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The role of food and land use systems in achieving India's sustainability targets

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Abstract

The food and land use sector is a major contributor to India's total greenhouse gas (GHG) emissions. On one hand, India is committed to sustainability targets in the Agriculture, Forestry and Other Land Use (AFOLU) sectors, on the other, there is little clarity whether these objectives can align with national developmental priorities of food security and environmental protection. This study fills the gap by reviewing multiple corridors to sustain the AFOLU systems through an integrated assessment framework using partial equilibrium modeling. We create three pathways that combine the shared socio-economic pathways with alternative assumptions on diets and mitigation strategies. We analyze our results of the pathways on key indicators of land-use change, GHG emissions, food security, water withdrawals in agriculture, agricultural trade and production diversity. Our findings indicate that dietary shift, improved efficiency in livestock production systems, lower fertilizer use, and higher yield through sustainable intensification can reduce GHG emissions from the AFOLU sectors up to 80% by 2050. Dietary shifts could help meet EAT-Lancet recommended minimum calorie requirements alongside meeting mitigation ambitions. Further, water withdrawals in agriculture would reduce by half by 2050 in the presence of environmental flow protection and mitigation strategies. We conclude by pointing towards specific cstrategic policy design changes that would be essential to embark on such a sustainable pathway.

1. Introduction

India's CO_2 emissions as a share of global emissions nearly doubled from 3.5% in 1997 to 7% in 2017 (Global Carbon Project 2020). The country is committed to reduce the emissions intensity of GDP by 33%–35% by 2030 from 2005 levels. More recently it has announced plans to reduce net emissions to zero by 2070 (MoE 2021). On the other hand, India faces the challenges of a growing economy and population which is projected to further grow up to 1.6 billion by 2050 (ONU 2017). This is poised to increase the challenges of ensuring food security and minimizing environmental disruptions such as loss of natural habitats, invasive alien species, land degradation and overexploitation of forests and fisheries (MoEF 2014). Additionally, climate change is expected to severely impact crop production and thereby, food security (IPCC 2014, Nadagoudar 2016, Eckstein *et al* 2019).

Any major economy-wide greenhouse gas (GHG) emissions reduction strategy will need to have the food and land-use sector in focus given its significant potential towards mitigation. Land-use is a central factor in achieving several sustainable development goals (SDGs) (UNDESA 2019), such as SDG2 (zero hunger), SDG7 (affordable and clean energy), SDG12 (responsible consumption and production), SDG13 (climate action) and SDG15 (life on land). One of the major challenges for India is to not only achieve the zero hunger (SDG2) target but also secure a sufficient and nutritious diet for its increasing population. Meeting the zero-hunger target can have direct trade-offs with SDG12, SDG13 and SDG15 thereby making it difficult to assess the possibilities of achieving these targets.

The real challenge in the AFOLU sector is to judiciously determine the trade-offs and synergies among different sub-sectors that are highly interlinked with complex relationships. This interaction impacts water availability, livestock feed and emissions simultaneously. Majority of the scientific assessments aimed at measuring sustainability in the sector often address targets in isolation and lack a multi-sectoral approach (Obersteiner *et al* 2016). Hinz *et al* (2020) analyzed pathways to productivity in agriculture, land use and land-cover changes in India and predicted that future food demands can be met either through extensive cropland expansion or agricultural intensification, with biodiversity losses being higher in the former. Mythili and Goedecke (2016), however, caution that arable land degradation poses severe limitations on agricultural intensification. They estimate that about 44% of the country's land area is lost to agriculture due to overuse of agrochemicals, mismanagement of irrigation, and natural hazards. This has become all the more relevant in light of the Covid-19 pandemic that has put additional strain on economic resources, thereby bringing about spiraling effects on food systems with an indirect implication on natural resources (Harris *et al* 2020, Kumar *et al* 2020). These notwithstanding, very little information is available on pathways to achieve AFOLU sustainability goals in harmonization with economic development and climate change.

To fill this gap, we adopt an integrated assessment approach by using a spatially explicit, recursive dynamic land-use optimization Model of Agricultural Production and its Impacts on the Environment (MAgPIE) (version 4.1) (Lotze-campen *et al* 2008, Dietrich *et al* 2019) that analyzes dynamic changes related to land use, food systems and associated environmental trade-offs (Prestele *et al* 2016, Alexander *et al* 2017, Li *et al* 2017). Details on model description are presented in section 1 of the supplementary material. For India, some studies have used land-use models to assess the effects of biofuels on land-use change (Ravindranath *et al* 2011, Schaldach *et al* 2011, Das 2020), and crop productivity (Hinz *et al* 2020). Other global studies with India as a sub-region have evaluated the effects on biodiversity (Newbold *et al* 2016, Delzeit *et al* 2017, Kok *et al* 2018), and carbon storage (Eitelberg *et al* 2016, Molotoks *et al* 2018). However, to the best of our knowledge, this is the first comprehensive integrated assessment being undertaken in India to determine the impact of climate change scenarios and socio-economic drivers on agricultural production, GHG emissions, agricultural water use and international trade.

We build upon shared socio-economic pathways (SSPs) (O'Neill *et al* 2017) to construct three specific trajectories for the food and land-use systems in India by 2050. The synergies and trade-offs between various environmental and development goals are further identified and the possibilities for meeting targets and India's pledge under the Paris Agreement are demonstrated. The focus is restricted to five key indicators such as GHG emissions, land-use change, food security, water use and food self-sufficiency consistent with of SDG2, SDG7, SDG12, SDG13 and SDG15.

2. Methods

The MAgPIE model (Lotze-campen *et al* 2008, Alexander *et al* 2017, Dietrich *et al* 2019) integrates spatially explicit biophysical factors such as land availability, potential crop yields, and available water into an economic decision-making process with population, economic growth and climate change scenarios as exogenous drivers (figure 1 in SM). The model's objective function is to fulfill the demand for crop, livestock, and material products from agriculture at minimum cost and under certain socio-economic and biophysical constraints. MAgPIE operates most of the economic constraints (e.g. trade, investments in technological change, cost structures, etc) on a level of 12 world regions. India is modeled as a separate world region and as such is used in this study. MAgPIE optimizes agricultural produce, land-use configurations, irrigation water use and variations in carbon stock (e.g. under a mitigation policy) at a spatially explicit level (figure S2 in SM). As a first step, biophysical information at $0.5° \times 0.5°$ resolution is fed to MAgPIE from the international hydrology and crop model—Lund–Potsdam–Jena managed land (Bondeau *et al* 2007). These inputs are then aggregated into spatial clusters which are characterized by similar biophysical conditions for agriculture and serve to facilitate the non-linear optimization program.

The MAgPIE model endogenously determines optimal patterns of agricultural land use for cropland (rainfed and irrigated), pastures, forest, and other natural vegetation, as well as optimal investment rates in yield-increasing technological change (i.e. production intensification), and international trade flows. Future trends in food demand are computed as a function of GDP per capita based on a cross-country regression (Bodirsky *et al* 2015). The dietary patterns account for changes in intake and food waste, share of plant and animal-based calories and their shifts, staples and processed products as well as fruits and vegetables (Weindl *et al* 2017, Bodirsky *et al* 2020).

Table 1. Key assumptions of current trend, current + EAT and sustainable pathways.

Scenarios	GDP	Population	Food demand (diet)	Climate change	Mitigation effort
Current trend	SSP2	SSP2 (1.73 billion by 2050)	SSP2	RCP 6.0 (likely 3 °C–4 °C in 2100)	Low mitigation
Current + EAT	SSP2	SSP2	EAT-Lancet	RCP 6.0 (likely 3 °C–4 °C in 2100)	Moderate mitigation (demand side)
Sustainable	SSP1	SSP1 (1.55 billion by 2050)	EAT-Lancet	RCP 2.6 (likely 2 °C in 2100)	High mitigation (demand and supply side)

Food demand in the model is based on historical food intake of the population that is also projected based on a regression over incomes. This regression estimates the actual food demand compared to food intake. Food intake in the model accounts for existing body mass index (BMI) distribution of the population, intake by BMI groups with the inclusion of pregnant and lactating women and the population's demographic characteristics. Food demand is entered as a constraint in the model which aims to fulfill this demand through the production and trade of agricultural commodities in every time step. International trade in the model occurs after meeting regional minimum self-sufficiency requirements, implying that some part of the food demand in every world region is produced domestically.

Technological change drives sustainable intensification to increase the production to meet domestic demand in the model. Technological change is an endogenous process which accounts for the increase in crop yields through R&D investment (Dietrich *et al* 2014). The remaining production is allocated internationally based on comparative advantages. The supply of livestock-based food products is divided into five livestock production systems such as ruminant meat, pig meat, poultry meat, eggs and milk. The demand for feed in the model is determined by the quantity of livestock production as well as regional and livestock-specific feed baskets (Weindl *et al* 2017). Livestock productivity change in the model is exogenous and based on the SSP storylines (O'Neill *et al* 2017, Popp *et al* 2017). Food price index in the model follows the Paasche price index by weighing current prices based on food baskets in the same period (Stevanovic *et al* 2017). Food prices are determined by shadow prices that are calculated using regional food demand constraints. In economic terms, shadow prices are the costs of production of an additional unit of output and are used to determine the marginal increase in costs as production increases. Various settings and assumptions within the model allow us to undertake the relevant analysis for India (section 2 in SM).

Among possible futures until 2050, we analyze three alternative pathways to guide AFOLU systems in India towards sustainability: (a) current trend, (b) current trend alongside dietary shift towards EAT-Lancet nutritional guidelines (Willett *et al* 2019), named as Current + EAT, and (c) an ambitious Sustainable pathway, as presented in table 1 below. These scenarios evaluate the different possible futures with varying policy contexts. We take SSP2 (Popp *et al* 2017) as the basis for current trend pathway, which is also referred to as 'middle-of-the-road scenario' for future socio-economic developments. We make similar assumptions for key parameters such as income, population, food demand and environmental protection. Under the Current + EAT pathway we assume that food demand transitions towards the recommendations of the EAT-Lancet Commission and use this scenario to identify the gains that can be had from shifting towards healthier diets solely. In the sustainable pathway, main assumptions follow SSP1, which is defined as a 'green road' with higher income per capita and slower growth in population, progressive environmental protection and faster technological change. The sustainable pathway is highly ambitious in meeting the national sustainability objectives, extending upon SSP1 (e.g. dietary shifts, afforestation target and bioenergy demand beyond SSP1).

The analysis is undertaken using representative concentration pathways (RCPs) which are a set of alternative trajectories for the atmospheric concentration of GHGs (van Vuuren *et al* 2011). These RCPs when coupled with a set of SSPs provide an opportunity to include pathways of future societal development. SSPs can be linked to climate policies in the form of RCPs to generate different radiative forcing outcomes for the end of the century. The SSP2 parameterization is assumed to follow the historical trend and represent medium challenges for mitigation and adaptation due to embedded social economic profiling and environmental policies. Several studies have found RCP 6.0 to be the most compatible with socio-economic dynamics of SSP2 (Riahi *et al* 2017). Similarly, to match the compatibility of sustainability parameters embodied under SSP1 scenarios and stringent climate mitigation targets, we couple SPP1 to RCP 2.6 which has a climate sensitivity of approximately 2 °C in 2100 (O'Neill *et al* 2020).

In the current trend pathway, the population of India is expected to grow by 24.8% by 2050. In this pathway, there are limitations imposed upon agricultural land expansion based on Bonn Challenge commitments that increases afforestation to 21 million hectares (Mha) by 2030. Moderate increases in crop productivity are also assumed. Projected future according to this pathway follows current policies with regards to food demand, moderate GDP growth as well medium investment costs to increase yields (Government of India 2015, ICAR 2015, NCAER 2015, MoAFW 2017, 2018, FAO 2019, FSI 2019). This pathway is also embedded with moderate mitigation strategies to minimize the impact of climate change, such as low environmental and biofuel ambitions. Dietary patterns tend towards increased animal proteins consistent with the SSP2 framework (O'Neill *et al* 2017). The Current + EAT pathway is an extension of current trend to include recommendations of the EAT-Lancet Commission (Willett *et al* 2019). These recommendations are prepared within the planetary boundaries framework and identify ranges of intake of certain food groups to manage human health as well as environmental sustainability (table 1 in SM). The mean global temperature increase is restricted between 3 °C and 4 °C by limiting the radiative forcing level of 6.0 W m^{-2} (RCP 6.0) under both the scenarios.

In the sustainable pathway, SDGs are considered a priority and the policy landscape is favorable towards the attainment of these goals specifically: SDG2, SDG7, SDG12, SDG13 and SDG15 (UN *et al* 2019). Efficient technologies in agricultural production are incorporated and EAT-Lancet healthy diet scenarios are targeted. Population growth in this scenario is lower while afforestation targets are higher, as compared to the other scenarios (section 2 in SM). India's participation in the Paris Agreement and Bonn Challenge are accounted for. Other aspirational goals such as production and greater dependence on biofuels and higher technological change with lower costs of technology change are included. The sustainable pathway uses a global GHG concentration trajectory that aims to keep global warming below 2 °C above pre-industrial temperatures by 2100 (RCP 2.6) (van Vuuren *et al* 2011). Further, this pathway includes mitigation strategies in the form of GHG prices and second generation bioenergy demand (figure 3 in SM) to make our climate policies more ambitious. Model drivers and other assumptions across the scenarios can be seen in figure 4 in SM. The modeled scenarios are harmonized from the model initialization for the year 1995 till 2015, while different scenario policy setups are projected from the year 2020 onwards.

3. Results

3.1. GHG emissions

Under current trend, GHG emissions from AFOLU increases to 1115 Mt CO_2e yr^{-1} in 2030 and to 1550 Mt CO_2e yr^{-1} in 2050 (figure 1). Higher emissions under this scenario are mainly due to higher demand for livestock products (figure 5 in SM). In Current Trend + EAT, we find that GHG emissions from AFOLU increases to 908 Mt CO_2e yr^{-1} in 2030 and then decreases to 479 Mt CO_2e yr^{-1} in 2050. In 2050, the total AFOLU emission is less than 70% of that in current trend. The emission reduction primarily comes from the livestock sector (84%) and partly from crop related emissions (15%) due to the implementation of EAT-Lancet recommendations which drives a reduction in demand for dairy products and cereals.

Emissions reductions are highest in the sustainable pathway—748 Mt CO_2e yr^{-1} in 2030 and 336 Mt CO_2e yr^{-1} in 2050. Compared to current trend and Current + EAT the emission reduction under the sustainable pathway is nearly around 80% (1214 Mt CO_2e yr^{-1}) and 30% (761 Mt CO_2e yr^{-1}) respectively. The additional emissions reduction in comparison to Current + EAT is 453 Mt CO_2e yr^{-1} in 2050. The major driver for this additional reduction is increase in crop productivity and feed efficiency. Mitigation strategies in the form of GHG prices along with RCP 2.6 serve as punishment factors for emissions and thereby bring the overall emissions down.

3.2. Land-use change

Our results for land-use are classified under the following major types—cropland, forests, pastures, urban and other lands (figure 2). We find that overall cropland area increases by 17 Mha (11%) in 2030 across the scenarios in comparison to 2010. For current trend and Current + EAT, this increase is caused due to higher population growth and higher demand for agricultural products. Under the sustainable pathway, modest increase in cropland area is observed, due to higher bioenergy demand. The main increase in forest area occurs from the year 2020 until the target of additional 21 Mha under forests is achieved by 2030. Compared to 2030, the cropland area slightly changes in 2050 under the current trend (increased by 5 Mha) and under the sustainable (7 Mha). In the current trend and Current + EAT scenario, we find that the main land cover changes occur through increase in forest area and decrease in other lands. This increase in forest area is larger under the sustainable pathway due to the implementation of India's revised afforestation target of 26 Mha. Pasture area decreases by approximately 50% under the Current + EAT pathway in 2050 (in comparison to 2030) due to the lower demand for livestock products which is explained by the EAT-Lancet recommendations. For the same reasons, under the sustainable pathway, pastureland decreases by 38% in 2030 in comparison to 2010. It increases by 47% in 2050 in comparison to 2030 due to high export of livestock products (figure 6 in SM).

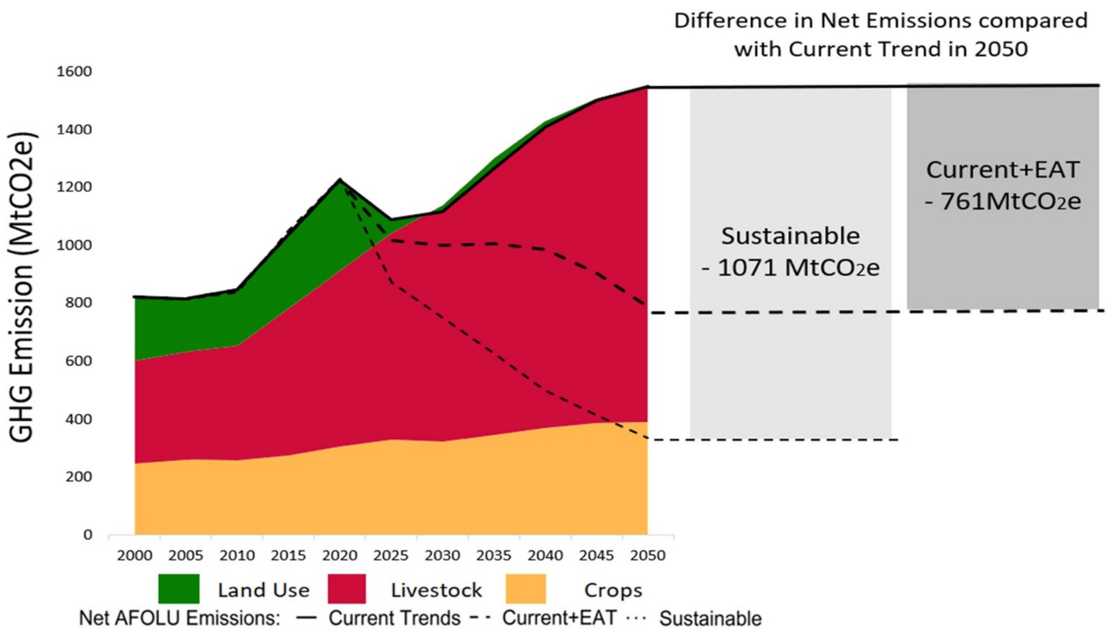

Figure 1. Projected GHG emissions (Mha) from (a) livestock, (b) crops, and (c) land use under the current trend, Current + EAT and sustainable pathways till 2050. The right-hand bar shows the total GHG emissions reduction under Current + EAT and sustainable scenario in comparison to current trend. The green area above the solid black continuous line shows the negative emissions from land use sector. Major drivers of emissions reduction under the Current + EAT and sustainable pathways are low demand for cereals and livestock products due to the implementation of recommendations of the EAT-Lancet Commission. In addition to that population growth, afforestation targets, sustainable intensification, bioenergy demand and pollution prices cause the additional reduction in emissions under sustainable pathway.

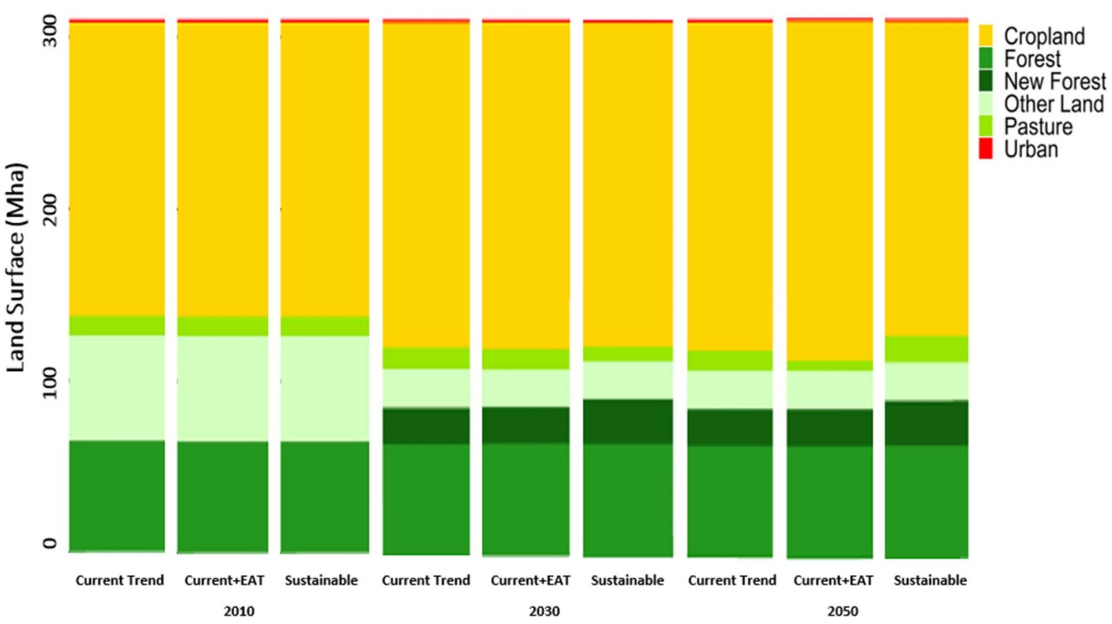

Figure 2. Projected land use (in Mha) from (a) cropland, (b) forest area, (c) other land, (d) pasture, (e) urban area in 2030 and 2050 under the current trend, Current + EAT and sustainable pathways. The dark green bar shows the additional forest area obtained due to the implementation of the Bonn Challenge (21 Mha) under the current and Current + EAT and revised afforestation target (26 Mha) under the sustainable scenario.

We observe that 'other land' area decreases by approximately 70% under the Current + EAT and sustainable pathways in comparison to current trend in 2030 and 2050 due the increase in new forest areas and cropland areas. The decrease in other natural vegetation land (figure 7 in SM) is projected till 2025 due to increased cropland and pasture area, as well as indirect increases of forests which displace arable land into other natural vegetation areas (figure 7 in SM). Consequently, the CO_2 emissions from land-use change increases till 2025 (figure 1) after which they decline to zero.

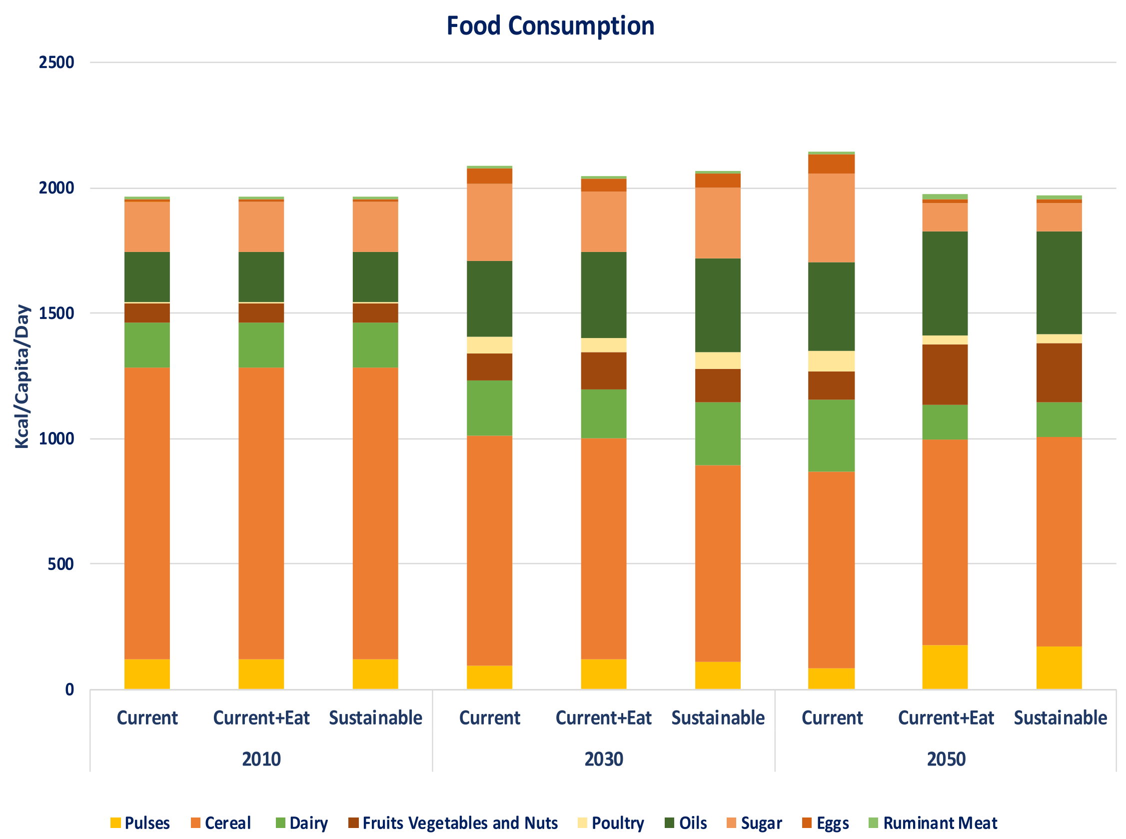

Figure 3. Projected calorie demand for major food groups under current trend, Current + EAT and sustainable pathways in 2030 and 2050. Food demand under the current trends is in the line of SSP2 and under the Current + EAT and sustainable pathways is in the line of recommendations of the EAT-Lancet Commission (Willet *et al* 2019). Food demand in the model is paired with business-as-usual population growth in the current trend and Current + EAT, and with low (SSP1) population growth in the sustainable pathway.

3.3. Food security

Food security in the model is measured by ability to meet food requirements of the population over time. Average food intake in the model mostly comprises cereals, sugar, oils, and animal products. Under the current trend, these food types represent 79% of the total nutritional requirements in 2030 and 76% in 2050. There is a projected increase in the consumption of dairy by 2050 and a decrease in the consumption of cereals between 2020 and 2050. In the other two pathways with EAT-Lancet diet recommendations, the overall dependence on pulses, fruits, vegetables and nuts, oils and other crops turn out to be high. In contrast, major reductions are observed in the consumption of dairy, eggs, and sugars in 2050 (figure 3) where intake of milk, fish, and sugars are almost halved of the consumption in current trend. Consumption of ruminant meats (beef, goat and sheep) forms a very small component of the total calorie consumption across all the pathways and very little change is observed. All pathways fulfill approximately 2000 kcal per capita per day food consumption requirements but there are differences in protein intake across them (figure 8 in SM). Protein intake from pulses is doubled in the Current + EAT and sustainable pathway as compared to the current trend in both 2030 and 2050, whereas protein intake from dairy and eggs is reduced by 50% and 70% respectively in 2050. These trends are in line with the recommendations of the EAT-Lancet Commission and demonstrate that nutritional security targets are attainable in the sustainable pathway. To this end, not all livestock production is consumed but is also exported (c.f. section 3.5). Food loss and waste (figure 9 in SM) is higher under the sustainable pathway despite our assumptions on low food wastage. This is due to the higher income levels and a mix of younger populations under SSP1, which is resulting in higher increases in calorie intake (figure 3 above). This could also arise out of the dietary shift towards fruits, vegetables, and nuts that are more prone to perishability and wastage (figure 10 in SM).

Impacts of changes in food demands across the scenarios and their feasibility can also be assessed using the food price index (figure 4). We find that the food price index is the highest under the sustainable pathway in 2050. While the immediate food prices under all the three scenarios are similar in 2025, there is a decline in the index under Current + EAT, ending in the lowest bracket by 2050. The increase in food prices is driven by both the demand and supply side scenarios. On the demand side we observe

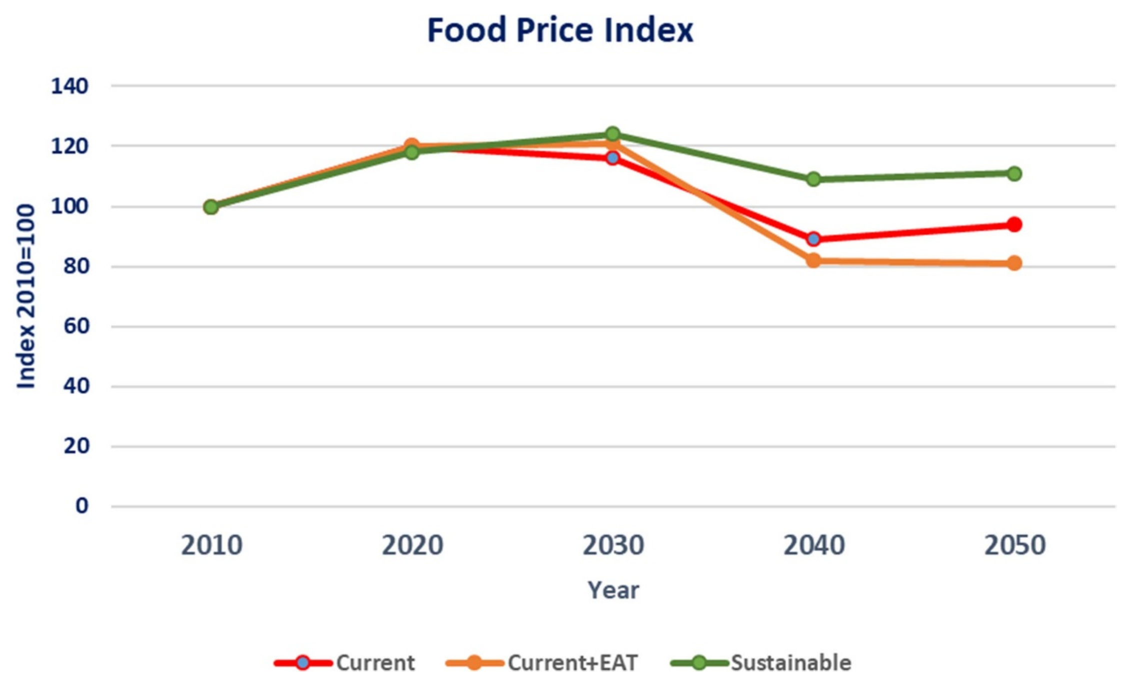

Figure 4. Changes in food price index between 2010 and 2050 under the (a) current trend, (b) Current + EAT and (c) sustainable pathway. Food price index in the model follows the Paasche price index by weighing current prices based on food baskets in the same period.

that demand for livestock products, mainly dairy, increases between 2020 and 2030 and then reduces afterwards. On the supply side, under the sustainable pathway, there are more restrictions on resources (e.g. environmental flows protection (EFP) policies related to irrigation water) and additional measures to reduce emissions, such as the biofuel policy and carbon taxes that increase the cost of agricultural production, thereby increasing the price of the food basket. By 2050, however, the food price index remains only a little above 2010 prices thereby suggesting that negative impacts of switching to the sustainable pathway are limited.

3.4. Water use

We observe that there is a decreasing trend in water use across all scenarios between 2010 and 2050 (figure 6). In the agricultural sector, 38% reduction in annual blue water[6] use between 2010 and 2050 is observed under both the current trend and Current + EAT pathways, while 63% reduction is observed in the sustainable pathway. Most reductions in water use are observed for rice, wheat and soybean across the three scenarios (figure 11 in SM). On the other hand, when EFP policies are implemented in the sustainable scenario, we observe a considerable reduction in the use of water for agricultural production (see figure 5). The inclusion of EFP policies and climate change impacts result in reduced agricultural water withdrawals by almost half by 2050 under the sustainable pathway. Carbon prices and second-generation biofuel energy demand further reduce water use in the sustainable pathway.

3.5. Self-sufficiency in agricultural products

Self-sufficiency in agricultural products is defined as a ratio of total domestic production over total domestic demand. A value of less than one implies the country is a net importer whereas values greater than one implies the country is a net exporter. We observe that India's self-sufficiency for major food groups remains less than one across all the pathways (figure 6). Under current trend, between 2020 and 2050, we observe that self-sufficiency declines for most products, except oils and fruits, vegetables and nuts. Under sustainable pathway, self-sufficiency falls marginally for pulses, fruits, vegetables and nuts, poultry, sugar and oils by 2050. This is likely due to changed food demand dynamics and additional demand side pressures of bioenergy demand. However, under the sustainable pathway, these additional pressures have a marginal effect on self-sufficiency of major food groups given low population, higher crop productivity and reduced climate impacts on crop production.

4. Discussion

The results from our integrated assessment modeling suggest that the increase in yields under the sustainable pathway not only helps to meet the increasing food demand but also helps reduce the pressure on land-use changes due to other demand-side factors

[6] Blue water is the water in surface and underground reservoirs and is the primary source of water in irrigated agriculture systems.

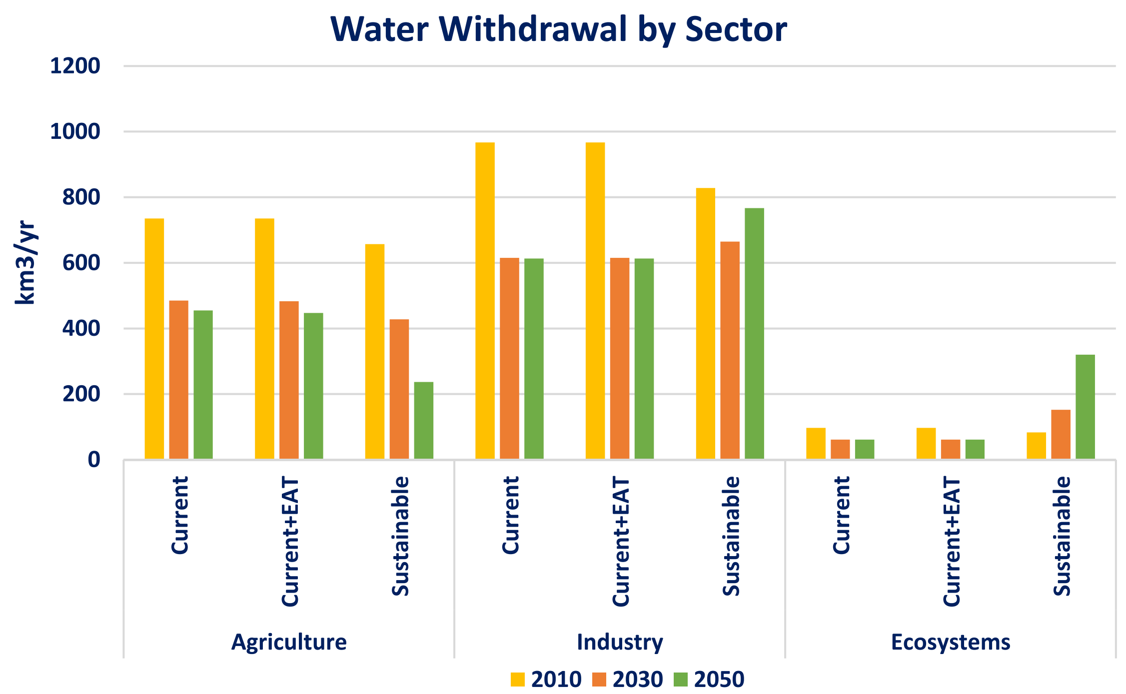

Figure 5. Trends in water withdrawals for different sectors under current trend, Current + EAT and sustainable pathways. Water withdrawals for agriculture includes crop production and livestock production systems. Environmental flow protection policies are incorporated only in the sustainable pathway.

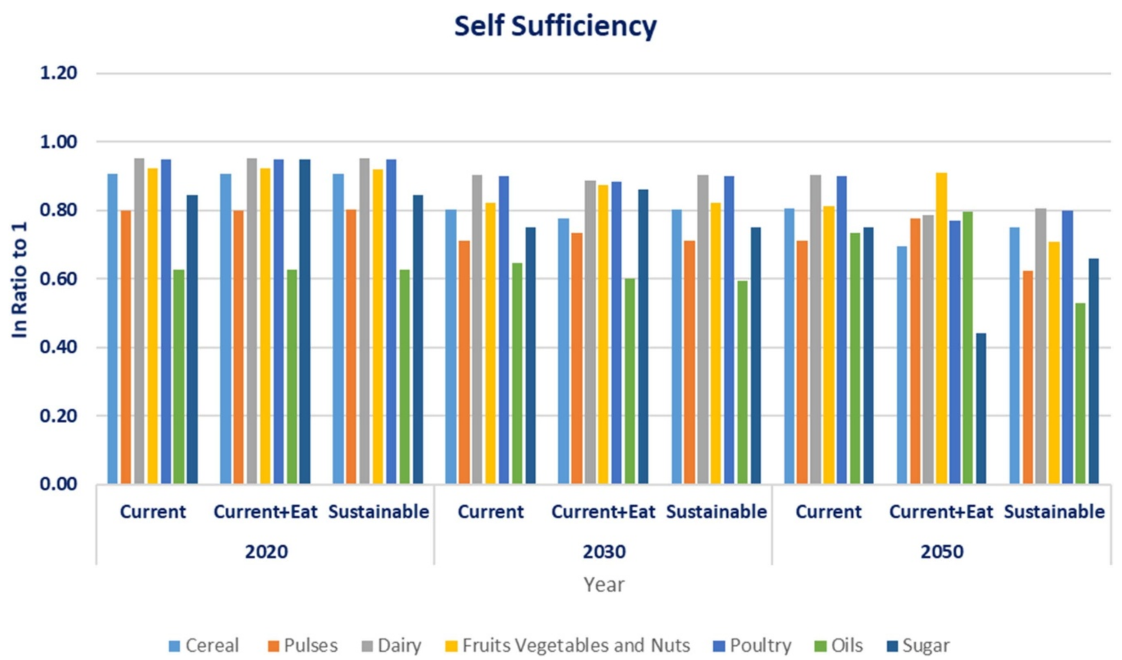

Figure 6. Projected trends in India's self-sufficiency in selected products under current trend, Current + EAT and sustainable pathways in 2030 and 2050. The self-sufficiency ratio defines how much of the demand of each region for each traded good has to be met by domestic production. Self-sufficiency ratios smaller than one indicate that the region imports from the world market, while self-sufficiencies greater than one indicate that the region produces for export. Trade costs, including trade margins and tariffs, are considered.

such as higher bioenergy demand. Benefits of higher crop yields are also obtained through assumptions of technological change and lower fertilizer use (SSP1 parameterization, details in section 2 in SM) which have environmental benefits in terms of reduced emissions. While the pressures on the land-use system can be seen across the pathways due to a shift in population trajectories, shift in diet, changes in crop productivity, and higher bioenergy demand, we observe that under the Current + EAT the cropland area increases in comparison to the current trend. This is mainly due to dietary shifts such as increased demand for pulses and fruits, vegetables, and nuts. Under the sustainable pathway, there is no change in cropland area in 2030 and a reduction by 2050 in comparison to Current + EAT driven by higher crop productivity, despite higher bioenergy demand. Our results are consistent with the findings by Hinz *et al* (2020) who demonstrate the role of sustainable intensification in increasing crop production, with only a moderate expansion of cropland.

Emission reductions are observed under the Current + EAT and sustainable pathway in comparison to the current trend to the tune of 30% and 80% respectively, by 2050. These are mainly because of adoption of EAT-Lancet dietary recommendations, higher bioenergy demand, GHG prices and improved livestock production systems (including the feed basket). The mitigation potential of changes in the dietary system concerning India has been extensively discussed in recent literature (Aleksandrowicz *et al* 2019, Damerau *et al* 2020). Consistent with Herrero and Thornton (2013) and Sapkota *et al* (2019), we find that reduced demand for livestock products and improvement in livestock productivity are the primary factors in these emissions reductions. One of the important concerns with sustainability targets is India's relying on imports to feed the projected population across the scenarios despite increasing crop yields and crop production. This possible scenario is supported by another recent study Beltran-Peña *et al* (2020) which indicates that import-reliance will remain crucial to fulfilling India's food demand requirements. This decrease in self-sufficiency of certain commodities such as poultry meat, food vegetables, and nuts and pulses under the sustainable pathways (figure 6) contrasts the environmental benefits of dietary shifts. Due to higher incomes in the sustainable pathway, calorie intake from animal protein increases causing an increase in imports to meet domestic demand. Moreover, there is increased food waste as demand for fruits, vegetables, and nuts is higher under EAT-Lancet recommendations. This puts pressure on the domestic availability of fruits, vegetables, and nuts and reduces self-sufficiency as well.

There is immense scope for reduction in over-dependence of certain food groups and inclusion of others. Historically, the average number of food groups consumed by households has increased from 8.8 to 9.7 in rural India. In urbanized regions, it rose from 9.3 to 9.5 between 1990 and 2012 (Pingali *et al* 2019). There remains great consumption of cereals, sugars and ultra-processed foods. We find that a strategic shift towards plant based healthy diets will bring long-term improvements in both human and environmental health indicators. While increased agricultural production can meet the growing demand for food under all the three pathways, the dietary composition changes more in favor of plant-based protein foods, less sugar, and a greater portion of fruits and vegetable intake in the Current + EAT and sustainable pathways. This could be made possible through a range of strategic policy initiatives that target the consumption of fruits and vegetables and reduction in the use of sugars.

Under the sustainable pathway, it is possible to meet the food demand requirements for a growing population despite the reduced use of water resources. Agricultural water use in India is about 90%, with most of it reported in the production of rice and wheat. We demonstrate that substantial reductions in blue water usage are possible through restrictions on over-use, improvements in irrigation efficiency and technological change (Dinesh and Dandy 2003, Damerau *et al* 2020). A transition towards healthy diets and bioenergy under the sustainable pathway can address the complex sustainability challenges in the AFOLU sector, without extensive effects on international trade and self-sufficiency. This is also observed by Rockström *et al* (2009), Foley *et al* (2011), Tilman and Clark (2014) on a global scale.

4.1. Limitations

We conduct our analysis using a global recursive dynamic land-use optimization model. In this model, only blue water for crop production is considered. It is endogenously calculated using cropland and livestock production requirements. The model also does not account for sub-regional differences in food consumption and dietary patterns. This prevents us from identifying intra-regional variation in access to healthy diets. However, there are certain benefits to this approach as well. As we use an adaptive global modeling framework to perform regional analysis, we are able to use global datasets to create relevant parameters in places of assumptions, accounting for international trade and projected land-use trajectories in other countries as well. When not enough national datasets or models exist, the use of validated global models that represent processes such as technological change and dynamic feed baskets accounting for emissions are useful in developing national parameters and conducting national-level analysis.

5. Conclusions

Our study provides results from an integrated assessment of the food and land-use pathways needed to meet sustainability targets for India. Dietary changes, somewhat consistent with the EAT-Lancet recommendations, improvements in livestock feed efficiency and shift to bioenergy can significantly reduce AFOLU sector emissions by nearly 80% by 2050. Moreover, there would be sizeable decline in pastureland and cropland areas as a result of these developments. Water withdrawals in agriculture would need to reduce by half by 2050, which is only possible when there is a shift away from current trends in rice, wheat, and soybean production. Self-sufficiency, on the other hand, would be negatively impacted for major crops reflecting a tension with the sustainability targets. It simply means that competition for land between food and bioenergy crops will increase over the next decades if India wishes to be on a sustainable development trajectory. Higher bioenergy production could also lead to higher emissions in the land use sector. However, they can be offset in the energy and other sectors where bioenergy is used.

Results also show an increase in crop yields under the sustainable pathway due to lower technology costs and improved climate scenario. It will help to meet domestic demand and reduce the trade-offs between food security and bioenergy demand. A sustainable future as predicted here cannot be realized without a strategic policy design. A planned transformation towards healthy diets is required for emissions reduction. India's National Food Security Act (2013) provides subsidized food grains to about two-thirds of the current population. Over-dependence on cereal crops creates twin problems of reduced nutritional security and high irrigation water use. By the inclusion of more diverse sources of plant proteins as well as fruits and vegetables, the goal of nutrition security can be met along with increased dietary diversity. In 2016, the Government of India released the Model Bill for Conservation, Protection, Regulation and Management of Groundwater to focus on the looming groundwater crisis and promote its sustainable use. An active and timely implementation of this policy with the focus on regions that can benefit from switching to alternate crops will ensure the objectives on the projected land-use and crop cultivation transformations are met. Our approach is relevant for all other countries that are struggling to identify ways of meeting global pledges towards afforestation, conserving biodiversity and a future towards net-zero emissions.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing interests.

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