricultural land in India is 3708 Gg (FAOSTAT 2019). The four major crops included in this estimation are rice, wheat, maize, and sugarcane. Rice contributes a little over 50% of this emission with 1881 Gg, followed by wheat (24.5%), maize (18.3%), and sugarcane residues (6.5%), as presented in Figure 2 (FAOSTAT 2019).

With the current public awareness, policy, and technological intervention in India, the emissions are projected to go down close to 3000 Gg by 2030 and are expected to remain nearly the same until 2050

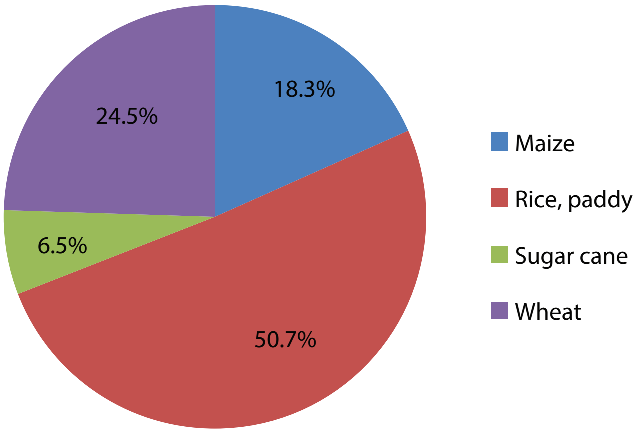

Figure 2: Major contributing crops for emissions from burning - crop residues

(Alexandratos and Bruinsma 2012). However, there are many technologies such as breeding new-generation genotypes for conservation agriculture in rice-wheat (RW) and maize-wheat cropping systems that are initiated in India to address this issue. A recent study comprehensively demonstrated that the burning of rice residues in northern India could be evaded by altering the overall cropping system or by implementing alternative RW management practices (Shyamsundar, Springer, Tallis, *et al.* 2019). Appropriate crop genotypes, management practices, and policies can address this problem keeping in view the concerns over air quality index in the Indus–Ganga plain.

ii) Crop residues

GHG emissions from crop residues consist of direct and indirect N_2O emissions from nitrogen (N) in crop residues and forage/pasture renewal left on agricultural fields by farmers. Specifically, N_2O is produced by microbes of nitrification and de-nitrification taking place on the deposition site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). The average emission (2005–2017) of CO_2e from crop residues of agricultural land is 23,685 Gg (9% of the total agricultural sub-sector emission) (FAOSTAT 2019). Emissions from this sector are projected to be unaltered much over the next 30 years with a minor initial decline (Alexandratos and Bruinsma 2012). Residues of nine major crops such as barley, beans, maize, millet, potatoes, rice, sorghum, soybeans, and wheat were considered for these emission estimates. Only three of these (rice, wheat, and maize) crop contributes 80% of the crop residual emissions. Therefore, specific technological interventions to manage these three crop residues can significantly dent the total emissions from this sub-sector.

iii) Cultivation of organic soils (cropland organic soils)

The 'cropland organic soil' sub-sector of the 'cultivation of organic soils' was considered to estimate the sector's GHG emissions. The estimate comprises assessments of N_2O emissions accompanying the drainage of organic soils – using histosols as a proxy – for agriculture. GHG emissions from this sector remained almost stable at 608 Gg since 2005 and are projected to rise little above 630 Gg, which is expected to remain unchanged until 2050, as shown in Figure 3. The prospects of targeting GHG mitigation options centred on the mapping approach of organic soils. Expansion of cultivated peat soils is not a sustainable option for India where economic importance for crop production in peat soils is comparatively low and thus its GHG mitigation potential is high. Emerging evidence demonstrates rewetted cropland organic soils can be emission-neutral or even sequester carbon (Kekkonen, Ojanen, Haakana, *et al.* 2019).

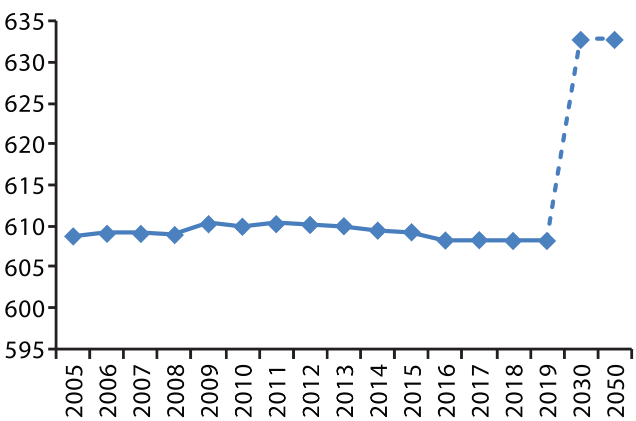

Figure 3: Current status and projections of GHG emission (Gg CO_2e) from cultivation of organic soils

iv) Manure applied to soils

GHG emissions from the application of manure to agricultural soils comprises direct and indirect N_2O emissions from the added compost by farmers. Specifically, N_2O is formed by microbial routes of nitrification and de-nitrification taking place on the application site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). To estimate the emissions from the sub-sector, manures from livestock species (asses, buffaloes, camels, cattle [dairy and non-dairy], chickens [broilers and layers], ducks, goats, horses, llamas, mules, sheep, swine [breeding and market] and turkeys) were considered. India's total emission (direct and indirect) average from this sub-sector is 15,147 Gg, which is expected to see a quantum jump of 143% by 2050 to 21,705 Gg (FAOSTAT 2019).

v) Manure management

Emissions from manure management consist of CH_4 and N_2O gases from aerobic and anaerobic manure decomposition processes. Similar to the preceding sub-sector, emission (Gg CO_2e) potential from livestock species (asses, buffaloes, camels, cattle [dairy and non-dairy], chickens [broilers and layers], ducks, goats, horses, llamas, mules, sheep, swine [breeding, market], turkeys) was considered here. India's total emission (direct and indirect) average from this sub-sector is 28,385 Gg and is expected to see a quantum jump of 126% by 2050 to 35,769 Gg (FAOSTAT 2019). Several manure management practices are proposed to reduce GHG emission potential including the wide use of small-scale dome digester anaerobic manure digestion for small farm holders (reduction potential of about 50%).

vi) Rice cultivation

Emissions from rice cultivation consist of CH_4 gas from the anaerobic decomposition of organic matter in paddy fields. India is the second-largest GHG emitter (96,697 Gg) from rice cultivation after China. This contributes majorly to India's total agricultural emissions (~11%). However, as per FAOSTAT (2019), emissions from this sub-sector are projected to be reduced significantly (77%) to 74,844 Gg by 2030 and expected to remain stable until 2050, which is also shown in Figure 4.

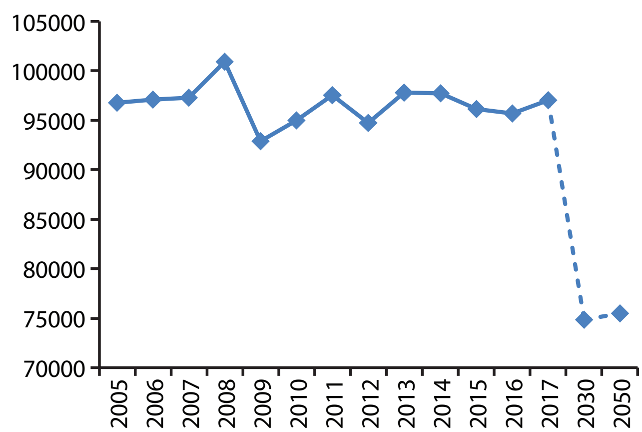

Figure 4: GHG emission (Gg CO_2e) current status and projections from Rice Cultivation

vii) Synthetic fertilizer

Emissions from synthetic fertilizers consist of N_2O gas from synthetic nitrogen additions to managed soils. Specifically, This is the second-largest contributor of GHG emissions from the sector after the enteric fermentation of agricultural emission. The average emission of CO_2e is 102,644 Gg, which is expected to steadily upsurge (57%) to 178,704 Gg by 2050 (FAOSTAT 2019). Therefore, massive emission from this sub-sector needs considerable attention to reduce emissions by the use of next-generation technologies and policy measures.

In total, the average emissions from 2005 to 2017 from these seven sub-sectors was 271,036 Gg, which is projected to be 305,164 Gg by 2030 and 341,829 Gg by 2050, also shown in Figures 5 and 6.

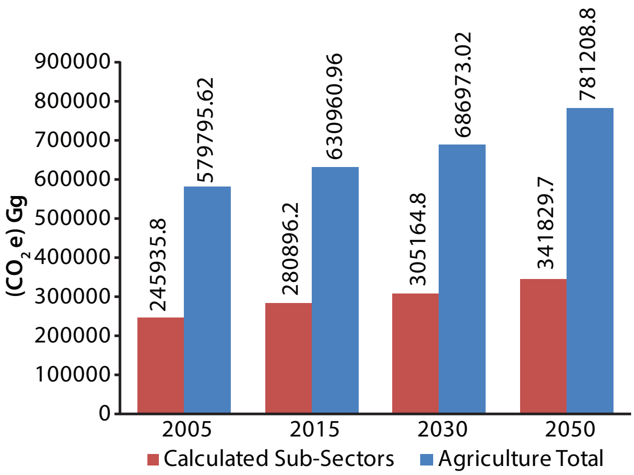

Figure 5: Comparative estimates of total agricultural emission and calculated sub-sectors

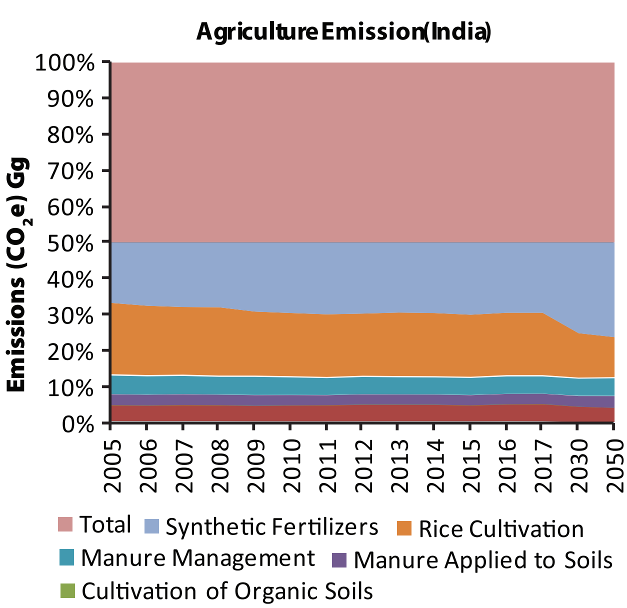

Figure 6: Emission highlights (CO_2e) Gg from the seven calculated sub-sectors

Land-use emissions (cropland)

GHG emissions in the 'cropland' domain are currently limited to CO_2 emissions from cropland organic soils. They are associated with carbon losses from drained histosols under cropland. India's current annual emission from this sub-sector is 5954 Gg CO_2e (expressed as net emissions/removal Gg CO_2e), which remained stable for the last 4 years, as shown in Figure 7.

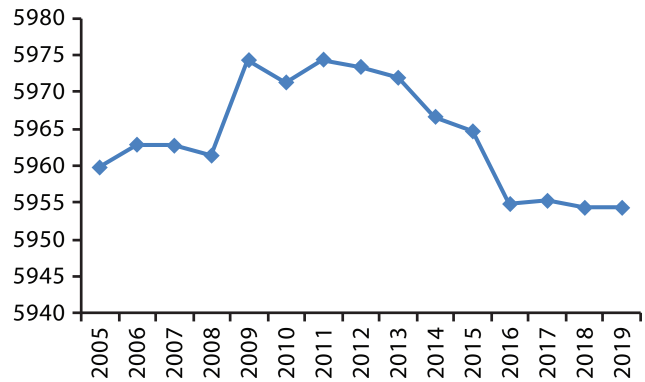

Figure 7: India's land-use emissions – cropland

IMPACT OF THE LAND-USE SECTOR ON CLIMATE CHANGE

Direct and indirect emission

India's agriculture is increasingly causing rapid alteration of lands and placing a greater burden on biological diversity and natural resource functions than ever before. By 2050, nearly 70% more food will be necessary to feed increasing populations, particularly in developing countries (UN 2009; FAO 2011). Empirical evidence of the impact of climate change attributed to the CO_2e emissions from agricultural and land use is available. Conversion of forestland to agriculture and harvesting of mature timber are the key factors responsible for major emission imbalances. Cropland is accountable for nitrogen dioxide emissions whereas manure management, irrigation water, and solid waste facilities are for the methane emissions. The GHG emission status of these two sectors (agriculture and land use) from 2005 are mentioned above which includes direct and indirect emissions. The average emission from the seven sub-sectors of agriculture was 271,036 Gg and if 2005 as the base year is considered, then this emission average is already raised by 25,101 Gg. These data provide direct evidence for the increase in GHG emissions due to land-use change and intensive agriculture. These extrapolations have led to the estimate that deforestation is liable to 5.6 $GtCO_2$ per year. It is important to mention that methods relying only on forest cover as the direct measure of carbon have their limitations. Moreover, India's growing population and changing dietary preferences (increased consumption of animal-based products and polished rice-based diet) pose a significant threat (potential for the environmental impacts) to future environmental consequences given the size of India's population (Green, Joy, Harris, *et al.* 2018, Vetter, Sapkota, Hillier, *et al.* 2017).

STATUS OF SEQUESTRATION

SOC is one of the most critical features of soil that results from the interaction of net primary producers, decomposers, and mineralogy. Over the past few decades, the potential of soil management for carbon sequestration in the form of SOC has been extensively studied. Nationally, 146.82 million ha (about 45% of the land area) is under different forms of land degradation. The 4 per 1000 (4PT) initiative, endorsed by the United Nations General Assembly at the 21st Conference of Parties 2015 (COP21), is an integrated approach to support SOC sequestration as a remedy to counterbalance fossil fuel CO_2 emissions. India's NDCs have recognized agriculture as one of the priority sectors for GHG emission reduction.

To meet the demands of the ever-growing population, land-use patterns have changed over the globe, considerably upsetting global climate change. The global average of SOC content per hectare is estimated to be 161 t (Minasny, Malone, McBratney, *et al.* 2017). Assuming that the SOC sequestration rates of the 4PT initiative can be accomplished, the average global rate would require to be 0.6 t C/ha/y which exceeds the rate for agricultural land. Powlson, Stirling, Thierfelder, *et al.* (2016) conducted a meta-analysis of SOC reserve changes under conservation agriculture practices in Indo-Gangetic Plains (IGP). They found that the annual rise in SOC stock compared to conventional practice was between 0.16 and 0.49 Mg C/ha/y which was caused by crop diversification. Thus, they suggested that crop diversification almost certainly constitute a genuine mitigation potential that should not be overlooked.

The implementation of the System of Rice Intensification in several rice growing areas in India led to an emission decline of 0.18 $MtCO_2$ during 2010–16, while the Direct Seeded Rice system resulted in an emission reduction of 0.17 $MtCO_2$ from 2014 to 2016 (MoEFCC 2018). It demonstrates the potential of economic agro-technologies for carbon sequestration.

ESTIMATION OF FUTURE POTENTIAL OF SEQUESTRATION AND MEASURES TO OPTIMIZE EMISSIONS FOR ACHIEVING CARBON NEUTRALITY

Agricultural lands receive more disturbance than other land areas as a result of inputs and soil management practices. Therefore, degraded (but not polluted) agricultural soils have a greater potential to sequester SOC. Carbon sequestration under the Kyoto Protocol or any post-Kyoto treaty not only encourages significant changes in land management but also mandates enhancing organic matter content. It can lead to significant direct effects on soil properties and a positive impact on environmental or agricultural qualities and biodiversity. The measurable impacts include increased soil fertility, land productivity for food production, and food security. This economic tool can also make agricultural processes more sustainable and help prevent or mitigate land resource degradation. Indian agro-ecosystems (food basket of India) have considerable potential for carbon sequestration. However, the carbon sequestration potential of soil oscillates due to agronomical management practices and cropping systems. Although RW is the principal cropping system in the IGP, it has both positive and negative influences on soil carbon sequestration. It is important to mention that the RW cropping system is one of the major cropping systems of IGP which is practised in 10.5 Mha of the region. The sustainability of RW is threatened due to various factors influencing farm productivity and profitability. Along with improving climate-resilient genotypes for RW cropping systems, crop diversification with several other cropping systems available can mitigate the problems arising from the RW cropping system.

Effective land use and management enable enhancing both SOC and above-ground carbon sequestration. Land degradation is a major concern for crop productivity loss in India. Restoration of eroded land with appropriate conservation measures can reverse soil degradation, improve productivity, and transform regenerated land as a potential sequestration tool. Further, degraded land is also associated with poverty and food security in this region. For instance, the Eastern Ghats region which constitutes a geographical area of 19.8 Mha is vulnerable to soil erosion and is considered the poorest part of the country. In contrast, production-enhancing quick-fix soil management strategies such as application of manure, fertilizers, and assured irrigation for semi-arid marginal land cropping systems although enhance the SOC status, but they are not net C sink because of associated carbon cost. Various studies have recommended several soil management measures. However, keeping the land use unaltered with conservation measures can compensate for on-site and off-site influences on soil and the environment. Carbon-neutral or negative management practices can have a synergistic impact on crop productivity, soil health, and GHG sequestration. These include integrated application of economic, simple, and scalable technologies such as laser land levelling (helps in saving irrigation water up to 20% and improves its use), the efficiency of applied N, conservation tillage (zero/minimal tillage), bed planting (narrow/broad beds), direct-seeded rice, Sesbania brown manuring, other bio-fertilizers (including arbuscular mycorrhizal fungi in carbon sequestration), use of leaf colour chart, residue retention for mulch, integrated nutrient and pest management, agroforestry (direct role: Carbon sequestration rates ranging from 1.5 to 3.5 Mg C/ha/y in agroforestry systems), application of biochar, etc.

Besides, the identification of GHG emission hotspots and cost-effective mitigation opportunities in agriculture can help in making informed decisions towards prioritizing the efforts to moderate emissions without conceding on food and nutrition security. It was estimated by an independent study that by 2030, under business-as-usual, GHG emissions from the agricultural sector in India would be 515 megatonne CO_2 equivalent ($MtCO_2e$) per year with a technical mitigation potential of 85.5 $MtCO_2e$ per year through the implementation of several mitigation practices (Sapkota, Vetter, Jat, *et al.* 2019). The study further highlighted that about 80% of the technical mitigation potential could be attained by implementing only cost-saving measures. It added that the three mitigation choices, i.e., effective use of fertilizer, zero-tillage, and rice-water management could bring more than 50% of the total technical reduction potential. Climate-compatible crop development for the future using new horizon technologies such as CRISPR/Cas9 has not been talked about much for GHG emissions. Employing GHG-focused genetic selection, breeding, and genome editing for designer traits (improved N utilization efficiency, photosynthetic capacity, climate resilience, cattle gut digestibility, etc.) could be critical in bringing newer genotypes for these specific purposes.

IMPROVING NITROGEN FERTILIZER MANAGEMENT AND PRODUCTION

Nitrous oxide emissions stem from nitrogen fertilizers (both synthetic and organic) on croplands that are not absorbed by plants, and leach instead into the environment. Fertilizer run-off contaminates surface and groundwater quality and creates GHG emissions in the form of nitrogen oxide. The global technical mitigation potential for reducing N_2O from soils is roughly 325 Mt CO_2e (Dickie, Streck, Roe, *et al.* 2014). Unfortunately, nitrogen balances in agricultural soils can vary greatly over space and time, therefore it is difficult for farmers to know precisely when plants need the nutrients and how much nitrogen (and other nutrients) needs to be applied at any one time. Consequently, farmers tend to over-apply fertilizer as an insurance mechanism against low yields.

The consumption of fertilizer nutrient in crops has increased substantially in the past decades (FAOSTAT 2016). The quantity of crops produced per unit of applied fertilizer has continuously decreased to very low values and fertilizer use efficiency following blanket fertilizer application has been generally observed below 50% (Ladha, Pathak, Krupnik, *et al.* 2005). To better manage fertilizer application, the basic approach is to increase the nitrogen use efficiency within the cropping system by better matching the nitrogen supply from fertilizers with the nitrogen demands of the crops. The main reason for low fertilizer use efficiency is an inefficient splitting of fertilizer doses coupled with fertilizer applications in excess of crop requirements. When managed inefficiently, a large portion of the applied fertilizers can escape the soil-plant system thus creating pollution problems. Sound fertilizer management practices need to be established and be followed to improve fertilizer use efficiency leading to high yield levels and minimal fertilizer loss to the environment.

The blanket recommendations consisting of two or three split applications of pre-set rates of total fertilizer during the growing season of crops are commonly used by farmers for managing fertilizer. The blanket fertilizer recommendations developed for large tracts have well served the purpose to produce optimum yields with the application of fertilizer above crop requirement and thus cannot help increase fertilizer use efficiency beyond a limit. Large field-to-field variability of soil fertilizer supply, agro-climatic conditions, and varietal differences restrict efficient use of fertilizer when broad-based blanket recommendations are used.

Approaches such as deep placement of super granules, controlled-release fertilizers, and nitrification inhibitors based on reducing N losses have been successful in improving fertilizer use efficiency but to a limited extent. In the mid-eighties and nineties, the emphasis was shifted from reducing fertilizer losses to matching crop fertilizer demand with fertilizer supply to achieve high fertilizer use efficiency (Buresh and Britt 2007). The research since then has been oriented more towards finding means and ways to apply fertilizer in real-time using crop and field-specific needs. There are several technologies and tools that can enable and improve optimal nitrogen use efficiency, including (Dickie, Streck, Roe, *et al.* 2014):

- Plant breeding and genetic modifications to increase the uptake of nitrogen by the crop so that less fertilizer is needed to achieve the same yields.

- Better accounting and use of organic fertilizers so that agricultural systems are less reliant on external inputs, and less likely to underestimate nitrogen inputs.
- Decision support tools for better managing input management (timing, rate, and type). These tools can vary from simple, regionally specific recommendations or leaf colour charts to advanced remote sensing tools and decision support computer models linked to easy-to-use mobile phones.
- Regular soil testing to develop appropriate nutrient management plans. In developing countries, soil testing can be done at a regional level, with recommendations made available to all farmers depending on region and crop.
- Technologically advanced fertilizers. Examples include slow-release fertilizers which control the release of nutrients in lieu of double application, and nitrification inhibitors which slow the degradation of nitrogen fertilizers so that the chemical components stay active and available to the plant for longer and do not leach into the environment. Advanced fertilizers are typically more expensive and are generally best considered second-phase technologies to be employed after basic improved management practices (e.g., better timing and rate of application) have been adopted.
- Compared to a bulk form of chemical inputs in crops, the use of nano nutrients can reduce nutrient run-off into ground and surface water, and thus can reduce environmental pollution. India is one of the few countries researching in the area of nano-enabled fertilizer products. The development and commercialization of nano-enabled controlled and smart release fertilizers will cater for the much needed demand in this sector with high resource use efficiency. The global total nutrient capacity in 2015 was 285.15 million tonnes (FAO 2017). With nano-fertilizers replacing the conventional forms, the consumption level is expected to go down to 40–50% leading to the revolution in the fertilizer sector. Nano-fertilizers are required to be applied only in a few grams per acre as compared to bulk fertilizers that are required in kilogram per acre and hence are of immense value not only to our farmers but also for the production and supply chain. Additionally, due to requirement in a very small amount, the threat of residue-related hazards and carbon footprints will be drastically reduced. If the conventional chemical fertilizer are replaced by nano-fertilizers, it will not only reduce environmental pollution but also offer an alternative to fertilizers import into the country.

In addition to the challenge of over application and fertilizer management, the production of synthetic fertilizer is also a major source of GHG emissions and air pollution as it requires significant energy to produce, and uses fossil fuels (natural gas or coal) as feedstocks. Substantial improvements could be made through advancements in industrial efficiency. Efficiency gains are typically cost-effective and would improve the productivity of the industrial sector. They are in the best interests of both producers and the government. There are no current figures for global mitigation potential from improved fertilizer production; estimates for China alone are 160 Mt CO_2e. Production of a few organic fertilizers such as mycorrhiza is less energy-intensive and can replace 50% of fertilizers, and thus a good mitigation option.

Table 1: Co-benefits and trade-offs (Reproduced from Dieckie, Streck, Roe, *et al.* 2014)

Co-benefits	**Trade-offs**
Cost savings Improving fertilizer application efficiency as well as improving industrial efficiencies in fertilizer production reduces capital costs	**Potentially reduced yields** Perceived risk from farmers is that reducing nutrient applications could reduce yields. This is true if the application is reduced below optimal application
Increased yields Optimal use of fertilizer promotes long-term soil fertility and increases yields	**Potentially higher labour and capacity needs** Changing fertilizer management practices can require either additional labour (e.g., split application) or technical knowledge on how and when to most efficiently apply the fertilizer

Pollution abatement	Availability of specific inputs
Increasing nitrogen efficiency within the cropping systems decreases leakage into the environment and contamination of surface and groundwater. Additionally, reduced demand for synthetic fertilizer and improvements in fertilizer production significantly reduce air pollution	Fertilizer availability is a problem in many regions. Making the right type of fertilizer available for the specific crop is often difficult
Enhanced health conditions	
Increased air and water quality from efficiencies in fertilizer management and production improves health conditions and reduces costs of public health systems	

COST-EFFECTIVE OPPORTUNITIES FOR CLIMATE CHANGE MITIGATION

The agricultural sector is responsible for 18% of the gross national GHG emissions in India (INCCA 2010) mainly through rice cultivation, livestock production, fertilizer use, and burning of crop residues. Given the significance of agriculture to the total national emissions, India has identified agriculture and the allied sectors as a priority area for emissions reduction in its NDC to the United Nations Framework Convention on Climate Change (UNFCCC) (Richards, Bruun, Campbell, *et al.* 2016).

A comprehensive study was carried out by Sapkota, Vetter, Jat, *et al.* (2019) to identify mitigation options, costs, and benefits in Indian agriculture, which is presented in Table 2.

Table 2: Greenhouse gas mitigation options along with their mitigation potential and cost of adoption in Indian agriculture† (Reproduced from Sapkota, *et al.* 2019)

GHG abatement options	Mitigation potential[a]	Gross cost of mitigation[b]	Net cost of mitigation[b]
Crops			
Improved water management in rice	2760	-1378	-3445
Adoption of zero-tillage	518 to 1796	-963 to -308	-1690 to 208
Stop residue burning	-3 to 522	-6278 to -498	-6278 to -498
Fertilizer production	57 to 529	Not considered	Not considered
Fertilizer consumption	47.83 to 198.46	-710 to -2327	-710 to -2327
Laser land levelling	1284 to 3055	1000	-5188
Increase nitrogen use efficiency through fertigation	170 to 4999	25,000	21,750
Sprinkler/micro-sprinkler irrigation	163 to 1276	10,000	8700
Livestock			
Green fodder supplement for large ruminants	32.23 to 38.84	2957 to 4106	-14,783 to -5493
Increased concentrate feeding for large ruminants	116.77 to 139.82	4654 to 6894	-2340 to 128
Monensin premix for large ruminants	32.23 to 38.84	61,685	57,973 to 60,316
Molasses urea product for large ruminants	116.77 to 139.82	1460	-5964 to -1278
High fibre diet for pigs	121.75	675	-325
Improved diet management for small ruminants	21.36	189	-1411

Improved manure management of large ruminants	30.63	13,358	-2235
Biogas from large ruminants' manure	500.23	2960	-1751
Restoration of degraded lands			
Reclamation of salinity/alkalinity through chemical amendment	495	85,000	85,000
Reclamation of waterlogged soil through sub-surface drainage	183	76,000	76,000
Restoration of wind/water-eroded land through Jatropha plantation	275	1833	-2000
Restoration of wind/water-eroded land through plantation	275	71,500	71,500
Controlling wind/water erosion through contour farming/wind breaks/water flow breaks, etc.	275	45,500	26,000

[†] The range of values indicates the mitigation potential and costs when mitigation options are applied to multiple crops or livestock. When mitigation options are applied to a single crop or livestock, a single value of mitigation potential and cost is given.

[a] kg CO_2e/ha/yr for options related to crop management and restoration of degraded land, and kg CO_2e/head/yr for the options related to livestock management.

[b] ₹/ha for options related to crop management and restoration of degraded land, and ₹/head for the options related to livestock management.

BARRIERS AND OPPORTUNITIES

Barriers and opportunities can enable and facilitate (opportunities) or hinder (barriers) the full use of agricultural mitigation measures. Regions being affected by many barriers need time, finance, and capacity support (Smith, Bustamante, Ahammad, *et al.* 2014).

Socio-economic barriers and opportunities

The design and coverage of the financing mechanisms are key to the successful use of agricultural mitigation potential. It needs to be understood what costs will be covered by financing mechanisms, e.g., transaction costs, monitoring costs, opportunistic costs, and also to which scale of financing. Another element to consider is the accessibility to agriculture financing for farmers and forest stakeholders.

High levels of poverty can limit the possibilities for using agricultural mitigation options, because of short-term priorities and lack of resources. In addition, limited skills and lack of social organization can limit the use and scaling up of mitigation options and can increase the risk of displacement, with other potential adverse side-effects (Smith and Wollenberg 2012; Huettner 2012). This is especially relevant when agricultural land or degraded land sparing competes with other development needs, e.g., promoting some types of production which is energy-intensive or input-intensive leading to higher GHG emissions, or when large-scale bioenergy compromises food security.

Cultural values and social acceptance can determine the feasibility of mitigation measures, becoming a barrier or an opportunity depending on the specific circumstances (de Boer, Cederberg, Eady, *et al.* 2011).

Institutional barriers and opportunities

Governance and institutional establishment are vital for the sustainable implementation of the mitigation measures. This includes the need to have clear land tenure, land-use rights regulations, and a certain level of enforcement, as well as clarity about carbon ownership (Palmer 2011; Thompson, Baruah, and Carr 2011; Markus 2011).

Lack of institutional capacity (as a means for securing the creation of equal institutions among social groups and individuals) can reduce the feasibility of mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the main stakeholders (Laitner, DeCanio, and Peters 2000; Madlener, Robledo, Muys, *et al.* 2006; Thompson, Baruah, and Carr 2011).

Ecological barriers and opportunities

Mitigation potential in the agricultural sector is highly site-specific, even within the same region or cropping system (Baker, Ochsner, Venterea, *et al.* 2007; Chatterjee and Lal 2009). Considering short- and long-term priorities and regional differences in resource use, the availability of land and water for different uses needs to be balanced. Consequently, limited resources can become an ecological barrier and the decision of how to use them needs to balance the ecological integrity and societal needs (Jackson 2009).

At the local level, the specific soil conditions, water availability, GHG emission-reduction potential as well as natural variability and resilience to specific systems determine the level of realization of the mitigation potential of each measure (Baker, Ochsner, Venterea, *et al.* 2007; Halvorson, Gonzalez, and Hagerman 2011). Ecological saturation (e.g., soil carbon or yield) means that some mitigation options have their limits. The fact that many measures can provide adaptation benefits furnishes an opportunity for increasing ecological efficiency (Guariguata, Cornelius, Locatelli, *et al.* 2008; van Vuuren, van Vliet, and Stehfest 2009; Robledo, Clot, Hammill, *et al.* 2011).

Technological barriers and opportunities

The technological barriers refer to the limitations in generating, procuring, and applying science and technology to identify and solve an environmental problem. Some mitigation technologies are already applied, e.g., afforestation, cropland, and grazing land management, whereas others, e.g., livestock dietary additives, crop trait manipulation, are still in the development stage.

The ability to manage and re-use knowledge assets for scientific communication, technical documentation, and learning is lacking in many areas where mitigation could take place. Future developments present opportunities for additional mitigation to be realized if efforts to deliver ease-of-use and range-of-use are guaranteed. There is also a need to adapt technology to local needs by focusing on existing local opportunities (Kandji, Verchot, and Mackensen 2006), as proposed in Nationally Appropriate Mitigation Actions (NAMAs).

Barriers and opportunities related to monitoring, reporting, and verification of the progress of the mitigation measures also need to be considered. Monitoring activities, aimed at reducing uncertainties, provide the opportunity of increasing credibility in the agriculture sector. However, exploiting the existing human skills within a country is essential for realizing full mitigation potential. A lack of trained people can, therefore, become a barrier to the implementation of appropriate technologies (Herold and Johns 2007).

Technology improvement and technology transfer are two crucial components for the sustainable increase of agricultural production in developed and developing regions with positive impacts in terms of mitigation, soil, and biodiversity conservation (Tilman, Balzer, Hill, *et al.* 2011). International and national policy instruments are relevant to foster technology transfer and to support research and development, overcoming technological barriers.

Table 3: Summary of potential co-benefits and adverse side-effects from mitigation measures (Reproduced from Smith, Bustamante, Ahammad, *et al.* 2014)

Issue	Potential co-benefit or adverse side-effect	Scale
Institutional		
Land tenure and use rights	Improving (↑) or diminishing (↓) tenure and using rights for local communities and indigenous people, including harmonization of land tenure and using regimes (e.g., with customary rights)	Local to national
Sectoral policies	Promoting (↑) or contradicting (↓) the enforcement of sectoral (forest and/or agriculture) policies	National
Cross-sectoral policies	Cross-sectoral coordination (↑) or clashes (↓) between forestry, agriculture, energy, and/or mining policies	Local to national
Participative mechanisms	Creation/use of participative mechanisms (↑) for decision-making regarding land management (including participation of various social groups, e.g., indigenous peoples or local communities)	Local to national
Benefit-sharing mechanisms	Creation/use of benefits-sharing mechanisms (↑) from mitigation measures	Local to national

Social		
Food security	Increase (↑) or decrease (↓) on food availability and access	Local to national
Local/traditional knowledge	Recognition (↑) or denial (↓) of indigenous and local knowledge in managing (forest/agricultural) land	Local/sub-national
Animal welfare	Changes in perceived or measured animal welfare (perceived due to cultural values or measured, e.g., through the amount of stress hormones)	Local to national
Cultural values	Respect and value cultural habitat and traditions (↑), reduce (↓) or increase (↑) existing conflicts or social discomfort	Local to transboundary
Human health	Impacts on health due to dietary changes, especially in societies with high consumption of animal protein (↓)	Local to global
Equity	Promote (↑) or not (↓) equal access to land, decision-making, value chain, and markets as well as to knowledge- and benefit-sharing mechanisms	Local to global
Economic		
Income	Increase (↑) or decrease (↓) in income. There are concerns regarding income distribution (↑)	Local
Employment	Employment creation (↑) or reduction of employment (especially for small farmers or local communities) (↓)	Local
Financing mechanisms	Access (↑) or lack of access (↓) to new financing schemes	Local to global
Economic activity	Diversification and increase in economic activity (↑) while concerns on equity (↑)	Local
Environmental		
Land availability	Competition between land uses and risk of activity or community displacement (↑)	Local to transboundary
Biodiversity	Monocultures can reduce biodiversity (↓). Ecological restoration increases biodiversity and ecosystem services (↑) by 44% and 25%, respectively. Conservation, forest management, and integrated systems can keep biodiversity (↑) and/or slow desertification (↓)	Local to transboundary
Albedo	Positive impacts (↑) on albedo and evaporation and interactions with ozone	Local to global
N and P cycles	Impacts on N and P cycles in water (↓/↑) especially from monocultures or large agricultural areas	Local to transboundary
Water resources	Monocultures and/or short rotations can have negative impacts on water availability (↓). Potential water depletion due to irrigation (↓). Some management practices can support regulation of the hydrological cycle and protection of watersheds (↑)	Local to transboundary
Soil	Soil conservation (↑) and improvement of soil quality and fertility (↑). Reduction of erosion. Positive or negative carbon mineralization priming effect (↑/↓)	Local
New products	Increase (↑) or decrease (↓) on fibre availability as well as non-timber/non-wood products output	Local to national

Ecosystem resilience	Increase (↑) or decrease (↓) in resilience, reduction of disaster risks (↓)	Local to transboundary
Technology		
Infrastructure	Increase (↑) or decrease (↓) in the availability of and access to infrastructure. Competition for infrastructure for agriculture (↑) can increase social conflicts	Local
Technology innovation and transfer	Promote (↑) or delay (↓) technology development and transfer	Local to global
Technology acceptance	Can facilitate acceptance of sustainable technologies (↑)	Local to national

CONCLUSION

Croplands in India are intensively managed, and offer many opportunities to impose practices that reduce net emissions of GHGs. All the crops and soil management practices aimed towards increasing efficiency of water, nutrients, energy, and other production inputs, and those that increase crop production lead to GHG mitigation.

Soil carbon sequestration is a significant cost-effective tool in the climate change mitigation land-use programme. Conservation agriculture practices along with organic farming (fertilizer-free zones), agroforestry, and biochar usage can easily be implemented. These practices have a positive influence on soil carbon sequestration, crop diversity, and agricultural productivity. Crop diversification, intercropping, organic farming, application of biofertilizers (e.g., mycorrhiza for broad host range) in place of chemical fertilizers could be the practical choices for GHG mitigation in changing climatic conditions. For GHG mitigation, sustainable practices, improved crop genotypes with climate resilience, and integrated nutrient and pest management have key roles. Advanced modern technologies such as gene editing have not been explored for a climate mitigation strategy. Such technologies can revolutionize the regenerative agricultural practices. Similarly, nano-fertilizers for precision agriculture (integrated nutrient management) could be a game-changer for climate-smart agriculture and to significantly reduce major N_2O emissions.

Effective GHG mitigation in the major cropping systems in India needs know-how, proper technology dissemination channel, financial reward system, and government policies. Any single practice cannot lead to GHG mitigation. Some studies suggest that 80% of the total technical mitigation potential (67.5 out of 85.5 $MtCO_2e$/y) in Indian agriculture can be obtained by adopting cost-beneficial mitigation options. Most of these measures are annual measures, which mean that they do not require more than 1 year of commitment on the part of farmers. However, the realization of the abatement potential of individual measures is dependent on the extent of adoption by individual farmers. In principle, farmers should already be adopting these apparent win–win measures without any additional incentives, but given that adoption at scale is not taking place it suggests that there are other barriers to overcome (Bustamante, Robledo-Abad, Harper, *et al.* 2014). There is a need for a multidisciplinary approach with multiple R&D institutions, and farmers and policymakers to collectively address this complex challenge and meet the national sustainable development goals.

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