An Inclusive agri-food systems transformation pathway for India

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Abstract

Although India has transformed from a food scarce to a food self-sufficient nation, the challenges of nutrition security, regional inequalities, and unsustainable agricultural practices persist. Existing policies lack an integrated vision for and implementation of holistic food system changes. This study undertakes a food system assessment for India using a global food system modelling framework, evaluating 23 food system measures on 14 indicators across dimensions of health, environment, inclusion, and economy. The food system measures include healthy diets, biosphere protection, agriculture management, equitable livelihood, and external reforms. Results indicate that 13 out of 14 indicators including nutrition and environmental outcomes improve due to synergistic effects driven by coordinated interventions, reducing trade-offs among the four dimensions of the food system. While progress is observed in most health and environmental indicators, challenges such as rising obesity and nitrogen pollution persist. Our attempt to quantify the dynamics of India's food system under different scenarios enables understanding the trade-offs across dimensions. The comprehensive and forward-looking food system outcomes that this study elucidates aid in the identification of pivotal intervention points and facilitate strategizing policies for transformative changes.

Main

India's food system is a paradigmatic example of the complexities and opportunities associated with feeding a vast and diverse population of over 1.4 billion people and navigating the complex interplay between economic development, sustainability, and public health in the national and global context. Its agricultural diversity, farming practices, and rights-based food policies engage multiple food systems with large socio-economic and environmental variations[1], making it a crucial case for understanding global food system transformation concerns. So far, India's food policy has remained focused on food production, adequacy, and access by ensuring food security through food safety nets and right-based access, rural livelihoods through employment generation programmes, and trade[2,3]. Policy recognition of the need to ensure nutritional security, dietary diversity, and environmental conservation while meeting future food requirements sustainably has been slow[4,5].

The need for transforming India's food system is now more urgent than ever [6,7]. Despite rising per capita incomes, progress in nutrition and health has been sluggish, primarily due to nutritionally deprived diets resulting in high levels of malnutrition[8–10], also causing huge productivity related economic losses[11]. Malnutrition is the major contributor to disease burden in India[12] with approximately 194 million people undernourished, 43.3 million children under the age of five stunted, and with obesity increasing at alarming rate[13,14]. Economic losses from reduced productivity of underweight and obese agricultural workers are equivalent to 2.34% of gross domestic product (GDP)[15]. Furthermore, cereal-intensive production and distortionary policies, such as energy and fertilizer subsidies, have aggravated environmental issues, such as excessive water withdrawals, soil degradation, and chemical runoff[16,17]. Currently, nearly 80% of freshwater is used for rice and wheat cultivation[18,19], while less than 5% of the land is effectively protected for conservation[20]. Being one of the global hotspots of nitrogen pollution, the country incurs an annual cost of around 75 billion USD[21,22], while emissions from rice and livestock contribute nearly 14% of India's economy-wide emissions[23,24]. Additionally, with agriculture engaging over 50% of the workforce, 82% farmers being smallholders, low absolute farm income and high disparity between agricultural and non-agricultural farm income raises concerns for equality and inclusivity[25].

Prioritizing specific aspects like health, environment, social factors, or economic development can lead to conflicts in sustainability[26]. Therefore, concerted and systemic interventions are necessary to facilitate the transition toward improved food systems, addressing interconnected domains such as health, environment, and inclusion[6,27]. Future visions of sustainable food system transformation pathways need an integrated systems perspective to effectively address potential co-benefits and trade-offs between multiple dimensions[28–30]. Recent studies have shown the potential of scenario modelling with Integrated Assessment Models (IAMs) in identifying key leverage points for transformations[31,32]. Globally, a multi-criteria assessment of various food system measures (FSMs) suggests that a healthy, environmentally sustainable, and inclusive food system is achievable with synergistically aligned policy interventions[27]. For India, previous studies have evaluated the impacts of isolated food system interventions, such as dietary changes and associated environmental impacts[33,34]. Other studies suggest the potential of India's natural resource capacity and food systems in achieving nutrition security, maintaining environmental sustainability, and meeting mitigation objectives associated with the agriculture, forestry and other land-use (AFOLU) sector[35,36]. However, these studies commonly indicate the need for systemic changes in food systems to realize long-term sustainable transformation.

This study attempts to conduct the first large-scale multi-indicator food system assessment for India in the context of health, environment, inclusion, and economic development. Central to our analysis are five distinct packages aligned with the United Nations Food System Summit (UNFSS) action tracks[37] - healthy diets and sustainable consumption patterns (Diets), nature-positive agricultural transition (Agriculture), biodiversity protection (Biodiversity), equitable livelihoods (Livelihoods), and a broader socio-economic development external to the food system (CrossSector). These packages are represented by 23 FSMs and five transformation measures outside the food system and includes a range of interventions, from shifts towards more sustainable and healthy diets, to the conservation of natural resources and the adoption of higher wages (for a full list see Extended data table 1).

The study explores the domestic changes resulting from both direct and indirect effects of large-scale food system changes across multiple policy goals specific to India. The baseline scenario (BASE_SSP2) of the study aligns with the 'middle-of-the-road scenario' of the Shared Socio-economic Pathways (SSP2) [38–40], where the future state of the food system continues with the current trends, without any targeted interventions for sustainable transitions. Deviating from this baseline, we quantify the impacts of each measure both individually and in packages for 14 diverse indicators (see Extended Data Table 2) representing multiple food system dimensions for India. The food system development pathway

(FST_SDP) represents an integrated and holistic transformation strategy that encompasses all FSMs and external transformations.

This study performs an extended analysis using modelling framework and scenario design used in the global FST study[27], but with a focus on the Indian context. The modelling framework includes the integrated food and land-use model MAgPIE[41], linked with a food demand model[42], the vegetation, crop, and hydrology model LPJmL[43,44], a dietary health model[45], and an income distribution and poverty model[31] to address a multitude of objectives within a food system (see Methods for details and the Supplementary material for validation of key variables). In the rest of the paper, we describe our results across the policy packages and their impacts on our selected indicators.

Results

India's current trends hinder long-term sustainable development goals

Projections in the reference scenario (BASE_SSP2) until 2050 reveal concerning trends for most indicators in our multi-dimensional framework (Fig. 1). Despite strongly rising per capita incomes compared to 2020, 307 million persons (including children) remain underweight by 2050. Transition towards more affluent and energy-dense foods due to rising income and urbanization levels accentuates India's overweight and obesity problem as the headcount of obese people increases from 58.6 million in 2020 to 176 million by 2050 (Fig. 2). Increasing health risks associated with diets and weight also contribute to an increase in the Years of Life Lost (YLL) (extended Table 2) from 50 to 72 million in 2020–2050 emanating from rising incidence of Noncommunicable diseases (NCDs) especially from diseases like cancer and type-2 diabetes. Cereals, sugar, oils, and animal-sourced foods (ASFs) including dairy make up a significant portion of calorie intake in India (Fig. 3a). This aligns with other research emphasizing high cereal consumption and insufficient intake of proteins, fruits, and vegetables in India[46].

Productivity enhancements in crop production result in a 32% reduction in irrigated croplands and 36% reduction in agricultural water use, compared to 2020. Increasing pressure on land resources to meet the food demand causes decline in biodiversity in cropland landscapes without any substantial improvement in crop area diversity represented by the Shannon Index (Extended Table 2) until 2050 (Fig. 1h, i). Nitrogen pollution rise by 41% in 2050 due to excessive nitrogen use on cropland and pastures, as higher food production and poor animal waste management drive nitrogen overload (Fig. 1j). GHG emissions from agriculture, forestry, and land use (AFOLU) also rise from 0.93 to 1.5 $GtCO_2eq$ by 2050 due to high methane and nitrogen emissions from rice and livestock production (Fig. 1m).

As the economy progresses in the SSP2 trajectory, positive societal gains result in improved wages and reduced poverty rates. 395 million people are uplifted from poverty and household expenditures on food as share of income, decline by 2050 (Figure SM2). This pattern corresponds to rising incomes and urbanization, leading consumers to invest luxury goods such as expensive foods including processed foods[1,47,48]. The agricultural wage index improves from 1.4 to 3.5 by 2050 as hourly labour costs per worker are higher, indicating improved agricultural livelihoods. Agricultural employment declines from 185 to 96 million people by 2050 due to increasing labour productivity and mechanization.

Essential demand-side measures for diverse, healthy diets in India

Strategies that encourage healthy food choices alongwith targeted efforts to address malnutrition result in positive health outcomes. Adoption of Planetary Health diets[49,50] and targeted reduction in obesity and undernutrition through calorie intake adjustments result in consumption of diverse foods with positive impacts on health outcomes (details in SI).

Our scenarios on targeted measures of specific food groups such as legumes results in higher intake of pulses by 117% and reduction of sugars by 66%, as compared to BASE_SSP2 in 2050 (Fig. 2). These yield positive effects on premature mortality rates and YLL which reduces maximum due to consumption of fruits, vegetables, and nuts (14%) (*HighVegFruitsNuts* scenario*)*, followed by reduction in *LowProcessed* (4%) and *HighLegumes* (3%) scenarios. The current low consumption rates of fruits, vegetables, and nuts in India need prioritized attention to promote positive health outcomes[51–53], alongwith concerted efforts towards healthy diets, as seen in our *Diets* scenario. No persons are underweight, overweight population is reduced by half (88 million people) and YLL is lower by more than half of the BASE_SSP2 values in 2050, when individual measures are combined (Fig. 2, Fig. 3c).

Measures that only focus on total calorie intake may not result in improved dietary quality. Cereals and sugar provide 52% of the calories in the *NoUnderweight* and *HalfOverweight* scenarios, whereas fruits, vegetables and nuts are 43%-46% lower in these scenarios compared to the *HighVegFruitsNuts* scenario (Fig. 3a). Food choices in India are heterogeneous and largely driven by cultural factors[54,55], with animal-sourced foods (ASFs) consumption, except milk, being substantially lower than the global average[56]. Therefore, measures that target protein-energy malnutrition in India through diverse, nutrition-sensitive foods, such as our *Diets* scenario are relevant[8,57].

Environmental sustainability demands dietary shifts, trade openness, and efficient agriculture

Compared to the BASE_SSP2 scenario, the *Diets* package creates positive environmental outcomes, improving agricultural biodiversity and reducing nitrogen overload by 25%. This package reduces emissions (CO2, CH4 and N2O combined) to 0.6 $GtCO_2$ in 2050 through a shift away from ASFs (*LowRuminants*) and reduction in food waste (*LowFoodWaste*). Measures promoting lower ASFs consumption (*LowMonogastrics* and *LowRuminants*), and reduced food waste (*LowFoodWaste*) offset nitrogen surplus caused by the increased cultivation of fruits, vegetables, and nuts, leading to a 6% rise in annual nitrogen pollution (Fig. 2). However, trade-offs with agricultural water use and environmental flow conservation emerge (Fig. 4d). In *HighVegFruitsNuts* and *LowRuminants* scenarios, agricultural water use is higher by 14% and 17% respectively, as water footprints of vegetable oils, nuts and seed, andASF are highest[58].

The introduction of liberal trade (*LibTrade*) in the *Livelihoods* package reduces nitrogen burden by 14% by 2050. This occurs due to a decline in demand of cereals, oil crops, sugarcane, pulses and ASFs and their associated production. By allocating crop production to competitive and efficient regions, this measure also results in reduced demand for agricultural water by 18% and conservation of environmental flows (Fig. 2, Fig. 4d).

Targeted sectoral policy measures can bring positive effects on key indicators such as water conservation and biodiversity intactness, as in the *Biosphere* package. *WaterConservation* measure results in the maximum savings of water and protection of environmental flows through efficient utilization of water for agricultural purposes. The *BiodivOffset* measure significantly improves Biodiversity Intactness Index (BII) in cropland and hotspot landscapes supporting enhanced species richness through improved Shannon Index. Land sparing measure (*LandConservation*) enhances biodiversity in hotspot areas but increases water environmental flow violations significantly. At the same time, trade-offs emerge with agricultural measures. In the *Agriculture* package, intensive livestock systems and improved feed efficiencies result in increased use of cropland for livestock feed, reducing the cropland BII and crop area diversity to 2.17 (Fig. 2). This has implications for biodiversity loss due to an expansion of pasturelands (Fig. 4a). *CropRotation* and *LivestockManagement* measures exacerbate water stress, causing a 55% surge in water withdrawals. The increase in nitrogen pollution through the *LivestockManagement* is offset by the specific *NitrogenEfficiency* measure, as it helps reduce nitrogen surplus by 35% to 20 Mt (Fig. 4b) and lower emissions. Intensive livestock systems, efficient feed replacement from roughages to concentrates and improved animal waste management contribute to lower emissions.

This has implications for India where despite lower per capita reactive nitrogen consumption, inefficiencies in feed conversions and manure management result in notable nitrogen losses across diverse production systems[59]. India being the second largest consumer of nitrogenous fertilizers with high subsidies, nitrogen mitigation measures are crucial, as demonstrated in the *Agriculture* package.

Expanding agricultural opportunities fosters an inclusive food system through improved livelihoods

Individual livelihood interventions may be insufficient in improving inclusion outcomes by 2050. Liberal trade measure (*LibTrade)* reduces agricultural employment by 9 million people (Fig. 2) but lowers domestic commodity prices and reduces food expenditures by 5% in 2050 (Figure SM5, SM6 in SI). This is due to reallocation of production processes to more competitive regions. Reduction in agricultural employment is also brought about by the *MinWage* measure by 89 million people (8%) as minimum wages rise and labour is substituted by capital (Figure SM7 in SI). Such large reduction in employment however results in higher commodity prices and increased food expenditures by 27% in 2050 as is being observed in India[59], thereby suggesting that higher wages improve farmer livelihoods, but also need inclusive transformative actions to promote inclusive development[60]. Measures to improve agricultural employment on the other hand, such as *CapitalSubst* project an increase in agricultural employment by 74% by 2050 (additional 9 million people). This may be possible by transformative measures such as post-harvest value chains and small agricultural enterprises that target capital substitution with labour can cause additional cost to the economy, as production expenses rise by 2% to 685 billion USDMER05 (Fig. 2).

Combination of these individual measures (*Livelihoods* package) results in lower agricultural employment, higher wages, and lower production costs (Fig. 2; Fig. 5a). Additionally, annual per capita expenditure for agricultural commodities rises to 652 USD by 2050, driven by higher food prices. On the other hand, the *Diets* package, with lower ASFs, creates employment for an additional 17 million people but raises expenditures by 8.2% due to high prices. This could negatively affect the affordability of healthy diets, particularly for the Indian rural poor, as seasonal price fluctuations for nutrient-dense foods like fruits and vegetables coupled with low wage earnings of unskilled workers[61–63] can have a detrimental impact on public health. It is important to note that the agriculture employment numbers presented here only include people employed in agriculture but not in activities related to the value chain, services, and retail; therefore, employment numbers may only represent lower-bound projections.

Packaging interventions exploits synergies and manages trade-offs across policy domains

Combining FSMs across policy domains can have varying impacts on sustainable food system goals has co-benefits and trade-offs across indicators (Fig. 2). India's transition to the EAT-Lancet recommended diet improves health and most environmental indicators but increases water stress. Focus on nutritional security to reduce underweight population results in higher production costs (23.1 billion USD annually) while overweight reduction potentially saves 17.4 billion USD (2.7% lower than baseline). The *Diets* package is synergistic with 11 indicators out of 14. The *Livelihood* package shows synergies for 7 indicators but trade-offs for 3 (Fig. 2), with *LibTrade* driving environmental benefits, especially in water use and emissions reduction. *MinWage* creates trade-offs due to higher production costs and food price inflation. Capital-intensive production may slow rural transformation and raise food security concerns by shifting agricultural labor to other sectors. The *Biosphere* package improves 5 environmental indicators with no significant trade-offs. The *Agriculture* package shows synergies for 4 indicators, reducing nitrogen overload and creating jobs, but worsens environmental flow, biodiversity, and agricultural expenditures, leading to high economic costs.

Concerted measures on demand and supply sides yield more co-benefits than trade-offs for food system goals.

The *FST_SSP2* scenario integrates 23 FSMs into a single pathway creating synergies that enhance the benefits of most individual measures (Fig. 2). The *Biosphere, Diets*, and *Livelihoods* packages jointly offset the environmental trade-offs enforced by the *Agriculture* package, leading to improved biodiversity and crop area diversity. This scenario enhances the emission reduction potential of the AFOLU sector as annual emissions decrease to zero and minimizing pressure on water resources. *FST_SSP2* shows food system issues can be fixed without increasing poverty. Agricultural expenditure rises by 11.8% to $608 per person per year, driven by *Livelihood* and *Agriculture* packages, while production costs drop 18.7% to $546 billion annually compared to the baseline.

Positive outcomes from measures from outside of the food systems (*CrossSector*) highlight the role of external transformations that enable sustainable and just human development. Due to the SSP1 trajectory of development in this scenario, a stable population reduces pressures on the agricultural sector. Higher education and incomes (*HumanDevelop*) reduce premature deaths by 22 million years but increase obesity without measures to curb processed food consumption. (Fig. 3a). Higher per capita incomes also result in greater affordability of food, reduction in poverty due to economic growth and reduced inequality. This also results in reduction of agricultural employment to 65 million people due to adoption of capital-intensive agricultural technologies.

Our full sustainable transformation pathway (*FST_SDP*) combines the FST_SSP2 with *CrossSector* projects an improvement in 13 out of the selected 14 indicators. Compared to *BASE_SSP2*, the agricultural wages are higher, and employment is reduced by 31 million persons. However, despite reduction in emissions and nitrogen pollution in the *FST_SDP*, further action is needed to meet global planetary boundaries of the 1.5°C climate target[27].

Discussion

Our analysis in this paper transforms visions of sustainable food system futures into actionable policy framework. This assessment underscores the need for concerted efforts to achieve a holistic, sustainable, and inclusive food system in India. While progress on objectives such as reducing obesity, creating farm sector employment, and lowering nitrogen pollution requires focused attention, our analysis highlights the complexity of achieving these multifaceted outcomes. We project changes in food systems in India across scenarios as policy measures which generate positive outcomes for all food system dimensions (health, environment, inclusion) but aggravate water distress and reduce agricultural employment. This result is reflective of assessments of India’s transformation towards ‘Lewis’s trap’ and ‘farmer excluding’ path with widening farm and non-farm incomes and reduced number of farmers[64]. Such transformations weaken food system inclusion prospects if other economic sectors fail to absorb surplus labour, with rural distress due to disparities between agricultural and non-agricultural incomes[65]. Addressing these challenges requires creation of additional green jobs, new social security nets and skill-based jobs in agriculture and post-harvest operations. These are measures beyond food systems and by evaluating them individually and combined, we uncover the interconnectedness among a wide range of indicators within the context of food system transformation potential in India.

Declarations

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Author contributions

VS, PD, MS, BLB, CKJ, HLC, AP, FB, FH and RKG designed the study

VS, BLB, JPD, FH, MSp, BS, DMC, MSt, DL, MC, PvJ, EMB, FB, AP, HLC developed the model framework and output routines.

FB, FH, DMC, MC, MSp, DL, BS, provided the model runs.

VS designed the figures with support from PvJ and FB

VS, PD, MSt, BLB, HLC and RKG analysed the results.

JPD provided software engineering solutions and technical support.

VS and PD wrote the manuscript with contributions and comments from all coauthors.

Data availability

Model runs and results shown in this paper are available under the Creative Commons Attribution license CC-BY-4.0 and archived at https://doi.org/10.5281/zenodo.7924160

Code availability

The MAgPIE code, including the food demand model, is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub (https://github.com/magpiemodel/magpie, last access: 5 May 2023). The release (version 4.7.3) used in this paper can be found via Zenodo (https://zenodo.org/records/10965921, Dietrich et al., 2023). The technical model documentation is available under https://rse.pik-potsdam.de/doc/magpie/4.7.3/ (last access: 5 May 2023).

The LPJmL code is available under the GNU Affero General Public License, version 3 (AGPLv3) and the code used here to generate inputs for MAgPIE can be found at Zenodo.org (https://doi.org/10.5281/zenodo.7912370).

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub (https://github.com/bs538/remind/tree/SDP_runs).
Model documentation of the health model is available in the appendix and in Springmann et al[66], model documentation of the poverty model in Soergel et al[67].

For processing the m4fsdp package has been used which is available at https://doi.org/10.5281/zenodo.7899913.

The code used to run MAGICC is available at https://gitlab.com/magicc/2022-fsec-integration.

Methods

To explore possible scenarios for food system transformation pathways for India, we use the underlying methodology of the global study[27] (Bodirsky et al., 2023) that is based on an extended modelling framework, with the Model for Agricultural Production and its Impact on the Environment (MAgPIE)[36,41] being the central model. The core outcome indicators considered in this study were addressed with the help of coupled models that includes a macroeconomic and energy model (REMIND)[68], the vegetation, crop, and hydrology model LPJmL [44,69], the reduced complexity climate model (MAGICC)[70] , food demand model [42], the dietary health model [50], and an income distribution and poverty model [31]. The food demand model is further linked with a dietary health model[50,71]. The parameterization of the baseline scenarios was harmonized between the models with the help of Shared Socioeconomic Pathways (SSPs) narratives [39,40].

The primary modelling framework utilized in this research is the MAgPIE (Model of Agricultural Production and its Impact on the Environment), which integrates various interconnected modules. The code and documentation for version 4.6.6 are publicly available. The model encompasses agricultural markets for 19 crop groups, eight processed plant-based products, five livestock food groups, three types of crop residues, grass, and two forestry products. Final demands include food, materials, and bioenergy. Livestock products necessitate feed, processed products require primary materials, and crop production requires seeds. Global production meets demand through regional trade. Land use allocation considers cost-effectiveness and conversion costs across different land uses. Land Use Change (LUC) impacts CO2 emissions, BII values, and soil carbon levels. Irrigated production requires water and infrastructure. Nitrogen for crop and grass production is sourced from organic materials, fixation, fertilizers, or soil depletion. Agricultural production emits non-CO2 GHGs like CH4 and N2O, mitigated by technical measures. The model minimizes costs under various constraints including biophysical, technological, and socio-economic factors. Internal costs within the model include feed, seed, land rents, and nutrient costs. Agricultural employment depends on factor requirements and labor productivity. Agricultural prices are derived from the Lagrange multiplier of food demand equations. Model inputs are aggregated using clustering algorithms for computational efficiency. The model simulates 200 clusters globally, including 6 in India, and incorporates interregional trade among 12 world regions, with India as an independent region. We analyse the results for India from the global model runs in this paper. The assessment approach and the interventions evaluated in this study are based on the guidelines of the Food Systems Economics Commission as also presented in the global assessment[27]. The modelling framework was run for 36 scenarios, including the reference scenario SSP2, a run for each of the 23 FSMs and five CrossSector measures in isolation, five packages of measures, the FST_{SSP2} and the FST_{SDP}. The implementation of the FSMs and the definition of the outcome indicators are described in the Extended Data Tables 1 and 2. The quantified effects of FSMs across policy pillars presents an extended analysis of the national case for India.

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Figures

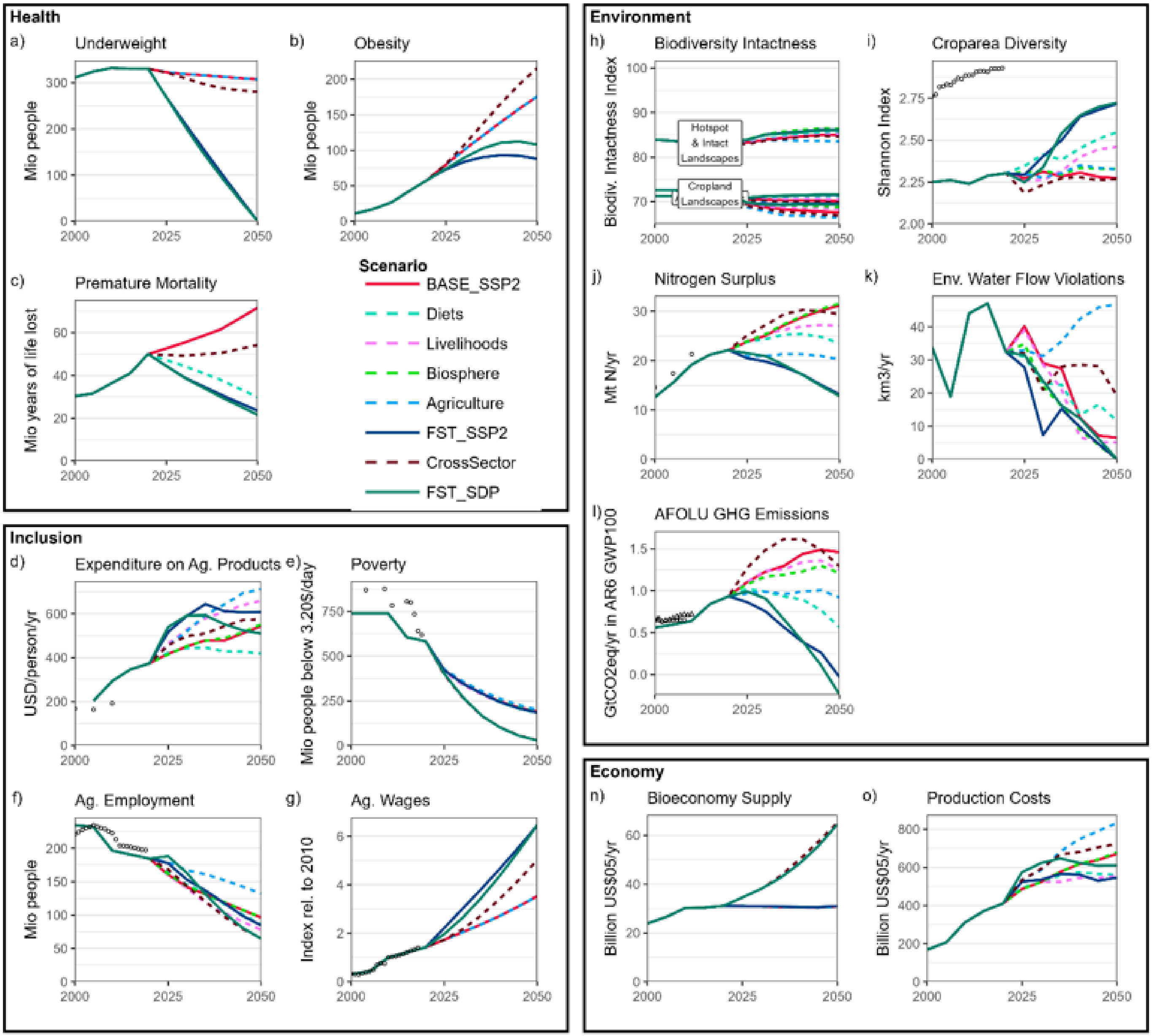
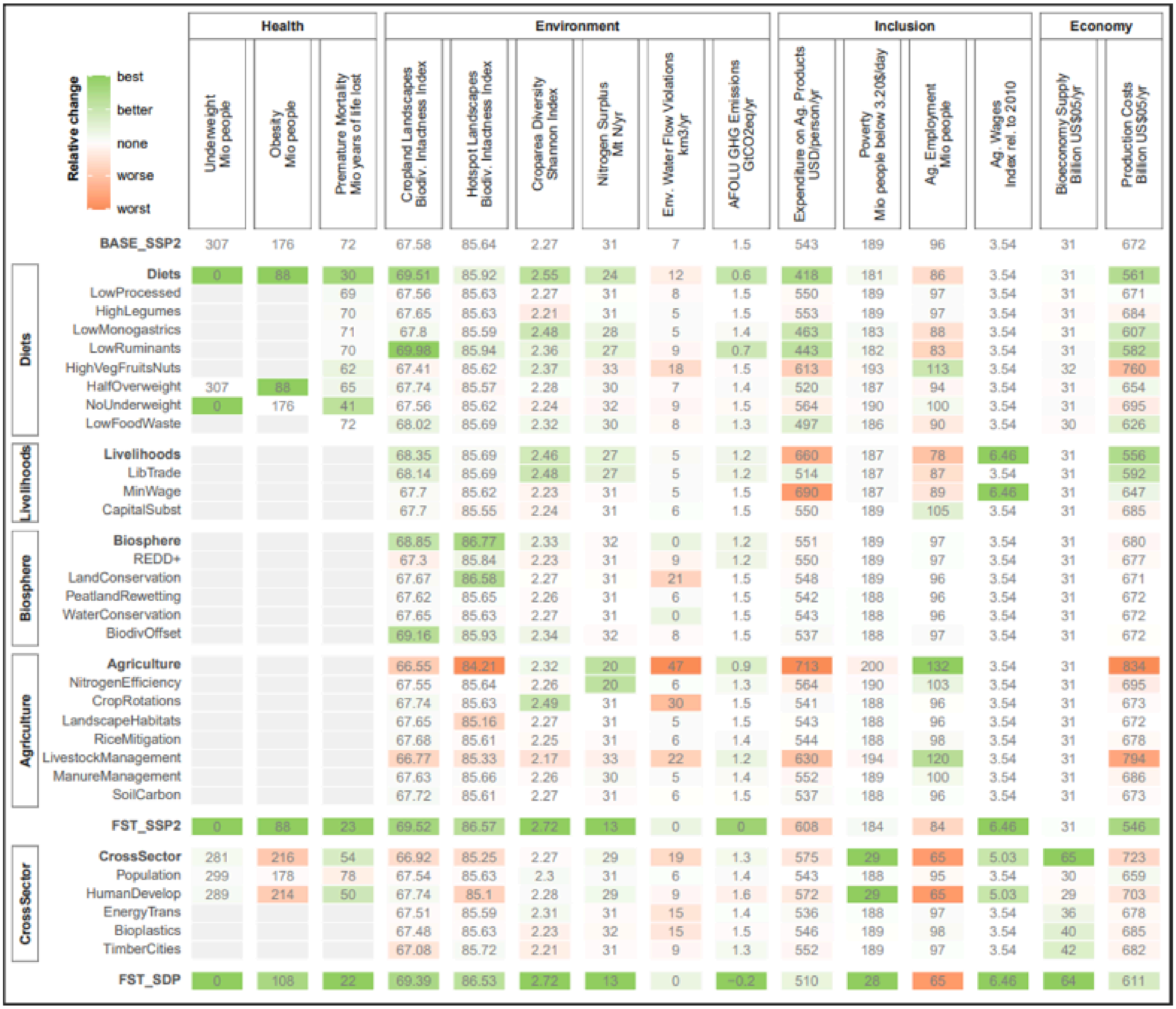


Figure 1

Trends of 14 food system outcome indicators for India up to 2050. *BASE_SSP2* (red line) describes a middle-of-the-road scenario. The Food System Transformation (*FST*$_{SSP2}$, blue line) describes a scenario that combines the four packages of food system measures targeting healthy diets (*Diets,* teal dashed line), livelihoods (*Livelihoods,* pink dashed line), biosphere integrity (*Biosphere,* green dashed line), and agricultural management (*Agriculture,* blue dashed line). Further, by combining sustainable socio-economic transitions outside the food system represented by package *CrossSector* (brown dashed line), we attain the Food System Transformation in the context of a Sustainable Development Pathway (*FST*$_{SDP}$, green line). Health indicators include Underweight population, Overweight population, and Years of life lost due to premature mortality. Environmental indicators include Biodiversity Intactness Index, Crop Area Diversity, Nitrogen Surplus, Environmental water flow violations, AFOLU GHG emissions. Inclusion indicators are represented by Expenditure on Agricultural products, Poverty, Agricultural employment, Agricultural wages. Economic indicators include Bioeconomy supply, Costs of Agricultural and Livestock production. All outcome indicators are described in Extended Data Table 2, and historical trends and data points (dots) are provided in SM 1.



		Health			Environment						Inclusion				Economy	
		Underweight Mio people	Obesity Mio people	Premature Mortality Mio years of life lost	Cropland Landscapes Biodiv. Intactness Index	Hotspot Landscapes Biodiv. Intactness Index	Croparea Diversity Shannon Index	Nitrogen Surplus Mt N/yr	Env. Water Flow Violations km3/yr	AFOLU GHG Emissions GtCO2eq/yr	Expenditure on Ag. Products USD/person/yr	Poverty Mio people below 3.20$/day	Ag. Employment Mio people	Ag. Wages Index rel. to 2010	Bioeconomy Supply Billion US$05/yr	Production Costs Billion US$05/yr
	BASE_SSP2	307	176	72	67.58	85.64	2.27	31	7	1.5	543	189	96	3.54	31	672
Diets	**Diets**	0	88	30	69.51	85.92	2.55	24	12	0.6	418	181	86	3.54	31	561
	LowProcessed			69	67.56	85.63	2.27	31	8	1.5	550	189	97	3.54	31	671
	HighLegumes			70	67.65	85.63	2.21	31	5	1.5	553	189	97	3.54	31	684
	LowMonogastrics			71	67.8	85.59	2.48	28	5	1.4	463	183	88	3.54	31	607
	LowRuminants			70	69.98	85.94	2.36	27	9	0.7	443	182	83	3.54	31	582
	HighVegFruitsNuts			62	67.41	85.62	2.37	33	18	1.5	613	193	113	3.54	32	760
	HalfOverweight	307	88	65	67.74	85.57	2.28	30	7	1.4	520	187	94	3.54	31	654
	NoUnderweight	0	176	41	67.56	85.62	2.24	32	9	1.5	564	190	100	3.54	31	695
	LowFoodWaste			72	68.02	85.69	2.32	30	8	1.3	497	186	90	3.54	30	626
Livelihoods	**Livelihoods**				68.35	85.69	2.46	27	5	1.2	660	187	78	6.46	31	556
	LibTrade				68.14	85.69	2.48	27	5	1.2	514	187	87	3.54	31	592
	MinWage				67.7	85.62	2.23	31	5	1.5	690	187	89	6.46	31	647
	CapitalSubst				67.7	85.55	2.24	31	6	1.5	550	189	105	3.54	31	685
Biosphere	**Biosphere**				68.85	86.77	2.33	32	0	1.2	551	189	97	3.54	31	680
	REDD+				67.3	85.84	2.23	31	9	1.2	550	189	97	3.54	31	677
	LandConservation				67.67	86.58	2.27	31	21	1.5	548	189	96	3.54	31	671
	PeatlandRewetting				67.62	85.65	2.26	31	6	1.5	542	188	96	3.54	31	672
	WaterConservation				67.65	85.63	2.27	31	0	1.5	543	188	96	3.54	31	672
	BiodivOffset				69.16	85.93	2.34	32	8	1.5	537	188	97	3.54	31	672
Agriculture	**Agriculture**				66.55	84.21	2.32	20	47	0.9	713	200	132	3.54	31	834
	NitrogenEfficiency				67.55	85.64	2.26	20	6	1.3	564	190	103	3.54	31	695
	CropRotations				67.74	85.63	2.49	31	30	1.5	541	188	96	3.54	31	673
	LandscapeHabitats				67.65	85.16	2.27	31	5	1.5	543	188	96	3.54	31	672
	RiceMitigation				67.68	85.61	2.25	31	6	1.4	544	188	98	3.54	31	678
	LivestockManagement				66.77	85.33	2.17	33	22	1.2	630	194	120	3.54	31	794
	ManureManagement				67.63	85.66	2.26	30	5	1.4	552	189	100	3.54	31	686
	SoilCarbon				67.72	85.61	2.27	31	6	1.5	537	188	96	3.54	31	673
	FST_SSP2	0	88	23	69.52	86.57	2.72	13	0	0	608	184	84	6.46	31	546
CrossSector	**CrossSector**	281	216	54	66.92	85.25	2.27	29	19	1.3	575	29	65	5.03	65	723
	Population	299	178	78	67.54	85.63	2.3	31	6	1.4	543	188	95	3.54	30	659
	HumanDevelop	289	214	50	67.74	85.1	2.28	29	9	1.6	572	29	65	5.03	29	703
	EnergyTrans				67.51	85.59	2.31	31	15	1.4	536	188	97	3.54	36	678
	Bioplastics				67.48	85.63	2.23	32	15	1.5	546	189	98	3.54	40	685
	TimberCities				67.08	85.72	2.21	31	9	1.3	552	189	97	3.54	42	682
	FST_SDP	0	108	22	69.39	86.53	2.72	13	0	-0.2	510	28	65	6.46	64	611

Figure 2

Effect of individual food system measures (FSMs) and packages (*Diets, Livelihoods, Biosphere, and Agricultur*e) on key food system indicators for India. Green fields indicate improvement in comparison to the reference scenario (BASE_SSP2) in 2050, whereas red indicate deterioration, and white indicate no change. The figure shows the quantified effects of the evaluated FSMs and packages for the 14 indicators across policy domains (Health, Environment, Inclusion, and Economy). The BII on cropland and hotspot landscapes has been separately displayed for clarity, but they together represent a single indicator of Biodiversity Intactness Index. The *Diets, Livelihoods, Biosphere, and Agricultur*e scenario combine the individual FSMs with respect to the policy domains. The Food System Transformation (FST_{SSP2}) is formulated combining all four packages (*Diets, Livelihoods, Biosphere,* and *Agriculture*) and is based on SSP2 pathway. The Sustainable Development Pathway (FST_{SDP}) includes combined effects of measures outside the food system represented by the *CrossSector* package. The quantified effects reported for all scenarios are the 2050 values. A detailed descriptions of the measures and the outcome indicators are provided in extended data table 1 and 2.

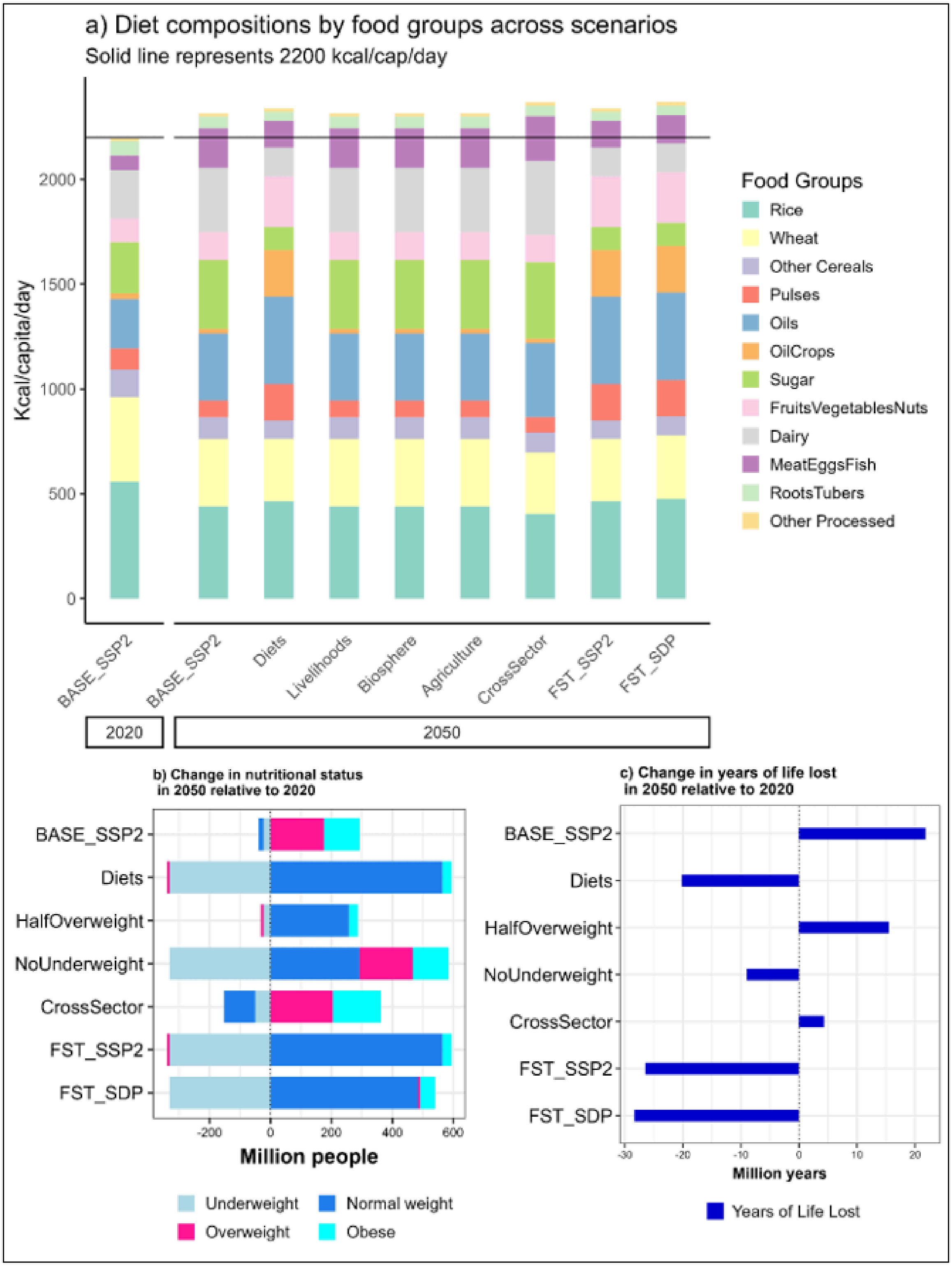


Figure 3

Changes in health and nutrition outcomes by different scenarios by 2050 for India. a) Changes in dietary composition by food groups (kcal/capita/day) across scenarios in 2050, The black solid line represents the 2200 kcal benchmark for daily calorie intake. b) Nutrition status in 2050 relative to 2020 across scenarios representing the change in underweight (light blue), overweight (dark pink), obese (sky blue) and normal weight (dark blue) population in million people, c) Change in years of life lost (million years) in 2050 relative to 2020. Figure b and c include HalfOverweight and NoUnderweight scenarios for representing the changes in malnutrition and YLL indicators. Other scenarios- Agriculture, Biosphere, and Livelihoods show no change in these indicators, therefore excluded.

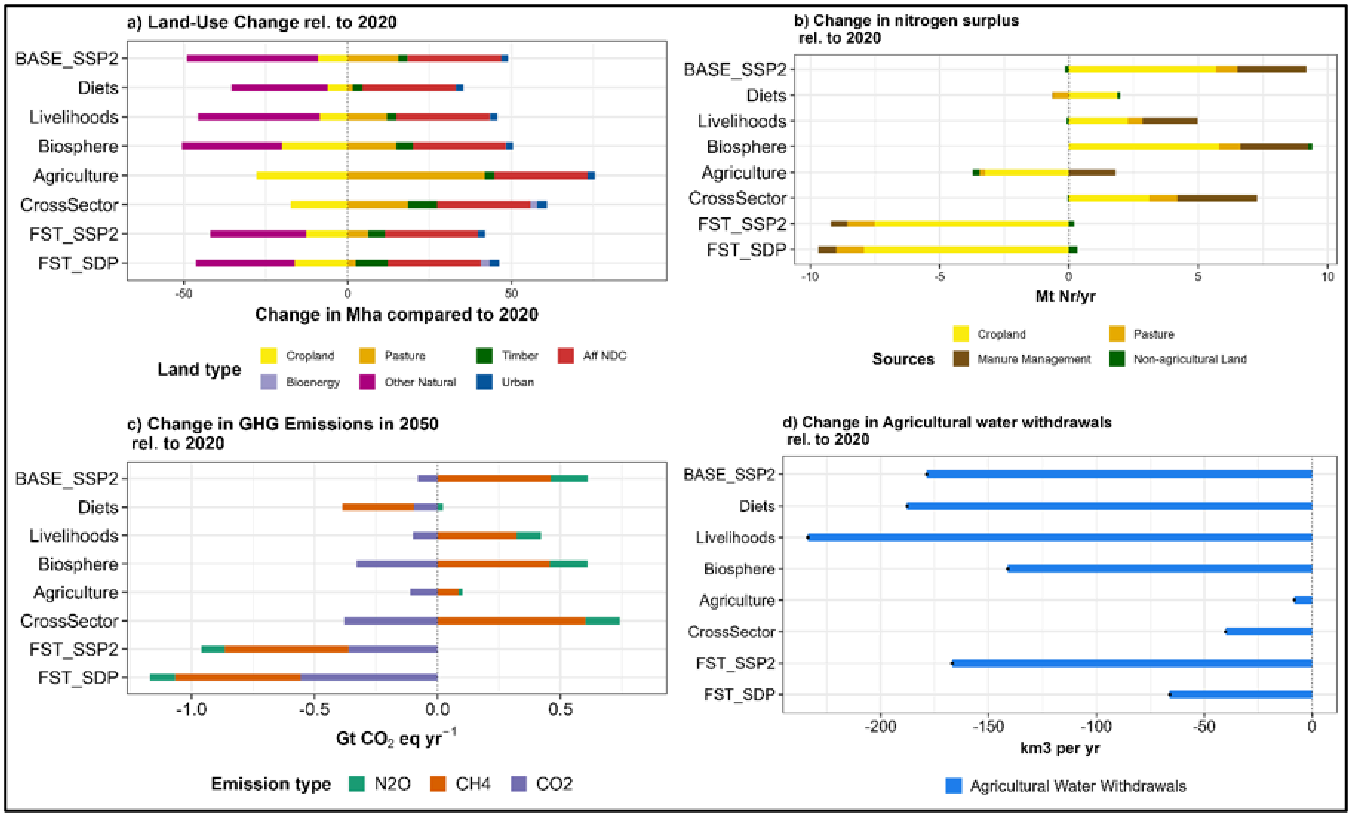


Figure 4

Changes in environmental outcomes for different scenarios by 2050. a) Land-use change in million ha in 2050 relative to 2020 for different land types- cropland (yellow), pasture (mustard), timber (green), Afforestation aligned with Nationally Determined Contributions (NDCs) (red), Bioenergy (Violet), other natural lands (purple), Urban (navy blue). Negative changes indicate reduced land use, while positive changes show an increase in land use by land type. b) Changes in nitrogen surplus (Mt Nr/year) in 2050 relative to 2020 for different scenarios from four sources- cropland (yellow), pastures (mustard), manure management (brown), and non-agriculture land (green). Negative changes indicate reduced nitrogen surplus in 2050 compared to 2020, while positive changes indicate higher nitrogen surplus on the environment. c) Changes in AFOLU emissions (Gt CO22 eq yr^{-1}) in 2050 relative to 2020 for different scenarios for three emission types, N_2O (green), CH_4 (orange), and CO_2 (blue), from the food and livestock sector. Negative changes represent reduced emission levels in 2050 compared to 2020 levels, while positive changes indicate higher emission levels. d) Change in agricultural water withdrawals (km^3 per year) in 2050 relative to 2020. Negative changes indicate reduced agricultural water use.

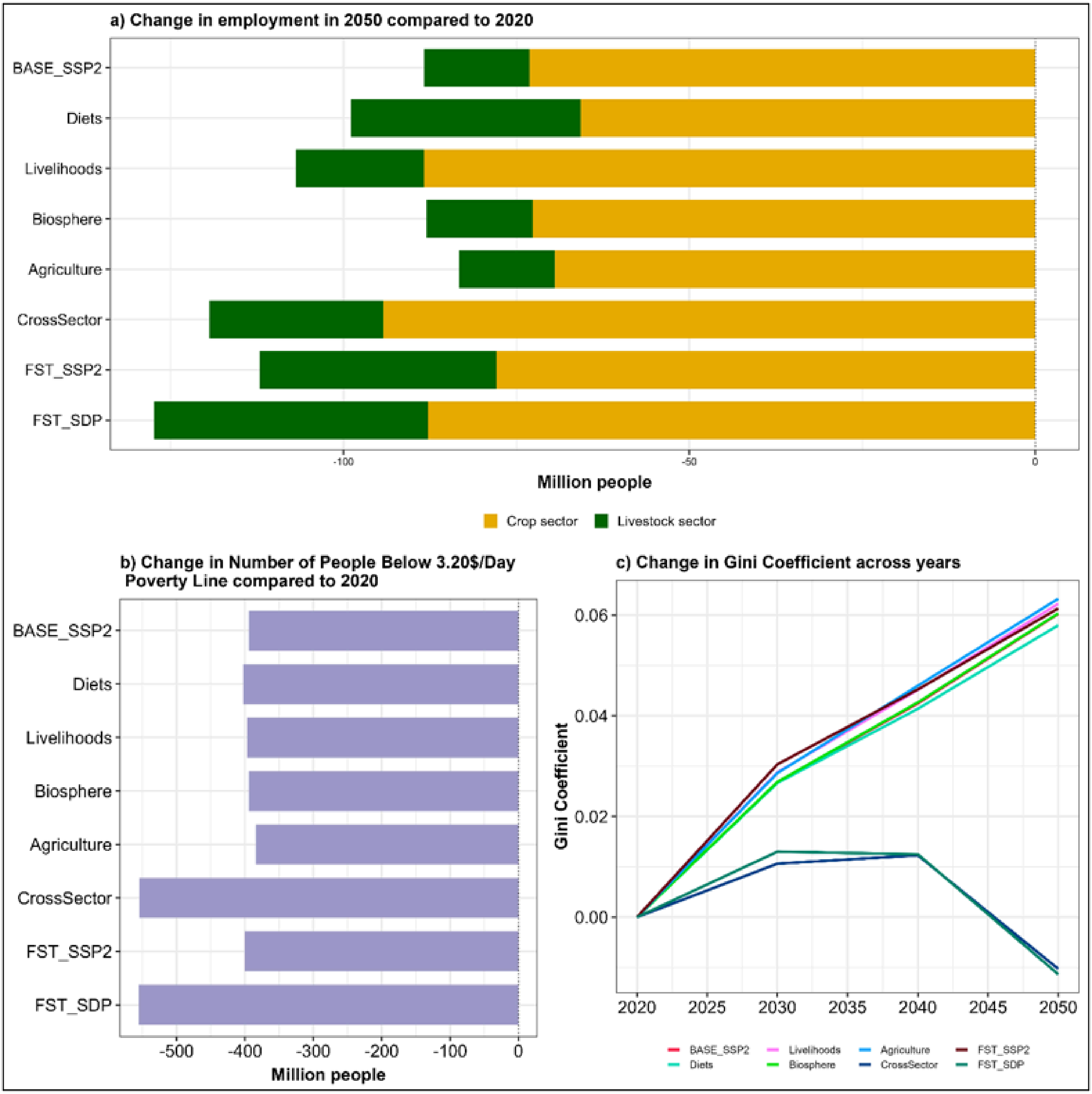


Figure 5

Changes in inclusion outcomes for different scenarios by 2050. a) Change in agricultural employment (million people) in the crop (mustard yellow) and livestock sector (green) in 2050 compared to 2020. Negative changes indicate a decline in employment. b) Change in number of people below the poverty line (3.20 USD/day) in millions by scenario. Negative changes suggest declining poverty levels. c) Change in Gini coefficient across years for different scenarios until 2050.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx
- ExtendedDataTables.docx