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WORKING PAPER

A Transformation towards a Healthy, Environmentally friendly, and Inclusive Food System in India

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Abstract

Over the past 50 years, India's agrifood system has undergone an extraordinary evolution, transitioning from a food scarce to a secured nation. Yet the challenges of nutrition security, regional inequalities, and unsustainable agricultural practices persist. While policies governing these areas prevail, they lack integrative implementation needed for bringing overarching food system changes. Moving forward from siloed policy evaluation towards an integrated system framework, this study attempts to conduct the first large-scale multi-indicator food system assessment for India using a global food and land system modelling framework. We evaluate the effect of 23 food system measures (FSMs) individually and in packages on 14 indicators encompassing the four dimensions of food systems, including health, environment, inclusion, and economy. Measures for transformative food system changes include biosphere, and agriculture (land, water, and soil), equitable livelihoods (poverty, wages, and employment), and sustainable external transitions (slow population, human development). Results indicate that 14 out of 15 indicators improve due to synergistic effects driven by coordinated interventions, which, in turn, reduces trade-offs among the four dimensions of food system. While progress is observed in most health and environmental indicators, challenges such as rising obesity and nitrogen pollution still persist. Our attempt to quantify India's food system changes under counterfactual scenarios enables understanding the trade-offs across dimensions, as illustrated by the food-based dietary scenario, which generates positive outcomes for most food system dimensions pertaining to health, environment, inclusion, but also aggravates water distress and falls short of delivering employment benefits for the society. However, declining agricultural employment in the FST_{SDP} scenario, explicates a larger role of external transformations beyond the food system, emphasizing the need for sustainable social transformations for supporting overarching food system changes. The comprehensive and forward-looking food system outcomes that this study elucidates aids in identification of pivotal intervention points and facilitates strategizing policies for transformative changes.

1. Introduction

India's food system serves as 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. India's agricultural diversity, smallholder farming practices, and initiatives for food security engage multiple food systems with large socio-economic and environmental variations (Athare et al., 2022), making it a crucial case for addressing concerns associated with global food system transformation. The urgency of India's food system transformation is more pronounced now than ever.

Despite rising per capita incomes, progress in nutrition and health has been slow, primarily due to nutritionally deprived diets resulting in high levels of malnutrition (Meenakshi, 2016; Tak et al., 2019). Currently, approximately 194 million people in India are undernourished, 43.3 million children under the age of five are stunted, and obesity affects nearly 21% of females and 19% of male adults (FAN, 2020). Cereal-intensive production, and distortionary policies, such as energy and fertilizer subsidies, have led to excessive water withdrawals, soil degradation, and chemical runoff (Pingali, 2012). Currently, nearly 80% of freshwater is used for rice and wheat cultivation (Kayatz et al., 2019), while less than 5% of the land is effectively protected for conservation (Srivathsa et al., 2023). Being one of the global hotspots of nitrogen pollution, the country incurs an annual cost of around 75 billion USD (Dhar et al., 2022; Sutton et al., 2017), while emissions from rice and livestock contribute nearly 14% of India's economy-wide emissions (MoEFCC, 2021, Vetter et al., 2017). Additionally, with agriculture engaging over 50% of the workforce and that a significant 82% farmers are smallholders, slow growth in rural employment despite nearly sevenfold increase in rural income over the past four decades (Chand et al., 2017) raises concerns for equality and inclusivity.

Therefore, concerted and systemic interventions are required to facilitate the transition towards improved food systems, encompassing the interconnected domains of health, environment, and inclusion (Bodirsky et al. 2023; Pingali et al., 2019). Achieving the desired outcomes necessitates employing a range of policy interventions and measures, which can be justified as favourable in a second-best world (Bennear and Stavins, 2007). Future visions on sustainable food system transformation pathways need an integrated systems perspective where potential co-benefits and trade-offs between multiple dimensions can be effectively addressed (Davis et al., 2019; Gaupp et al., 2021; Ruben et al., 2019). Recent studies have demonstrated the potential of Integrated Assessment Models (IAMs) and Shared Socio-Economic Pathways in identifying the key leverage points of transformations (Gaupp et al., 2021; Soergel et al., 2021; van Vuuren et al., 2015). At the global scale studies have conducted multi-criteria assessment of several food system measures (FSMs) indicating a plausibility of a better food system with synergistically aligned packages of policy interventions (Bodirsky et al. 2023). For the Indian case, previous studies have evaluated impacts of isolated food system interventions such as, dietary changes and the associated environmental impacts, (Aleksandrowicz et al., 2019; Milner et al., 2017). Other studies also suggests the potential of India's natural resource capacity and the food systems in achieving nutrition security, maintaining environmental sustainability, and meeting mitigation objectives associated with the AFOLU sector (Damerau et al., 2020; Jha et al., 2022). However, alll these studies commonly indicate the need to drive systemic changes in food systems to realize long-term sustainable transitions.

Country specific policy strategy requires quantitative details on the synergies and trade-offs between multitude of objectives associated with complicated food system changes to support policy decision. Using the underlying methodology of the global study (Bodirsky et al., 2023) that is based on an extended modelling framework, our study provides a detailed evaluation of the direct and indirect impacts of coordinated, coherent, and integrated policy action for large scale food system changes specific to India. Pursuing alternate scenarios across policy domains enables understanding the interaction effects between the measures that can potentially generate co-benefits and trade-offs at scale.

2. Objectives

We evaluate how different FSMs contribute toward social welfare outcomes across the three food system goals. Our primary objectives are the following

a. Conduct the first large-scale multi-indicator food system assessment for India, in the context of health, environment, inclusion, and economic development up to 2050.
b. Identify the synergies and trade-offs specific to key food system measures (FSMs) across dimensions.
c. Present how the FST_{SDP} and the different FSMs framework can help policymakers identify actions, solutions, and strategies to build healthier, more environmentally friendly, and equitable food systems for India.

3. Methodology

To explore the pathways for food system transformation, we use the underlying methodology of the global study (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) (Humpenoder et al., 2022, Jha et al., 2022, Dietrich et al., 2019) 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) (Baumstark et al., 2021), the vegetation, crop, and hydrology model LPJmL (Schaphoff et al., 2018; von Bloh et al., 2018), the reduced complexity climate model (MAGICC) (Meinshausen et al., 2011), food demand model (Bodirsky et al., 2020), the dietary health model (Springmann et al., 2018; Springman et al., 2021), and an income distribution and poverty model (Soergel et al., 2021). The parameterization of the baseline scenarios was harmonized between the models with the help of Shared Socioeconomic Pathways (SSPs) narratives (O'Neil et al., 2017; Popp et al., 2017).

Moving forward from siloed policy evaluation towards an integrated system framework, this study makes a novel attempt to probably 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 (von Braun et al., 2023) - healthy diets and sustainable consumption patterns (*Diets*), nature-positive agricultural transition (*Agriculture*), biodiversity protection (*Biodiversity*), equitable livelihoods (*Livelihood*), and a broader socioeconomic development external to the food system (*CrossSector*). These packages are represented by 23 FSMs and 5 transformation levers outside the food system (see extended table 1 in the SI). These packages represent a range of interventions like increased intake of fruits and nuts, leguminous crops, reduced food waste and loss, nitrogen efficiency, water conservation through environmental flow protection, biodiversity protection, higher minimum wages, liberalized trading, slow population growth, better socio-economic advancements, energy transition, and other measures that can potentially enable attaining a healthy, sustainable, and inclusive food system for India (see extended table 1 details of the packages). We quantify the effects of all measures assuming that the same trajectories of future transitions are followed globally.

The reference baseline scenario ($BASE_{SSP2}$) in the study aligns with the 'middle-of-the-road scenario' of the Shared Socio-economic Pathways (SSP2) (Riahi et al., 2017; O Neill, 2017;

Popp, 2017), where the plausible future state of the food system continues with the current trends, without any targeted interventions for sustainable transitions. Initiating from the baseline, the FSMs and the external transitions are included individually and in packages to evaluate their contribution towards the desired transformational change, represented by the food system development pathway (FST_{SDP}). Altogether, 14 social-welfare outcome indicators (see extended table 2) are quantified systematically across all the scenarios to enable an understanding of the multidimensionality of overall change in India's food system.

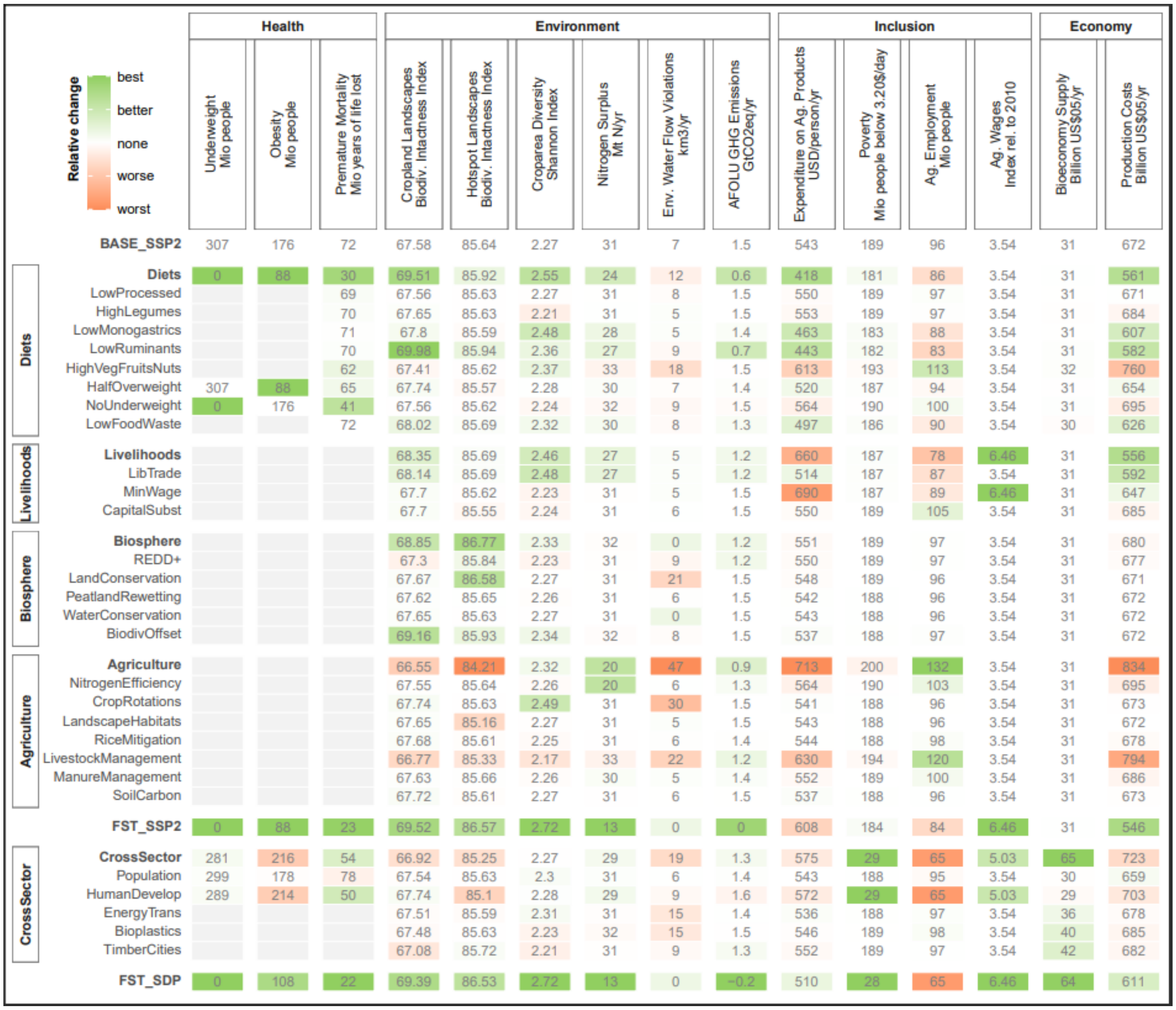
4. Results

4.1. Current trends in India restrict achieving multiple food system goals in the long run.

Projections in the reference BASE_SSP2 scenario until 2050 reveal concerning trends for most food system indicators pertaining to health, environment, and inclusion dimensions (Fig. 1). Despite rising per capita incomes, the underweight population reduces only by 6.1% by 2050 to 307 million people, as population increases by nearly 18.2%, (Fig. 2). The nutrition transition towards more affluent and energy-dense foods due to rising income and urbanization levels is likely to accentuate India's overweight and obesity problem as the headcount of obese people increases alarmingly 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) (refer to extended table 2) from 50 to 72 million in 2020-2050. Staples (including cereals, legumes, and pulses), sugar, oils, and animal products, especially dairy, remain the primary source for meeting calorie requirements (Figure 3a), consistent with increasing income, population, and urbanization trends in India. These trends are similar to studies suggesting unhealthy consumption patterns in India due to overconsumption of cereals and insufficient intake of proteins, fruits, and vegetables (Sharma et al., 2020).

Environmental indicators show an overall deterioration, except for water environmental flow violations which reduces to 7 km^3 until 2050 (Fig. 1) as food production is mainly carried out in rainfed areas. Increasing pressure on land resources to meet the food demand causes a continuous decline in biodiversity in cropland landscapes without any substantial improvement in crop area diversity represented by a Shannon Index (refer to extended table 2) until 2050. Nitrogen pollution, defined as excessive environmental losses of nitrogen from croplands, pastures, animal waste management, and natural vegetation, increases from 22 in 2020 to 31 MtN per year in 2050, as increased food production compared to the 2020 level, increases nitrogen overload from cropland and animal waste by 42.7%. GHG emissions from agriculture, forestry, and land use (AFOLU) also increase from 0.93 to 1.5 $GtCO_2eq$ by 2050 (Figure 1) due to high methane emissions from rice and livestock.

Trends of improved wages and reduced poverty are expected to yield positive societal gains in terms of inclusion. In the reference scenario, about 395 million people are pulled out of poverty (at 3.20 USD/day) by 2050. Although household expenditure for agricultural products for food consumption (estimated as the annual value of primary agricultural commodities, excluding the value added from processed food) declines as a share of income (Figure SM3), the value of food consumption increases per person from 374 in 2020 to 543 USD in 2050. This is due to rising income levels and urbanization as consumers spend more on affluent diets comprising more processed and ready-to-eat food (Mottaleb and Mishra, 2021; Pandey et al., 2020; Athare et al., 2022). Agricultural wage index improves to 3.5 as hourly labour costs per worker is projected to increase from 0.66 to 1.64 USD_{05MER} by 2050, indicating improved livelihoods but also contributes towards higher agricultural costs of production (from 385 to 661 billion USD/05 per year). However, despite the notable annual increase in agricultural Gross Domestic Product (GDP) of ~1.7% for the 2020-2050 period (Fig. SM1), agricultural employment is projected to decline substantially from 185 to 96 million people by 2050 due to increasing labour productivity and mechanization.



		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 1: Effect of individual food system measures (FSMs) and packages (*Diets, Livelihoods, Biosphere, and Agriculture*) on key food system indicators. Green fields indicate improvement, whereas red fields indicate deterioration, and white fields indicate no change in comparison to the reference scenario (*BASE*$_{SSP2}$) in 2050. The grey fields have not been quantified. The *Diets, Livelihoods, Biosphere, and Agriculture* scenario combines the individual FSMs with respect to the policy domains. The Food System Transformation (FST) is formulated with context to SSP2 (*FST*$_{SSP2}$), combining all four packages (*Diets, Livelihoods, Biosphere, and Agriculture*) and the Sustainable Development Pathway (*FST*$_{SDP}$) that combines *CrossSector* effects from outside the food systems. The quantified effects reported in the figure are the 2050 values for all scenarios. Detailed descriptions of the measures are provided in the extended table 2 in the appendix.

4.2. Health: Comprehensive demand-side measures promoting both food-based dietary diversity and calorie sufficiency are important for achieving a healthy food system for India.

Achieving improved health and nutrition outcomes is possible with explicit measures that promote healthy food consumption. Dietary interventions in our study engage the socioeconomic transformations aligned with the SSP2 pathway and include measures promoting exogenous transformations towards healthy diets as recommended by the EAT-Lancet Commission (Willett et al., 2019). This includes minimum intake levels of legumes (*HighLegumes*), vegetables, fruits, and nuts (*HighVegFruitsNuts*), low animal-sourced foods (*LowRuminants*, *LowMonogastrics*) and less processed foods like sugar (*LowProcessed*) by 2050 (Willett et al., 2019). Additional measures include targeted reduction in obesity and undernutrition through calorie intake adjustments and promoting sustainable consumption patterns (details in Extended table 1in SI).

Compared to BASE_SSP2 in 2050, targeted measures augmenting the intake of healthy food and promoting dietary diversity among the population through increased calorie intake from a range of plant-based foods like pulses (from 81 to 174 kcal/capita/day) (*HighLegumes*), excluding starchy staple consumption like cereals and reduced empty calories from sugar (from 325 kcal/capita/day to 110 kcal/capita/day) reduces premature mortality, with substantial gains from increased intake of horticultural products (from 133 to 241 kcal/capita/day) as YLL reduces from 72 to 62 million years of life lost (Figure 2). While the benefits of fruits, vegetables, and nuts in reducing diet-related deaths and health risks are established by other studies (WHO 2003; Willet et al., 2019), their current consumption in the Indian diet being considerably low (Choudhury et al., 2020), measures to facilitate diversity of fruits and vegetables should be prioritized (Minocha et al., 2018; Thow et al., 2018). Compared to the BASE_SSP2, weight management measures like reducing underweight (*NoUnderweight*) and overweight (*HalfOverweight*) can potentially reduce premature mortality from 72 to 41 and 65 million years of life years lost by 2050, respectively. However, reducing underweight to normal weight comes at an additional annual production cost of 23.1 billion USD (3.5% higher than baseline) while reducing the prevalence of overweight and obesity can potentially contribute towards annual cost savings of 17.4 billion USD (2.7% lower than baseline). When discrete measures are bundled together as a package (*Diets*), overall health outcomes have stronger positive effects as the underweight population reduces to zero, the obese population reduces to 88 million people, and the years of life lost reduces to 30 million years (Figure 2, Fig. 3c). Implementation of the *Diets* package supports diversified dietary composition with the food consumption basket comprising more fruits, nuts and vegetables, legumes, whole grains, and less sugars (Figure 3a). Consequently, the population having substantially increases by 564 million people under the *Diets* scenario as the underweight population reduces by 330.5 million people compared to the 2020 level, along with nearly 29 million people overcoming obesity issues (Figure 3b). The effect of other packages (*Livelihoods*, *Biospher*e, *Agriculture*) on health indicators are not modelled.

While calorie-oriented weight management interventions may help reduce anthropometric failures, the resulting dietary composition may not meet the requirements for healthy diet quality, failing to address micronutrient deficiencies. In the *NoUnderweight and HalfOverweight* scenario, nearly 52% of the calorie requirement is fulfilled by cereals and sugars, lacking in plant-based protein sources such as legumes, as well as lower intake of fruits and vegetables. Calorie intake from leguminous protein sources in these scenarios are lower by 52% and 54% respectively compared to the healthy recommended intake as in *HighLegumes* scenario. Intake of fruits, vegetables, and nuts are 43% to 46% lower under these scenarios than the healthy intake requirement as in the *HighVegFruitsNuts* scenario (Figure 3a). In India, where protein-energy malnutrition is a significant concern (Bhutia, 2014), animal-sourced food (ASF) is a beneficial source of nutrition for most rural populations (Dasi et al., 2019; Neumann et al., 2002). With food choices in India being heterogeneous and largely driven by cultural and socioeconomic factors (Sammaddar et al., 2020; Custodio et al., 2021), the consumption of ASF in the current Indian diets is mainly dairy based. Further, with the current consumption of meat being substantially lower than the global average (Adegbola et al., 2020) it is not a significant concern for India (Sharma et al., 2020; Miller, 2022). Particularly in the *NoUnderweight*, and *HalfOverweigh*t scenario, ASF contributes approximately 19% of the calorie intake, with milk serving as the primary source within these food groups (70%), aligning with findings from other studies (Carew et al., 2019). However, in the *Diets scenario*, ASF comprises nearly 9% of calorie intake as food choices move towards a healthy reference diet, as recommended by the EAT-Lancet commission (Willet et al. 2019, Springmann et al. 2018) which includes maximum food intake limits for red meat, poultry, eggs, and milk products. These findings emphasize the need for a comprehensive approach that combines anthropometric measures with food-based dietary diversity interventions to ensure a healthy nutrition transition (Meenakshi, 2016; Nair et al., 2016; Beckerman et al., 2020; Chaudhary et al., 2022).

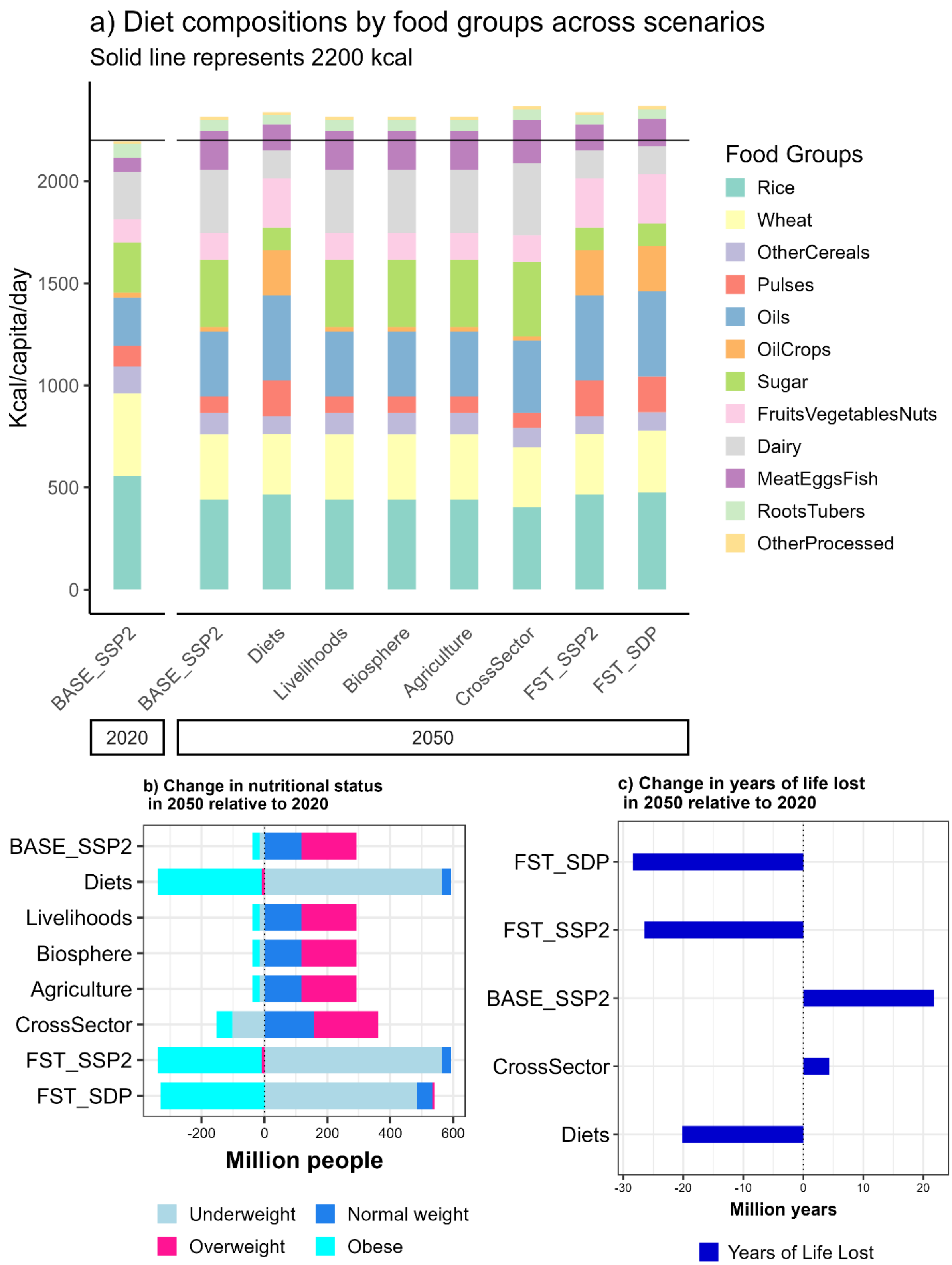


Figure 3: Changes in health and nutrition outcomes for different scenarios by 2050. a) Diet compositions by food groups (kcal/capita/day) across scenarios by food commodity group in

2050- Rice, Wheat, OtherCereals, Pulses, Oils, OilCrops, Sugar, FruitsVegetablesNuts, Dairy, MeatEggsFish, RootsTubers, and OtherProcessed. The black solid bar represents the 2200 kcal benchmark for daily calorie intake. b) Change in nutrition status in 2050 relative to 2020 across scenarios representing the underweight (light blue), overweight (dark pink), and 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 for five scenarios including baseline.

4.3. Environment: Achieving environmental sustainability requires comprehensive action on biodiversity protection, improved agricultural management and dietary transition.

Overall environmental sustainability can be achieved through effective combinations of FSMs related to dietary changes, livelihood measures like liberal trade, biodiversity protection, and agricultural management (Fig. 2).

Compared to the BASE_SSP2 scenario, the *Diet* package demonstrates a 2.9% decrease in water withdrawals (see Fig. 4d), but the annual environmental flow violations increase to 12 km^3 by 2050 (see Figure 2). This is mainly attributed to a 13.5% increase in agriculture water consumption in the *HighVegFruitsNuts* scenario along with lower crop productivity, leading to a significant expansion in irrigated cropland (32.7%) thus, exacerbating the annual environmental flow violations to 18 km^3 compared to the reference scenario (Fig. SM4). On the other hand, the *Livelihood* package manages to reduce agricultural water use by 18%, thus, improving the environmental flow violation indicator to 5 km^3/year (Fig. 2; Fig. 4d). This positive outcome can be mainly attributed to the *LibTrade* FSM, which individually reduces agricultural water use by nearly 19% by shifting crop production to more competitive and efficient regions globally, particularly for crops like rice and maize. The *Biosphere* package demonstrates the highest potential for water savings, primarily due to the implementation of the *WaterConservation* FSM that limits environmental flow protection, implying reduced water availability for agricultural use. Conversely, *CropRotation* and *LivestockManagement* measures in the *Agriculture* package substantially exacerbates water stress, as agricultural water withdrawal increases by 55% compared to the baseline scenario increasing the annual flow violations to 47 km^3.

In the *Diets* package, consumption patterns composing less ASFs and reduced food loss and waste (*LowFoodWaste*) offsets the increased nitrogen surplus caused by the *HighVegFruitsNuts* FSM. Producing more fruits, vegetables, and nuts needs increased fertilizer application which aggravates the annual nitrogen pollution by 5.6% to 33 Mt Nr/year by 2050 (Fig. 2). The *Livelihood* package reduces nitrogen burden through trade liberalization (*LibTrade*), resulting in a nearly 14% lower nitrogen surplus to 27 Mt Nr/year in 2050 as the domestic food production reduces. The *Agriculture* package substantially contributes to reducing nitrogen surplus (Fig. 4b) leading to a decrease in annual nitrogen surplus by 35% to 20 Mt through the *NitrogenEfficiency* FSM, countering increased nitrogen pollution from *LivestockManagement* FSM.

Individual dietary measures that promote increased demand for diversified and nutrient-rich food groups in daily calorie intake do not significantly impact biodiversity. However, by 2050, the combined effects of changes in consumption patterns favouring more fruits, vegetables, and nuts, less intake of ASF from ruminants especially milk and monogastric sources, along with reduced food loss and waste in the *Diets* scenario, improve crop diversity to 2.55 from 2.27 in the baseline by 2050. In the *Agriculture* package, most individual measures have no clear effect on biodiversity indicators, except for the *LivestockManagement* measure. The adoption of intensive livestock systems and improved feed efficiencies results in the use of cropland for livestock feed, reducing crop diversity (Fig. 2) to 2.17. Additionally, this leads to the expansion of pastureland (Fig. 4a), causing biodiversity loss and habitat fragmentation.

Combined interventions, as demonstrated by the *Diets* and *Agriculture* packages can potentially reduce annual AFOLU emissions to 0.6 and 0.9 GtCO2 respectively, from 1.5 GtCO2 in the baseline by 2050. Dietary patterns favouring lower intake of ASFs especially, milk (*LowRuminants*) significantly contributes towards emission reduction along with some contribution from food loss and waste (*LowFoodWaste*) in the food supply chain. Trade liberalisation (*LibTrade*) also reduces AFOLU emissions to 1.2 GtCO2 as food production shifts to other world regions.

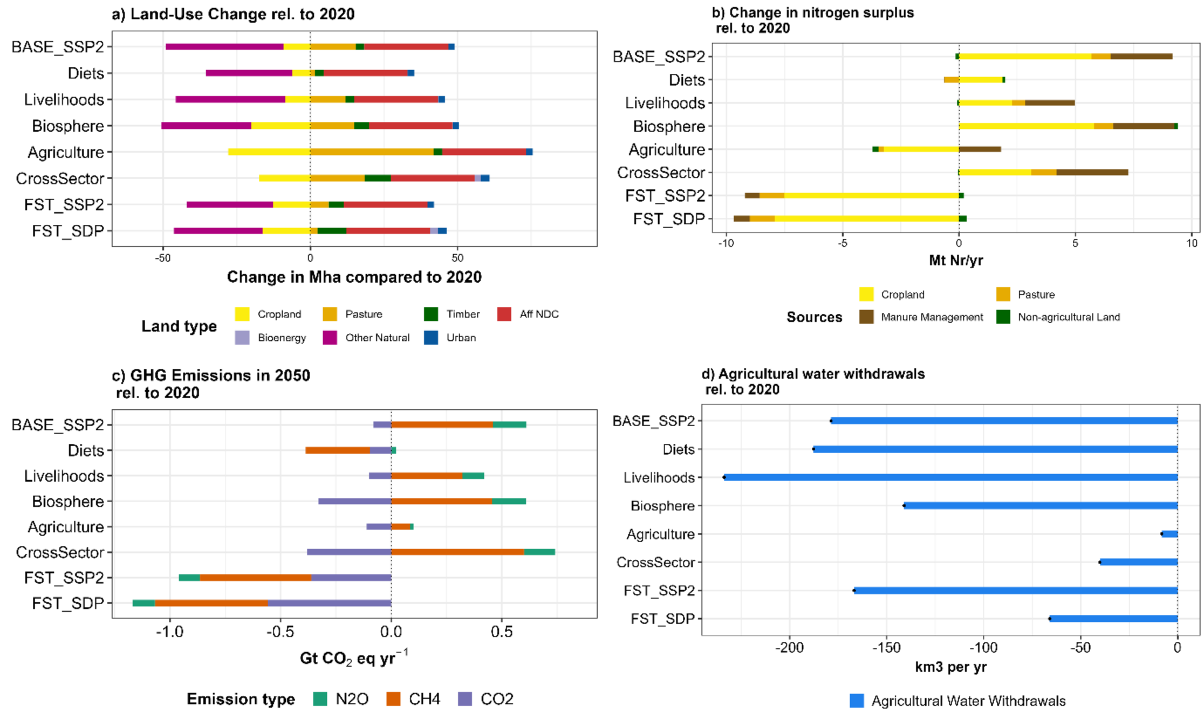


Figure 4: Changes in environmental outcomes for different scenarios by 2050. a) Land-use change in million ha in 2050 relative to 2020 for different land types- cropland (yellow), pasture (mustard), timber (green), Aff NDC (red), Bioenergy (Violet), other natural lands (purple), Urban (navy blue). Negative changes indicated 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 pollution levels in 2050 compared to 2020, while positive changes indicate higher nitrogen overload on the environment. c) Changes in AFOLU emissions 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 as 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.

4.4. Inclusion: Managing agricultural unemployment is necessary for an inclusive food system in India.

Individual livelihood interventions may be insufficient in improving all inclusion outcomes by 2050. By only liberalizing trade where trade reflects competitive advantage (*LibTrade),* agricultural employment reduces by 9 million people without any improvement in hourly labour wages (Fig. 2). As crop production relocates to more efficient regions globally, domestic agricultural activities shrink, resulting in increased dependence on imports (Fig. SM5). However, trade liberalization also facilitates the effective allocation of resources for food production, leading to a moderation in domestic food prices (Fig. SM6) and a modest reduction in food expenses by 5.6% to 514 USD per person per year.

To improve the well-being of Indian farmers to drive an inclusive food system, policy emphasis in India has been laid on enhancing farmers' income by improving livelihood through higher wages and promoting diversified high-valued agricultural products (Sendhil et al., 2017; Chandrashekhar and Mehrotra, 2016). Although transformative actions aligning with these agendas of change can promote inclusiveness, the distributional outcomes can vary by socio-economic context. Our analysis suggests that while the *MinWage* FSM raises agricultural income with a higher hourly labour costs of 3 USD_{MER05} increasing the wage index to 6.46, surge in labour costs on the production side (Fig. SM7), can further encourage substitution of labour with capital leading to decreased agriculture employment by nearly 7.9% to 89 million people. The higher production costs further contribute to elevated food prices, which can potentially enable better price realization for farmers but can negatively affect the consumers as the annual per capita food expenditures substantially increase by 27% to 690 USD compared to the baseline scenario. Currently, India is experiencing acute agriculture labour shortages, leading to an increase in agricultural wages and costs of cultivation[1], which, in turn, has prompted a shift towards capital-intensive production (farm mechanization). However, the widespread adoption of labour-saving technologies can potentially result in labour displacement, which raises significant concerns regarding equity (Rajkhowa and Kubik, 2021). Transformative actions encouraging agricultural labour engagements (*CapitalSubst* FSM) can potentially increase the share of labour requirement to 73.5% by 2050, compared to 67% in the baseline scenario, thereby enhancing employment

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[1] https://www.icrisat.org/labor-scarcity-and-rising-wages-in-indian-agriculture/

opportunities for 9 million individuals. However, the substitution of capital with labour comes at an additional cost to the economy, as production expenses rise by 2% to 685 billion USD_{MER05} (Fig. 2).

Combining individual livelihood transformative measures into a comprehensive package as *Livelihood*, result in substantial job losses, impacting a staggering 18 million people, despite the positive effects associated with higher wage income as suggested by the agricultural wage index of 6.46 and 17.3% lower economic costs (Fig. 2; Fig. 5a). Additionally, annual per capita food expenditure rises to 652 USD by 2050, primarily driven by inflated food prices compared to the baseline scenario. On the other hand, in the *Diets* package, fruits, vegetables, and nuts being a labour-intensive production process (*HighVegFruitsNuts*), promote inclusion by providing employment to additional 17 million people, bu, also raises agricultural expenditures by 8.2% due to higher food prices, without substantial improvements in livelihood through wages. High food prices are likely to negatively affect the affordability of healthy and nutritious diets, which is particularly concerning without any corresponding changes in income. While several studies raise concerns over the affordability of healthy and nutritious food, particularly for the Indian rural poor, seasonal price fluctuations for nutrient-dense foods like fruits and vegetables coupled with low wage earnings of unskilled workers (Raghunathan et al., 2021; Gupta et al., 2021; Herforth et al., 2020) can have a detrimental impact on public health.

However, dietary transitions engaging lower ASFs can potentially cause lesser economic opportunities in the agriculture and livestock sector causing reduced employment by nearly 8-13% (*LowMonogastrics*, *LowRuminants*). The *Agriculture* package, which focuses on mitigation activities in the crop and livestock sector to improve nitrogen efficiency and reduce enteric fermentation, achieves the maximum increase in agricultural employment, adding 36 million people to the agricultural labour force. However, none of the evaluated FSMs and packages contributes significantly towards poverty alleviation (Fig.2; Fig. 5b). Income inequality indicated by the Gini Coefficient (Fig. 5c) is projected to be high in the *Agriculture*, *Livelihood, and Diets* packages largely driven by increased food expenditure due to high food prices.

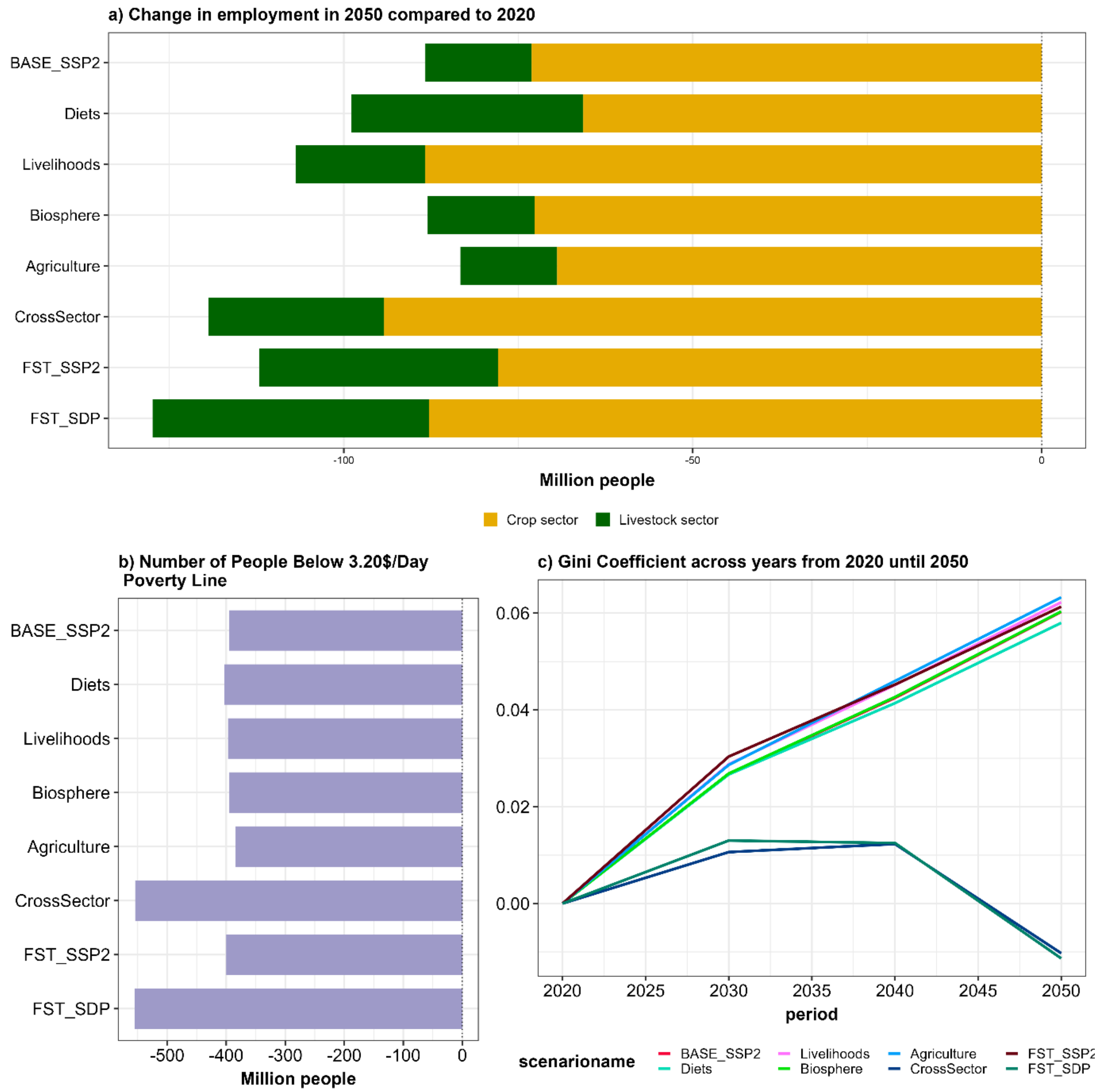

Figure 5: Changes in inclusion outcomes for different scenarios by 2050. a) Change in agricultural employment (in million) in the crop (mustard yellow) and livestock sector (green) in 2050 compared to 2020. Negative changes indicate a decline in employment. b) Number of people below the poverty line (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.

4.5. Across policy domains, trade-offs and synergies linked with individual interventions are evident, but grouping them into packages can either enhance or weaken these effects.

Combining FSMs according to major policy domains generates interaction effects that can have varying impacts on multiple sustainable food system goals, either jointly enhancing or weakening them, resulting in increased or decreased co-benefits and trade-offs across outcomes. The *Diets* package generates positive synergies for 11 out of 14 indicators but issues trade-offs with 2 indicators (Figure 2). While India's transition to EAT-Lancet flexitarian diet along with global world regions by design, strongly improves all health and most of the environmental indicators including emissions from AFOLU sector, increased water stress is evident. Inclusion outcomes associated with dietary transition indicate synergistic improvements as household food expenditures and the economic costs of transition declines but, reduction in agricultural employment causes concern for rural transformation.

The *Livelihood* package showcases synergistic effects for 7 indicators but generates trade-offs with 3 indicators (Fig. 2). The *LibTrade* measure is the main driver of synergies with environmental indicators especially, water use and emissions, as specialised agriculture production reduces pressure on land and water resources. The *MinWage* measure is the main driver of trade-offs, as higher wages negatively impact agricultural producers and consumers through high production costs and food price inflation. As factor shares adjust towards more capital-intensive production, releasing agriculture labour to other economic sectors, high unemployment, and high food prices may slow rural transformation and raise food security concerns. The *Biosphere* package improves 5 environmental indicators but has no significant trade-offs with other indicators. The *Agriculture* package brings more synergies with 4 out of 14 indicators by reducing nitrogen overload and generating new employment opportunities but worsens other indicators, especially environmental flow violations, biodiversity, and agriculture expenditures, incurring high economic costs to the society.

4.6. Concerted demand and supply side measures, including sustainable structural transformations, generate larger co-benefits than trade-offs among diverse food system sustainability goals.

Integration of all 23 FSMs into a single transformation pathway represented by the *FST_{SSP2}* scenario suggests a synergistic effect that reinforces the benefits from most individual measures (Fig. 2), improving 11 out of 14 indicators across policy pillars. *Biosphere, Diets,* and *Livelihoods* packages jointly compensate for the environmental trade-offs enforced by the *Agriculture* package leading to improved biodiversity in cropland and hotspot landscapes and crop area diversity in the FST_{SSP2} scenario. Concerted demand and supply side measures (*Diets, Agriculture, Biosphere*) in the FST_{SSP2} scenario enhance the emission reduction potential of the AFOLU sector as annual emissions reduce to zero. Restricted environmental flows in the *Biosphere* package and reduced agricultural water withdrawals in the *Livelihood* package compensate for high water usage in the *Agriculture* and *Diets* packages which altogether minimizes the pressure on water resources reducing water environmental flow violations to zero. Reduced employment in the *Diets* and *Livelihood* package together weakens the positive employment effects in the *Agriculture* package contributing to its decline up to 84 million people in the FST_{SSP2}. However, none of these packages effectively alleviate poverty, resulting in a rise in the poverty headcount to 184 million people in the FST_{SSP2} scenario. Expenditure on agricultural products experiences a significant surge of nearly 11.8% to reach 608 USD/person/yr due to the combined impact of the *Livelihood* and *Agriculture* packages, reinforcing the effects of high food prices. Nevertheless, the *Livelihood* package helps alleviate the high economic costs of production imposed by the *Diets* and *Agriculture* packages in the FST_{SSP2} scenario, resulting in a modest 18.7% decrease to 546 billion USD05/yr compared to the baseline.

However, external transformations, as represented by the *CrossSector* scenario suggest that India's food system transformation must be anchored in sustainable structural changes outside the food system. Slow population growth in India (*Population*), expected to stabilize at 1.6 billion by 2050, reduces pressure on the agricultural sector, stagnating the environmental degradation. Sustainable and just human development along the SSP1 trajectory, characterized by high income, enhanced fairness, social justice, improved institutional quality, and education (*HumanDevelop*) increases obesity issues for nearly 38 million individuals but reduces premature deaths by 22 million years when compared to *BASE_SSP2*. Human development also provides increased means for consuming expensive foods like processed food (sugar and oils) and animal products (meat, eggs, and milk) (Fig. 3a). Even other studies suggest similar patterns associated with India's structural transition and economic growth leading to changing food preferences towards more diverse and processed foods, including sugary and fat-based products, which may increase obesity and premature deaths from non-communicable diseases (Pingali et al., 2007; Tak et al., 2022; Kumar et al., 2022).

By 2050, projections indicate that overall socio-economic development (*CrossSector*) will lead to a more affordable food system without a substantial rise in food expenditures compared to the baseline scenario. This is achieved by generating a higher demand for well compensated non-agricultural jobs, resulting in an improved wage index to 5.03 for those continuing to work in agriculture. As a result, agricultural livelihoods improve, poverty levels decrease by 160 million people, and a portion of the labour force is freed up from agriculture to pursue opportunities in other sectors. By the year 2050, agricultural employment is projected to decrease to 65 million people, enabling the adoption of capital-intensive farming methods and enhancing labor productivity in the agricultural sector.

The Food System Transformation in the context of the Sustainable Development Pathway (FST_{SDP}) integrates 23 FSMs and represents an economy-wide sustainable development pathway combining the FST_{SSP2} and *CrossSector* transitions. The FST_{SDP} improves 13 out of 14 indicators. Health outcomes significantly improve with the elimination of underweight and the reduction of obesity, and premature mortality further reduces by 69.4%. Overall, the environmental degradation is halted. Reduced emissions in the FST_{SDP} from strong demand and supply side mitigation activities help meet the 1.5 degree C climate target (Bodirsky et al. 2023). Although, nitrogen pollution significantly reduces to 13 Mt/year, a reduction of 59%, India's nitrogen burden will continue to challenge the global planetary boundaries of 57 Mt/yr (Schulte-Uebbing et al., 2022; Moring et al., 2021), unless more actions in this sector are initiated.

Compared to the baseline, the agricultural workforce experiences significant livelihood gains through improved hourly payments, while a more balanced human development beyond the food system results in a notable decrease in absolute poverty, reducing the headcount by 161 million to reach 28 million. Moreover, despite concerted measures to manage all food system dimensions simultaneously, agricultural employment declines to 65 million by 2050 from 96 million in the baseline. Moving forward towards 2050, our findings on reduced agriculture employment in the *FST_{SDP}*, *Livelihood,* and *CrossSector* package, despite improved livelihood from wage increases, clearly indicate that India's transformation is expected to follow the 'Lewis trap' and 'farmer excluding' path with widening farm and non-farm incomes, increasing agriculture workforce and reduced number of farmers (Patel et al., 2022, Dorin 2021). Such transformations weaken food system inclusion prospects if other economic sectors are not prepared to absorb the increased labour flows, which may have further implications for poverty and health without adequate investment in other sectors (Ghosh, 2004). However, it is important to note here that our agriculture employment numbers only include people employed in agriculture and livestock production, but not activities related to the value chain, services, and retail, therefore, employment numbers may only represent lower-bound projections.

5. Conclusions

The assessment presented here shows that rigorous collaborative efforts will be necessary to achieve a healthy, environmentally friendly, and inclusive food system in India. However, achieving some of the goals like reduced obesity, increased employment in the farm sector and nitrogen pollution will need special attention. Our attempt to quantify India's food system changes under counterfactual scenarios enables choice of instruments, illustrated by the food-based dietary scenario, which generates positive outcomes for all food system dimensions (health, environment, inclusion), but also aggravates water distress and misses on delivering employment benefits for the society. Our analysis explicates a larger role of external transformations outside the food system, support of which would be needed to ensure larger outreach of food system benefits. The intent behind evaluating alternative measures in this study, however, was not to prescribe specific interventions or policy measures ready for implementation, but rather to uncover the interconnectedness among a wide range of indicators within the context of large food system changes.

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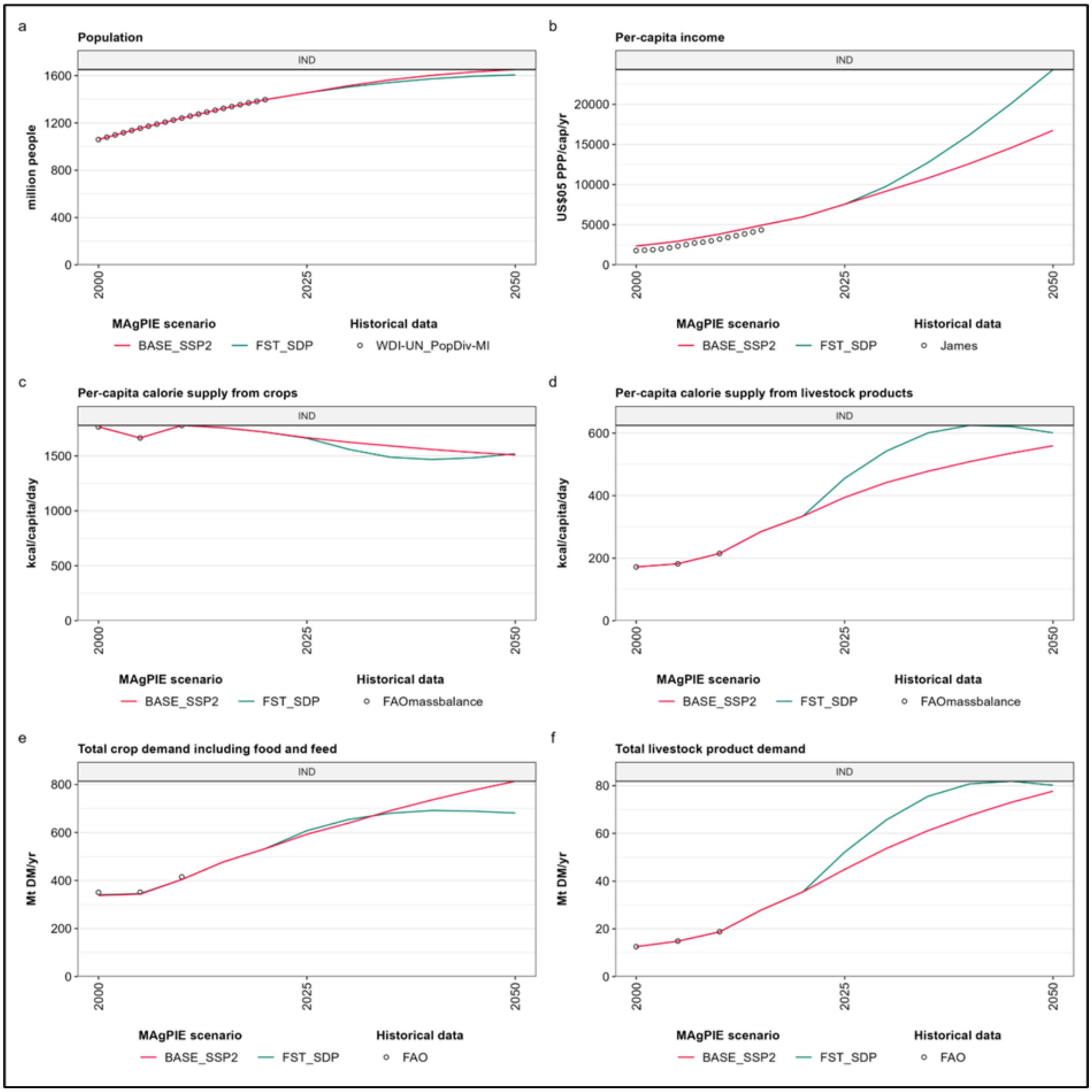
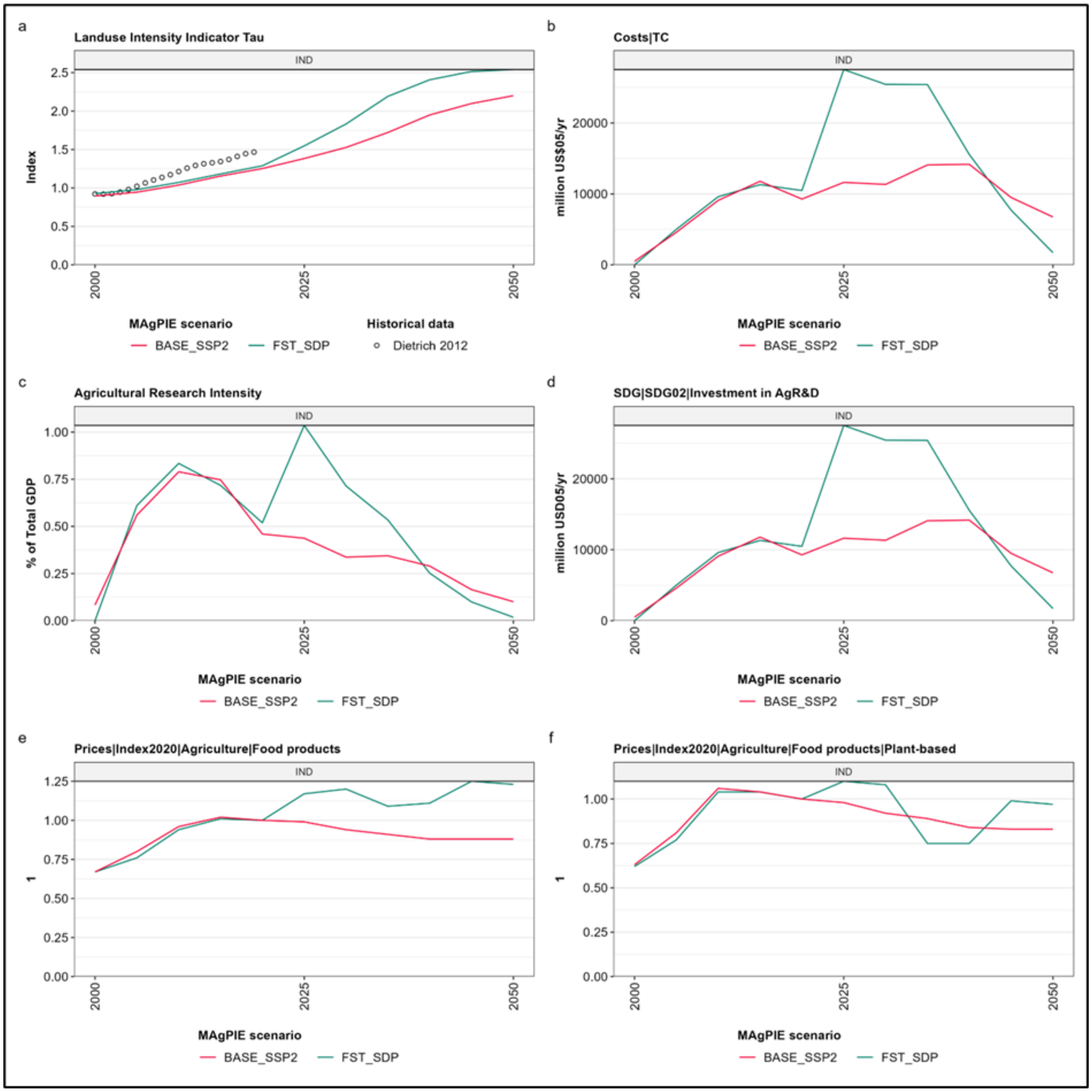
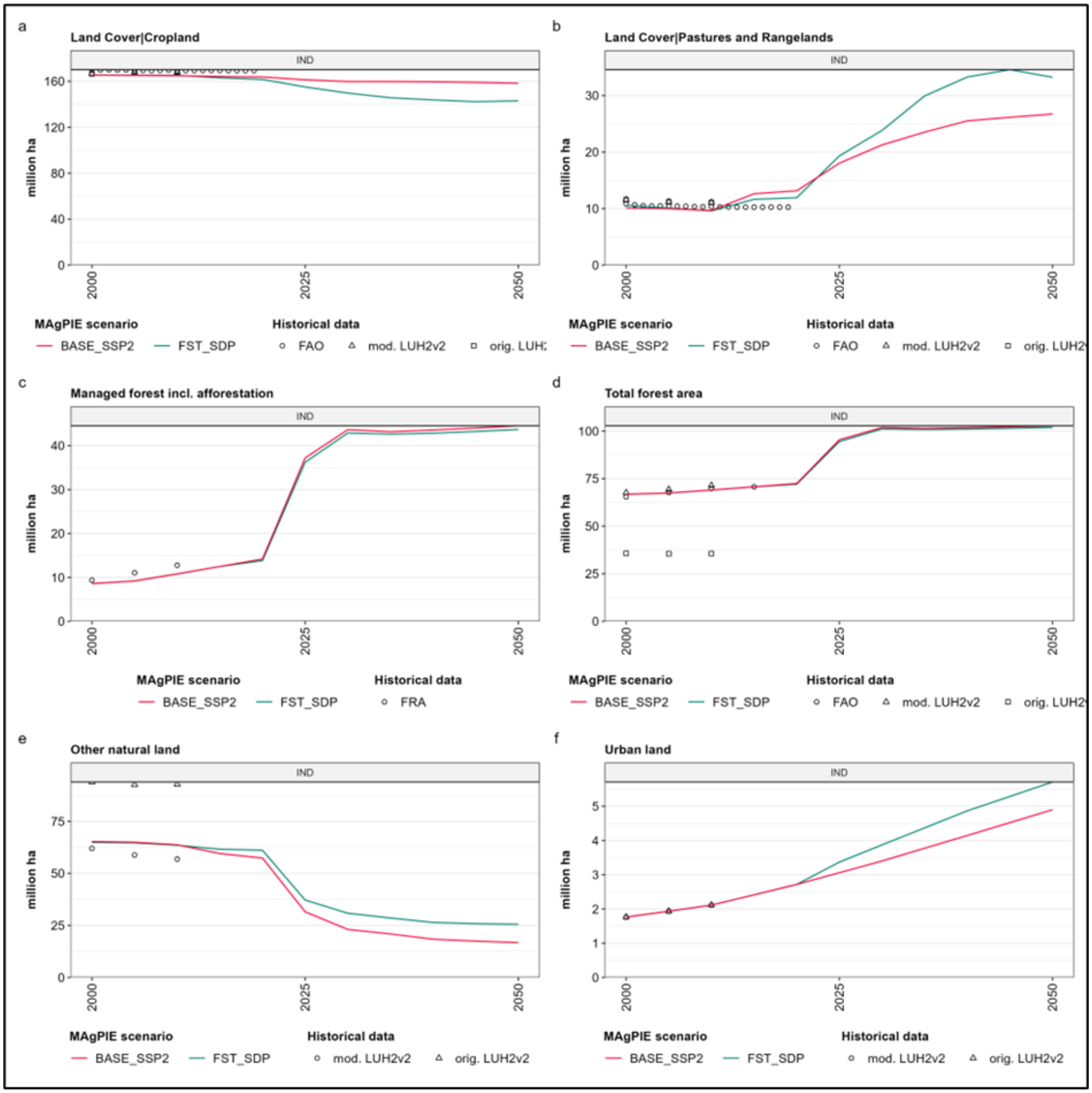
Supplementary Information

SM1: Validation plots and historical trends




a
Landuse Intensity Indicator Tau
IND
Index
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
Dietrich 2012
b
Costs|TC
million US$05/yr
c
Agricultural Research Intensity
% of Total GDP
d
SDG|SDG02|Investment in AgR&D
million USD05/yr
e
Prices|Index2020|Agriculture|Food products
f
Prices|Index2020|Agriculture|Food products|Plant-based



a
Land Cover|Cropland
IND
million ha
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
FAO
mod. LUH2v2
orig. LUH
b
Land Cover|Pastures and Rangelands
IND
million ha
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
FAO
mod. LUH2v2
orig. LUH2
c
Managed forest incl. afforestation
IND
million ha
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
FRA
d
Total forest area
IND
million ha
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
FAO
mod. LUH2v2
orig. LUH2
e
Other natural land
IND
million ha
MAgPIE scenario
BASE_SSP2
FST_SDP
Historical data
mod. LUH2v2
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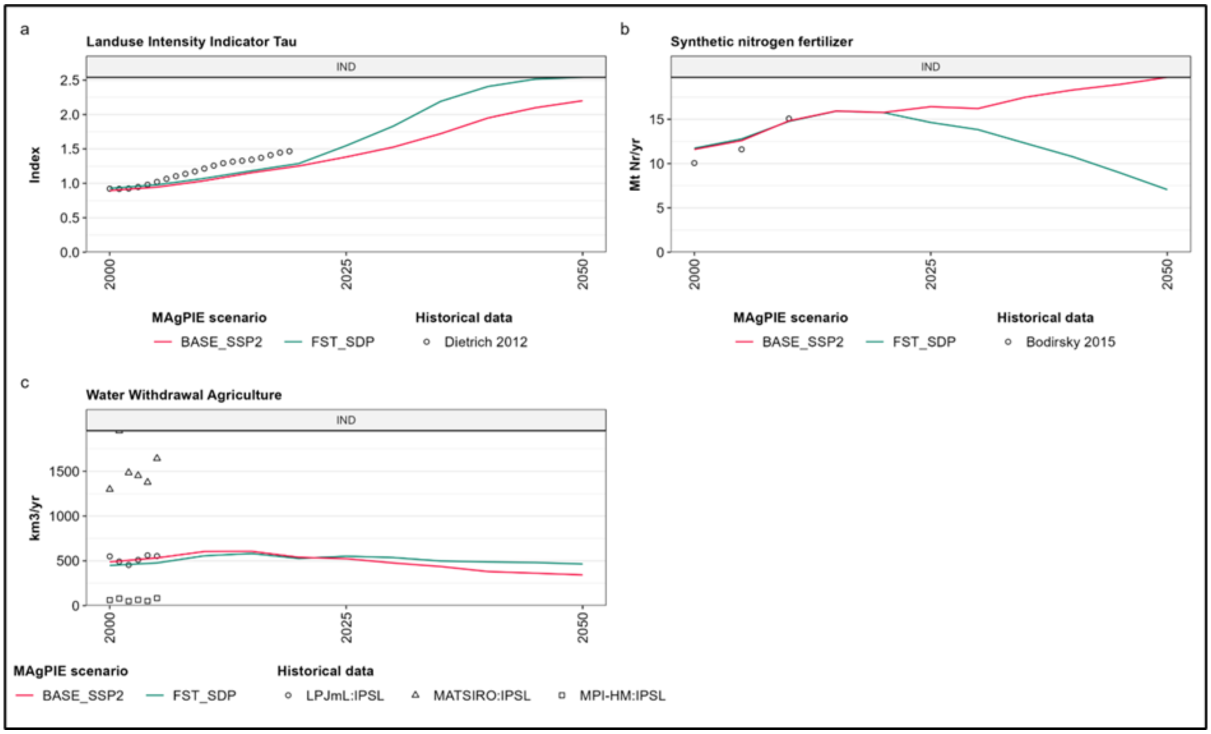

Figure SM1: Comparison of central model indicators with historical trends for the Base_SSP2 and the FST_SDP scenario.

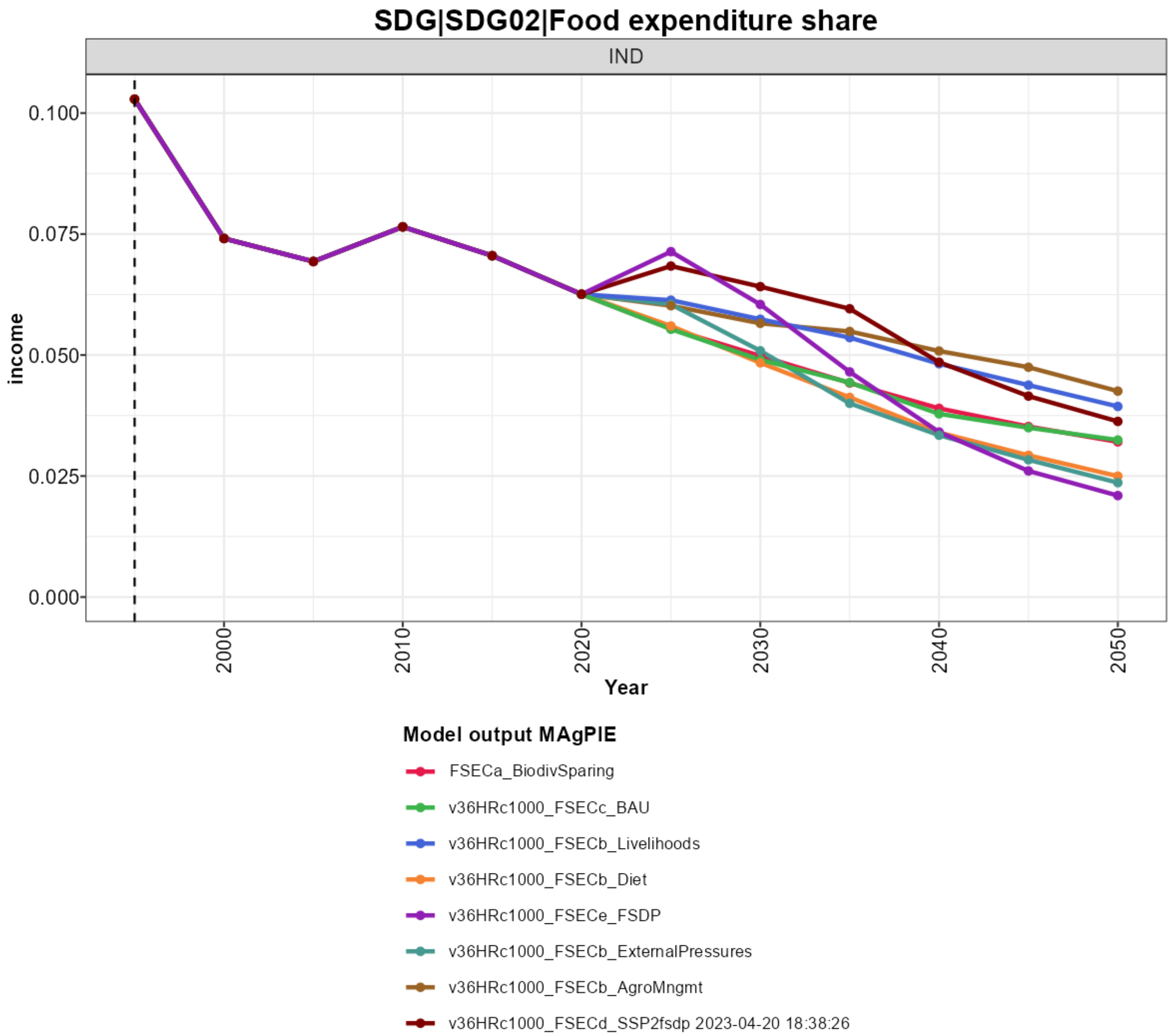

Figure SM3: Food expenditure out of total expenditure over the years up to 2050 for all scenarios

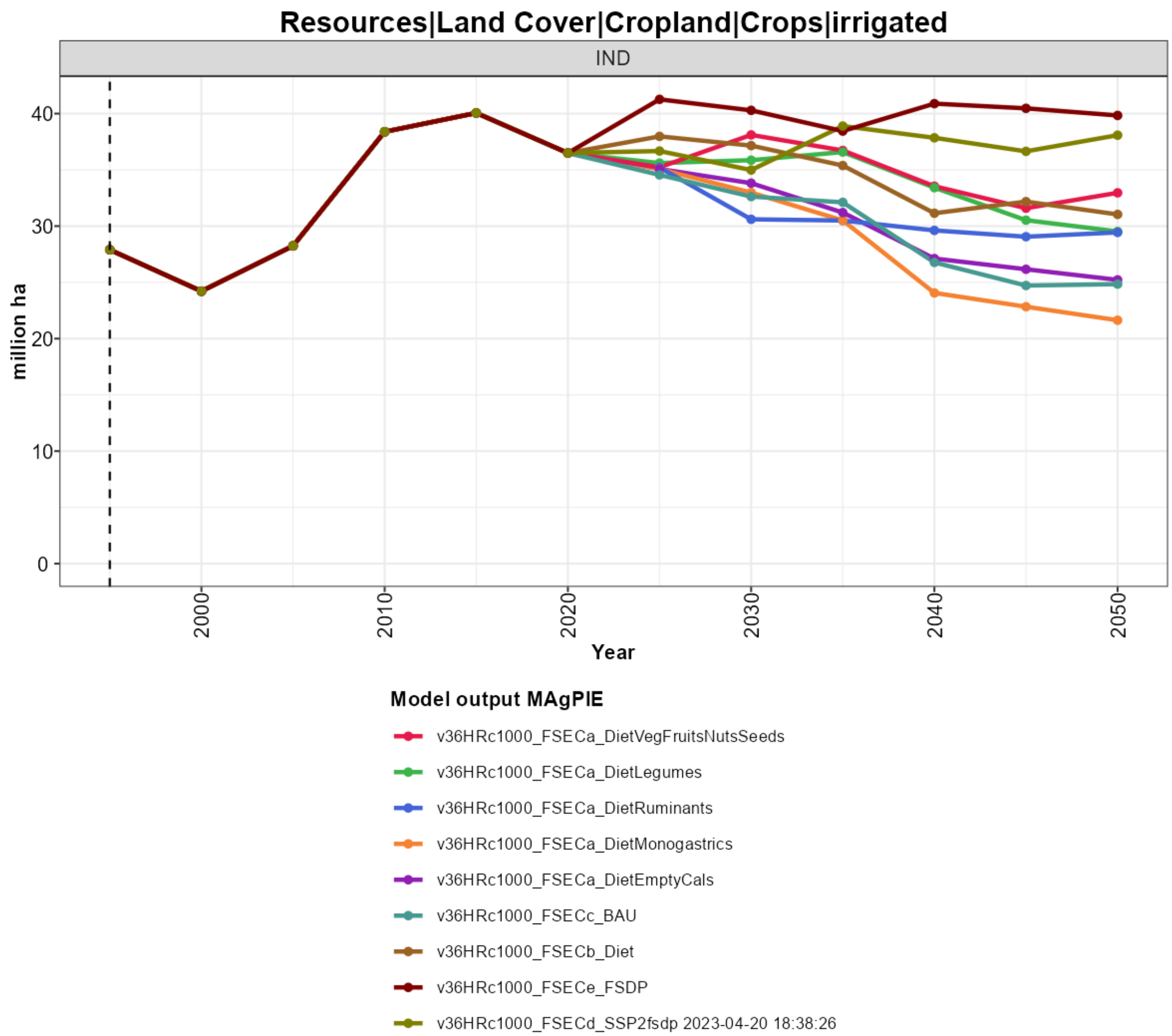

Figure SM4: Irrigated cropland for food based dietary scenarios over the years up to 2050

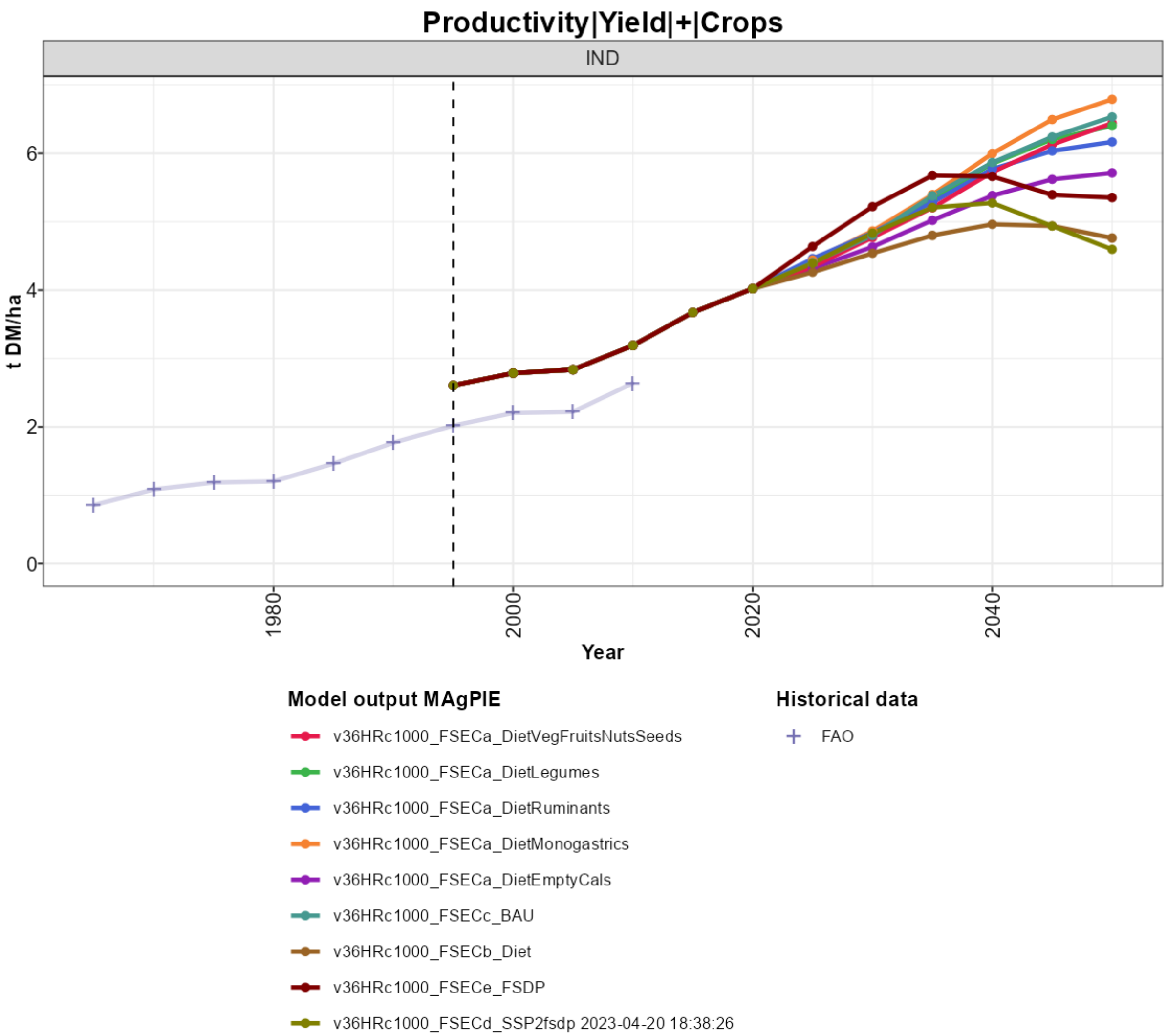

Figure SM5: Crop productivity for food based dietary scenarios over the years up to 2050

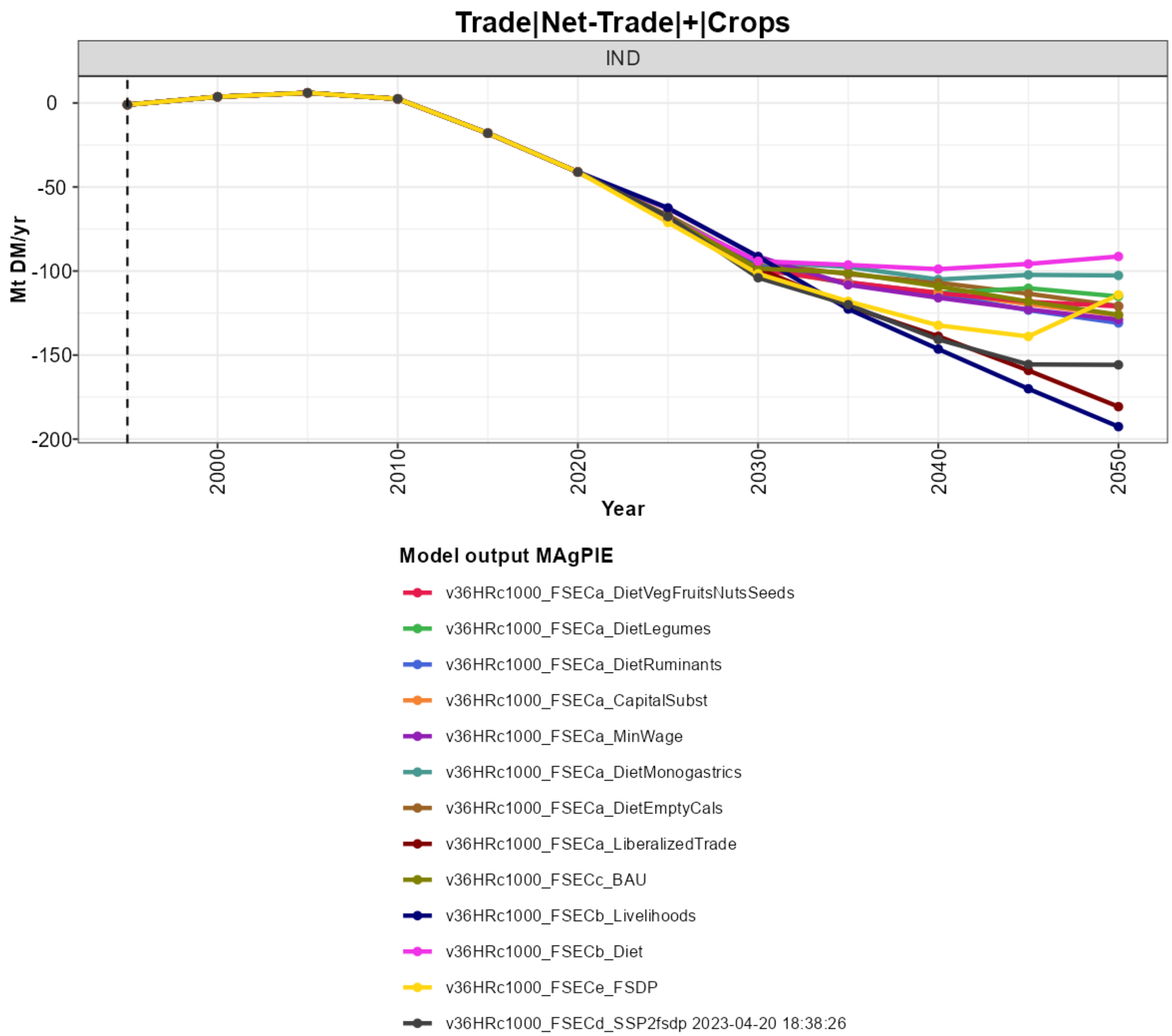

Figure SM5: Net trade under food based dietary and livelihood scenarios over the years up to 2050

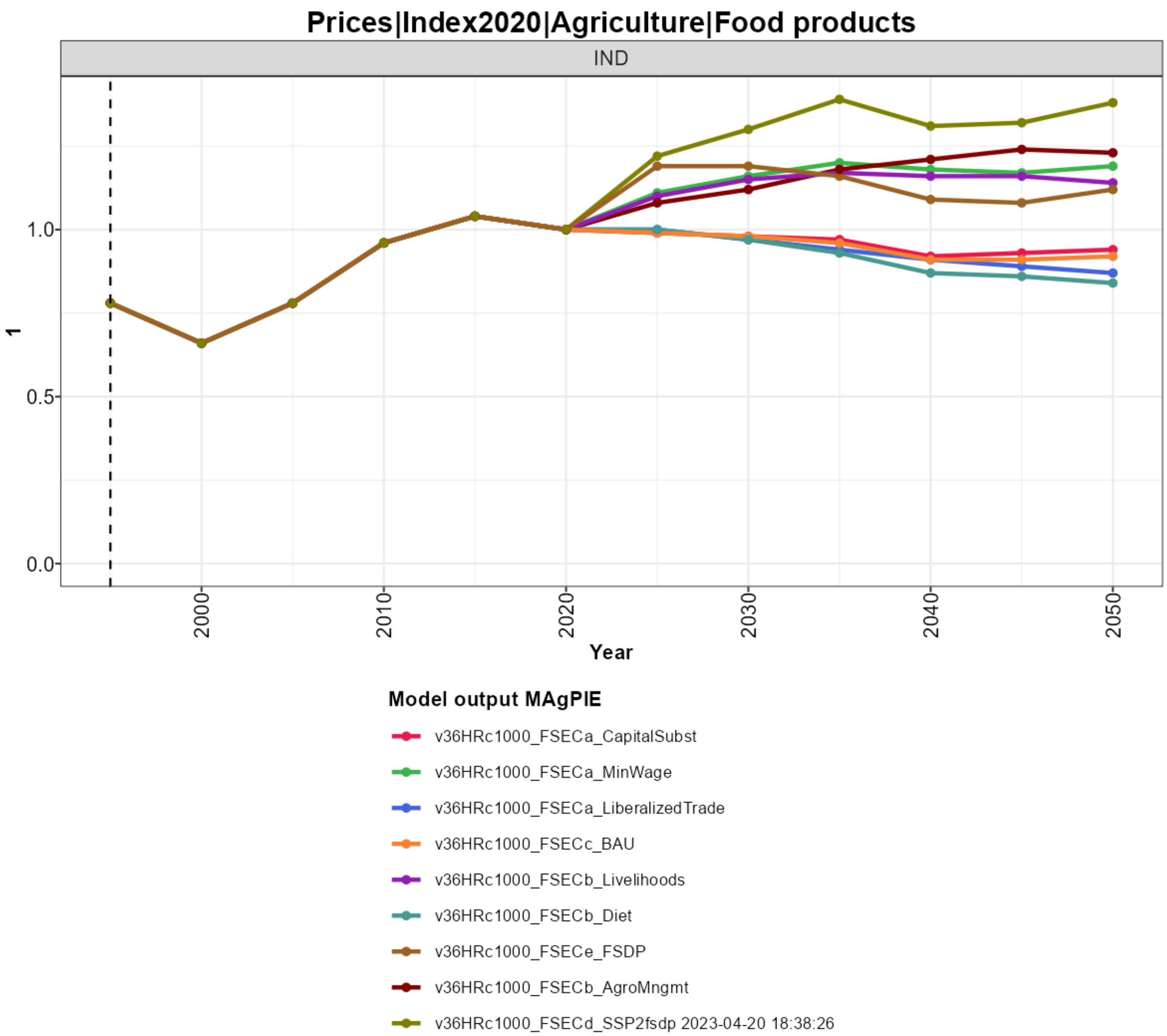

Figure SM6: Food price index across scenarios over the years up to 2050

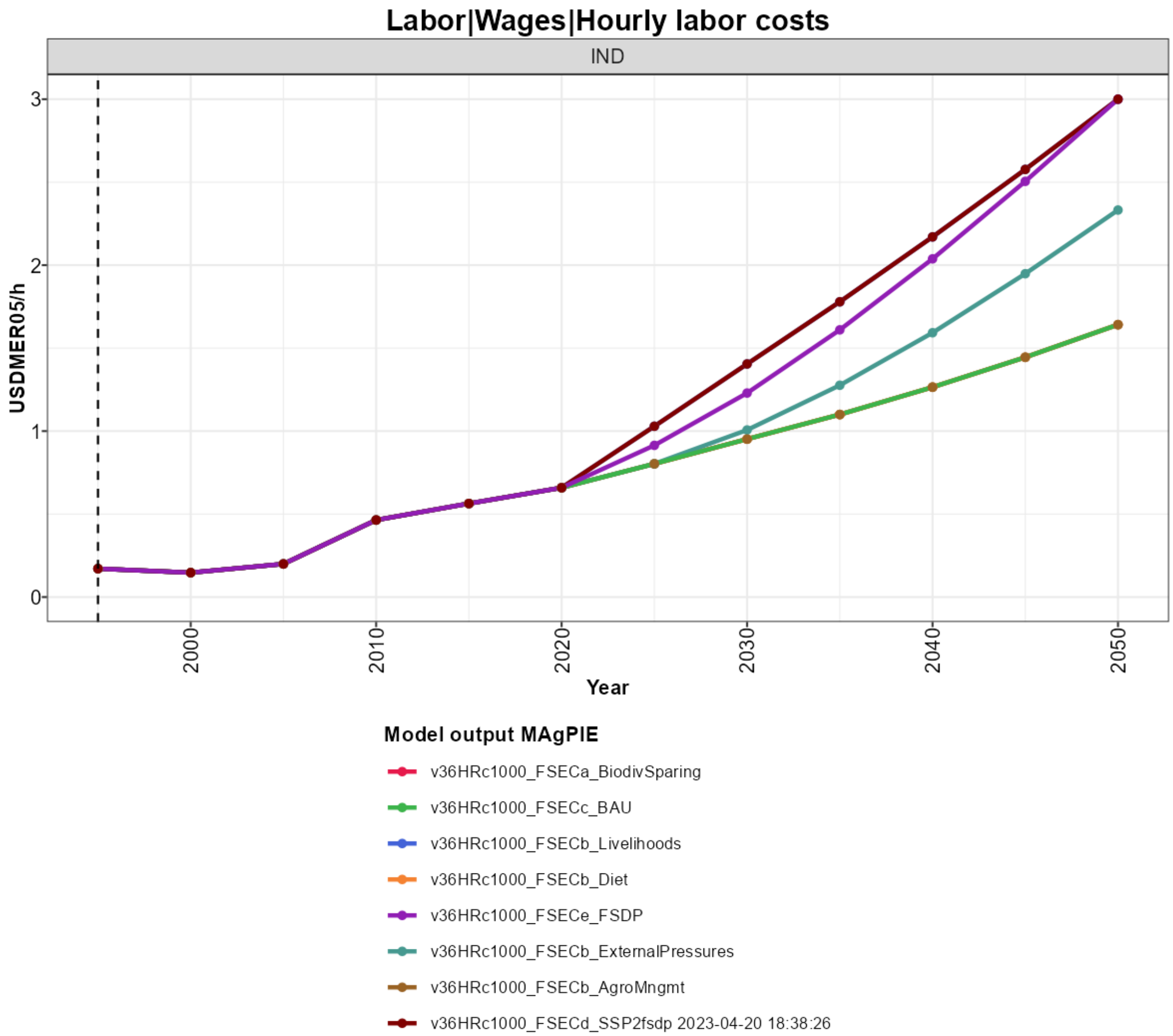

Figure SM7: Change in hourly costs of labor over the years up to 2050 under BAU and FSDP scenario

Extended table 1

FSM name	Short description	Implementation
LowProcessed	Recommended intake of sugar, vegetable oils and fats, alcohol, wholegrain	Until 2050, the scenario gradually converges towards recommended intake values for sugar, vegetable oils & fats, and alcohol, and all grain consumption is switched to wholegrain. Recommended intake values were adopted from EAT Lancet (Willet et al 2019, Springmann et al 2018). Because the original formulation of the healthy diets did not include a target for alcohol consumption, the cut-off for alcohol consumption was taken from a nationally adapted healthy plant-based diet developed for Denmark based on the EAT-Lancet reference diet (Lassen et al. 2020). Sugar and alcohol intake was capped at the healthy intake level recommended by the EAT Lancet commission where ever it exceeds this threshold in the baseline. Intake levels of vegetable oils was adjusted both upwards or downwards to meat the recommendation by EAT Lancet. The consumption of staple foods (cereals, roots, tubers) is adjusted to keep total food calorie intake constant.
HighLegumes	Recommended intake of legumes	Calorie intake for legumes is gradually increased until 2050 to the level suggested by the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems (Willet et al 2019, Springmann et al 2018). In countries exceeding these levels in the baseline, no changes are made. The consumption of staple foods (cereals, roots, tubers) is reduced to keep total food calorie intake constant.
DietVegFruisNutsSeeds	Recommended intake of vegetables, fruits, nuts and seeds	Calorie intake for vegetables, fruits, nuts and seeds is gradually increased until 2050 to the level suggested by the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems (Willet et al 2019, Springmann et al 2018). In countries which already exceed these levels in the baseline, no changes are made. The consumption of staple foods (cereals, roots, tubers) is reduced to keep total food calorie intake constant.
HalfOverweight	Reduces prevalence of overweight and obesity	Food calorie intake of all adults with a BMI>25 and of children with > +1 standard deviation (SD) from the reference BMI, aged 0-14 years, is reduced until they reach a BMI of 20--25 and a BMI between -1 SD and +1 SD from reference BMI, respectively. Food intake of population subgroups with a BMI below the scenario threshold is not changed compared to endogenous model projections. The described exogenous modifications in total caloric intake for specific population subgroups do not imply changes in relative food composition.
NoUnderweight	Overcoming undernutrition	Food calorie intake of all adults with a BMI<20 and of children with < -1 standard deviation (SD) from the reference BMI, aged 0-14 years, is increased until they reach a BMI of 20--25 and a BMI between -1 SD and +1 SD from reference BMI, respectively. Food intake of population subgroups with a BMI above the scenario threshold is not changed compared to endogenous model projections. The described exogenous modifications in total caloric intake for specific population subgroups do not imply changes in relative food composition.
LowFoodWaste	Food waste reduction	Projected household food waste, which is calculated based on GDP regressions (Bodirsky et al 2020), is gradually reduced to a level of 20% waste on calory basis in 2050 in regions that exceed this scenario threshold.
LibTrade	Trade liberalization	MAgPIE uses two trade pools: The "historic trade pool" is based on historical trade patterns, with importing countries importing a constant share of their domestic demand, and exporting countries providing a constant share of global trade. This reflects also trade distortions and historically grown dependencies. The "liberal trade pool" is based on relative cost-competitiveness. In the LibTrade scenario, the share of the free trade pool is increased from 20% to 30% for crops, and from 10 to 20% for livestock and secondary products.
MinWage	A global minimum wage	A linear term is added to the baseline hourly labor payments, starting from 0 zero in 2020 and increasing such that resulting hourly labor payments will match the minimum wage of 5$/h in 2050. The additional wage increase does not affect labor productivity. Therefore labor costs per production increase proportional to hourly labor payments, leading to a substitution from labor to capital as input to crop production.

CapitalSubst	In countries with high capital intensity, capital is substituted by labor	The global target for the labor share (labor/(labor+capital)) in crop production is set to 80% by 2050. The target fulfillment share is set to 50%, which indicates the share by which a region moves from its baseline labor share towards the target value. The transition towards the target labor share is implemented as a linear increase starting in 2020, and the labor share is kept constant after 2050. Regions with a higher labor share than the global target value will follow their decreasing baseline labor share until at the target value and are kept constant after that point. Setting the resulting labor shares as a constraint leads to substitution of capital by labor.
REDD+	Avoided deforestation and afforestation.	The “REDD+” scenario provdes carbon-price induced incentives for reducing deforestation and for the regeneration of original vegetation(Humpenöder et al, 2014). Regneration uses growth curves and carbon targets of natural vegetation based on LPJmL. The growth curves are parameterized based on Braakhekke et al. 2019.
LandSparing	Enlargement of protected areas	By 2030 the land area under protection (currently about 15%) is doubled so that protected areas make up 30 % of the global land surface. Here, we assume that the enlargement of protected areas includes both a reactive and proactive component (Brooks et al., 2006, Kreidenweis et al 2016). In the reactive component the focus is on biodiversity hotspots (BH). Biodiversity hotpots are characterised by a loss of native habitat of >70%, while they harbour nearly 43% of the world's bird, mammal, reptile and amphibian species and more than halt of the world's plant species as endemics. The proactive component considers large areas (>500 km2) of unprotected intact forest landscapes (IFL), mainly in the Amazon and Congo basins and in the boreal zone.
WaterSparing	Environmental Flow Protection	Spatially explicit minimum environmental flow requirements (EFR) are derived from LPJmL monthly discharge using the Smakhtin method taking high- and low-flow requirements into account (Smakhtin et al. 2004). These volumes are then aggregated to the required spatial (1000 simulation clusters) and temporal resolution (yearly values, accounting for growing-period months only).
BiodivSparing	Compensation of biodiversity loss	First aggregated biodiversity intactness index (BII) values in each biome type of each biogeographic realm are derived. After 2020 aggregated BII values in each biome type are not allowed to further decrease. Any BII reduction (e.g. through cropland expansion) at the biome level must therfore be compensated by increasing the land area of land types with higher BII values (e.g. forest and other natural vegetation).
NitrogenEff	Nitrogen uptake efficiency is increased	Soil nitrogen uptake efficiency(SNuPE) is an exogenous parameter in MAgPIE. Nitrogen surplus is (1-SNUpE). We use the marginal mitigation curves of Harmsen et al (2019), and apply the relative mitigation to the nitrogen surplus. We use the most ambitious level of mitigation, including the connected costs. Costs are added to the production costs and are split between labor and capital based on the share prevalent in agriculture in this world region.
LandscapeElements	Permant habitats within agricultural landscapes	The area of available potential cropland at grid cell level is derived from Zabel et al. (2014). Cropland expansion at the grid cell level is constrained to 80 % of the available cropland. This allows to conserve at t least 20% permanent semi-natural habitats at the landscape level, in order to support biodiversity conservation and to provide a stable supply of multiple key regulating ecosystem services (e.g. pollination, pest control, soil protection). Semi-natural habitats include forest, non-forest and grassland habitats that can maintain and restore native species diversity.
RiceMitigation		We use the marginal mitigation cots curve by Harmsen et al (2019) to reduce baseline emissions.

LivestockMngmt	Improved livestock management	Improved livestock management is represented via exogenously assuming improved future livestock productivity developments according to SSP1 instead of SSP2 parametrization. As a result of higher productivity increases, especially in low-income countries, feed conversion improves and the relative contribution of different feed types changes, from roughage-based feeds such as grazed biomass or residues to concentrate feeds cultivated on cropland (Weindl et al 2017 a,b). Additionally, we include the full set of technical mitigation measures from Harmsen et al (2019) to reduce methane emissions from enteric fermentation.
ManureMngmt		For nitrogen and N2O emissions, the shares of different animal waste management systems are shifted such that 50% of manure are managed in anaerobic digesters, while the remainder is still managed according to the current mix. Anaerobig digesters are assumed to have a 90% recycling rate of manure, accounting for some remaining losses in stables and waste collection. For CH4 emissions, we activate the full set of technical mitigation measures described by Harmsen et al (2019)
SoilCarbon	Protecting soil carbon	Based on the revised IPCC 2019 stock change factors, dependent on climate regions and account for irrigation and crop system (perennial, annual and paddy rice).
Population	Reduced population growth	Switch from SSP2 to SSP1 population projections (Kc and Lutz, 2017)
HumanDevelop	Faster and more equal human development, better institutions	Human development is fairer, with higher social justice and better institutions and education. Switch from SSP2 to SSP1 projections (A) for per-capita gross domestic product and Gini-coefficient, which implies fast economic growth in particular in low-income regions, and a more equal income distribution between countries and within countries; (B) for non-food related health risks; (C) for the parametrization of the diet model, choosing a different functional form for the regressions which leads e.g. to a slight decline of animal product demand when income levels become very high (similar to Bodirsky et al 2012) (D) for risk premiums on interest rates for long-term investments (e.g. irrigation, yield-increasing technological change) due to poor institutions (Wang et al 2016) in low-income regions by 4 percentage points and to a lesser extent in middle-income regions. (E) for the technological progress of the base soil nitrogen uptake efficiency, increasing it by 5 percentage points in all countries with an upper limit of 75% for each country.
EnergyTrans	Sustainable transformation of economic sectors outside the food system.	Bioenergy demand for energy transition increases from X to X, water demand for non-agricultural use changes from X to X, urbanisation scenario changes from SSP2 (X Mio ha) to SSP1 (X mio ha), active transportation changes physical activity levels from sedentary to moderate activity

Extended table 2

Indicators	Definition	Level of aggregation, timely resolution
Population underweight	Defined as the number of adults with a BMI <18.5 (for people older 15 years) and children and adolescents with a BMI that is 2SD below normal (0-14 years).	Country level, by age cohorts and sex, for a specific year.
Population obese	Defined as the number of adults with a BMI >30 (for people older 15 years) and children and adolescents with a BMI that is 2SD above normal (0-14 years).	Country level, by age cohorts and sex, for a specific year.
Life years lost	Years of life lost (YLL) is a measure of premature mortality that takes into account both the frequency of deaths and the age at which it occurs, using the "Global Burden of Disease standard abridged life table" to represent the standard life expectancy. Definition: One YLL represents the loss of one year of life.	Country-level, by sex, for a specific year.
Cropland Landscape Biodiversity Intactness Index	The BII accounts for net changes in the abundance of organisms based on the loss of forest and non-forest vegetation cover and age class of natural vegetation, which are expressed relative to a reference land-use class (forested or non-forested vegetation) and weighted by a spatially explicit range-rarity layer (unitless). For the cropland landscape BII, only cells which contain at least 100 ha of cropland are considered.	0.5°, for a specific year.
Key conservation landscapes Biodiversity Intactness Index	The BII accounts for net changes in the abundance of organisms based on the loss of forest and non-forest vegetation cover and age class of natural vegetation, which are expressed relative to a reference land-use class (forested or non-forested vegetation) and weighted by a spatially explicit range-rarity layer (unitless). For the key conservation landscapes, we considered only cells in biodiversity hotspots (BH) intact forest landscapes (IFL).	0.5°, for a specific year.
Shannon crop diverstiy index	Measure of crop diversity that takes into account the richness and abundance of different crop types (unitless).	0.5°, for a specific year.
Nitrogen Surplus	Nitrogen surplus in croplands, pastures, natural vegetation and animal waste management in Tg Nr	0.5°, for a specific year.
Water environmental flow violations	Water withdrawals exceeding the volume that could be withdrawn when taking minimum environmental flow requirements of aquatic and riverine ecosystems into account, in km³	spatial cluster, for a specific year (during growing period). [calculated from monthly data at 0.5° resolution]
Greenhouse gas emissions	Greenhouse gas emissions from land use and land-use change in Gt CO2 equivalents using a 100 year global warming potenial (GWP100 based on AR6).	World region level, cumulated over the period 2020-2050.
Expenditure for agricultural products	Million dollars	Country-level, for a specific year.
People living below 3.20$ a day	Number of people in millions with a per capita daily income below X $ USD05 PPP in each country, based on poverty lines estimated by the Wolrd Bank	Country-level, for a specific year.
Agricultural Employment	People working in agriculture (crop and livestock production), in million people	World region level, for a specific year.
Agricultural wages	Wage index describing the development of wages relative to 2020, ratio	Country-level, for a specific year. Aggregation to global level using constant 2010 country-level population data.

Bioeconomy supply	Value stream from the food and land system to other economic sectors, including the value of bioenergy, bioplastics, timber, and material use of products at fixed prices of 2010. Food demand is considered internal to food system.	World region level, for a specific year.
Costs	Value stream from other economic sectors to food and land system, including labor and capital for agricultural prodution, R&D expenditures, land expansion expenditures, transport costs, in USD05MER/year. Rents, e.g,. land scarcity rents or water scarcity rents, are excluded from costs as they are transfer payments. Similarly, the difference betweeen minimum wage and labor productivtiy is excluded as a transfer payment which does not reduce the production capacity of the country.	World region level, for a specific year.