Carbon Footprints

Review

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Carbon footprints of the Indian AFOLU (Agriculture, Forestry, and Other Land Use) sector: a review

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Abstract

Stabilizing greenhouse gas (GHG) emissions from croplands as agricultural demand grows is a critical climate change mitigation strategy. Depending on management, the Agriculture, Forestry, and Other Land Use (AFOLU) sector can be both a source as well as a net sink for carbon. Currently, it contributes 25% of the global anthropogenic carbon emissions. Although India's emissions from this sector are around 8% of the total national GHG emissions, it can contribute significantly to the country's aspirations of reaching net-zero emissions by 2070. In this review, we explain the carbon footprints of the AFOLU sector in India, focusing on enteric fermentation, fertilizer and manure management, rice paddies, burning of crop residues, forest fires, shifting cultivation, and food wastage. Furthermore, using the standard autoregressive integrated moving average method, we project India's AFOLU sector emission routes for 2070 under four scenarios: business as usual (BAU) and three emission reduction levels, viz., 10%, 20%, and 40% below BAU. The article focuses on how the AFOLU sector can be leveraged proactively to reach the net-zero emission goals. Increasing forest cover, agroforestry, and other tree-based land-use systems; improving soil health through soil management, better crop residue, and livestock feed management; emission avoidance from rice ecosystems; and reducing food waste are all important strategies for lowering India's AFOLU sector carbon footprints.

Keywords: Greenhouse gas emissions, net-zero emission, enteric fermentation, agroforestry, food wastes

INTRODUCTION

India, the most populous and largest country in South Asia, faces the challenge of rapid economic growth without increasing carbon emissions that threaten the climate system. At the COP26 session in Glasgow (31 October to 12 November 2021), India vowed to meet its climate change commitments by setting a net-zero target for 2070. Being a megadiverse country endowed with abundant natural resources[1], India envisions achieving a carbon-neutral green growth and development pathway. The relatively rapid pace of urbanization (34.93% of the overall population in 2021 in the urban areas compared to 17.93% in 1960[2]), quick economic growth (gross domestic product growth of 9.5% in 2021[3]), industrialization, and agricultural intensification, however, have resulted in increasing levels of greenhouse gas (GHG) emissions in India in the past. The total GHG emissions (in million metric tons CO_2 equivalent, $MtCO_2e$) increased almost linearly from 746.5 in 1970 to 3375 in 2018[4]. Currently, India is the third-largest contributor to global energy-use and anthropogenic carbon emissions, after China and the USA, with its energy sector contributing 75% (2129 $MtCO_2e$) of overall emissions[5].

While fossil fuel combustion remains the principal driver of rising GHG levels, agriculture and land-use changes also contribute to it substantially. The agriculture sector of India, according to India's Third Biennial Update Report to the United Nations Framework Convention on Climate Change[5], produced emissions of 407.8 $MtCO_2e$ in 2016 (14.37% of the country's total emissions). Enteric fermentation, fertilizer and manure management, rice paddies, food waste, and crop residue burning are the major sources of GHG emissions in Indian agriculture[5,6]. Although forest fires, shifting cultivation, and forest degradation have been sources of GHG emissions, the Land Use, Land Use Changes, and Forestry (LULUCF) sector is a net sink in India. In 2016, LULUCF sequestered 330.76 Mt of CO_2, which is about 15% of India's total CO_2 emissions from all sectors[5]. This paper analyzes the nature and magnitude of GHG emissions from the Agriculture, Forestry, and Other Land Use (AFOLU) sector of India and identifies cost-effective countermeasures.

METHODOLOGY

We searched the Scopus and Google Scholar databases for articles published after 2000 on carbon footprint issues in the AFOLU sector, with a particular focus on India using the keywords "carbon footprint", "India", "GHG emissions", "adaptation", "mitigation", and "AFOLU". We also checked the references of the papers selected for any additional sources including original research articles, book chapters, and review papers. The search returned 114 articles including four databases. Among the databases, Dhingra *et al.*[7] provided time-series GHG emission data (2005-2015) from India's AFOLU sector, calculated based on the Global Warming Potential-AR5 values relative to CO_2, which is the only available time-series database on Indian AFOLU sector. We performed a non-stationary time-series analysis on this using the traditional autoregressive integrated moving average (ARIMA) method[8]. Since a systematic pattern of changes in emission levels was not repeated at regular intervals in the Dhingra *et al.*[7] database, we fitted a non-seasonal ARIMA model, which is a regression-type equation in which the predictors consist of lags of the dependent variable (Y, emission levels) and lags of the forecast errors. In our model, the predictors consist only of lagged values of Y, and thus it becomes a pure autoregressive ("self-regressed") $ARIMA(p,d,q)$ model, where p is the number of autoregressive terms, d is the number of non-seasonal differences needed for stationarity, and q is the number of lagged forecast errors in the prediction equation. This can be represented as:

$$\hat{Y}_t = f\ (Y_{t-1} + \varepsilon_{t-1}) \tag{1}$$

where X is the predicted value of Y at time t, Y_{t-1} is the weighted sum of one or more recent values of lagged Y, and ε_{t-1} is the weighted sum of one or more recent values of the prediction errors.

Considering the slow mean reversion of the time-series data at hand, the best fitted model possibly was the *random walk* specification *without drift* or *ARIMA* (0,1,0)[8], and the prediction equation [Equation (1)] for this specification can be written as:

$$\hat{Y}_t = \mu + Y_{t-1} + \varepsilon_{t-1} \quad (2)$$

where μ is the model intercept, which is "0" when the best fit is *without drift* as in our case ("drift" in forecasting refers to the unknown and hidden relationship between input and output variables influenced by other factors not considered in the model, e.g., unforeseeable events). The upper and lower bounds of the confidence intervals representing uncertainty in our forecast were also quantified by adding and subtracting the margin of error (ε_{t-1}) from the mean predicted X. ARIMA modeling was implemented in *R* statistical software (ver. 4.1.2) using the "forecast" package[9] to forecast per capita emissions from AFOLU under four possible scenarios, business as usual (BAU) and three emission reduction levels, viz., 10%, 20%, and 40% below BAU. The corresponding emission reduction strategies for the AFOLU sector in India, alongside the projected emissions under each of these scenarios, are described in Section "Pathways and scenarios towards sustainable development". In this study, the assessment boundaries were limited to: (1) the emissions from rice cultivation; (2) agricultural soils; (3) crop residue burning; (4) forest fires; (6) cropland use; (7) enteric fermentation from livestock; (8) grasslands; (9) manure and fertilizer management; and (10) other land uses. With respect to carbon sinks, removals by croplands, forests, and grasslands were considered.

We also derived the carbon footprints of household food waste (kitchen and municipal food wastes) in India in the current scenario from the Gustavsson *et al.*[10] emission factor (2.5 ton CO_2e ton^{-1}) and the annual household food waste estimates of Sinha and Tripathi[6], which exclude food waste in post-harvest, transport, and retail. Although post-harvest losses are a significant contributor to CO_2 emissions, consistent and reliable data on this are lacking in India.

RESULTS AND DISCUSSION

Major Sources of GHG Emissions and Removals in the AFOLU Sector of India

The AFOLU sector contributed to about 8% of India's total GHG emissions in 2015 (derived from the databases[4,7]), which is much lower than the global share of AFOLU (~25% of the total emissions[11,12]). This sector encompasses GHG emissions and removals (sinks) arising from carbon stock changes in biomass, CO_2 and non-CO_2 GHG [methane (CH_4) and nitrous oxide (N_2O)] emissions from detritus (dead organic matter) and mineral soils, and CO_2 and non-CO_2 GHG emissions from fire [carbon monoxide (CO), CH_4, non-CH_4 organic compounds (NMOC), nitrogen oxides ($NOx = NO + NO_2$), NH_3, and SO_2]. Rice paddies and livestock production systems (enteric fermentation) emit the most CH_4, managed soils emit N_2O, and manure management systems emit both CH_4 and N_2O[7]. Fossil fuel CO_2 emissions on croplands from the use of agro-machineries such as tractors, irrigation pumps, etc., according to the IPCC accounting protocols[12], are a component of the energy sector rather than the AFOLU sector, and hence they are not considered here. However, fossil fuel GHG emissions from the use of agricultural machinery on croplands globally added 0.4-0.6 $GtCO_2$eq/year in 2010[12], and the exclusion of farm machinery probably underestimates the AFOLU sector emissions. The photosynthetic process in plants, especially in forest trees, represents a significant CO_2 removal mechanism. While permanent removal of trees will lead to increasing emissions, increasing forest cover and other tree-based production systems such as agroforestry can contribute substantially to CO_2 removals (see the next section).

Forest carbon stock changes

The forestry sector is both a source as well as a sink for carbon, and forest policies and programs have implications on the standing stock of carbon in the forests. While forest degradation and destruction caused large-scale emissions of CO_2 and other GHGs, the Forest Survey of India (FSI) data indicate that total forest carbon stocks increased during the period from 2004 to 2019, from 6663 Mt in 2004 to 7204 Mt in 2021. Forests and other land-based sequestration accounted for approximately 117 $MtCO_2e$ in 2015, making it a net sink of CO_2 [Figure 1]. The land-related estimates of CO_2 absorption, however, showed a notable decline in 2012 and 2013 (65 million t CO_2e), which is intriguing. Nonetheless, it stabilized above the 2011 levels in the succeeding year.

Historically, India's forest cover declined almost linearly until the mid-1970s, owing to agricultural expansion and other development activities. With 55.52 million ha of forest cover in 1975, India had the lowest forest cover in history[13]. This trend, however, was reversed subsequently. The forest cover of India increased steadily in recent times[13] and currently accounts for 21.71% (71.38 million ha) of the geographic area[14]. The total area under forest and tree (which includes forests of less than 1 ha) cover in 2021 was 80.95 million ha (24.62% of the geographic area)[14].

Although the forest cover of India has been increasing continuously in recent times, with 51 ha of forests per 1000 people and a forest cover change rate of + 0.22% between 2019 and 2021[14], India is a "low forest/low deforestation country". Land-use changes, logging, forest fires, encroachment, shifting cultivation, and conversion of forests for other purposes are the major causes of forest degradation/destruction. Based on the forest inventory records, 54.40% of forests in India are exposed to occasional fires, 7.49% to moderately frequent fires, and 2.41% to high incidence levels[15]. Forest fires emit significant amounts of CO_2, and the majority of forest fires in India are anthropogenic[16].

Shifting cultivation, swidden farming, or jhumming, a traditional method of farming, adversely affects the forest carbon stocks and contributes to CO_2 and other GHG emissions. The area under shifting cultivation, which was over 3.5 million ha at the turn of the last century, has been progressively declining, with about 0.84 million ha in 2015-2016, mostly in the northeastern states of India - where the practice is still widespread[17,18]. Clearing and burning of the forests for cropping cause emissions of CO_2 and other GHGs, besides leading to reductions in the biomass and soil carbon stocks. Opening up the canopy and exposure of bare soil is also likely to increase CO_2 emissions through accelerated soil organic matter decomposition. The post-abandonment establishment of natural vegetation, however, may restore some of the carbon stocks in soil and vegetation. Incentivizing the traditional *jhum* farmers to practice agroforestry may augment the carbon stocks in soil and biomass and help in balancing biodiversity conservation and economic growth[19].

CO_2, CH_4 and N_2O emissions from agroecosystems

While intensive agriculture ("high inputs/high outputs" model) led to spectacular increases in food grain production, it also led to rising levels of non-CO_2 GHG emissions, e.g., CH_4 and N_2O. Livestock (enteric fermentation) accounts for the bulk of the CH_4 emissions in the AFOLU sector of India [Figure 1]. Rice paddies, fertilizer and manure management systems, crop residue burning, and food waste also contribute to substantial GHG emissions. The agriculture sector of India produced emissions of 407.82 $MtCO_2e$ in 2016 (14.37% of the country's total emissions)[5].

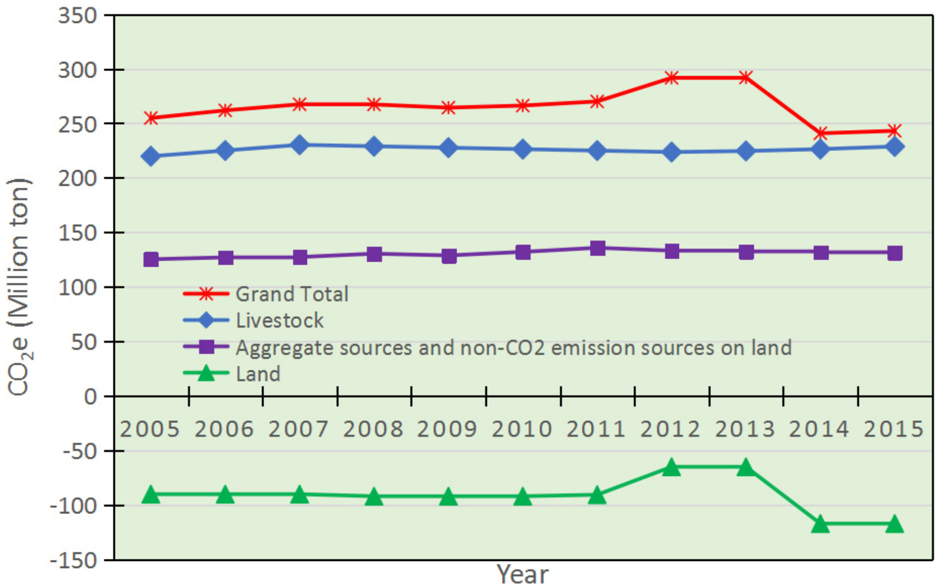

Figure 1. Greenhouse gas emission estimates (million-ton CO_2 equivalent) from the AFOLU (Agriculture, Forestry and Other Land Use) sector in India for the period from 2005 to 2015. Estimation of GHG emissions and removals from the AFOLU sector includes CO_2 emissions and removals (negative values) resulting from carbon stock changes in biomass, dead organic matter, and mineral soils, for all managed lands; CO_2 and non-CO_2 emissions from fire on all managed lands; N_2O emissions from all managed soils; CO_2 emissions associated with liming and urea application to managed soils; CH_4 emissions from rice cultivation; CO_2 and N_2O emissions from cultivated organic soils; CH_4 emission from livestock (enteric fermentation); and CH_4 and N_2O emissions from manure management systems. Based on Global Temperature Potential (GWP)-AR-5 (Assessment Report 5; tCO_2e) (data source[7]).

CH_4 emissions from the livestock sector: Enteric fermentation

Livestock production is integral to the Indian agricultural and socioeconomic systems. The 2019 Livestock Census indicates that there are 535.78 million livestock in the country, the world's largest livestock population, with a total bovine (cattle, buffalo, mithun, and yak) population of 302.79 million[20]. About 44% of the livestock emissions are in the form of CH_4[21], and enteric fermentation by ruminants, the largest biogenic source of CH_4, accounted for 54.6% of the GHG emissions from agriculture in 2016 [Figure 1], while animal manure management represented 6.68%[5].

Various attempts have been made to determine CH_4 emissions from Indian livestock. Such estimates, however, are variable given the differential methodologies adopted. Singhal *et al.*[22] reported that CH_4 emissions from enteric fermentation of Indian livestock were 10.08 Mt in 1994. The total CH_4 emission including enteric fermentation and manure management was 11.75 Mt in 2003, according to Chhabra *et al.*[23]. Although the Indian livestock sector contributes substantially to the CH_4 budget, the per capita emission is low, only 24.23 kg CH_4/animal/year[23]. Kumari *et al.*[24] estimated CH_4 emissions in 2007 as 14.08 Mt (296 $MtCO_2e$) for baseline scenarios with a projected 68.49 Mt (1438 $MtCO_2e$) in 2032.

Methane production in ruminants depends on the quality and quantity of feed consumed, type of animal, and digestibility of forage and feeds[22]. Cattle contribute the highest CH_4 emissions (more than 50%), followed by buffalo, goats, and sheep. Attributes such as the low feed intake of Indian ruminants as well as the low digestibility of the feed resources (low-quality forages and crop residues) lead to not only low productivity but also lower CH_4 emission levels[22] than ruminants elsewhere.

Methane emissions from wetland rice ecosystems

Approximately 11% of the global anthropogenic CH_4 emissions originate from rice fields[25]. Natural wetlands constitute another source. Mosier *et al.*[26], summarizing the previous studies, reported the global CH_4 emission from rice paddies in the range of 25.4-54 Mt year^{-1}. For India, according to Parashar *et al.*[27], the values ranged from 2.4-6 Mt year^{-1}. Rice cultivation in India occurs on 43.19 million ha (23% area share[28]) and contributes 3% of the total GHG emissions[5]. Rice ecosystems emitted 3.37 Mt of CH_4 (84.25 $MtCO_2e$) in 2007, according to Bhatia *et al.*[29]. In 2015, it was 90.46 $MtCO_2e$ [Figure 2]. Estimates of CH_4 emissions from rice production systems in India, however, do not follow a consistent pattern and vary depending on the prevailing ecological and environmental conditions.

Major factors contributing to such variability are differences in the availability of easily degradable crop residues, fallow weeds, and soil organic matter, which are the substrates for initial CH_4 production, and root exudates, decaying roots, and aquatic biomass, which constitute important sources at later stages of crop growth. Methane production is negatively correlated with soil-redox potential and positively correlated with soil temperature, soil carbon content, and rice growth[30]. Nitrogen fertilizers and biogas slurry liquid fertilizers from a CH_4-generating tank increased CH_4 emission in paddy soils[31]. Changes in the conventional crop management regimes, such as alternate wetting and drying irrigation, could significantly reduce CH_4 emissions compared to continuous flooding[32] by introducing periodically aerobic conditions during rice-growing seasons[33].

Manure management entails storing and treating manure before it is used on-farm or burned as fuel. The livestock manure management chain accounts for about 10% of the global GHG emissions from agriculture[34]. In India, manure management accounted for 27.237 $MtCO_2e$ in 2016, or 6.68% of the GHG emissions[5]. Starting from excretion in barns or other areas of the farm, through storage and manure management systems, until application and incorporation into soils, livestock excreta and applied manure emit CO_2, CH_4, and N_2O as well as reactive species of N such as NH_3 and NO_3[35,36].

Several processes are involved, including decomposition, hydrolysis, nitrification, denitrification, and fermentation, resulting in CO_2, CH_4, N_2O, and NH_3 emissions and NO_3^- leaching[37]. The complex organic compounds (e.g., carbohydrates and proteins) contained in animal manure are broken down, microbially releasing CH_4 under anaerobic and CO_2 under aerobic conditions. Indeed, livestock manure management represents one of the biggest anthropogenic sources of CH_4 and globally contributed about 470 Mt CO_2 e/year in 2010[38]. Nitrous oxide is also produced during nitrification–denitrification of the nitrogen contained in livestock waste during storage and after its application in the soil. The total N_2O emission from Indian livestock was estimated at 1420 tons in 2003[23]. Poultry, pigs, indigenous cattle, and exotic cattle contributed 86.1%, 7.3%, 5.7%, and 1.0% of the total N_2O emissions, respectively[23].

The production and emission of CH_4 and N_2O from manure are affected by a range of factors: feed digestibility and composition, animal species and physiology, manure management practices, the duration and method of storage, the type of treatment, and environmental conditions such as sunlight, temperature, precipitation, and wind[39]. Dietary manipulation influences the composition and amount of cattle excreta, which has a direct impact on field-based GHG emissions[36]. Sajeev *et al.*[40] observed a 71% increase in manure CH_4 with increased carbohydrate content. Grass-based systems with maize silage supplements (low N, high starch) reduced manure N excretion, as well as N_2O and NH_3 emissions per ton of milk produced[41]. Manure type (e.g., wet versus dry; slurry from swine emits more GHG than that from cattle[42]) also influences the quantity of CH_4 produced[43].

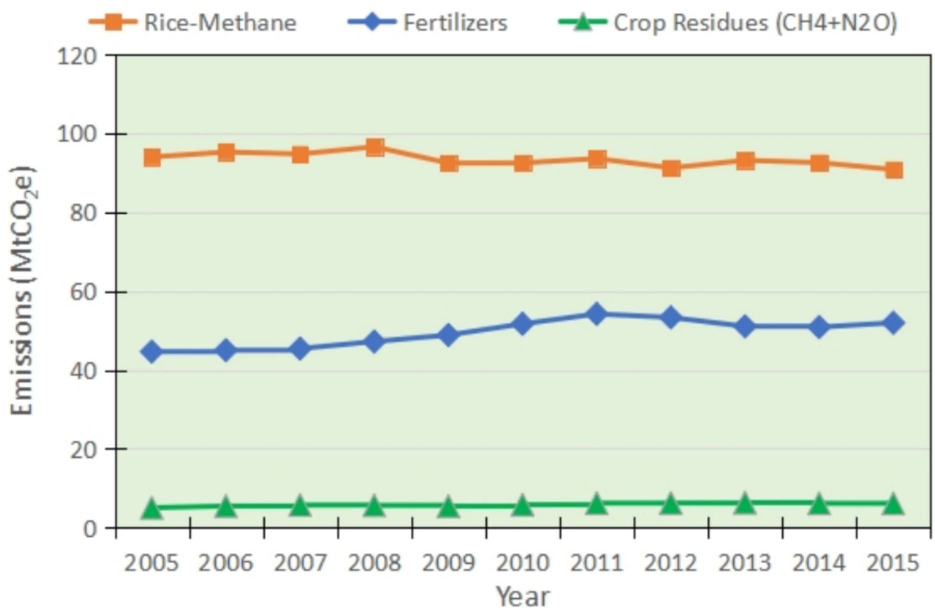

Figure 2. Total methane emissions from rice cultivation, N_2O emissions from fertilizers, and CH_4+ N_2O emissions from crop residue burning in India as CO_2 equivalent (million tons) based on AR-5 values (Assessment Report 5) (data source[7]).

Livestock manure is managed in India through solid storage and slurry/lagoon for manure, dung cake production, and biogas generation, and different manure management systems produce variable levels of GHG emissions. Storing liquid manure for long periods without processing contributes the most to GHG emissions. When manure is stored or treated as a liquid in a lagoon, pond, or tank, it tends to decompose anaerobically and produce significant quantities of CH_4. In contrast, when manure is handled as a solid or deposited on pastures, it tends to decompose aerobically with little or no CH_4 production[44]. High temperature, high moisture level, and neutral pH conditions generally favor CH_4 production[45]. Excessive application of livestock manure, similar to an excess of applied mineral fertilizers, generates reactive N emissions, primarily NH_3 and nitrate (NO_3^-)[35]. Volatilization, leaching, and runoff also cause indirect emissions from manure management systems, for example, NH_3[46].

Nitrous oxide emissions from agricultural soils

Agriculture is responsible for over 60% of worldwide anthropogenic N_2O emissions[12,47], which increased by 17% between 1990 and 2005[48]. Between 2007 and 2016, global N_2O emissions were about 17.0 Mt N per year[48]. N_2O emissions from agricultural soils of India accounted for 19.07% of total GHG emissions (15.88% from direct N_2O and 3.20% from indirect N_2O)[5]. Rice paddies are one of the most important sources of N_2O emissions, along with CH_4. Storage of bovine manure and biomass combustion also emit N_2O and the latter accounts for about 6%-12% of the N_2O emissions from agriculture[12]. Direct emission of N_2O occurs through nitrification (aerobic conditions) and denitrification (anaerobic conditions) reactions in which chemical fertilizers (both synthetic and organic) and biologically fixed nitrogen are broken down. In addition, organic manures, crop residues, grazing animals, and soil N mineralization also contribute to N_2O emissions. Indirect N_2O emissions occur from leaching and runoff of N from N-fertilized soils as well as volatilization of NH_3 and NO_x from N additions and the subsequent redeposition of these gases and their derivatives, NH_4 and NO_3, to soils.

Overall, managed soils contribute between 35% and 86% of agricultural N_2O emissions, depending on the region[49]. Countries such as Brazil, China, and India emit significant amounts of N_2O[48], mainly because of the large area under paddy cultivation in these countries. Puddled rice accounts for 18% of India's total agricultural GHG emissions[29]. Nitrogen fertilization and water management are two key determinants of N_2O flux from wetland paddy soils[50], in addition to the form and mode of fertilizer-N application[51]. Denitrification losses in India were predicted to range from 4 to 1600 g N ha^{-1} depending on the supply of nitrogen, the soil, the crop, water management (in rice), and the application of nitrification inhibitors[52].

Bhatia *et al.*[29] prepared a state-wise inventory of N_2O emissions from agricultural soils in India for the year 2007, using the IPCC national inventory preparation guidelines[44]. Total N_2O-N emissions (1980-2007), according to them, ranged from 50,000 to 138,000 tons per year. The GHG Platform dataset shows that the N_2O emissions in India have been increasing [Figure 2], and in 2015 it was about 52 $MtCO_2e$. The annual direct and indirect N_2O-N emissions from Indian agricultural soils were estimated to be 118,670 tons (55.5 $MtCO_2e$) and 19,480 tons (9.1 $MtCO_2e$), respectively[29]. Inorganic fertilizer use has resulted in a 176% rise in N_2O emissions from agricultural soils in India (1980-2007); in 2007, 13.77 Mt of inorganic nitrogenous fertilizers were used, which accounted for 69% of the total N_2O emissions[29]. Fertilizer-induced N_2O-N emissions are predicted to rise further as more chemical fertilizers are likely to be applied to croplands to meet the growing population's food demands.

Soil pH and cumulative N_2O emissions have a negative linear relationship, and liming acidic soils to neutrality reduces N_2O emissions[53]. According to Žurovec *et al.*[54], limed plots emit up to 39% less N_2O than the unlimed control. Liming improved the efficiency of N_2O reduction, the final step in the denitrification pathway (i.e., conversion of N_2O to N_2). When soil pH falls below 6.8, it impedes N_2O reduction[53]. Mineral N fertilization-induced soil acidification also adversely affects N_2O reduction, leading to increased N_2O emissions[55]. Therefore, N fertilizer type and application rates are important determinants of N_2O emissions, which are modulated by soil conditions[56]. The use of ammonium sulfate, rather than urea, reduced N_2O emissions[57]. Likewise, no-tillage decreased soil pH[58] and promoted N_2O emissions by slowing down N_2O reduction.

Field burning of agricultural crop residues (see Section "Biomass burning" and [Figure 2]) is another major source of N_2O emissions in India, accounting for roughly 10% of total N_2O emissions (base year: 2007), according to Bhatia *et al.*[29]. The total quantity of residues burned in the country was estimated to be 92.86 Mt[29], resulting in the release of 7890 tons of N_2O[5]. According to Bray *et al.*[59], in 2016 and 2017, N_2O emissions from agricultural residue burning during April-May in the Indo-Gangetic Plains (IGP) ranged from ~81 to 562,000 kg day^{-1} (standard deviation ± 92,000 kg day^{-1}), while N_2O emissions during October-November ranged from ~0.32 kg day^{-1} to $2.68*10^6$ kg day^{-1} (standard deviation ± $2.87*10^5$ kg day^{-1}), implying wide variability in the amount of crop residues burned as well as the associated N_2O emissions.

Fertilizer management

Fertilizer production and application to farmlands are two processes that emit substantial amounts of GHG. The manufacture of N fertilizers is a very fossil fuel-intensive process; natural gas is the main fuel and feedstock used by the fertilizer industry in India and represents 27.84% of the country's natural gas use[5]. Synthetic N fertilizer production in India increased nearly 500-fold from 28,900 tons in 1950-1951 to 13.72 Mt in 2019-2020[60]. In 2016, the Indian fertilizer industry accounted for 6.01 $MtCO_2$ equivalent (13.49% of CO_2e emissions from the manufacturing and construction sectors[5]). However, emissions related to fertilizer manufacture are often not reckoned in AFOLU sector emission databases (e.g.,[7]), although fertilizer consumption does figure into that. Fertilizer consumption in India also increased nearly 75-fold between 1961 (249,800 tons) and 2019 (18.86 Mt[61]). The total N_2O emission (CO_2e) caused by synthetic N fertilizers in India in 2015 was 51.98 $MtCO_2e$ of N_2O [Figure 2] or 167,680 tons of N_2O[7], and it has been mostly increasing since 2005 [Figure 2].

Increased fertilizer consumption also causes increased losses of reactive nitrogen (Nr) species, as demonstrated by the rising annual emission levels of ammonia (NH_3), which is the primary fertilizer-related atmospheric Nr loss. Indian agriculture emits 4.73 Mt of NH_3 per year and has shown a growing trend in the last six decades[62].

Overall, GHG emissions from fertilizers in India have been increasing, and they are expected to increase further in the coming years if chemically intensive agriculture continues to advance and if India can produce all of the synthetic N fertilizer it requires[63]. Many researchers have also shown that N_2O emissions from agricultural soils are proportional to the N application rates[64-66], implying that higher application rates contribute to greater emission levels. The problem is exacerbated by the low use efficiency of applied N in soils[52]. Sutton *et al.*[67] reported that, for the global food system, including crop and livestock production systems, the use efficiency of applied N is only around 15%.

The major determinants of N_2O flux from soils are the amount of N fertilizer applied, its source, timing, crop type, soil pH, soil texture, climate, soil organic matter content, and fertilizer placement[68-70]. In India, cereal production accounts for roughly 70% of total fertilizer-N use[71], and the input-intensive rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system (RW) in the northwest IGP accounts for 95%-98% of the fertilizer-related emissions[72]. Level of N fertilization and water management are indeed the main factors influencing N_2O emissions[50], especially in systems such as RW, where fertilizer N is frequently applied based on blanket recommendations, implying either under-fertilization or over-fertilization and increasing N_2O emissions[65].

Biomass burning

Forest fires (Section "Major sources of GHG emissions and removals in the AFOLU sector of India"), burning of crop residues in the agricultural fields, deforestation, shifting cultivation, and fuelwood burning constitute the principal forms of biomass burning, all of which contribute to GHG emissions. On a global basis, forest burning is the major source of "fire emissions" due to its high carbon density, and the burning of agricultural wastes is the second most important source, representing nearly 2020 Mt (approximately 25% of the total biomass burnt[73,74]). However, fires on farmlands in the densely populated agricultural regions of China and India are on the rise[75].

Being an agrarian economy, India generates large quantities of agricultural waste, and the quantities of residues will rise in the future. Although crop residues are used as livestock feed, household fuel in rural areas, and industrial feedstock, a large proportion of it remains unutilized and is left in the fields. Its disposal is a major challenge, especially in the northwestern plain zone of the country, where the window available for sowing the winter (*rabi*) wheat crop after the harvest of the summer (*kharif*) rice is very small. Hence, to clear the field rapidly and inexpensively and to allow farm operations to proceed unhindered by the crop residues, the farmers burn the residues *in situ,* and such burning involves difficult trade-offs between environmental quality and economic gains[75].

Significant amounts of air pollutants are emitted when crop residues are burnt. CO_2, N_2O, CH_4, CO, NH_3, NO_x, SO_2, non-methane hydrocarbons, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and particulate matter such as elemental carbon are important in this respect[76,77]. Indeed, air pollution and the production of short-lived atmospheric pollutants have lately reached alarming rates in northwestern India owing to paddy straw burning in October-November. Field burning of crop residues accounts for 2.2% of the GHG emissions from agriculture in India[5].

Various estimates of crop residue burning are available in India, which vary profoundly depending on the crops considered, residue-to-grain ratio, and the fraction of residues burnt. Although IPCC[44] estimates that about 25% of the crop residues are burnt on-farm, Jain *et al.*[78] suggested that the fraction of crop residues burnt is variable and may range from 8%-80% for rice across the Indian states. The total amount of residue generated in India was 620 Mt, of which ~15.9% was burnt on farms[78]. The Ministry of New and Renewable Energy indicated that India generated 501.73 Mt of crop residues, of which 92.81 Mt were burnt[79]. In a more recent study, Ravindra *et al.*[80] showed that India produced 488 Mt of total crop residues during 2017, of which about 24% was burnt *in situ*.

Field burning of agricultural residues, according to Bhatia *et al.*[29], resulted in an annual emission of 250,000 tons of CH_4 and 6500 tons of N_2O. Jain *et al.*[78] reported that the burning of crop residues emitted 8.57 Mt CO, 141.15 Mt CO_2, 0.037 Mt SO_x, 0.23 Mt NO_x, 0.12 Mt NH_3, 1.46 Mt non-methane volatile organic compounds, 0.65 Mt nonmethane hydrocarbons, and 1.21 Mt particulate matter in 2008-2009. According to Bray *et al.*[58], NH_3, NOx, organic carbon (OC), and N_2O emissions from crop residue burning in the IGP are highly variable. Ravindra *et al.*[80] reported emissions of 211 Mt CO_2e of GHGs (CO_2, CH_4, and N_2O). Total CH_4 + N_2O emissions in 2015 due to residue burning were 6.16 MtCO_2e [Figure 2].

Crop residue burning has received a lot of attention recently because of its impact on seasonal air quality, especially in the IGP[78,81,82]. Numerous studies have shown that crop residue burning has adversely impacted the air quality of Delhi and the surrounding areas (e.g.,[83-85]). Seasonal biomass burning and the associated spike in black carbon aerosols have major consequences because of their propensity to absorb solar radiation and influence the climate[86,87]. Despite governmental efforts, through numerous campaigns designed to promote sustainable management methods such as converting crop residue into energy, there has been an alarming rise in air pollution levels caused by crop residue burning, especially in northern India in recent years.

Emissions from food wastage

India emits more GHGs from food waste than any other country except China and the USA[88]. Post-harvest losses accounted for about US $ 15.19 billion worth of food in India in 2014, according to Agarwal *et al.*[89]. Indeed, more than 40% of the agricultural produce is damaged before reaching consumers[90]. Of these, post-harvest loss of cereals from mishandling and lack of storage accounts for a major share. Highly perishable commodities such as fruits, milk, and vegetables are also wasted during post-harvest handling, primarily due to unhygienic handling and lack of cold chain facilities. Households in India also generate significant amounts of food waste. According to the Food Waste Index Report 2021[91], food wastage per capita in India is around 50 kg per year, which accounts for a total food wastage of 68.76 Mt per annum[6]. Such food wastes from households and eateries usually end up in landfills, emitting GHGs.

Practices to offset the carbon footprints of the Indian AFOLU sector

Enhancing the biomass and soil carbon stocks

The woody perennial components of agroforestry systems (AFS) exhibit tremendous potential for biological carbon sequestration (vegetation and soil). Kumar and Kunhamu[92], in a recent review, found that vegetation carbon sequestration aboveground in AFS in India ranged from 0.23 to 23.55 ton C ha^{-1} $year^{-1}$ and belowground (roots) varied from 0.03 to 5.08 ton C ha^{-1} $year^{-1}$, implying great variability in the carbon sequestration potentials (CSP) of AFS. The "diverse range of ecoclimatic conditions and the disparate array" of AFS and practices representing profound variability in species and management regimes explain such variations in CSP[93,94]. The Western Himalayan and the humid tropical AFS are generally characterized by higher CSPs than those in the arid and semiarid regions. Soil carbon C stocks (0-100 cm depth) also varied from 10.0 ton C ha^{-1} for the *Ziziphus mauritiana* + grass system in arid western Rajasthan to as high as 229.5 ton C ha^{-1} in the multistrata homegarden systems of Mizoram. In 2014, the government of India launched the National Agroforestry Policy (NAP) for conserving natural resources and forests, protecting the environment, and increasing the forest/tree cover[95], which aligns well with the national strategies for offsetting carbon emissions.

Enteric fermentation

To reduce livestock CH_4 emissions, nutritional strategies such as high cereal diets, biohydrogenation of unsaturated fatty acids, increased propionic acid production, protozoal inhibition, and supplementation with ionophores, fats, organic acid, probiotics, acetogens, and bacteriocins have been recommended[96]. Furthermore, research on developing vaccines against rumen methanogens and animal breeding and selection for inhibition of CH_4 production is underway; the outcomes of such efforts will have the potential to lower CH_4 emissions[96].

Livestock manure management

Storage and application of livestock excreta emit GHGs (CO_2, CH_4, and N_2O) as well as NH_3 and NO_3. Stockpile aeration[97], composting[98], and long-term covering of the stockpile with plastic films[99] can reduce CH_4 emissions. Adding urease inhibitors to manure stockpiles will stop or also reduce the rate at which urea in animal urine and manure is converted to N_2O[100]. Anaerobic digestion of manure is another approach to reducing GHG emissions. Injection of manure below the soil surface enhances direct N_2O emissions but reduces NH_3 emissions, resulting in an overall neutral effect on atmospheric emissions[101].

Inhibition of methane formation in wetland soils

About 20% of the CH_4 produced in rice soils is oxidized to CO_2 by the CH_4 oxidizing methanotrophs[102]. Soil water regimes are an important driver of CH_4 oxidation in rice fields[103]; alternate wetting and drying irrigation can significantly reduce CH_4 emissions. Since sulfate reducers and methanogens compete for the same substrates, sulfate amendment is another mitigation strategy to lower CH_4 emissions from rice fields. Indeed, the long-term application of sulfur-coated urea reduced CH_4 emissions from rice paddies[104]. Nan *et al.*[105] found that annual fresh biochar addition could reduce CH_4 emissions by 38%-41% in four years, owing to increased methanotroph populations. Likewise, ammonium fertilizer application stimulated methanotroph growth and CH_4 oxidation in the rhizosphere of rice-paddy soils[106].

Nitrous oxide emissions from agricultural soils

Globally, the use efficiency of exogenous N supply is very low, and the surplus N is susceptible to emission as N_2O. The development of site-specific nutrient management (SSNM) practices involving balanced NPK doses, timely fertilizer application using appropriate methods, development and application of slow-release nitrogen fertilizers and indigenous nitrification inhibitors, and integrated plant nutrient supply systems are important N_2O emission reduction strategies[51]. Combining nitrification inhibitors with urea, or substituting urea entirely with neem oil-coated urea, can dramatically reduce N_2O emissions in maize–wheat rotations in the upper IGP[107]. Intermittent flood irrigation for rice resulted in a small but statistically significant increase in N_2O emissions but decreased CH_4 emissions[108]. Conversely, Datta *et al.*[109] found that the integration of rice and fish production increased CH_4 emissions while lowering N_2O emissions, implying a trade-off. Coated urea increased the nitrogen use efficiency (NUE) of rice and was a good substitute for conventional fertilizer to minimize N_2O emissions[110].

Balanced N and P application with sufficient quantities of potassium and secondary and micro-nutrients will minimize N_2O emissions[65]. Indeed, N fertilizers constitute a major hotspot for mitigation in the RW production systems of northwestern India[111]. Improved N use efficiency and a shift away from synthetic fertilizers could reduce total fertilizer emissions. Consistent with this, experimental studies in Colombia showed that cumulative N_2O emissions from organic cassava production (1.28 kg N_2O-N ha^{-1}) were lower than those from inorganic fertilizer-based cassava production (1.74 kg N2O-N ha^{-1}) systems[112].

Crop residue management

Trend analysis using a BAU model showed that emissions from crop residue burning will increase by 45% in 2050 from the base year of 2017 in the northwestern regions of India[80]. However, the crop residues can be put to various productive uses, such as incorporation in the crop fields. Crop stubbles, if managed properly, have the potential to provide enormous economic benefits to farmers while also protecting the environment from pollution. It can be used as a feedstock for energy production in biomass power plants and has the potential to generate ~120 TWh of electricity, according to Ravindra *et al.*[80]. The use of crop residues as a feedstock for energy production, composting, biochar production, and mechanized farming practices[80,113] are a few effective techniques that can resolve the vexed problem of field burning of crop residues while also fostering soil nutrient recycling.

Cultivated soils as a carbon sink

There are 126 million small and marginal landholdings in India, representing 86.5% of the total operational holdings, cultivating over 74 million ha of land and meeting 50%-60% of India's food requirements[114]. According to Nath *et al.*[115], smallholder plots contain 1370-1770 MtC in the soil, which can be augmented to 2460-2650 MtC by 2050 by adopting best management practices (BMPs) such as balanced nutrient/compost application, agroforestry, conservation agriculture, etc. Adoption of BMPs on a large scale will augment the sink strength of agricultural soils and increase C sequestration by 70-130 $MtCO_2e$ per year[115]. To further accelerate this benefit, the "4 per mille Soils for Food Security and Climate (4p1000)" initiative was adopted at the COP21 in Paris (2015), with the goal of making agriculture a solution to climate change while also increasing food and nutritional security[116]. The 4p1000 represents an aspirational goal to augment global soil organic matter (SOC) stocks by 4 per mille or 0.4% per year as compensation for global anthropogenic GHG emissions. Apart from being a feasible alternative for reducing CO_2 levels in the atmosphere, soil carbon sequestration offers many co-benefits, such as improved crop productivity by enhancing SOC in degraded soils, increased input use efficiency, and improved soil quality. While as a strategy for climate change mitigation, SOC sequestration has merits, progress in 4 per mille requires collaboration and communication among multiple stakeholders such as scientists, practitioners, non-government organizations, the private sector, and policymakers[117]. There are also numerous biophysical, socioeconomic, and political barriers[117] to augmenting SOC stocks, which need to be overcome by region-specific actions and the development and implementation of innovative technologies.

Pathways and scenarios towards sustainable development

The total emission levels of India will increase, given its developmental aspirations. However, our ARIMA model forecasts for 2070 show that, in a business-as-usual scenario, AFOLU sector CO_2e emissions increased only slightly (10.5% with a projected per capita emission of 0.21 tons) from the 2015 levels (0.19 tons). Despite the importance of energy transitions and decoupling economic growth and resource use from GHG emissions, AFOLU is arguably the best-bet, cost-effective choice for India to become a net carbon sink. India's plans to achieve a net-zero carbon footprint by 2070, therefore, should refocus attention on the AFOLU sector as a vital mechanism for both mitigating and adapting to climate change. Indeed, the AFOLU sector has the potential to create large natural CO_2 reservoirs through ecorestoration of degraded forests, afforestation programs, and agroforestry. Being low-cost options, agroforestry and other ecorestoration programs hold considerable importance in the national climate change mitigation debate.

Table 1 and Figure 3 present four probable scenarios for India's AFOLU sector, as well as the corresponding emission reduction strategies. The ARIMA model implies an emission reduction of 21%-42% relative to the BAU scenario [Figure 3]. The "moderate" scenario (emissions 10% below BAU) will, however, necessitate an increase in forest cover of 3%-4% above the current level of 21.71%[14]. Any further increase in forest cover to 33% of the land area ("ambitious" scenario) might necessitate land-sharing options that integrate agriculture and forestry, which benefit both emission reduction and food security.

Interventions to prioritize climate-smart agriculture and precision farming, sustainable animal husbandry, and the use of green energy in agriculture are also important because they can provide both mitigation and adaptation options. To foster community support, it might require optimal investments. Simultaneously, strategic and policy initiatives to minimize emissions from rice fields and livestock production systems are required. Through better water and nutrient management (e.g., alternate wet and dry treatment, direct seeding of rice in upland situations, and the system of rice intensification), a 2% reduction in CH_4 emissions from rice farming is attainable. Crop improvement, in conjunction with sustainable land management approaches such as conservation agriculture and management practices to improve nutrient and water use-efficiency, can help to further reduce agricultural emissions.

Higher efficiency and productivity of the livestock sector, focusing on feed management and breeds with high feed to protein conversion efficiency and reduced methane emissions, have already started receiving research attention. Under the moderate emission scenario, nutrition and feeding approaches may be the most appropriate to reduce a further 5% emission from current levels of enteric fermentation in tropical conditions without compromising milk production[118].

Eliminating residue burning and forest fires requires awareness creation among the farmers and forest-dwellers. In the case of biomass burning emissions, a 50% reduction is possible through *ex situ* utilization of crop stubbles for composting and other uses. To achieve a 100% reduction in biomass burning, *ex situ* strategies may work in the case of crop residues, but, to mitigate forest fires, a combination of strategies such as early warning systems for the control of forest fires using modern technological tools and community participation would be needed.

Based on the FAO's food waste emission factor of 2.5 ton CO_2e ton^{-1}[10], India's emission from food waste works out to 172 MtCO_2e per year. Avoiding the wastage of agricultural produce will not only alleviate the shortage of food supply but also eliminate emissions due to the need to cultivate additional crops to make up for food shortages. To achieve a higher level of sustainability, agri-food waste valorization pathways (e.g., biofuel production and composting) must be explored, which would offset emissions from this source[119], apart from reducing the food waste.

The strategies discussed above will probably act as a benchmark for other developing regions to plan or reframe their emission reduction strategies. Nonetheless, relying too much on planting trees or protecting forests or farmlands to absorb emissions *vis-à-vis* the green transformation of India's electricity and industrial sectors can jeopardize the country's path towards net-zero emissions.

LIMITATIONS OF THE STUDY

According to the GHG platform[7] database, India's AFOLU sector emissions increased only modestly from 2005 to 2015, despite the country's total anthropogenic GHG emissions increasing almost linearly (1970-

Table 1. Possible AFOLU sectoral emission scenarios, corresponding strategies, and model predictions based on ARIMA modeling on time-series data of Dhingra *et al.*[7]

Scenarios	Description	Strategies	Predicted emission levels in 2070 ($MtCO_2e$)
No regret	Business as usual (BAU)	No significant change in policies or any major changes in the management of forests and croplands	323
Moderate	Emissions 10% below BAU	25% of the total geographical area under forest cover: agroforestry, no shifting cultivation 5% lower emissions from enteric fermentation from the 2015 level	253
Co-benefits	Emissions 20% below BAU	30% of the total geographical area under forest cover: agroforestry, no shifting cultivation 8% lower emissions from enteric fermentation from the 2015 level 2% less emission from rice farming from the 2015 level 50% reduction in biomass burning	235
Ambitious	Emissions 40% below BAU	33% of the total geographical area under forest cover: agroforestry, no shifting cultivation 15% lower emissions from enteric fermentation from the 2015 level 5% less emission from rice farming from the 2015 level Emission from manure management was reduced by 2% from the 2015 level 100% reduction in biomass burning	189

The National Forest Policy, 1988 (India) envisages having 33% of its geographical area under forest cover, and agroforestry is a strategic option to achieve it[95]. Emissions from rice paddies decreased by 1%-10% under climate-smart agriculture[122]. Improved irrigation, higher fertilizer use efficiency, and high-yielding rice varieties may reduce global methane emissions by ~10 %[123]. Lower enteric CH_4 emissions of up to 15.7% from dairy cattle are possible through management interventions[124]. A reduction in biomass burning can reduce agricultural emissions[113].

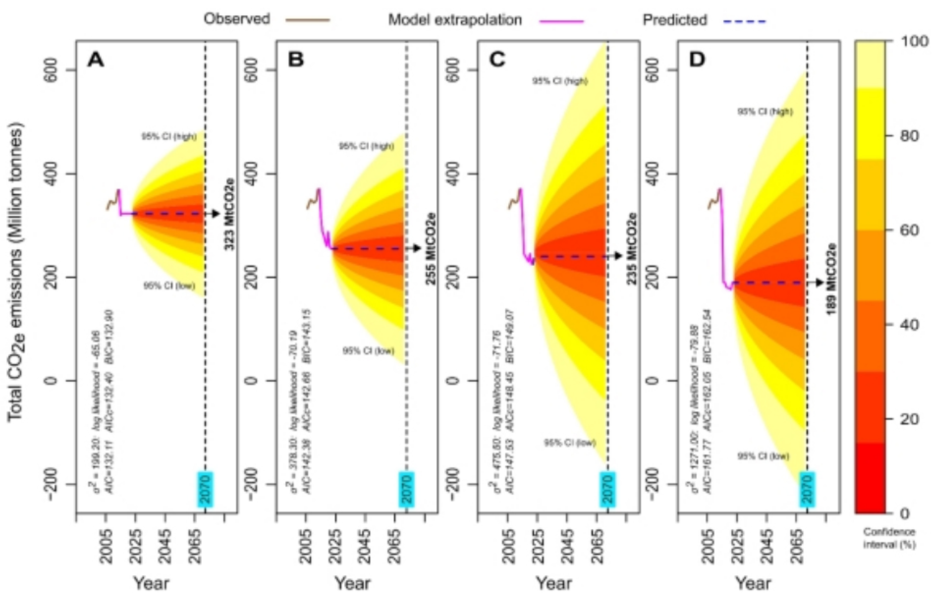

Figure 3. India's AFOLU sector GHG emissions (CO_2e): observed (2005 to 2015) and predicted (2015 to 2070) emission levels. The autoregressive integrated moving average (ARIMA) model was used for the projections under different scenarios: (A) business as usual (BAU) scenario, no new policies and few strategies for emission reduction; (B) moderate, emissions 10% below BAU (25% forest cover and 5% reduction in enteric fermentation); (C) fairly beneficial, emissions 20% below BAU scenario (30% forest cover, 8% reduction in enteric fermentation, 2% reduction in emissions from rice farming, and a 50% reduction in biomass burning); and (D) ambitious, emissions 40% below BAU scenario (33% forest cover, 15% reduction in enteric fermentation, 5% reduction in emission from rice farming, and 100% reduction in biomass burning). All emission reduction targets mentioned above are based on the 2015 emission data[7].

2018)[4] and the global AFOLU emissions increasing by 0.8% per year since 2000[120]. The ARIMA model projections, which rely on the GHG platform database[7], also showed only a modest increase until 2070

[Figure 3]. Implicit in this are certain uncertainties in the GHG Platform (AFOLU sector) emission data. Such uncertainties associated with historical GHG emissions estimates are not unusual, and they are also much higher for AFOLU CO_2 emissions than in other sectors. For example, Friedlingstein *et al.*[121] in the Global Carbon Budget reported uncertainties of AFOLU CO_2 emissions of around 46% for the 2009-2018 period. Lamb *et al.*[120] also assumed ± 50% uncertainty for AFOLU CO_2 emissions with a ± 60% uncertainty for N_2O emissions.

Furthermore, the proportion of AFOLU sector emissions to total Indian GHG emissions (8%) is lower than the global average (~25%). This raises questions about the boundaries and the accounting system used in the GHG platform database of Dhingra *et al.*[7]. The GHG platform database disregards certain segments of the AFOLU sector emissions, signifying its truncated nature. For example, subsectors such as the manufacture of chemical fertilizers (or other inputs), fossil fuel consumption for operating agricultural machinery on farmlands, and food waste (from post-harvest handling and storage to household wastages), although substantial, have been disregarded in this database. Experience shows that following narrowly defined estimation protocols will generally lead to large underestimates of carbon emissions for providing products and services. Therefore, approaches based on comprehensive environmental life-cycle assessment methods that are available to track total emissions across the entire supply chain are necessary. The carbon footprints of the Indian AFOLU sector should ideally be derived from all relevant subsectors, and the efforts to reduce the carbon footprints should also encompass all these sectors, which calls for more rigorous efforts on GHG data compilation to create robust databases. There are large hidden C costs of all inputs, which need to be reflected in the databases. Research on cross-cutting themes and participating in national and international assessments to evaluate past, current, and likely future scenarios of global change and their impacts would also be desirable.

CONCLUSIONS

The AFOLU sector represents one of the low-cost strategies for attaining net-zero emissions by 2070 in India. Agroforestry and other tree-based land-use systems, improved livestock feed management (for reducing enteric fermentation), and soil health maintenance through better soil management, as well as methane avoidance strategies (manure management and wetland paddy soils) and crop residue and food waste valorization (including bioenergy), have the potential for lowering carbon footprints. What still needs to be done in the AFOLU sector of India for it to become carbon negative are to reduce emissions from land-use change, land management and livestock management, augment the terrestrial carbon stocks by sequestration in soils and biomass, reduce emissions from energy production through the substitution of fossil fuels by biomass, and offset emissions from food wastes. Although anthropogenic forest degradation is a global issue, the Indian forest resource base has stabilized. Increasing the extent of natural forests in India from the current level, however, may be a challenge in view of the competition between different land uses and the need for food grain production to meet the rising demands. However, agroforestry, a sustainable land use activity, can augment the tree cover on agricultural lands and improve the terrestrial carbon stocks by sequestration in soils and biomass. Reforestation and afforestation activities on the degraded landscape also aid in this process. Biomass burning (agricultural burning and forest fires) is widespread in several parts of India and calls for proactive measures (e.g., using agricultural residues for biomass energy production) to counter them. However, land-related mitigation, including bioenergy, needs policy coordination, and implementation issues are challenging. Likewise, a national integrative management policy for reducing food waste during the "farm-to-fork cycle" would have multiple positive outcomes in terms of resource conservation, income, and emission reduction.

DECLARATIONS

Authors' contributions

Made contributions to the conception, the collection of literature, and the first draft: Kumar BM
Provided additional inputs including the ARIMA model predictions: Aravindakshan S

Availability of data and materials

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Conflict of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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Consent for publication

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