Pathways to Sustainable Land-Use and Food Systems in India by 2050

by Chandan Kumar Jha, Vartika Singh, Miodrag Stevanovic, Philipp Dietrich, Satyam Saxena, Aline Mosnier, Isabelle Weindl, Benjamin Bodirsky, Alexander Popp, Ranjan Ghosh, Hermann Lotze-Campen, and Guido Schmidt-traub

Pathways to Sustainable Land-Use and Food Systems in India by 2050

1. Introduction

India's footprint in global greenhouse emissions is small but on a rise. India's CO2 emissions as a share of global emissions almost doubled from 3.5% in 1997 to 6.88% 2017 (Global Carbon Project, 2020) . The land use and forestry, and agriculture sectors contribute about 23.4% of India's total GHG emissions (WRI, 2017). India has taken efforts to adapt and mitigate climate change effects by being party to various international commitments, including the Paris Agreement, the Convention on Biological Diversity (CBD), and the Bonn Challenge. India is also committed to achieving the 17 Sustainable Development Goals (SDG's) and the 169 associated targets. However, scientific assessments aimed at policies to achieve SDGs often address targets in isolation and lack a multi-sectoral approach, thereby necessitating an integrated outlook towards various policy goals (Obersteiner et al., 2016). Little information is available on pathways to achieve those goals in coordination with economic development and climate change. Countries are expected to renew and revise their climate and biodiversity commitments ahead of the 26th session of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) and the 15th COP to the United Nations Convention on Biological Diversity (CBD). Agriculture, land-use, and other dimensions of the FABLE analysis are key drivers of both greenhouse gas (GHG) emissions and biodiversity loss and offer critical adaptation opportunities. Similarly, nature-based solutions, such as reforestation and carbon sequestration, can meet up to a third of the emission reduction needs for the Paris Agreement (Roe et al., 2019). Countries' biodiversity and climate strategies under the two Conventions should therefore develop integrated and coherent policies that cut across these domains, in particular through land-use planning which accounts for spatial heterogeneity. According to the NDC, India has committed to reducing carbon emissions intensity of its GDP by 33–35% compared to 2005 levels by 2030. This includes emission reduction efforts from agriculture, forestry, and other land use (AFOLU). Envisaged mitigation measures from agriculture and land-use change include National Initiative of Climate Resilient Agriculture (NICRA), National Mission on Sustainable Agriculture (NMSA), *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY), Prime Minister's Micro-Irrigation Scheme—and measures to minimize residue burning and livestock intensification policies (Ministry of Environment, Forest and Climate Change, 2018). Under its current commitments to the UNFCCC, India mentions biodiversity conservation.

In this paper we outline how sustainable food and land-use systems can contribute to raising the climate ambition, aligning climate mitigation and biodiversity protection policies, and achieving other sustainable development priorities in India. It presents two pathways for food and land-use systems for the period 2020-2050: Current trend and Sustainable High Ambition (referred to as "**Current Trend**" and "**Sustainable**" in all figures throughout this chapter). These pathways examine the trade-offs between achieving the FABLE targets under limited land availability and constraints to balance supply and demand at national and global levels. For our integrated assessment of climate scenarios in the context of sustainable development for India, we use the global land-use recursive dynamic optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment) (Lotze-Campen et.al., 2008). This assessment was undertaken as part of a global exercise under the Food, Agriculture, Biodiversity, Land-Use and Energy (FABLE) Consortium whereby 20 countries across the globe collaborated to create mid-century pathways as part of a Scenathon (FABLE, 2020).

MAgPIE integrates various spatially explicit biophysical factors such as land, yield, and available water into an economic decision-making mechanism with GDP, population growth, and climate change scenarios as exogenous drivers. We undertake our analysis using representative concentration pathways (RCPs) which are a set of alternative trajectories for the atmospheric concentration of GHG's (Van Vuuren et.al., 2011). These RCPs when coupled with a set of Shared Socio-economic Pathways (SSPs) provide an opportunity to include pathways of future societal development. SSPs together with the RCPs allow us to assess the future climate, environmental and societal scenarios using integrated assessment models (Moss et.al., 2010). We introduce the scenario setup and the various indicators used in the next section.

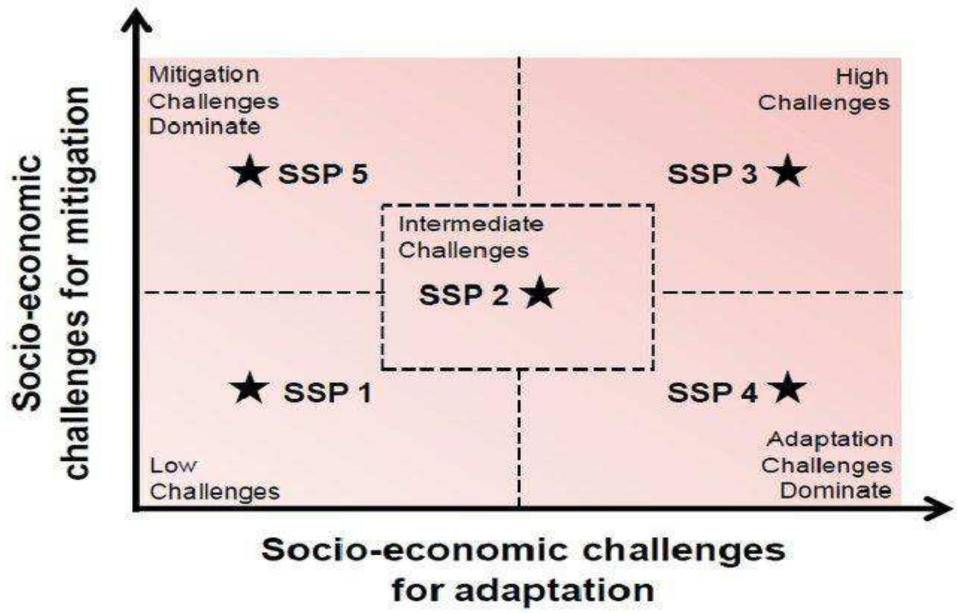
2. Methodology

Among possible futures, we present two alternative pathways (cf. FABLE Targets) for food and land-use systems in India termed as ***Current Trend*** pathways and ***Sustainable*** pathways. The

Sustainable pathways is a high ambition path to meet the sustainability objectives. Our underlying assumptions for ***Current Trend*** and ***Sustainable*** pathways are in the line of Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014) (Figure 1). We assume SSP2 parameterization for ***Current Trend*** pathways and a storyline that extends upon the SSP1 (e.g. dietary shift beyond SSP1) for ***Sustainable*** pathways, including greenhouse gas mitigation efforts and dietary changes (Figure 2) (c.f. Annex 3 for more details on the underlying assumptions). We have used the MAgPIE 4[1] open-source framework for our analysis, which is a recursive dynamic cost-minimization model of global land systems (Dietrich et al., 2019). The model simulates crop production, land-use patterns, water use for irrigation, and carbon stock changes at a spatial resolution of 0.5° × 0.5° (Fig in SM). This spatially explicit biophysical information is provided to MAgPIE from the global gridded crop and hydrology Lund–Potsdam–Jena managed Land (LPJmL) model (Bondeau et al., 2007). Under certain socioeconomic and biophysical constraints, this model's objective function is to fulfill the demand for food, livestock, and material products at minimum cost (Lotze-Campen et al., 2008; Popp et al., 2012). The production function takes land, water, yield information, and monetary costs as inputs. Under equilibrium conditions, MAgPIE endogenously determines optimal land use patterns of agricultural land (rainfed and irrigated), forest, and other natural vegetation patterns, as well as optimal investment rates in technological production intensification, land expansion, and optimal trade flows. Below, we briefly describe the main model features for the study.

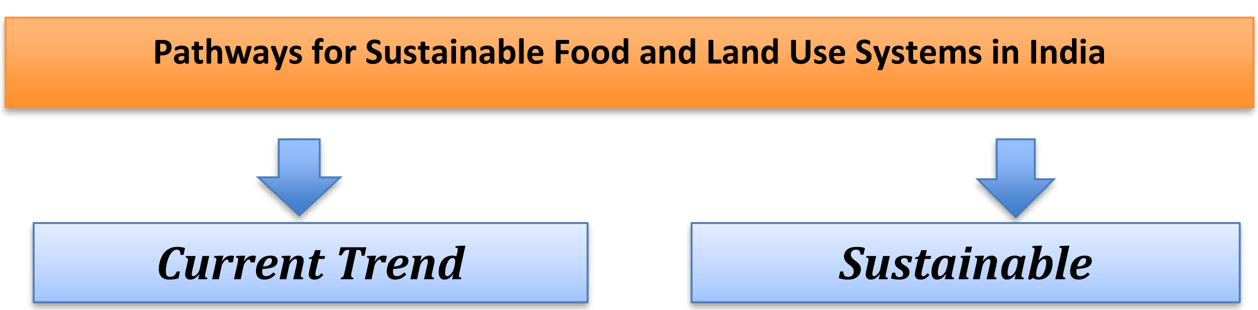
Figure 1: Shared Socio-economic pathways (SSPs)

[1] The model version used here is MAgPIE 4.1, and the technical model description of the used version 4.1 is available at https://rse.pik-potsdam.de/doc/magpie/4.1/.



Our ***Current Trend*** pathway corresponds to the medium boundary of feasible action. It is characterized by medium population growth (from 1,389 million in 2020 to 1,734 million in 2050), significant constraints on agricultural expansion, a medium afforestation target (21 Mha by 2030) with no change in the extent of protected areas, medium crop productivity increases in the agricultural sector, an evolution towards an SSP2 narrative of diets which defines relatively high consumption of animal based products (O'Neill et al., 2017), and other important assumptions (cf. Annex 3). This corresponds to a future based on current policies and historical trends that would also see considerable progress with regards to population growth and increasing demand for food, growth rate and inequalities, nutrition requirements and changes in dietary pattern with changes in income, continuous yield improving technological change and high use of fertilizers to increase productivity, moderate mitigation activity to cope with climate change with low enforcement of environmental protection and low targets of renewables and first generation biofuels

Figure 2: Description on pathways for sustainable food and land use systems.



RCP 6.0
SSP2

Moderate Mitigation

Increasing Demand for Meat and Dairy

RCP 2.6
SSP1

High Mitigation

Low Demand for Meat and Dairy (EAT-Lancet)

These factors underpinning the ***Current Trend*** pathways are based on country level historical trends and current situation (FAO, 2019; Forest Survey of India, 2019; Government of India, 2015; Indian Council of Agricultural Research, 2015; Ministry of Agriculture & Farmers Welfare, 2018; Ministry of Agriculture and Farmer's Welfare, 2017; National Council of Applied Economic Research, 2015). Moreover, as with all FABLE country teams, we embed these ***Current Trend*** pathways in a global GHG concentration trajectory that would lead to a radiative forcing level of 6.0 W/m^2 by 2100 (RCP 6.0). Our model includes the corresponding climate change impacts on crop yields by 2050 for cereals, oil crops, sugar crops, fruits and vegetables and for all crops simulated within the model (cf. Annex 3).

Our ***Sustainable*** pathway represents a future in which substantial efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action. Compared to the ***Current Trend*** pathway, we assume that this future would lead to higher afforestation targets and lower population growth (cf. Annex 3). This corresponds to a future based on India's pledges to international commitments and targets such as Paris agreement, Bonn challenge, Aichi targets, higher production of renewables and biofuels with more efficient technologies and transition towards healthy diets i.e. according to recommendations of the EAT-*Lancet* Commission (Willett et al., 2019), that would also see considerable progress with regards to the achievement of sustainable development goals. We assume higher water use efficiency scenario under this pathway along with climate change impact. We, therefore include environmental flow requirements in our model assumptions, that reserve a certain fraction of water for environmental purposes, that are not available for agricultural activities. We also assume that the interest rate and technological cost will be low in the line of SSP1 which led to higher crop yield. These pledges and targets are the major factors underpinning our ***Sustainable*** pathways where progress would be made to achieve sustainable development goals (Borah, Bhattacharjee, and Ishwar, 2017; Ministry of New and Renewable Energy, 2018; Ministry of Statistics and Programme Implementation, 2020; Ministry of Environment, Forest and Climate Change, 2018). With the other FABLE country teams, we embed these ***Sustainable*** pathways in biophysical drivers consistent with a global GHG concentration trajectory that would lead to a lower radiative forcing level of 2.6 W/m^2 by 2100 (RCP 2.6), in line with limiting warming to 2°C.

3. Results

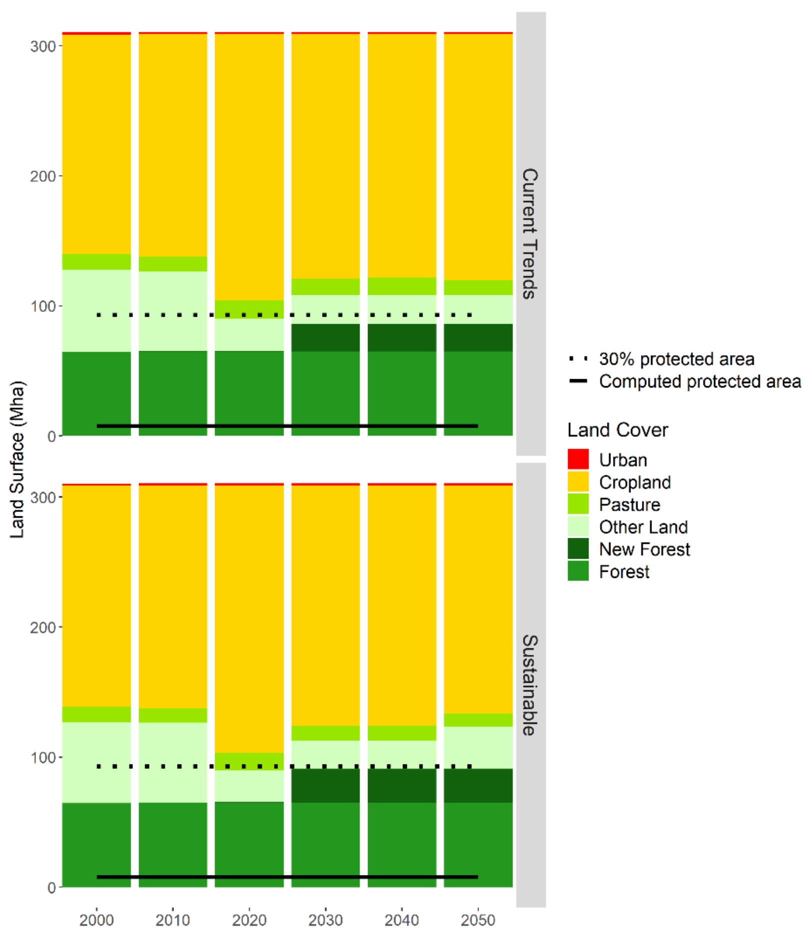
Projected land use in the ***Current Trend*** pathways is based on several assumptions: deforestation will be halted beyond 2005 and no agricultural land expansion into natural forests is allowed. Agricultural land can be increased by converting other natural vegetation areas that have lower carbon densities than natural forests. Moreover, 21 Mha are reforested or afforested by 2030, and protected areas remain at 181,404 km^2, representing 6% of total land cover in 2050 (cf. Annex 3).

By 2030, we estimate that the main changes in land cover in the ***Current Trend*** pathways will result in an increase of forest cover area and a decrease of other land areas. Decreases in other land occurs due to cropland area expansion between 2010 and 2025, after which other land remains stable. Forest area remains stable until 2025, increases between 2025 and 2030, before stabilizing (Figure 3) due to our assumption of Bonn challenge target for India (21 Mha by 2030). The expansion of the planted area for corn and soybean explains 99% of total cropland expansion between 2010 and 2025. For corn, the expansion is largely explained by an increase of feed use. For soybean, the expansion is primarily due to an increase in exports of soybean. The marginal pasture expansion between 2010 to 2035 is driven by the increase in demand for livestock products, in particular dairy products. Between 2030-2050, the increase in forest area is explained by actions to meet afforestation targets set under the Bonn challenge (Borah et al., 2017). There is no change between 2000 and 2050 in the area of land where natural processes predominate, explained by zero decrease in cropland or pasture area.

For soybean, the expansion is primarily due to an increase in exports of soybean. The marginal pasture expansion between 2010 to 2035 is driven by the increase in demand for livestock products, in particular dairy products. Between 2030-2050, the increase in forest area is explained by actions to meet afforestation targets set under the Bonn challenge (Borah et al., 2017). There is no change between 2000 and 2050 in the area of land where natural processes predominate, explained by zero decrease in cropland or pasture area.

In the ***Sustainable*** pathways, assumptions on agricultural land expansion remain the same as ***Current Trend***, except for the additional afforestation assumption includes 26 Mha of new forest area by 2030 based on the revised Bonn target for India. Protected areas remain constant at 6% of the total land area (cf. Annex 3).

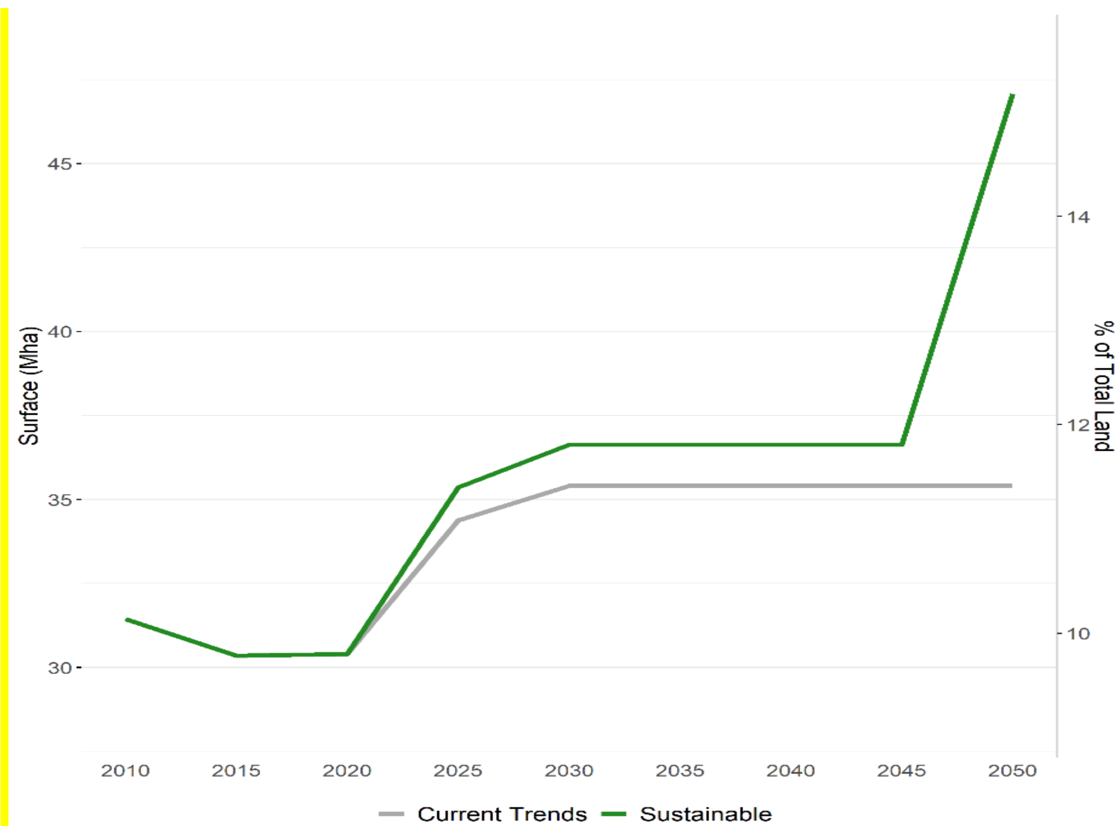
Figure 3: Evolution of area by land cover type and protected areas under each pathway



Sources. Authors' computation based on FAOSTAT (FAO, 2020) for the area by land cover type for 2000, and the World Database on Protected Areas data (UNEP-WCMC & IUCN, 2020) for 2020

Compared to the ***Current Trend*** pathways, we observe the following changes regarding the evolution of land cover in India in the ***Sustainable*** *pathways*: (i) decrease in loss of natural land, (ii) moderate increase in agricultural land, and (iii) increase in afforested land. In addition to the changes in assumptions regarding land-use planning, these changes compared to the ***Current Trend*** are explained by crop land expansion and afforestation targets. Under the ***Current Trend*** pathway, natural processes increase by 1.5% between 2010 and 2030, then stabilize. Under the ***Sustainable*** pathway, land where natural processes predominate increases by 1.8% between 2010 and 2030, then stabilizes until 2045, then sharply increases by a further 3% by 2050 (Figure 4).

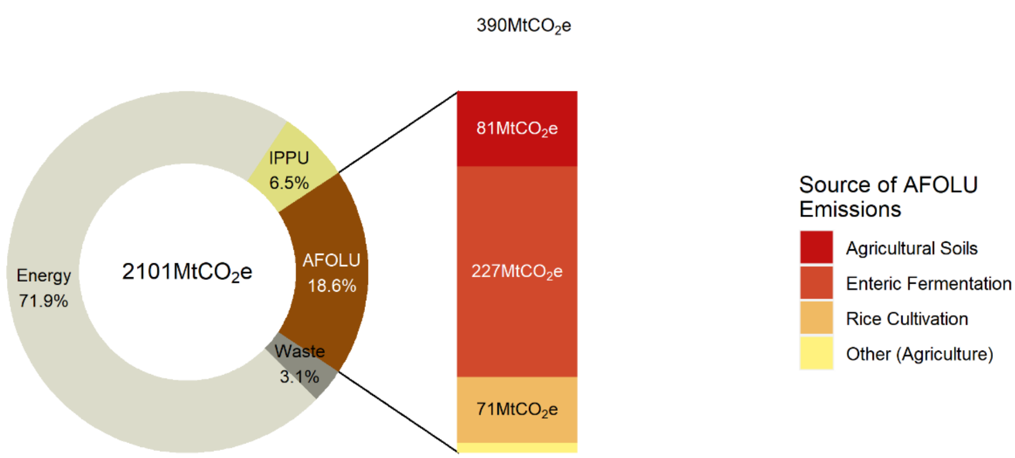
Figure 4: Evolution of the area where natural processes predominate



3.2 GHG emissions from AFOLU

Direct GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) accounted for 18.6% of total emissions in 2010 (Figure 5). Enteric fermentation and field burning of agricultural residues is the principal source of AFOLU emissions, followed by agricultural soil and rice cultivation. This can be explained by India's mitigation effort to meet the pledge under Paris agreement.

Figure 5: Historical share of GHG emissions from Agriculture, Forestry, and Other Land Use (AFOLU) to total AFOLU emissions and removals by source in 2010



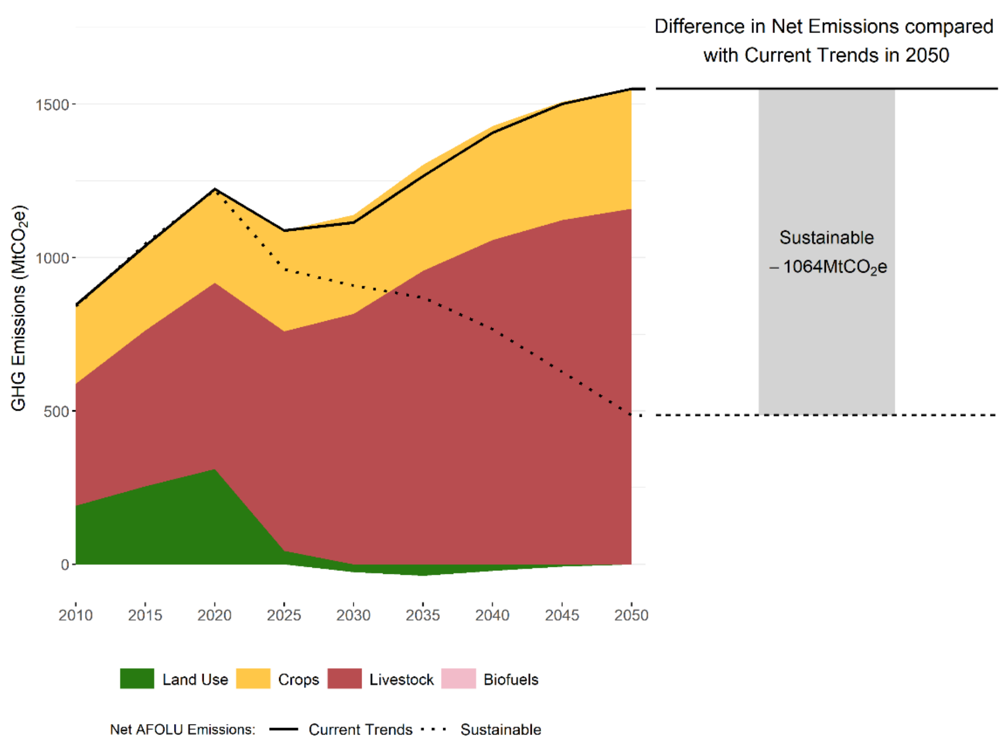
Source. Adapted from GHG National Inventory (UNFCCC, 2020)

Note. IPPU = Industrial Processes and Product Use

Under the *Current Trend* pathway, annual GHG emissions from AFOLU increase to 1,140 Mt CO_2e/yr in 2030, before reaching 1,550 Mt CO_2e/yr in 2050 (Figure 6). In 2050, enteric fermentation is the largest source of emissions (1,067 Mt CO_2e/yr), while emissions from other land-use changes act as a sink (13 Mt CO_2e/yr). Over the period 2020–2050, the strongest relative increase in GHG emissions is computed for enteric fermentation (170%), while a reduction is computed for emission from rice cultivation (40%).

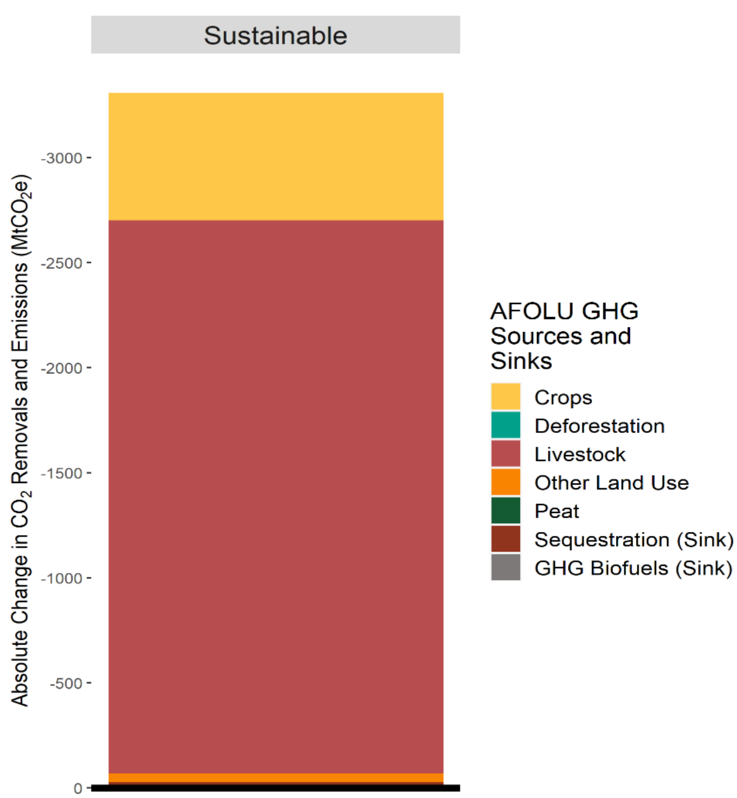
In comparison, the *Sustainable* pathway leads to a reduction of AFOLU GHG emissions by 300% in 2050 compared to *Current Trend* (Figure 6). The potential emissions reductions under the *Sustainable* pathway are dominated by a reduction in GHG emissions from the livestock sector. Our assumptions related to food and diet (EAT-*Lancet* recommendations) under the *Sustainable* pathway, which assume the reduction in demand for livestock products and other assumptions in line with the SSP1 narrative, are the most important drivers of this reduction.

Figure 6: Projected AFOLU emissions and removals between 2010 and 2050 by main sources and sinks for the *Current Trends* pathway



Our results show that AFOLU could contribute moderately to the total GHG emissions reduction objective by 2030 (reduce the emissions intensity of its GDP by 33 to 35% by 2030 from 2005 level). Such reductions could be achieved through the following policy measures such as dietary change, improvement in the livestock feeding system, meeting afforestation targets, and increasing bioenergy production. These measures could be particularly important when considering targets to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030 as per India's commitment to UNFCC (INDC, 2015). The policy in particular relates to India's new biofuel targets (Ministry of New and Renewable Energy, 2018) which is also important to meet India's commitment to UNFCC.

Figure 7: Cumulated GHG emissions reduction computed over 2020-2050 by AFOLU GHG emissions and sequestration source compared to the *Current Trends* pathway



3.3 Food Security

Under the ***Current Trend*** pathway, compared to the average Minimum Dietary Energy Requirement (MDER) at the national level, our computed average calorie intake is 0.3% higher in 2030 and 3% higher in 2050 (Table 4). The current average intake is mostly satisfied by cereals, sugar and oils, and animal products represent 13% of the total calorie intake. We assume that the consumption of animal products and in particular poultry meat (106% increase), will increase by 57% between 2020 and 2050. The consumption of dairy, sugar and fruits, vegetables and nuts will also increase while consumption of oil crops, cereals and pulses will decrease. Compared to the EAT-*Lancet* recommendations (Willett et al., 2019), which is in line with the assumptions of our ***Sustainable*** pathway, only sugars are over-consumed whereas no products are under-consumed (Figure 8).

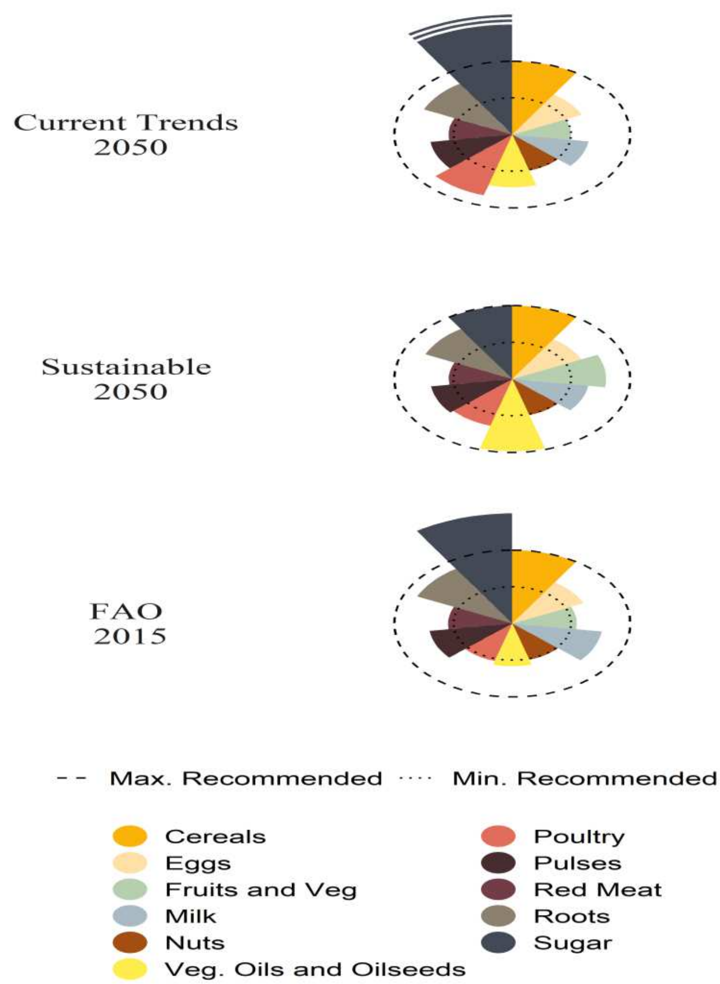
Table 4: Daily average fats, proteins and kilocalories intake under the ***Current Trend*** and ***Sustainable*** pathways in 2030 and 2050

	2010	**2030**		**2050**	
	Historical Diet (FAO)	**Current trend**	**Sustainable/Sustainable Medium Ambition**	**Current trend**	**Sustainable/Sustainable Medium Ambition**
Kilocalories *(MDER)*	2,097 *(2,181)*	2,260 *(2,252)*	2,286 *(2,281)*	2,325 *(2,255)*	2,274 *(2,284)*

Under the ***Sustainable*** pathway, we assume that diets will transition towards EAT-*Lancet* recommendations. The ratio of the computed average intake over the MDER increases to 0.3% in 2030 and decreases to 0.4% in 2050 under the ***Sustainable*** pathway.

India's changing food demand landscape partially promotes the transition to healthy food systems. While we find that on average, the number of food groups consumed by the households in India has increased from 8.8 (out of 12 food groups) to 9.7 between 1990 and 2012 in rural India and from 9.3 to 9.5 in urban India (Pingali, Aiyar, Abraham, & Rahman, 2019), there is still a need to reduce the over-dependence on certain food groups, particularly ultra-processed foods, sugars and cereals, to achieve overall dietary diversity as recommended by our ***Sustainable*** pathway (EAT-

Figure 8: Comparison of the computed daily average kilocalories intake per capita per food category across pathways in 2050 with the EAT-*Lancet* recommendations.



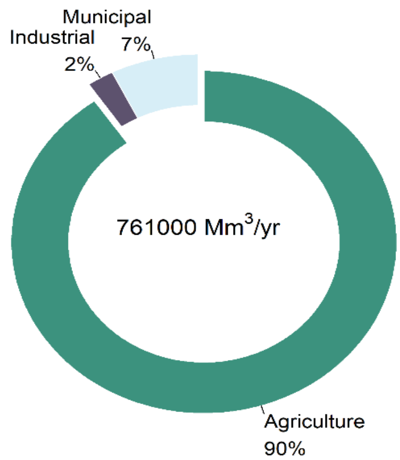
Lancet recommendations). A shift from the current over-dependence on cereal consumption, which is rooted in existing regulatory reforms that highly subsidize the production and consumption of cereals, towards a focus on diversifying the food basket to include more fruits, vegetables, nuts and pulses will be important to achieve the EAT-*Lancet* dietary recommendations.

These figures are computed using the relative distances to the minimum, average and maximum recommended levels (i.e. the rings), therefore different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is smaller than the average recommendation it is displayed on the minimum ring and if it is higher it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge of sugar indicate that the average kilocalorie consumption of this food category is significantly higher than the maximum recommended The shortfall in Indian diets as compared to EAT-Lancet recommendations calls for public health and nutrition policies addressing malnutrition but additionally needs agriculture, trade and consumer awareness policies that can address broader context affecting the accessibility, acceptability and affordability of healthier dietary options (Sharma, Kishore, Roy, & Joshi, 2020).

3.4 Water

India is characterized by tropical monsoon climate with unreliable rainfall and 1,183 mm average annual precipitation that mostly occurs over the period June–September. The agricultural sector represented 90% of total water withdrawals in 2010 (Figure 9; FAO, 2017). Moreover, in 2013, 70.4 Mha of agricultural land was equipped for irrigation, representing 50% of estimated irrigation potential (FAO, 2017). The three most important irrigated crops, rice, soybean and pulses, account for 26%, 15% and 7% of total harvested irrigated area. India exported 61% of soybean, 23% of cotton lint and 6% of rapecake in 2020.

Figure 9: Water withdrawals by sector in 2010

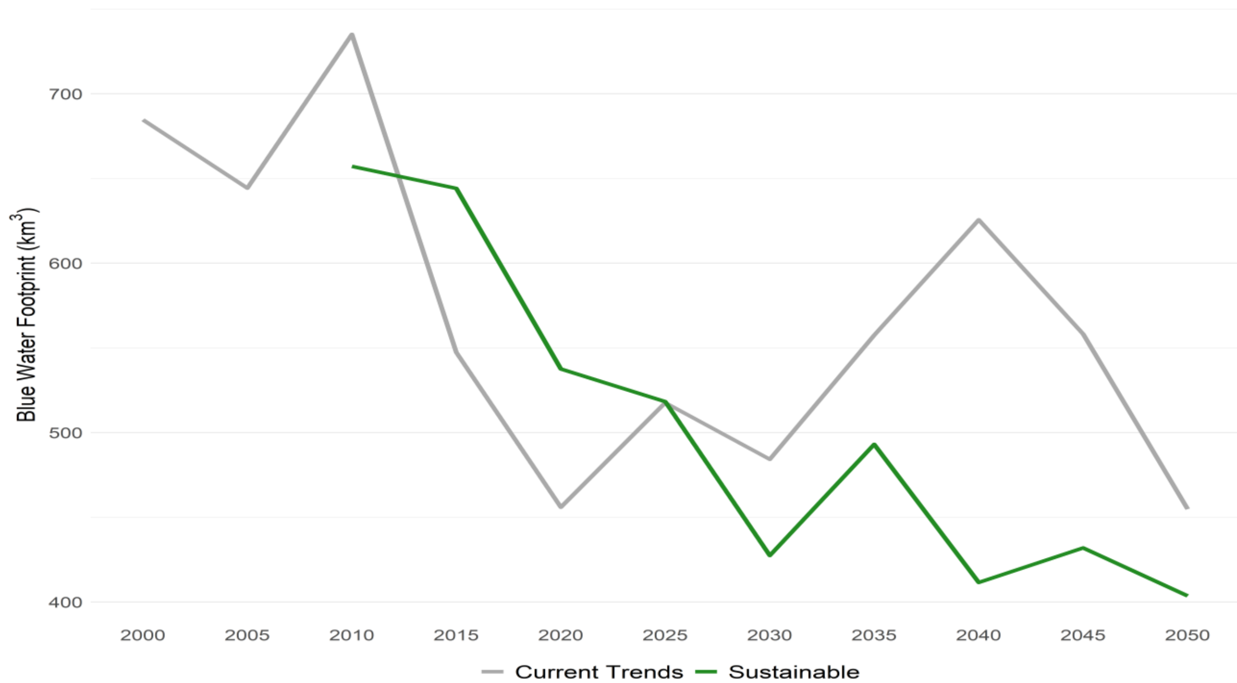


Source. Adapted from AQUASTAT Database (FAO, 2017)

Under the ***Current Trend*** pathway, annual blue water use decreases between 2000–2015 (685 and 547 km^3/yr), before reaching 484 km^3/yr and 455 km^3/yr in 2030 and 2050, respectively (Figure 10), with rice, wheat and chicken accounting for 37%, 23%, and 12% of computed blue water use for agriculture by 2050[2]. In contrast, under the ***Sustainable*** pathway, blue water footprint in agriculture reaches 427 km^3/yr in 2030 and 403 km^3/yr in 2050, respectively. This is explained by accounting for environmental flow protection policy as well as climate change impacts in the MAgPIE model (Annex 3) that have led to a 11% decrease in water withdrawals in agriculture by 2050 and changes in the production of rice, wheat and raw sugar due to a decline in internal food demand as well as demand for biofuels.

Figure 10. Evolution of blue water footprint in the ***Current Trend*** and ***Sustainable*** pathways

[2] We compute the blue water footprint as the average blue fraction per tonne of product times the total production of this product. The blue water fraction per tonne comes from Mekonnen and Hoekstra (2010a, 2010b, 2011). It is assumed constant over time, except if a specific scenario on increasing water efficiency has been selected. The impact of climate change on water availability is taken into account in this study.



3.5 Resilience of the Food and Land-Use System

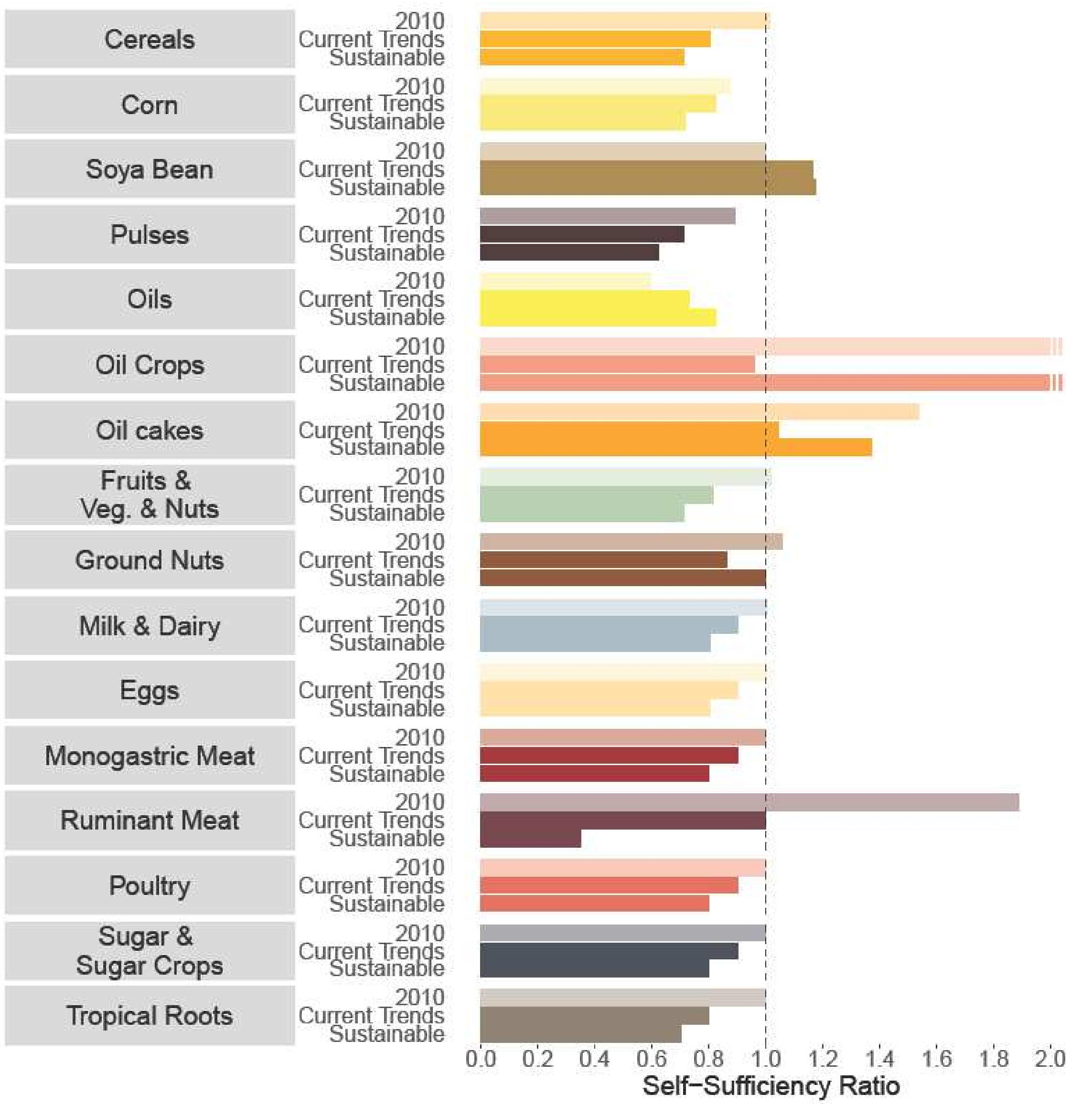
The COVID-19 crisis exposes the fragility of food and land-use systems by bringing to the fore vulnerabilities in international supply chains and national production systems. Here we examine two indicators to gauge India's resilience to agricultural trade and supply disruptions across pathways: the rate of self-sufficiency and diversity of production and trade. Together they highlight the gaps between national production and demand and the degree to which we rely on a narrow range of goods for our crop production system and trade.

3.5.a Self-Sufficiency

According to the historical data (2010), India is self-sufficient for the major food categories, such as cereals, fruits and vegetables, nuts, oilseeds and vegetable oils, soya bean, ruminants, eggs, sugar and sugar crops, oil crops, mild and dairy, fruits, vegetables and nuts and poultry meat. Self-sufficiency is low for corn and oils.

Under the Current Trends Pathway, we project that India would be self-sufficient in pulses, fruits vegetables and nuts, and ruminant meat in 2050, with self-sufficiency by product group remaining stable for the majority of products between 2010 and 2050 (Figure 11). The product groups for which India depends the most on imports to satisfy internal consumption are roots and tubers, poultry meat, milk and dairy, sugar and sugar crops, and eggs. According to our projections, this dependency will decline until 2050. In contrast, under the Sustainable Pathway, India's self-sufficiency remains stable overall, with full self-sufficiency for pulses, fruits and vegetables, ruminant meat, and nuts but with a further decline in the self-sufficiency for roots and tubers, dairy, and sugar crops by 2050. This is explained by changes in the volume of imports and exports, productivity, and change in diets.

Figure 11. Self-sufficiency per product group in 2010 and 2050



3.5.b Diversity

The Herfindahl-Hirshman Index (HHI) measures the degree of market competition using the number of firms and the market shares of each firm in a given market. We apply this index to measure the diversity/concentration of:

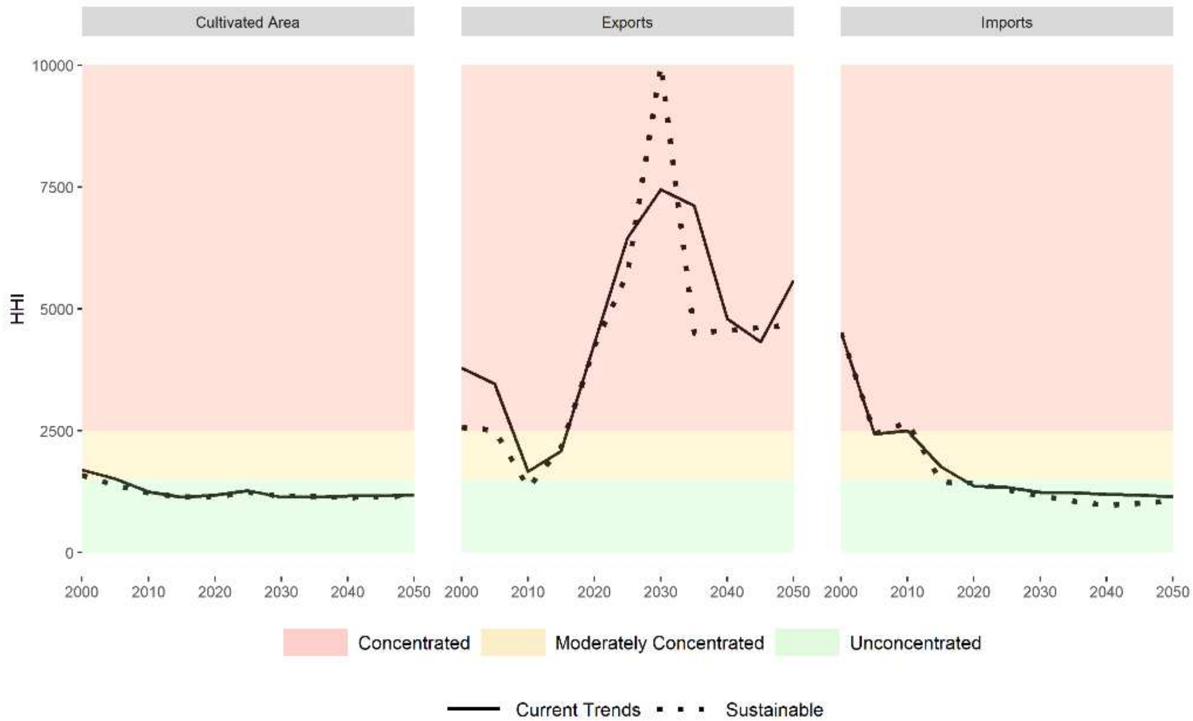
- ❑ **Cultivated area**: concentration means that cultivated area is dominated by a few crops with large shares of the total cultivated area, while diversity means that the cultivated area is characterized by many crops with equivalent shares of the total cultivated area.

- ❑ **Exports and imports**: concentration means that a few commodities represent a large share of total exported and imported quantities, while diversity means that many commodities account for significant shares of the total exported and imported quantities.

We use the same thresholds as defined by the U.S. Department of Justice and Federal Trade Commission (2010, section 5.3): diverse under 1,500, moderate concentration between 1,500 and 2,500, and high concentration above 2,500.

Figure 12 shows HHI index for the planted area in quite diverse in 2010 and this behavior continues during the historical period. The import is moderately concentrated for the historical period 2010 to 2015 at the same time export is highly concentrated.

Figure 12. Evolution of the diversification of the cropland area, crop imports and crop exports of the country using the Herfindahl-Hirschman Index (HHI)



Under the ***Current Trend*** pathway, we project high concentration of crop exports and imports and low concentration in the range of crops planted in 2050, trends which stabilize over the period 2010 - 2050. This indicates high levels of diversity across the national production system and imports and exports. In contrast, under the ***Sustainable*** pathway, we project high concentration of crop exports and imports, and low concentration in the range of crops planted in 2050. Sustainable scenarios don't change the diversification patterns of crops in spite of range of different assumptions. This is explained by several changes in the assumptions related to population, diets, crop productivity, biofuel policy etc. among the pathways.

4. Discussion and Recommendations

To explore viable ways for a sustainability transformation of land use system for India, this study developed ***Current Trend*** and ***Sustainable*** pathways using the global land systems model MAgPIE. The differentiation in ***Current Trend*** and ***Sustainable*** pathways will be useful for stakeholders and policy makers to understand the differences between existing scenarios and the potential future trends of sustainable indicators to support the setting of national targets and monitor their progress. Our results will be useful in developing the framework of policy actions aimed to achieve several international commitments for climate mitigation and forest conservation such as the Paris Agreement, the Convention on Biological Diversity, the Sustainable Development Goals, and the Bonn Challenge. Our analysis shows an emission reduction of 1064 Mt CO_2e per year under ***Sustainable*** pathway compared to ***Current Trend*** pathway by 2050. This reduction is primarily due to our assumptions around dietary change (transition towards healthy diets), improvements in livestock production system including feed basket content, afforestation target (26 Mha by 2030) and the overall narrative in line with SSP1. We find the livestock sector to be the major contributor towards emission reductions. The inclusion of the national level policy emphasizing the biofuel mandate (Ministry of New and Renewable Energy, 2018) in our analysis, provides the impact on land use dynamics and potential bioenergy crop use to meet India's blending targets.

Results of our analysis also point towards the need to focus on balanced diets supported by the production of crops and livestock products with limited implications on water-use in the country. About 90% of India's water use is for the agricultural sector, with rice and poultry production having the largest blue water footprint. Under the ***Current Trend*** scenario, the consumption of livestock products and cereals is expected to increase - in line with historical trends and rising household incomes, thereby placing additional pressures on land use systems. While in the past, Indian diets have relied on cereals and a greater share of plant proteins, India currently faces the triple-burden of malnutrition with high incidences of both under-nutrition and obesity in the population. High production and consumption of ultra-processed foods, sugars and cereals leaves little room for protein and fiber-rich foods in the food basket. In the ***Sustainable*** pathway, we assume that future dietary requirements will be inclined towards plant-based nutrients, per the recommendations of EAT-*Lancet* Commission. The recommendation suggests low demand for livestock products and higher demand for fruits and vegetables. Our results point towards large environmental benefits from a shift to healthy diets, without the need for expansion of cropland cover.

Our analysis and assumptions have been made within the dynamic global partial-equilibrium model MAgPIE and our results have been extracted for the Indian region. Applying such a global modelling framework for a regional case study has certain advantages and disadvantages. Advantages include that the work can build on an existing model, where so far no national land system model exists with a comparable scope of represented processes and indicators. As such, the model includes many processes such as dynamic feed baskets, endogenous technological change, fertilization management or emission accounting that are likely superior to static assumptions, even though they are only parametrized through international datasets. Moreover, in case several FABLE case studies will apply the MAgPIE model, the results can also be compared consistently across different applications. Finally, a global long-term model might be better suited to account for international drivers such as trade, or for long-term trajectories of Indian land systems in case it follows similar trajectories as other countries. On the other hand, applying a global model for a regional case study also has its downsides. Firstly, as the input data is required on a global scale, more comprehensive and detailed data that may exist on the national scale cannot be easily incorporated into the model. For example, the MAgPIE model accounts for irrigation efficiency as a global weighted average of water losses from source to field ("conveyance efficiency times management factor") from Rohwer, Gerten, and Lucht (2007) and we continue to use the same irrigation efficiency for India for both Current Trend and Sustainable pathways. Also, our findings with regard to dietary patterns and consumption remain restricted at the national level as we are unable to account for sub-national and regional variations in dietary patterns across the country. In addition, the simulated processes were chosen based on their relevance for the global food system, and may neglect important dynamics of high relevance for national food systems. For example, processes that may drive dietary patterns in India such as religious affiliation are not explicitly accounted for.

Moving ahead, while our analysis and assumptions have greatly benefitted from inputs from various stakeholders, we aim to continue to improve our assumptions within the model to generate specific and actionable results through continued stakeholder engagement in the future. Our high ambition pathway to achieve a transition towards sustainable futures already includes ambitions for healthy diets, sustainable agricultural practices and low emission targets. Through additional assumptions, we will be able to address additional sustainability objectives at national level that may be relevant for our stakeholders.

References

Akhtar, S., Ahmed, A., Randhawa, M. A., Atukorala, S., Arlappa, N., Ismail, T., & Ali, Z. (2013). Prevalence of vitamin A deficiency in South Asia: Causes, outcomes, and possible remedies. *Journal of Health, Population, and Nutrition*, *31*(4), 413–423. https://doi.org/10.3329/jhpn.v31i4.19975

Alae-Carew, C., Bird, F. A., Choudhury, S., Harris, F., Aleksandrowicz, L., Milner, J., … Green, R. (2019). Future diets in India: A systematic review of food consumption projection studies. *Global Food Security*, *23*, 182–190. https://doi.org/10.1016/j.gfs.2019.05.006

Alexandratos, Nikos, & Bruinsma, Jelle. (2012). *World agriculture towards 2015/2030: The 2012 Revision* (No. 9781844070077). https://doi.org/10.1016/S0264-8377(03)00047-4

Andersson, M., Karumbunathan, V., & Zimmermann, M. B. (2012). Global Iodine Status in 2011 and Trends over the Past Decade. *The Journal of Nutrition*, *142*(4), 744–750. https://doi.org/10.3945/jn.111.149393

Aradhey, A. (2019). Biofuels Annual 2019. *Global Agricultural Information Network*, *GAIN Report Number:IN9069*, 25.

BirdLife International. (2019). Digital boundaries of Important Bird and Biodiversity Areas from the World Database of Key Biodiversity Areas. Retrieved February 8, 2019, from BirdLife International website: http://datazone.birdlife.org/site/requestgis

Bodirsky, B. L., Rolinski, S., Biewald, A., Weindl, I., Popp, A., & Lotze-Campen, H. (2015). Global Food Demand Scenarios for the 21st Century. *PLOS ONE*, *10*(11). https://doi.org/10.1371/journal.pone.0139201

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., … Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, *13*(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Borah, B., A Bhattacharjee, & N.M Ishwar. (2017). Bonn Challenge and India: Progress on Restoration Efforts across States and Landscapes. New Delhi, India: IUCN and MoEFCC, Government of India.

Cadena, M., Supples, C., Ervin, J., Marigo, M., Monakhova, M., Raine, P., & Virnig, A. (2019). *Nature is counting on us: Mapping progress to achieve the Aichi Biodiversity Targets*. United Nations Development Programme.

Carriquiry, M., Dong, F., Du, X., Elobeid, A. E., Fabiosa, J. F., Hart, C., Hayes, D. J., Kovarik, K., Mulik, K., Wailes, E., Chavez, E., Moreira, M., Binfield, J., Brown, D. S., Gerlt, S., Madison, D., Meyer, S., Meyers, W. H., Thompson, W., … Womack, A. W. (2010). FAPRI 2010 U.S. and World Agricultural Outlook. *FABRI Staff Reports. 4*. https://lib.dr.iastate.edu/fapri_staffreports/4

CBD. (2020). India—National Targets. Retrieved May 8, 2020, from Convention on Biological Diversity website: https://www.cbd.int/countries/targets/?country=in

Chindarkar, N., & Grafton, R. Q. (2019). India's depleting groundwater: When science meets policy. *Asia & the Pacific Policy Studies*, *6*(1), 108–124. https://doi.org/10.1002/app5.269

Dietrich, J. P., Leon, B., Benjamin, Florian, H., Isabelle, W., Miodrag, S., Kristine, K., … Alexander, P. (2019). MAgPIE 4 – a modular open-source framework for modeling global land systems. *Geoscientific Model Development*, (December), 1299–1317. https://doi.org/10.5194/gmd-12-1299-2019

Dietrich, J. P., Schmitz, C., Lotze-Campen, H., Popp, A., & Müller, C. (2014). Forecasting technological change in agriculture-An endogenous implementation in a global land use model. *Technological Forecasting and Social Change*, *81*(1), 236–249. https://doi.org/10.1016/j.techfore.2013.02.003

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N. D., Wikramanayake, E., … Saleem, M. (2017). An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *Bioscience*, *67*(6), 534–545. https://doi.org/10.1093/biosci/bix014

ESA. (2017). *Land Cover CCI Product User Guide Version 2. Tech. Rep.* Retrieved from maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

FAO. (2017). *AQUASTAT* [Database]. Retrieved from http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

FAO. (2019). FAOSTAT, Crops [Data set]. *Food and Agriculture Organization of the United Nations, Database on Crops*.

FAO. (2020). *FAOSTAT* [Database]. Retrieved from http://www.fao.org/faostat/en/#home

Forest Survey of India. (2019). India's State of Forest Report 2019. *Ministry of Environment Forest and Climate Change*. Retrieved from http://www.fsi.nic.in/forest-report-2019

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., … Riahi, K. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004

GADM. (2020). *Global Administrative Areas. Version 3.6.* Retrieved from https://gadm.org/data.html.

Global Burden of Disease Collaborative Network. (2018). Global Burden of Disease Study 2017 (GBD 2017) Reference Life Table [Data set]. *Seattle, United States: Institute for Health Metrics and Evaluation (IHME)*.

Global Health Observatory. (2018). WHO | Overweight and obesity [Data set]. Retrieved from https://www.who.int/gho/ncd/risk_factors/overweight_obesity/obesity_adolescents/en/

Government of India. (2015). *India's Intended Nationally Determined Contribution*. Retrieved from http://www.indiaenvironmentportal.org.in/files/file/INDIA%20INDC%20TO%20UNFCCC.pdf

Gulati, M. P., Priya, S., & Bresnyan, E. W. (2020). *Grow Solar, Save Water, Double Farmer Income: An Innovative Approach to Addressing Water-Energy-Agriculture Nexus in Rajasthan*. World Bank. https://doi.org/10.1596/33375

Hattori, T. (2019). *IGES NDC Database v7.1*. Retrieved from https://www.iges.or.jp/en/pub/iges-indc-ndc-database/en

https://doi.org/10.2305/IUCN.CH.2018.12.en

Indian Council of Agricultural Research. (2015). *Vision 2050*. Retrieved from ICAR website: https://icar.org.in/files/Vision-2050-ICAR.pdf

Indian Institute of Population Sciences. (2016). *India Fact Sheet—National Family Health Survey 4 (2015-16)* [Data set]. Retrieved from http://www.rchiips.org/nfhshttp://www.iipsindia.org

Indian Ministry of Water Resources. (2011). *Strategic plan for ministry of water resources*. Retrieved from http://onlineasdma.assam.gov.in/kmp/pdf/1485858668Waterstrategic%20plan%20ministry.pdf

Jacobson, A. P., Riggio, J., M. Tait, A., & E. M. Baillie, J. (2019). Global areas of low human impact ('Low Impact Areas') and fragmentation of the natural world. *Scientific Reports*, *9*(1), 14179. https://doi.org/10.1038/s41598-019-50558-6

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Alexander, P., & Lucht, W. (2008). Global food demand, productivity growth, and the scarcity of land and water resources: A spatially explicit mathematical programming approach. *Agricultural Economics*, *39*(3), 325–338.

Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., … Wise, M. (2014). Impacts of increased bioenergy demand on global food markets: An AgMIP economic model intercomparison. *Agricultural Economics*, *45*(1), 103–116. https://doi.org/10.1111/agec.12092

Mekonnen, M.M. and Hoekstra, A.Y. (2010a). The green, blue and grey water footprint of crops and derived crop products, Value of Water Research Report Series No. 47, UNESCO-IHE, Delft, the Netherlands. Retrieved from http://www.waterfootprint.org/Reports/Report47-WaterFootprintCrops-Vol1.pdf.

Mekonnen, M.M. and Hoekstra, A.Y. (2010b). The green, blue and grey water footprint of farm animals and animal products, Value of Water Research Report Series No. 48, UNESCO-IHE, Delft, the Netherlands.

Mekonnen, M.M. and Hoekstra, A.Y. (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series No. 50, UNESCO-IHE, Delft, the Netherlands.

Milner, J., Joy, E. J. M., Green, R., Harris, F., Aleksandrowicz, L., Agrawal, S., … Dangour, A. D. (2017). Projected health effects of realistic dietary changes to address freshwater constraints in India: A modelling study. *The Lancet Planetary Health*, *1*(1), e26–e32. https://doi.org/10.1016/S2542-5196(17)30001-3

Ministry of Agriculture & Farmers Welfare. (2018). Agricultural Statistics at a Glance 2018. *Government of India*. Retrieved from http://agricoop.gov.in/sites/default/files/agristatglance2018.pdf

Ministry of Agriculture and Farmer's Welfare, G. of I. (2016). *State of Indian Agriculture 2015-16*. New Delhi, India.

Ministry of Agriculture and Farmer's Welfare. (2017). Report of the Committee on Doubling Farmer's Income. *Government of India*. Retrieved from http://agricoop.nic.in/doubling-farmers

Ministry of Environment and Forests (2014). *India's Fifth National Report to the Convention on Biological Diversity*. Retrieved from www.moef.nic.in

Ministry of Environment, Forest and Climate Change. (2018). *India: Second Biennial Update Report to the United Nations Framework Convention on Climate Change.* New Delhi: MoEFCC, Government of India.

Ministry of New and Renewable Energy. (2018). National Policy on Biofuels 2018. *Government of India*. Retrieved from http://petroleum.nic.in/sites/default/files/biofuelpolicy2018_1.pdf

Ministry of Statistics and Programme Implementation (2020). *Sustainable Development Goals: National Indicator Framework Progress Report, 2020* (2.0) [Data set]. New Delhi: Government of India.

Mogollón, J. M., Beusen, A. H. W., van Grinsven, H. J. M., Westhoek, H., & Bouwman, A. F. (2018). Future agricultural phosphorus demand according to the shared socioeconomic pathways. *Global Environmental Change*, *50*, 149–163. https://doi.org/10.1016/j.gloenvcha.2018.03.007

Müller, C., & Robertson, R. D. (2014). Projecting future crop productivity for global economic modeling. *Agricultural Economics*, *45*(1), 37–50. https://doi.org/10.1111/agec.12088

National Council of Applied Economic Research. (2015). Agricultural Outlook and Situation Analysis Reports: Fourth Semi-annual Medium-term Agricultural Outlook Report. *Ministry of Agriculture and Farmer's Welfare*. Retrieved from http://agrioutlookindia.ncaer.org/Agri_Outlook_Report_September_2015.pdf

NLIS. (2018). *WHO | Nutrition Landscape Information System (NLiS)* [Data set]. Retrieved from https://www.who.int/nutrition/nlis/en/

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., … Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., … van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, *122*(3), 387–400. https://doi.org/10.1007/s10584-013-0905-2

Pingali, P., Aiyar, A., Abraham, M., & Rahman, A. (2019). *Transforming Food Systems for a Rising India*. Retrieved from http://www.palgrave.com/gp/series/14651

Planning Commission. (2012). *Report of the working group on animal husbandry & diary, 12th five-year plan (2012-2017).*

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenoder, F., Stehfest, E., & Bodirsky, B. L. (2017). Land-use features in the shared socio-economic pathways. *Global Environmental Change*, *42*, 331–345.

Potapov, P., Hansen, M. C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., … Esipova, E. (2017). The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances*, *3*(1). https://doi.org/10.1126/sciadv.1600821

Prime Minister's Office. (2019). *Text of PM's address at the 14th Conference of Parties of the UN Convention to Combat Desertification*. Retrieved from https://pib.gov.in/PressReleasePage.aspx?PRID=1584534

Rajan, A., Ghosh, K., & Shah, A. (2020). Carbon footprint of India's groundwater irrigation. *Carbon Management*, *11*(3), 265–280. https://doi.org/10.1080/17583004.2020.1750265

Ritchie, H., Reay, D., & Higgins, P. (2018). Sustainable food security in India—Domestic production and macronutrient availability. *PLOS ONE*, *13*(3), e0193766. https://doi.org/10.1371/journal.pone.0193766

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., … Lawrence, D. (2019). Contribution of the land sector to a 1.5 °C world. Nature Climate Change, 9(11), 817–828. https://doi.org/10.1038/s41558-019-0591-9

Rohwer, J., Gerten, D., & Lucht, W. (2007). *Development of functional irrigation types for improved global crop modelling* [Technical Report]. Germany, PIK.

Rosegrant, M. W., Leach, N., & Gerpacio, R. V. (1999). Alternative futures for world cereal and meat consumption. *Proceedings of the Nutrition Society*, *58*(2), 219–234. https://doi.org/10.1017/S0029665199000312

Sharma, M., Kishore, A., Roy, D., & Joshi, K. (2020). A comparison of the Indian Diet with the EAT-Lancet Reference Diet. *BMC Public Health*. https://doi.org/10.21203/rs.2.19833/v2

Springmann, M. (2019). *Supplementary data to "EAT-*Lancet *Commission on healthy diets from sustainable food systems"* [Data set]. https://doi.org/10.5287/BODLEIAN:7JZQR8EE2

Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M., & Scarborough, P. (2018). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level detail. *The Lancet Planetary Health*, *2*(10), e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7

Stehfest, E., van Zeist, W.-J., Valin, H., Havlik, P., Popp, A., Kyle, P., … Wiebe, K. (2019). Key determinants of global land-use projections. *Nature Communications*, *10*(1), 2166. https://doi.org/10.1038/s41467-019-09945-w

U. S. Department of Justice, & Federal Trade Commission. (2010). *Horizontal Merger Guidelines*. Retrieved from https://www.justice.gov/atr/horizontal-merger-guidelines-08192010#5c

U.S. Department of Health and Human Services and U.S. Department of Agriculture. (2015). *2015-2020 Dietary Guidelines for Americans, 8th Edition* (p. 144). Retrieved from U.S. Department of Health and Human Services website: http://health.gov/dietaryguidelines/2015/guidelines/.

UN DESA. (2015). *World Population Prospects: The 2015 Revision*. Retrieved from https://population.un.org/wpp/publications/files/key_findings_wpp_2015.pdf

UN DESA. (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables* [Working Paper]. Retrieved from United Nations website: https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf

UNEP-WCMC, & IUCN. (2020). *Protected Planet: The World Database on Protected Areas (WDPA)*. Retrieved from UNEP-WCMC and IUCN website: www.protectedplanet.net

UNFCCC. (2020). *Greenhouse Gas Inventory Data—Flexible Queries Non-Annex I Parties* [Database]. Retrieved from https://di.unfccc.int/flex_non_annex1

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., & Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: Trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, *8*(3), 035019. https://doi.org/10.1088/1748-9326/8/3/035019

von Grebmer, K., Bernstein, J., Mukerji, R., Patterson, F., Wiemers, M., Ní Chéilleachair, R., … Fritschel, H. (2019). *2019 Global Hunger Index: The Challenge of Hunger and Climate Change*. Retrieved from https://www.globalhungerindex.org/download/all.html

Wang, X., Biewald, A., Dietrich, J. P., Schmitz, C., Lotze-Campen, H., Humpenöder, F., … Popp, A. (2016). Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, *122*, 12–24. https://doi.org/10.1016/j.ecolecon.2015.11.018

Wanner, N., Cafiero, C., Troubat, N., & Conforti, P. (2014). Refinements to the FAO Methodology for estimating the Prevalence of Undernourishment Indicator. *ESS Working Paper No. 14-05*. Retrieved from http://www.fao.org/3/a-i4046e.pdf

Weindl, I., Bodirsky, B. L., Rolinski, S., Biewald, A., Lotze-Campen, H., Müller, C., … Popp, A. (2017). Livestock production and the water challenge of future food supply: Implications of agricultural management and dietary choices. *Global Environmental Change*, *47*, 121–132. https://doi.org/10.1016/j.gloenvcha.2017.09.010

West, K. P., Jr. (2002). Extent of vitamin A deficiency among preschool children and women of reproductive age. *The Journal of Nutrition*, *132*(9), 2857S-2866S. https://doi.org/10.1093/jn/132.9.2857S

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., Vries, W. D., Sibanda, L. M., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–*Lancet* Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Wirsenius, S. (2000). *Human use of land and organic materials: Modeling the turnover of biomass in the global food system* [Thesis, Chalmers Univ. of Technology]. Sweden. Retrieved from https://www.osti.gov/etdeweb/biblio/20104445

Annex 1.

List of changes made to the model to adapt it to the national context

- MAgPIE is a recursive dynamic cost-minimization model of global land systems. The model simulates crop production, land-use patterns, water use for irrigation, and carbon stock changes at a spatial resolution of 0.5∘ × 0.5∘. An additional feature of this model is the inclusion of international trade between defined world regions A detailed description of the modeling framework can be found in (Dietrich et al., 2019). The technical model description of the used version 4.1 is available at https://rse.pik-potsdam.de/doc/magpie/4.1/.

- MAgPIE uses spatially explicit biophysical information from the global gridded crop and hydrology Lund–Potsdam–Jena managed Land (LPJmL) model (Bondeau et al., 2007).

- To adapt the model at the national context to outline sustainable food and land use system, we first conduct the validation to make it more in the line of national-level context and policies (e.g. improvement in productivity of pastures and grazelands).

- We have created two pathways "***Current Trend***" and "***Sustainable***" by setting the narratives around the Shared Socioeconomic Pathways (SSPs). Under the Current trend, our assumptions are in the line of SSP2, which is regarded as a "Middle of the Road", and for Sustainable, our assumptions are in the line of SSP1 Sustainability – Taking the Green Road scenario (O'Neill et al., 2014; Popp et al., 2017; c.f. the underlying assumptions behind the scenarios in Section 10, Annex 3).

- In the sustainable pathways, we have implemented the biofuel mandate of 20 % blending target in petrol and 5 % in biodiesel according to India's New Biofuel Policy (Ministry of New and Renewable Energy, 2018).

- For the purpose of Scenathon, we have implemented exogenous trade setting for the trade adjustment of few commodities. In an iterative process ("Scenathon") country teams adjust their assumptions and pathways to ensure balanced trade flows and to aim towards achieving the global FABLE targets.

- To convert the MAgPIE output to Scenathon reporting tab we have disaggregated MAgPIE commodities group in to Scenathon commodity group by calculating the historical shares of each commodity within their respective product group by using FAOSTAT data for 2010/2015.

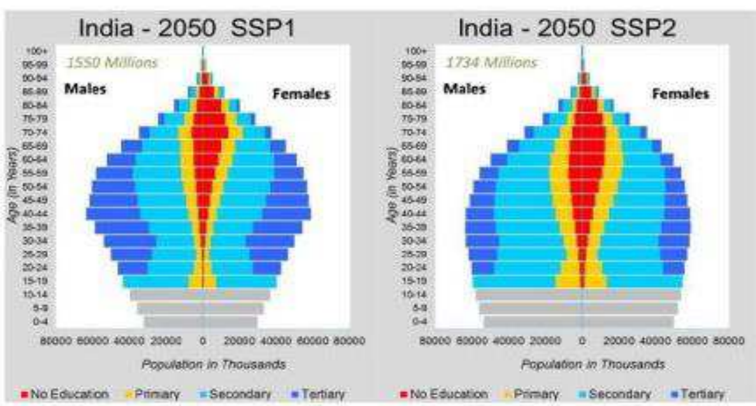
- We have implemented FABLE target of Biodiversity i.e. No net loss by 2030 and an increase of at least 20% by 2050 in the area of land where natural processes predominate and Protected areas cover at least 30% of global terrestrial land by 2030 by using evolution in the land cover category.

Annex 2.

Underlying assumptions and justification for each pathway

Current Trend Pathways	***Sustainable Pathways***
Population : *Population projection (million in habitants)*	

The population is expected to reach 1.73 billion by 2050 based on our underlying assumption of SSP2 parameterization (Kc & Lutz, 2017). *Currently, India's population is 1.31 billion and it is expected to reach approximately 1.4 billion by 2022. The projection suggests that India's population will continue to grow for several decades up to 1.5 billion in 2030 and 1.8 billion in 2050* (UN DESA, 2015).	*The population is expected to reach 1.55 billion by 2050 based on our underlying assumption of SSP1 parameterization. The SSP1 parameterization is towards sustainable pathways which assumes that investments in health and education will accelerate the demographic transition, leading to a relatively low world population* (Kc & Lutz, 2017). *Research indicates that under the SPP1 scenario for India, female education levels will be higher along with lower assumed education-specific fertility rates, thereby resulting in much lower birth rates.*



Population of India by age, sex and educational attainment under SSP1 and SSP2 scenario (Source:* Kc and Lutz, 2017*).

Land : Constraints on agricultural expansion

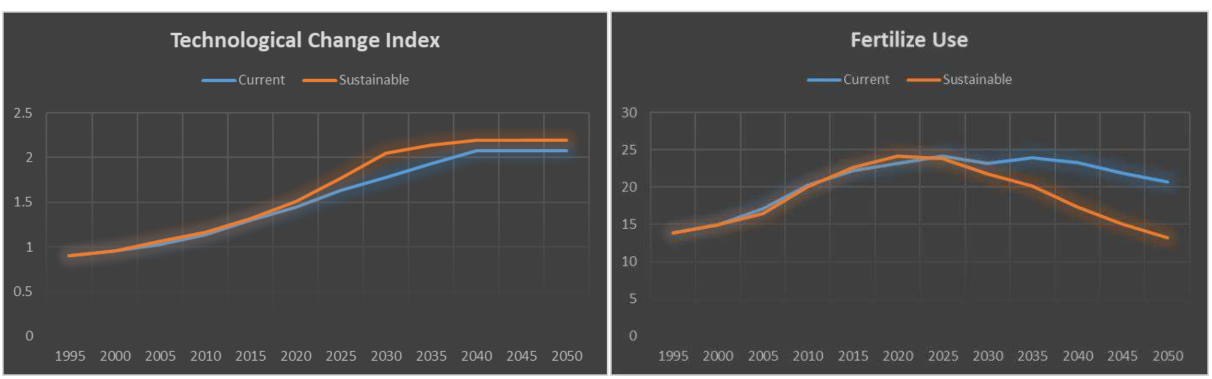
We assume that deforestation will be halted beyond 2005. The assumption is based on several national policies that have been implemented (e.g. the Indian Forest Act and Indian Forest Conservation Act) and based on historical trends (FAO, 2020). Therefore, no agricultural land expansion into natural forests is allowed. *Agricultural land can be increased by converting other natural vegetation areas that have lower carbon densities than natural forests.* *Areas under the industrial forestry sector are assumed to be constant and therefore cannot be converted in other land uses.*	*We assume that deforestation will be halted beyond 2005. The assumption is based on several national policies that have been implemented (e.g. the Indian Forest Act and Indian Forest Conservation Act) and based on the historical trends (FAO, 2020). Therefore, no agricultural land expansion into natural forests is allowed.* *Agricultural land can be increased by converting other natural vegetation areas that have lower carbon densities than natural forests.* *Areas under the industrial forestry sector are assumed to be constant and therefore cannot be converted in other land uses.*
Afforestation or reforestation target (1,000 ha)	
We assume total afforested/reforested area to reach 21 Mha by 2030. These assumptions are based on India's Bonn Challenge Commitment (2014) whereby India has pledged to restore 13 Mha of degraded and deforested land by 2020, and an additional 8 Mha by 2030. According to B Binod et al., 2017 *India has brought an area of 9.8 million hectares under restoration since 2011, meaning that work to restore these landscapes is already underway.*	*We assume total afforested/reforested area to reach 26 Mha by 2030. This assumption is based on India's additional commitment of 5 Mha in line with the existing Bonn Challenge Commitment (2014). This new commitment was announced by the Government at the UN Summit in 2019* (Prime Minister's Office, 2019).

<table>
<tr><td colspan="2">Biodiversity : Protected areas (1,000 ha or % of total land)</td></tr>
<tr><td>We assume that protected areas remain stable until 2050: by 2050 they represent 6% of total land. Indian protected areas were computed using the data from World Database on Protected Areas (UNEP-WCMC & IUCN, 2020). The assumptions are in line of India's commitment to CBD.</td><td>We assume that protected areas remain stable until 2050: by 2050 they represent 6% of total land. Indian protected areas were computed using the data from World Database on Protected Areas (UNEP-WCMC & IUCN, 2020). The assumptions are in line of India's commitment to CBD.</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Crop productivity for the key crops in the country (in t DM /ha)</td></tr>
<tr><td>By 2030, crop productivity reaches:
4. 5 tonnes DM per ha for Rice.
1.9 tonnes DM per ha for Corn
6.7 tonnes DM per ha for Soybean.
We assume a moderate increase in the crop productivity over 2010. This dynamic change in crop productivity is based on our assumptions of medium technological cost and medium interest rate i.e 7% that influences investment in yield-increasing technologies. The assumed investment horizon is provided by the interest rate, which is a risk-accounting factor associated with investment activities (Dietrich, Schmitz, Lotze-Campen, Popp, & Müller, 2014; Wang et al., 2016). Along with the technological change, the</td><td>By 2030, crop productivity reaches:
6.5 tonnes DM per ha for Rice.
2.5 tonnes DM per ha for Corn.
7.8 tonnes DM per ha for Soybean.
We assume a high increase in the crop productivity over 2010. This dynamic change in crop productivity is based on our assumptions of low technological cost and lower interest rate i.e 4%. The assumed investment horizon is provided by the interest rate, which is a risk-accounting factor associated with investment activities (Wang et al., 2016). Alsso due to underlying SSP1 parameterization the yield growth is proportional to the growth in fertilizers use (Mogollón, Beusen, van</td></tr>
</table>

change in crop yield is also driven by high use of fertilizers due to the underlying SSP2 parameterization and yield growth is proportional to the growth in fertilizers use (Valin et al., 2013; Mogollón et al. 2018). The elasticity of variable input including fertilizer use w.r.t technological change is 1.00 (Fricko et al., 2017) *which means the use of moderate use of yield improving technology with moderate use of fertilizer.*

Grinsven, Westhoek, & Bouwman, 2018; Valin et al., 2013). *The elasticity of variable input including fertilizer use w.r.t technological change is 0.75* (Fricko et al., 2017) *which means high use of yield improving technology and low use of fertilize.*

Our assumptions are based on National Council of Applied Economic Research (2015) *that suggests that due to technological innovation and diffusion through institutional arrangements, growth in yield will be high in the coming decades. In addition, several subsidies will reduce the cost of technologies and increase economies of scale. The study suggests that the area expansion for several cereal crops including wheat is going to be weak and production, and growth will mostly be driven by yield increase.*



Difference in fertilizer use under Current trend(SSP2) and Sustainable Pathways(SSP1)

Livestock productivity

We assume that by 2050, livestock productivity moderately increases based on improvements in feed basket content and livestock production systems. Following the methodology of Wirsenius (2000) *feed conversion (total feed input per product output in dry matter) and feed baskets (demand for different feed types per product output in dry matter) are derived by compiling system-specific feed energy balances. To facilitate projections of feed conversion and feed baskets, we create regression models with livestock productivity (annual production per animal [tonne fresh matter/animal/year]) as predictor, which permit the construction of livestock feeding scenarios. Currently, feeding scenarios are derived based on exogenous livestock productivity scenarios consistent with the storylines of the Shared Socioeconomic Pathways* (Weindl et al., 2017). *We assume SSP2 storyline which implies moderate efficiency growth for feed basket along with medium livestock system transition for livestock productivity* (Fricko et al., 2017). *Based on* National Council of Applied Economic Research (2015)*, the increase in income levels, population, and urban space, as well as the increased use of livestock product will expand the production of livestock products in coming decades. Despite a major dependency on cereals, rising protein consumption will necessitate increasing livestock*	*By 2050, livestock productivity increase at a higher rate than 2010 based on the improvement in feed basket and livestock production systems. The feed conversion calculation is same as described in* ***Current Trend****. We assume SSP1 storyline which implies high efficiency growth for feed along with high livestock system transition for livestock productivity* (Fricko et al., 2017). *The extent to which growth in livestock production can be accelerated will depend on how technology, institutions and policies address constraints facing the livestock sector. Production growth dependent on larger animal stock is not sustainable in the long run, due to adverse effect on carrying capacity of land and available resources; hence, future growth in production should essentially come from improvements in productivity. This will require overcoming feed and fodder scarcity and improvements in delivery of animal health and breeding services. A key driver of growth and concerted the desired efforts will be the generation and dissemination of yield-enhancing and yield-saving technologies* (Ministry of Agriculture and Farmer's Welfare, 2017).

and dairy production. To meet the domestic protein demand, the Government of India is focusing on livestock intensification systems to improve yield in animal products (Planning Commission, 2012).	
Pasture stocking rate	
By 2050, the average ruminant livestock stocking density per hectare will be higher than 2010 as we assume higher yield of pasture. Several initiatives were taken to improve livestock feeding systems because by 2025, India is likely to experience a fodder deficit of about 65% for green fodder and 25% for dry fodder (Indian Council of Agricultural Research, 2015; Ministry of Agriculture and Farmer's Welfare, 2017; Planning Commission, 2012).	*By 2050, the average ruminant livestock stocking density per ha will be higher that 2010 as we assume higher yield of pasture. Several initiatives were taken to improve livestock feeding systems because by 2025, India is likely to experience a fodder deficit of about 65% for green fodder and 25% for dry fodder* (Indian Council of Agricultural Research, 2015; Ministry of Agriculture and Farmer's Welfare, 2017; Planning Commission, 2012).
Trade	
Share of consumption which is imported for key imported products (%)	
By 2050, the share of total consumption which is imported is: ● *17% for Corn.* ● *14% by 2050 for Groundnut.*	*By 2050, the share of total consumption which is imported is:* ● *28% by 2050 for Corn.* ● *21% by 2050 for Dairy.*

● *10% by 2050 for Poultry Meat*	● *21% by 2050 for Poultry Meat*
Evolution of exports for key exported products (1,000 tonnes)	
By 2050, the volume of exports is: ● *9,037 tonnes by 2050 for Soybean.* ● *3,409 tonnes by 2050 for Fibers.* ● *2,428 tonnes by 2050 for Cotton Lint.* *Based on our assumption of 10% trade liberalization for secondary and livestock products in 2030, 2050, 2100 and 20% for crops.*	*By 2050, the volume of exports is:* ● *7,747 tonnes by 2050 for Soybean.* ● *1,4370 tonnes by 2050 for Oils cake.* ● *195 tonnes by 2050 for Cotton Lint.* *Based on our assumption of 10% in 2030, 20% in 2050, 2100 crops: 20% in 2030, 30% in 2050, 2100.*
Food	
Average dietary composition (daily kcal per commodity group)	
By 2030, the average daily calorie consumption per capita is 2,260 kcal and is: ● *1,207 kcal from crops.* ● *363 kcal from livestock products.* ● *626 from secondary products.* *Our assumption is in the line SSP2 parameterization which assume moderate*	*By 2030, the average daily calorie consumption per capita is 2,286 kcal and is:* ● *1,170 kcal from crops.* ● *385 kcal from livestock products.* ● *668 kcal from secondary products.* *We implemented a transition to a sustainable and healthy diet into the framework of the*

consumption growth and increasing share of livestock products in the diet (Fricko et al., 2017). *We assume that expected rise in per capita income, commercialization and urbanization will cause a shift from main staples to high value products, for example livestock products in India* (Alae-Carew et al., 2019; Ritchie, Reay, & Higgins, 2018; Rosegrant, Leach, & Gerpacio, 1999)*, and substantial increases in projections for vegetable oils and sugar* (Alexandratos, Nikos & Bruinsma, Jelle, 2012; Carriquiry et al., 2010)	*model-internal calculations of food demand, which are designed for long-term scenarios of food intake, dietary composition, body mass index distribution, body height and food waste. The food demand model is established based on a regression analysis with historical data to estimate consumption patterns using only changing GDP and population levels over time as drivers* (Bodirsky et al., 2015; Dietrich et al., 2019). *For the Sustainable Pathway we assume a linear convergence during the period 2020 and 2050 from the model-internal calculations using the SSP1 parametrization towards dietary patterns according to recommendations for a healthy and sustainable diet by the EAT*-Lancet *Commission* (Springmann, 2019; Springmann et al., 2018).
Share of food consumption which is wasted at household level (%)	
By 2030, the share of final household consumption which is wasted at the household level is 20%. This value is based on an exogenous food waste target comparing to approximately half of those of High-Income countries. These exogenous values are derived on FAO historical data and calibrated to FAO Food supply values globally.	*By 2030, the share of final household consumption which is wasted at the household level is 10%. This value is based on an exogenous food waste target comparing to approximately a quarter of those of High-Income countries. These exogenous values are derived on FAO historical data and calibrated to FAO Food supply values globally.*

In India, since food loss is mainly determined by the loss of fruits and vegetables during transportation and retail, we assume medium reduction of food losses and waste by 2050 under the SSP2 scenario (Fricko et al., 2017) *as there is little available information on food waste at the household level.*	*Under the SSP1 scenario, the expectation is a more sustainable use of food at household level, owing to changes in consumer behavior, better storage facilities and better food education* (Stehfest et al., 2019) *as there is little available information on food waste at the household level.*
Biofuels: *Targets on biofuel and/or other bioenergy use (Mt DM/Year)*	
By 2050, biofuel production accounts for: ● *79.633 Mt DM/Year of Sugarcane production.* ● *2.388 Mt DM/Year of Corn production.* ● *28.967 Mt DM/Year of Temperate Cereals production.* *Based on our assumption that the demand for bioenergy will increase till 2030 and constant after that. The demand energy is defined total demand for first-generation bioenergy, which is mainly determined by public policy measures, rises to about 6 EJ of final energy globally in 2030 and 0.5 EJ of final energy for South Asian Region in 2030* (Lotze-Campen et al., 2014). *India's average blending rate for ethanol in gasoline is expected to reach a record 5.8%, up from a previous record 4.1% last year and considerably higher than historical levels. A*	*By 2050, biofuel production accounts for:* ● *540 Mt DM/Year of Sugarcane production.* ● *33.91 Mt DM/Year of Corn production.* ● *39.13 Mt DM/Year Temperate Cereals production.* *Based on the implementation of India's New Biofuel Policy, 2018. The policy has an indicative target of 20% blending of ethanol in petrol and 5% blending of biodiesel in diesel is proposed by 2030. Under these scenarios we assume that the demand for ethanol will increase from 0.4 PJ/yr to 788 PJ/yr over the period from 2015 to 2030 and to 1838 PJ/yr in 2050. To meet the biodiesel mandate we assume that the demand for vegetable oils will also increase from 0.837 PJ/yr to 292 PJ/yr over the period from 2015 to 2030 and to 680 PJ/yr in*

surplus sugar season coupled with a stronger incentive to convert excess sugar to ethanol helps oil-marketing companies procure upwards of 2.4 billion liters this year (Aradhey, 2019)	*2050 under the scenario with continued increase after 2030. In our scenario we assume that there will be constant demand after 2030 till 2050* (Ministry of New and Renewable Energy, 2018)
Water: *Evolution of irrigation water use efficiency*	
By 2050, average blue water use for irrigation per tonne produced is reduced by 34% compared to 2010. *These assumptions are based on population projections and changing food demand, increased urbanization and the re-allocation of water for other purposes than agriculture* (Indian Ministry of Water Resources, 2011)	*By 2050, average blue water use for irrigation per tonne produced is reduced by 35% compared to 2010. These assumptions are based on calculations where blue water footprint per person is expected to be reduced by 30.3% based on population projections* (Indian Ministry of Water Resources, 2011; Milner et al., 2017). *India's commitments to reduce over-extraction of water in various states (Gujarat, Punjab, Haryana and Rajasthan) also hints towards more sustainable use of water for irrigation in the future* (Chindarkar & Grafton, 2019; Gulati, Priya, & Bresnyan, 2020; Rajan, Ghosh, & Shah, 2020). *We, therefore include environmental flow requirements in our model assumptions, that reserve a certain fraction of water for environmental purposes, that are not available for agricultural activities.*

Climate change: *Crop model and climate change scenario*	
By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 6). Impacts of climate change on crop yields are computed by the crop model LPJmL (Bondeau et al., 2007; Müller & Robertson, 2014).	*By 2100, global GHG concentration leads to a radiative forcing level of 6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model LPJmL* (Bondeau et al., 2007; Müller & Robertson, 2014).

Annex 4. Correspondence between original ESA CCI land cover classes and aggregated land cover classes displayed on Map 1

FABLE classes	**ESA classes (codes)**
Cropland	Cropland (10,11,12,20), Mosaic cropland>50% - natural vegetation <50% (30), Mosaic cropland<50% - natural vegetation >50% (40)
Forest	Broadleaved tree cover (50,60,61,62), Needleleaved tree cover (70,71,72,80,82,82), Mosaic trees and shrub >50% - herbaceous <50% (100), Tree cover flooded water (160,170)
Grassland	Mosaic herbaceous >50% - trees and shrubs <50% (110), Grassland (130)
Other land	Shrubland (120,121,122), Lichens and mosses (140), Sparse vegetation (150,151,152,153), Shrub or herbaceous flooded (180)
Bare areas	Bare areas (200,201,202)

Snow and ice	Snow and ice (220)
Urban	Urban (190)
Water	Water (210)

Units

°C – degree Celsius

% – percentage

/yr – per year

cap – per capita

CO_2 – carbon dioxide

CO_2e – greenhouse gas expressed in carbon dioxide equivalent in terms of their global warming potentials

EJ – Exa Joule

g – gram

GHG – greenhouse gas

ha – hectare

DM – Dry Matter

kcal – kilocalories

kg – kilogram

kha – thousand hectares

km^2 – square kilometer

km^3 – cubic kilometers

kt – thousand tonnes

m – meter

Mha – million hectares

mm – millimeters

Mm^3 – million cubic meters

Mt – million tonnes

PJ- Peta Joule

t – tonne

TLU –Tropical Livestock Unit is a standard unit of measurement equivalent to 250 kg, the weight of a standard cow

t/ha – tonne per hectare, measured as the production divided by the planted area by crop by year

t/TLU, kg/TLU, t/head, kg/head- tonne per TLU, kilogram per TLU, tonne per head, kilogram per head, measured as the production per year divided by the total herd number per animal type per year, including both productive and non-productive animals

USD – United States Dollar

W/m^2 – watt per square meter

yr – year