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Distribution matters: Long-term quantification of the Sustainable Development Goals with household detail for different socio-economic pathways

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ABSTRACT

Knowledge about upcoming sustainability challenges is crucial to tackle them by political incentives, not at least to reach the United Nations' 17 Sustainable Development Goals (SDGs). SDGs are multi-dimensional and require detail beyond an aggregate household approach to assess income inequality and other differences across households in transformative processes. Incorporating these aspects, we develop an SDG indicator framework for dynamic Computable General Equilibrium Models with a total of 68 endogenous indicators related to 15 SDGs. This enables a more differentiated assessment of the SDGs in forward looking analysis compared to existing approaches, by considering additional SDG indicators and household level detail based on micro-simulation. We apply the indicator framework in a global analysis of 3 Shared Socioeconomic Pathways (SSPs) until 2050 with a focus on selected low- and lower-middle income countries from different continents. The analysis finds sustainability gaps by 2030 and 2050 for all focus countries, especially in the environmental domain. In none of the analyzed SSPs, all indicators develop in the desired direction, underlining trade-off among and within SDGs, but also across the SSPs. Based on household detail, we find increasing inequality over time for several indicators regardless of developments at average aggregate household level, pointing at the need for targeted redistribution and compensation policies. These results highlight the importance of including distributional aspects and disaggregated data in policy and socioeconomic development studies.

1. Introduction

To address multidimensional aspects of human and planetary well-being, the United Nations' (UN) Member States agreed in 2015 on the so-called Agenda 2030 with 17 Sustainable Development Goals (SDGs) to be reached in 2030. These goals and their associated targets are strongly interlinked, leading to synergies and trade-offs among them (e.g. Refs. [1–5]). A wider range of literature assesses the advancements towards these goals (e.g. Ref. [6]), or develops approaches for their quantification (e.g. Refs. [7–9]). The degree to which the SDGs will be reached depends on complex interactions, including socio-economic and demographic dynamics, governance and climate change. Modelling these dynamics in ex-ante assessments can inform society how policies affect the different SDGs. Suitable tools need to capture interactions between economic variables including production, demand, income and prices, to acknowledge global interrelations and to quantify indicators for the different SDGs. For this task, multi-regional dynamic Computable General Equilibrium (CGE) models are well suited due to their multi-sectoral and global perspective. Furthermore, their recursive-dynamic nature permits them to capture relevant societal and economic adjustment processes in the long-run following exogenous macro-economic projections such as the shared Socioeconomic Pathways (SSPs [10]).

For quantification of SDGs in CGE analysis, indicator frameworks processing model outcomes are partly available. For example, Campagnolo et al. [11] quantified 23 individual indicators based on the results of their CGE model, from which they calculated country-

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level composite indicators (FEEM SI) to assess progress toward the SDGs. Philippidis et al. [12] used a CGE model to depict synergies and trade-offs between SDGs under different development pathways. Using the MAGNET SDG Insights Module (that captures indicators linked to 13 SDGs), they selected 12 indicators related to 7 SDGs for this assessment. Liu et al. [13] conducted a CGE analysis on the potential achievement of SDGs using the SSPs projections combined with climate policy assumptions, quantifying indicators related to 5 SDGs.

While CGE models will never capture the full multi-dimensionality of the SDGs, existing indicator work still misses some SDGs and targets that can be quantified from model results. To the authors knowledge, distributional impacts regarding income, food security and equality, have not yet been covered in SDG-related CGE model analysis. This reflects that suitable household level data are often scarce and their consistent link to CGE modelling challenging. However, several SDG indicators specifically focus on the distributional aspects (e.g., SDG1 "No Poverty", SDG2 "Zero hunger", SDG10 "Reduced inequalities"). To advance here, we develop and apply a post-model micro-simulation approach, on harmonized household level data from FAO [14] available for low- and lower-middle income countries. This data fits the special attention paid to low- and lower-middle income countries in the Agenda 2030 and allows to cover countries from different continents.

In addition to the household heterogeneity, this work addresses research gaps by adding more detail in the sectoral coverage and by quantifying results for single countries in a global model [15] rather than regional aggregates. Specifically, we disaggregate the agri-food sectors and incorporate nutrient accounting in diets to address substitution and to capture aspects in many SDGs [16] where detail so far was missing. Another contribution of this work consists of adding heterogeneity gender differentiated labor categories in the model allowing for further extension of the SDG coverage in the developed indicator framework.

The extended indicator framework is applied to the three baselines SSP1, SSP2, and SSP3 to quantify developments of the SDGs for selected low and lower-middle income countries. We link our work to the SSPs which provide narratives of broad future scenarios of the global economy, focusing on developments relevant for climate change [10]. These narratives are quantified into projections of income (real Gross Domestic Product, GDP) [17], demography and educational attainment levels and made available to the international research community.[1] Applying this data with further scenario specific assumptions, we assess the SDG achievement both until 2030 and 2050.

2. Methodology

2.1. Database development

We depart from the GTAP-Power Data Base Version 10 [18] which extends the GTAP Data Base [19] commonly used for global CGE analysis with detail for power generation,[2] which allows quantifying the contribution of renewable energy production and improves climate change emission accounting. With 76 sectors, it presents a snapshot of the entire global economy in 2014, reporting economic transactions in USD for a total of 141 countries and regional aggregates. Available extensions such as greenhouse gas (GHG) emissions factors [20] and air pollution [21] linked to production and trade are also incorporated in the database. To provide further detail for our SDG indicator framework presented in Section 2.4, we extend this database by splitting the initial data in three steps as depicted in Fig. 1 drawing on the method developed in Britz [22]. In the first step ("Split 1"), we introduce high detail for agri-food sectors based on the FABIO MRIO [23] and FAO [24] data as detailed in Britz [25]. This adds 34 agri-food sectors, improving the assessment related to food security, nutrition and land use. In parallel, we add data on gender differentiated labor, provided from the World Bank [26], to differentiate labor by male and female for skilled and unskilled, respectively. We aggregate the 141 single countries and regions encompassed in the GTAP 10 Data Base to 31 model regions, of which fifteen are individual countries (Table A.1 lists the regional aggregation). To set the regional focus on countries that are specifically targeted in the Agenda 2030, ten of the single countries represent low- and lower-middle income countries for which uniformly structured household surveys are available (see subsection 2.3). This step results in the intermediate data base termed FABIO_DB in Fig. 1.

The second step ("Split 2") splits the fisheries sector into open catch and aquaculture using FAOSTAT [27] data on production quantities of open catch and aquaculture, providing the second intermediate database FABIO_FISH_DB. A final third step ("Split 3") introduces irrigation water as a production factor and related resource depletion. It uses a data set by the [24] to split up crop activities into a rainfed and irrigated variant, similar to earlier work by Ref. [28]. This provides the final data base (FINAL_DB) with 100 products, 138 activities and 8 primary factors (capital, male/female skilled labor, male/female unskilled labor, natural resources, land, irrigation water) for 31 regions.

2.2. CGE modelling framework and model set-up

The model employed is configured in the flexible and modular platform for CGE modelling CGEBox [29,30]. Its core consists of the widely used GTAP Standard Model version 7 [31] realized in GAMS by van der Mensbrugghe [32]. It employs the usual assumptions of CGE analysis: competitive markets for products and factors, utility-maximizing consumers, cost-minimizing firms operating under constant returns-to-scale and revenue-maximizing factor supply. Drawing on the modularity of CGEBox, we add further model components relevant to quantifying SDG indicators. This includes detail in land use, incorporated based on the GTAP-AEZ (agro-ecological zones) data [33] and model [34]. Elements of the GTAP-E model [35] improve the presentation of energy use, while features from GTAP-AGR [36] consider specifics of agri-food sectors. More detail on CGEBox can be found in the Annex A1.1.

While income and population growth broadly shape many SDGs, details depend on structural changes. Addressing these details requires a framework that considers besides broad macro developments also relevant structural change processes and its consequences for agri-food sectors, here provided by the G-RDEM module [37] realized in CGEBox. It reflects the interaction of multiple supply and demand side drivers, including changes in primary factor stocks, technology, and final demand patterns. G-RDEM is specifically developed for long-term baseline construction and analysis, and extends the standard GTAP model [38] by the following features.

Changes in primary factor stocks reflect firstly capital accumulation which interacts with the endogenous updates of macro-saving rates in G-RDEM, depending on changes in income per capita and demography [37, p. 64–69], and its debt accumulation mechanism from foreign investments [37], p. (69–70). The used stock of labor by skill force follows projections provided for each SSP taken from the IIASA SSP portal.

[1] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html.

[2] base load: nuclear, coal, gas, oil, hydro, wind, other; peak load: gas, oil, hydro, solar; transmission and distribution.

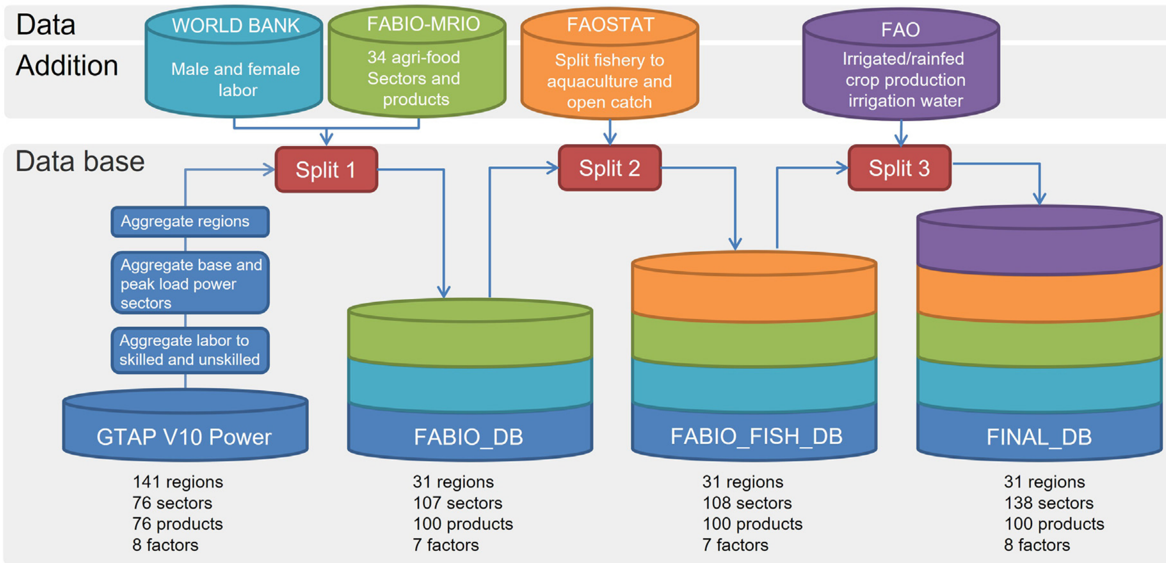

Fig. 1. Overview on the generation of the final database. Detailed references to the sources can be found in the text. Source: authors own.

During the constructions of our three baselines (see Fig. 2), G-RDEM uses exogenous projections for real GDP, population, demography, and workforce based on the narratives of SSP1, SSP2 and SSP3 [10]. Based on these exogenous developments, the model is solved for a simultaneous equilibrium in all commodity and factor markets globally at each period *t*. As it is typical of recursive dynamic models, net investments from step *t* update the capital stocks at *t+1*. Extending this, saving rates, input-output coefficients, population size and labor stocks by skill level are also updated between periods depending on income and demographic developments. During the process, sector-specific productivity shifters adjust, reflecting the change in aggregate total factor

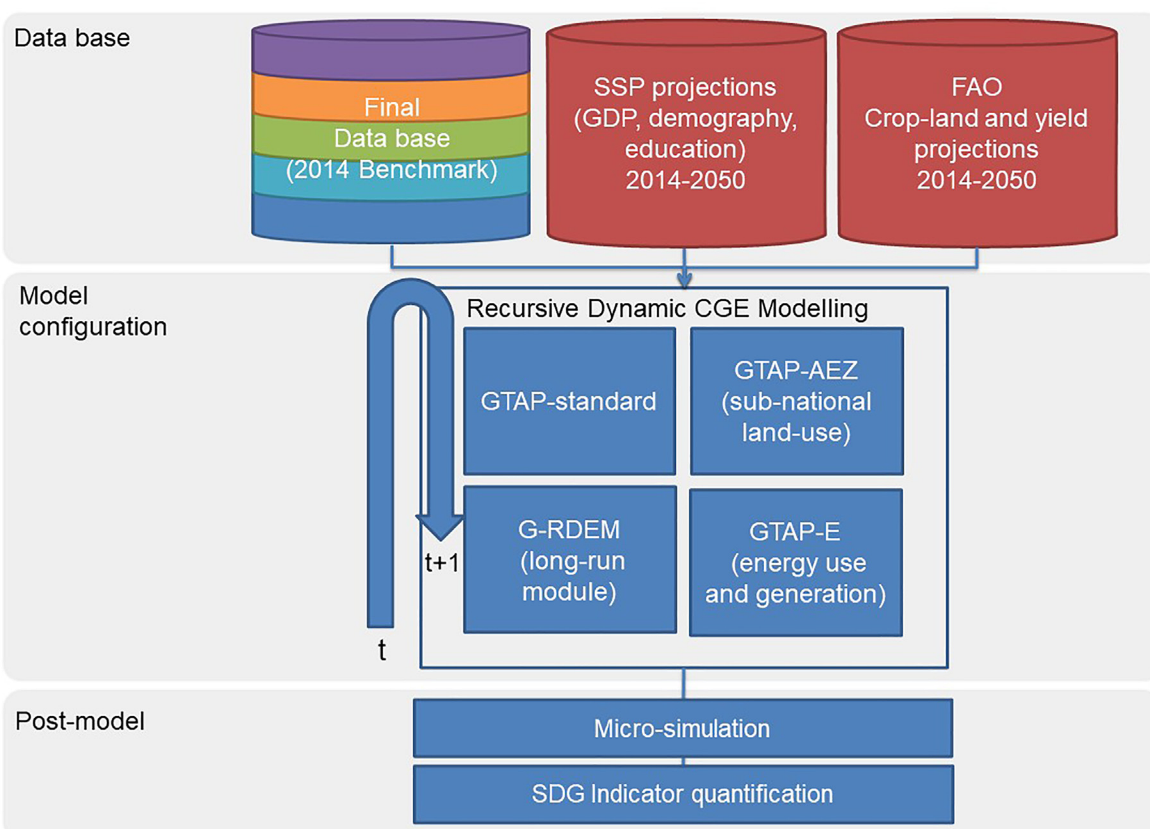

Fig. 2. Overview of the recursive dynamic modelling approach. Source: authors own.

productivity needed to replicate the given trajectory of real GDP. Detailed changes of technology in the decades ahead are hard to project. Instead of having uniform change in total factor productivity across sectors driven by the exogenous given income dynamics, G-RDEM employs empirical estimates to render productivity changes in three broad sectors group depending on the speed of economic growth [37], p. (61–63). Specific productivity changes for crop and livestock products recover crop yield and crop land forecasts by FAO [24], while built-up land is driven by GDP growth and changes by urbanization and population density, based on empirical work similar to Chen et al., [39]. Additionally, input-output coefficients in G-RDEM are not static, but are updated instead depending on projected income growth [37], p. (71–70). These supply side drivers interact with changes in demand. Especially budget shares for food in total and individual food items are quite sensitive to income developments [40] which motivates the use of the rank 3-MAIDADS (Modified An Implicit Additive Demand System) demand system estimated by Ref. [41]. Its exponential Engel curves capture for instance saturation effects with regard to the consumption of certain food categories. To improve here further, calorie intakes follow an empirically estimated relation to income changes [42]. Equally, expenditure shares for investment and government demand are rendered income dependent in G-RDEM which is solved in bi-yearly steps from the 2014 benchmark year until 2050.

2.3. Post-model micro-simulation: adding household level detail

CGEBox, as the standard GTAP model, considers only one representative household in each model region. Using multiple ones instead can better inform on links between economic growth, structural change, and well-being [43]. Households can, for instance, be differentiated by urban and rural as well as the size of owned land [44], income levels and the households' links to agricultural and non-agricultural sectors [45] or by a combination of income, rural or urban and gender [46]. Micro-simulation allows for a far richer analysis by depicting many different households of a population, revealing detail beyond average effects at country or aggregate household level.

Structural change affects households both on the income and consumption side. Top-down micro-simulation consists of projecting earnings and spending for each household in the survey based on aggregate model results. The “Data Portrait of Small Family Farms” [14] is used here. It provides data for 19 low- and lower-middle income countries from which ten (Nigeria, Ghana, Kenya, Nicaragua, Bolivia, Vietnam, Indonesia, Malawi, Ethiopia, and Bangladesh) are chosen to keep the assessment manageable. The selection covers different continents and the latter three countries are classified as least developed countries (LDCs [47]) for which partly more ambitious SDG targets are defined. Each survey covers tens of thousands of households along with their aggregation weights.

The income positions provided by the FAO [14] for the base year are updated post-model for each report year and individual household until 2050, based on simulated changes in factor stock, prices, transfers, and taxes. The household survey data provides besides income levels also income shares for self-employment and wages by different sectors and skill levels, from crop and livestock production, from public and private transfers, plus a residual category. As a first step, initial FAO income shares of the first four income sources are used to derive share parameters of a CET (Constant Elasticity of Transformation) function, from which price and quantity indices are calculated. These are then updated based on CGE model results. To do this, the definitions of sectors and skills from the household survey are mapped to the more detailed ones in the CGE model to update single household results (see Table A.2 in the Annex). Here, for wages, changes in factor returns to labor by skill category are used. For example the skilled wage income category stemming from agricultural production is linked to the respective labor category of all agricultural sectors in the Social Accounting Matrix. For other sectors a direct mapping to the skill category of a single GTAP sector is made. The same sectoral mapping holds for the other factor incomes (i.e., self-employment and crop and livestock production), while here changes in all factor returns are considered, i.e., labor, land, capital, and natural resources. From there, the CET function determines each household's new factor allocation, assuming a transformation elasticity of five [30]. Resulting incomes by factor are then scaled, considering household-specific aggregation weights, to exhaust economy-wide totals (see Annex A1.2).

The remaining sources of income are updated as follows: Income derived from public transfer at country level are linked to changes in total tax income; Income derived from private transfer, including remittances are shifted in line with country level changes in total private consumption; Income derived from the ‘other’ position, are adjusted following changes in regional income [30]. Finally, we assign to each household a share of total government consumption according to the number of household members while household specific saving rates are estimated based on the regression coefficient used in the G-RDEM excluding negative savings or values that exceed 50 % of income.

Since the household survey misses information on spending, consumption patterns are estimated and updated based on the exponential Engel curves of the MAIDADS demand system as applied in CGEBox [41]. Specifically, an estimated relation derives a utility metric from each household's income in every year. This metric determines household-specific parameters of the demand system, which estimate the demands at given prices and the household's income. Demands are then multiplied by nutrient contents to derive daily per capita calories, protein, and fat intakes.

For reporting, we aggregate the micro-simulation results for the several thousand households in each country to 500 percentiles based on income per capita, to calculate metrics such as the Gini Index to characterize the income distribution. Further detail on the micro-simulation provides the model documentation ([30], pp. 109–116).

2.4. Indicator collection and implementation

The starting point for the indicator development and choice in this study provides a literature review of the studies [11–13] that used CGE models to measure SDG indicators in future pathways provides. Not all indicators found in these studies could be quantified based on our database.[3] Others were dropped as they are exogenous to our model; some were excluded due to the different focus of this study. We also explored potential indicators in studies that quantify SDGs in other model types, such as Integrated Assessment Models (e.g. Refs. [48,49]).

The next step scanned the 169 SDG targets and the related indicators (231) published by the UN [50], the indicators used by the FAO to measure food security [51] and the ones applied by Sachs et al. [52]. Our study excludes targets that are qualitative, addressing inter alia means of implementation, such as legal frameworks. Remaining indicators were checked for data

[3] These include for example corruption, waste and the share of endangered animals or plants from Campagnolo et al. [11] or the ration of rural wages to cereal prices and the difference between agricultural and non-agricultural wages from Philippidis et al. [12].

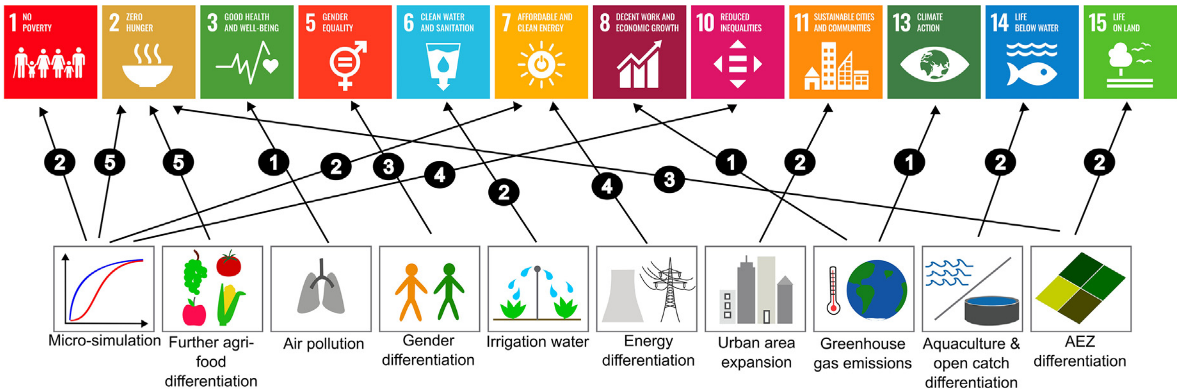

Fig. 3. Number of new indicators by data source and link to the respective Sustainable Development Goal. The arrows indicate the link between the data and the Sustainable Development Goal with which the indicators are associated. The number in the black circles represents the new indicators calculated from the data source. The total number of indicators quantified is sometimes larger. Source: authors own.

availability and compatibility with CGEBox. We discard indicators solely based on exogenous drivers, following Campagnolo et al. [11].

In total, our indicator framework, quantified based on results from CGEBox, covers 68 indicators linked to 15 SDGs. Here, we briefly discuss the additional indicators not found in the CGE-based SDG studies so far, see also in Fig. 3, with a focus on their data requirements. The complete list of 68 indicators can be found in the annex (Table A.3). Employing the GTAP standard model and using the GTAP V10 Data Base allows to quantify two indicators so far not calculated in CGE analysis, which are "Proportion of total government spending on essential services" (UN indicator 1.a.2, SDG1 'No Poverty') and the FAO Food Security Indicator: Cereal Import Dependency Ration (Stability Domain) for SDG2 'Zero Hunger' [51].

Adding the auxiliary data available from the GTAP Center (AEZ, non-CO2 emissions, air pollution) as well as the details in electricity generation from GTAP V10 Power allows to quantify (additional) indicators for six SDGs. Specifically, we add (1) partial productivity for different crop groups, linked to SDG2 'Zero Hunger', (2) a human health hazard indicator, calculated from 4 different air pollutants,[4] following the characterization factors for human health of ReCiPe [53], linked to SDG3 'Good Health and Well-being', (3) the share of total biomass that flow into energy production, linked to SDG7 'Affordable and Clean Energy', (4) the decoupling of GHG emissions growth and environmental degradation of economic activity, linked to SDG8 'Decent Work and Economic Growth', (5) the CO_2 emissions embodied in fossil fuel exports, linked to SDG13 'Climate Change Action', and (6) the share of unmanaged forest and the intensification (stocking rate) of grassland, linked to SDG15 'Life on Land'.

The additional detail in our base (FINAL_DB in Fig. 1) allows quantification of indicators for five additional SDGs and additional ones related to three SDGs (see Fig. 3), drawing on gender-differentiated labor and its agri-food detail, including the differentiation into rain-fed and irrigated crops and the disaggregation of fisheries to open catch and aquaculture. Micro-simulations deliver indicators for five SDGs by assessing distributional impacts, adding indicators not found in existing CGE analysis. For the representation of SDG1, for instance, we quantify indicators that address income distribution, namely household income per capita and the share of the population living below international poverty lines ($1.90 and $3.20), included in the UN official indicators (1.1.1). Concerning SDG2 'Zero Hunger', the share of total expenditure spent on food per household per capita links to food security, while calories, protein and fat consumed per capita per household indicate the level of malnutrition. Dietary diversity, i.e., the share of different food groups in total food consumption, further quantifies SDG2. Food groups from Kennedy et al. [54],[5] here slightly adopted, allow to calculate the Shannon Index both for the income spent on these food groups and the calories derived from their consumption. Further, we implement as indicators for SDG7 'Affordable and Clean Energy' the households' budget share spend on energy and electricity. To address equality issues, we apply the SDG10 'Reduced Inequalities' indicator (10.1.1) "Growth rates of household expenditure or income per capita among the bottom 40 per cent of the population and the total population". The Palma and Gini index are calculated from the model results, as well as the share of the population living below 50 % of the national median income (listed as indicator 10.2.1). Regarding SDG5 'Gender Equality', the gender labor price gap and the share of female versus male labor per sector serve as indicators. For SDG6 'Clean Water and Sanitation', the water use per total output of agricultural production links to the target of increased water use efficiency. The nutrient information also allows to calculate the share of total calories used as input for energy production linked to SDG7. Addressing SDG11 'Sustainable Cities and Communities', the "ratio of land consumption rate to population growth rate" (UN indicator 11.3.1) is calculated. From the differentiation of open catch and aquaculture production, we finally calculate the share of fish demand derived from open catch for SDG14 'Live below Water'. Solely, SDG4 'Quality Education' and SDG16 'Peace, Justice and Strong Institutions' could not be quantified.

2.5. Scenario definition until 2050

The baselines for SSP1, SSP2, and SSP3 incorporate the projections of demographics and GDP, educational attainment, and the urbanization rate by Riahi et al. [10], and consider matching crop yield projections from technological progress by FAO [24]. Furthermore, in line with the underlying narratives, we add own assumptions for each SSP on meat consumption as well as on CO_2

[4] With the pollutants being Ammonia (NH3), Sulfur dioxide (SO2), Nitrogen oxides (NOx) and Particulate matter 2.5.

[5] We differentiate 11 food groups adopted to our sector differentiation, namely cereals; roots and tubers; legumes, nuts and seeds; other vegetables; fruits; meat; raw milk and dairy; fish; Veg. oils and cakes; sugar and rest.

Table 1
SDGs grouped following the 'wedding cake' scheme as presented graphically in Folke et al. [55].

SDG17: 'Partnership for the Goals'		
Biosphere	Society	Economy
SDG6: 'Clean Water and Sanitation' SDG13: 'Climate Action' SDG14: 'Live below Water' SDG15: 'Life on Land'	SDG1: 'No Poverty' SDG2: 'Zero Hunger' SDG3: 'Good Health and Well-being' SDG4: 'Quality Education' SDG5: 'Gender Equality' SDG7: 'Affordable and Clean Energy' SDG11: 'Sustainable Cities and Communities' SDG16: 'Peace, Justice and Strong Institutions'	SDG8: 'Decent Work and Economic Growth' SDG9: 'Industry, Innovation and Infrastructure' SDG10: 'Reduced Inequality' SDG12: 'Sustainable Consumption and Production'

prices and related energy-saving technical progress (see Table A.4 for detail). Given the sustainability narrative of SSP1, CO_2 price assumptions and percentage meat consumption reduction are higher than in SSP2 as the business-as-usual scenario. Our SSP3 baseline does not comprise changes compared to the 2014 benchmark for these exogenous drivers but considers increases in tariffs (except for intra-EU trade) and a preference shift towards domestic production, reflecting the 'regional rivalry' character of SSP3. To capture the first order effect of these differences in baseline developments, we refrain from including any redistribution policies in the three baselines. The given projections and these assumptions drive the baselines in CGEBox at the full level of the final database in bi-yearly steps from 2014 until 2050. These model outcomes allow us to calculate the 68 indicators which assess how SDG achievement develop until 2030 and 2050.

3. Results

This section is structured along the so-called SDG 'wedding cake' [55], which groups the SDGs into the economy, society, and biosphere-related goals, with SDG17 being described here in the 'economy' subsection, see Table 1. SDG indicators outcomes are presented under the assumptions of SSP1, SSP2 and SSP3, and where available, compared to target values or ranges in 2030 and 2050 from the UN [50] and other literature [49,52]. Results for 2030 can be found in Figure B.1-B.3, target values applied are listed in Table A.3. Result graphics show an improvement in an indicator always as green, irrespective of whether this implies a reduction (as for emission) or an increase (as for income) in the indicator value, shown by the two scales of the color bar. All indicators are additionally marked with an arrow indicating the desired direction. If indicator outcomes fall outside the color range of the heatmaps, values are shown as annotations, i.e. as numbers in the respective cell.

3.1. Biosphere results

Fig. 4 maps the relative change from the base year 2014 to2050 for biosphere-related indicators per study country and SSP. They show similar trends across the three SPPs, but of different magnitudes. Regarding SDG6 'Clean Water and Sanitation', increases in water demand for irrigation in 2050 are projected for all countries and SSPs, driven by growing food production. However, as factor productivity improves, less water is generally needed per agricultural output over time, implying a positive development towards Target 6.4, addressing water use efficiency in all sectors.

Strong output expansion in all SSPs and countries translates into higher total and per capita GHG emissions associated with SDG13, 'Climate Action'. SSP1 results in the lowest increases, with substantial deteriorations only observed for the five African countries. In the other two SSPs, most countries' total GHG emissions increase strongly. Exemptions exist, in Nicaragua where emissions decrease most per capita in SSP3. The GHG emission intensity per unit of GDP tends to decrease, with only Nigeria (SSP2 and SSP3) and Kenya (SSP3) showing increasing intensities. Likewise, lower CO_2 emissions linked to fossil fuel exports per capita are found for most countries, except for SSP2, however they missing the target value of zero set by Sachs et al. [52] in 2050. The medium-term prospects are even bleaker, as in 2030 some countries show deteriorations in all three SSPs (Figure B.1). The strong increase in total GHG emissions stands in contrast to current ambitions to limit climate change and overshadows improvements on a per capita or GDP basis.

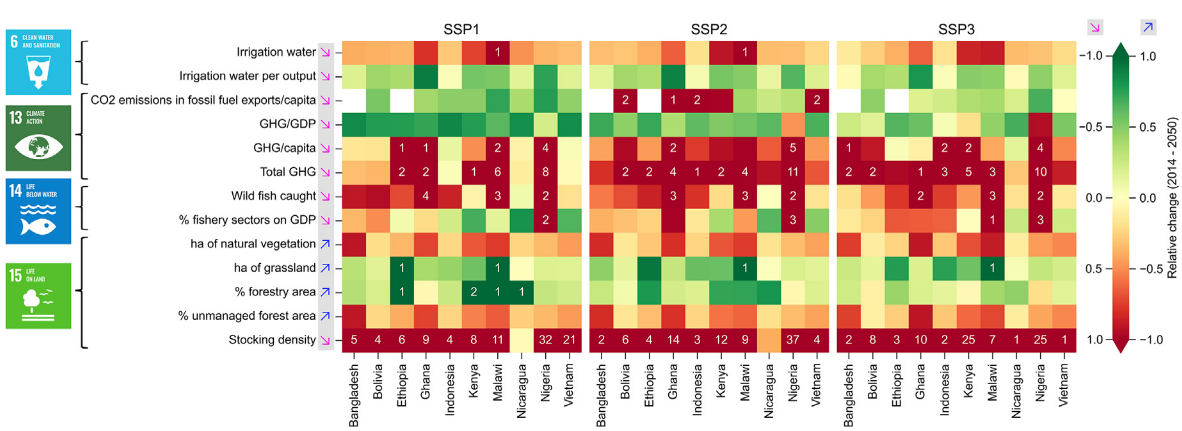

Fig. 4. Heatmap of Sustainable Development Goal indicators quantified in the biosphere layer in terms of their change until 2050. Indicators are abbreviated for better readability; complete full information can be found in Table A.3 in the annex. The color bar is fixed to values between 1 and -1; exceeding values are shown as numbers in the respective cell. All indicators show improvements as green and regressions as red, while the pink and blue arrows indicate the desired direction. Source: model results.

The two indicators linked to SDG14: 'Live below Water' generally worsen. Especially, for three African countries, namely Ghana, Malawi, and Nigeria wild fish catch keeps on expanding strongly until 2030 and 2050, which would hamper the targeted reduction to prevent overfishing. Solely Nicaragua in SSP1 and SSP2 shows the desired trend of reduced open catch. Surprisingly, despite the assumed preference shift away from fish and meat consumption in SSP1, it does not show the lowest levels of open catch. The reason is that solid income elasticities for fish and meat dominate over the preference shifts, as SSP1 projects the smallest population in tandem with the highest GDP growth for most countries. However, the lowest share of fishery sectors on GDP over time is found under SSP1 assumptions for most countries, with some countries even reducing the share, as other economic sectors grow stronger.

Similarly, adverse developments for indicators associated with SDG15 'Life on Land' emerge. While directions are similar among SSPs, changes differ in magnitude mainly for forestry shares and stocking densities. Total hectares of natural vegetation show downwards trends in all countries and SSPs. Substantial percentage reductions are observed predominantly in Bangladesh, Ghana, and Malawi, also due to their low initial area. Conversion of natural land is funneled by the increased food and feed demand of a growing and richer world population. It is mainly observed in the five African countries where population growth is much higher than in the other countries. To meet rising meat demand in all countries and SSPs, grasslands expand and are managed more intensively as seen from higher stocking densities, rendering a positive contribution of these areas to biodiversity conservation unlikely. The share of unmanaged forest as part of natural vegetation decreases while managed forestry mainly expands in all SSPs (Indicator 15.1.1).

3.2. Society results

As seen from the first line of Fig. 5, the macro projections assume growing average incomes per capita for all regions, especially in SSP1. To assess if this improves SDG1 'No Poverty', the shares of households living on less than 1.9$ per day per capita and less than 3.2$ per day per capita are quantified. In SSP1, we project the best progress. All countries except Malawi reduce the population share below the poverty line of 1.9$ by more than 90 % to (almost) zero by 2050, reaching the goal to eradicate extreme poverty (Target 1.1), however, mostly not yet in the target year 2030. Solely Malawi and Ethiopia do not reach zero households living below 3.2$ per day per capita by 2050 under SSP1. In SSP2, more countries miss the targets, with meager improvements in poverty shares for the three LDCs, while SSP3 generally leads to the highest shares of poor, with only two countries (Bolivia and Indonesia) achieving the target in 2050, however, not yet in 2030.

Total governmental expenditure on essential services (including the health, security and education sectors) rises over time, while their budget shares remain constant in all SSPs, except for minor improvements observed in Vietnam and Kenya. However, in 2014, these sectors already encompass the major share of the government expenditure in all countries, indicating that the UN target for SDG1 to "ensure significant mobilization of resources" for these essential services would be met by 2030 and 2050. Thus, in terms of SDG1 we see a clear positive trend until 2050 in all SSPs.

Trends of indicators related to SDG2 'Zero Hunger' are more ambiguous. Higher food prices, except for Nigeria and Vietnam in SSP2, reflect strong demand growth per capita in tandem with limited land resources. Nevertheless, food budget shares decline primarily due to the higher income per capita, especially in SSP1. In terms of eradicating hunger, we observe the desired increase in food consumption for almost all income quantiles in the distributional graphs (see Figure B.4). In general, SSP1 results in the highest consumption per household with the lowest budget shares for food, while SSP2 and SSP3 lag. The graph also indicates that the inequality of food consumption is simulated to increase. This is especially found for some outliers in the upper values in SSP1 for the majority of the countries. Figure B.5 showing the distribution of the budget shares indicates mostly higher equality. Regarding food security, advances are projected since more nutrients are consumed per capita in all countries, except for slight decreases in calories intake in Bangladesh and Ghana in SSP3. By 2030, calories intake is higher on average in all countries, compared to 2014, developing towards eradicating undernourishment. At household level, the distributional graphs (Figure B.6-B.8) show that the scenarios develop similarly regarding the rising nutrient intake, with SSP3 showing the lowest nutrient uptake in most countries and some strong outliers in the upper right end of the distribution. For some countries, we observe lower calorie intake in the left end of the distribution than in 2014, especially in SSP3, indicating a shift towards less calorie-intensive food consumption. In contrast, average expenditure-weighted food diversity is generally lower in 2050 in all SSPs, with SSP1 projecting the smallest shares for seven countries. Thus, households distribute food expenditure more unequally, focusing their income on fewer food groups. The related distributional graphs (Figure B.9) reveal that food diversity values mostly become more equal and that, in six countries, parts of the households still diversify food consumption in terms of expenditure over time. Regarding calorie-weighted food groups most countries diversify consumption, with Bolivia showing a decline. Again, the distributional graphs (Figure B.10) suggest higher equality is achieved over time, particularly in SSP1. As an additional aspect of food security, the share of imported cereals on total cereal demand is assessed. Most countries become more dependent on imports in all SSPs thus more vulnerable to trade shocks. Under SDG2 'Zero hunger', also goals for agricultural productivity are set, which show improvements in all SSPs, as depicted in Fig. 5. However, Target 2.3, to double the average productivity of food producers by 2030, is met by Nigeria for the aggregate 'export crops' and Bolivia for 'other crops' only in SSP1 (Figure B.2). By 2050, more countries reach the target for other crop groups as well, in particular in SSP1.

Air pollution related to domestic and imported products strongly increases over time. Of the air pollutants mapped in Fig. 5, the strongest deteriorations are projected for Ethiopia, Kenya, and Malawi, under SSP1. While for the other countries (except for Ghana), it generally rises least in SSP1. Likewise, the indicators of human health hazards (results for Ammonia, Sulfur dioxide, Nitrogen oxides, and particulate matter 2.5 can be found in Figure B.11) develop negatively, compared to the base year for all countries and SSPs, indicating a development away from achieving SDG3 'Good Health and Well-being'.

The gender wage gap, associated with gender equality under SDG5 'Gender Equality', shrinks until 2050 for the skilled labor category, except for Nicaragua, Malawi, and Bangladesh in SSP3, meaning that wages of female workers increase more vital towards 2050. This reflects that male skilled labor, owing to higher years of schooling, is growing stronger. In terms of the unskilled labor, the projections show instead a higher gender wage gap for the majority of the countries in all three SSPs. The ratio between female and male workers decreases over time because the share of the male population with no education decreases faster until 2050, thus, more male labor generally is available over time.

Energy gets more affordable over time, which relates to SDG7 'Affordable and Clean Energy', with only four countries in SSP3 projecting higher prices by 2050. Nevertheless, half of the average households spend a higher budget share on energy over time,

Fig. 5. Heatmap of Sustainable Development Goal indicators quantified in the society layer in terms of the relative change to 2050. Indicators are listed in a brief form, for better readability, full information can be found in Table A.3 in the annex. The color bar is fixed to values between 1 and -1, exceeding values are shown as numbers in the respective cell. All indicators show improvements as green and regressions as red, while the pink and blue arrow indicate the desired direction. Source: model results.

especially in SSP1. The distributional graphs (see Figure B.12) show more similar budget shares across the household percentiles compared to 2014. The energy budget share is still less relevant than the food budget share for all households. From a sustainability perspective, energy sourcing is of great relevance. While shares of renewables in the energy mix should increase (Target 7.2), the opposite is found for SSP1 where the share of electricity from renewables in total electricity consumption shrinks and more is produced from fossil fuels (Fig. 5). This is also primarily found in SSP2. In contrast, in SSP3, developments are (mostly) in line with the target. However, Ethiopia, as the sole country, reaches the optimal value listed in Sachs et al. [52] with a share above 51 % (but here it is calculated for total electricity, not total energy).

Similar trends among the SSPs are observed for the share of fossil fuels in total energy demand in the three scenarios. It might be seen as positive that a larger share of total biomass produced tends to flow into the energy sector over time. In SSP1, despite this trend, a smaller proportion of the total calories produced flow into the energy sector in Indonesia and Vietnam, while Bolivia is projected to expand the share. In contrast, in SSP3, for all countries, stronger competition between food and energy production is projected in 2050, while in SSP2 the calorie share used in the energy sector declines in Indonesia. For most countries and SSP1, a higher share of electricity and energy is produced domestically, indicating less dependency on energy imports which is interpreted as a positive development towards energy self-sufficiency. SSP1 is generally the least energy-intensive scenario of all three SSPs, with the lowest mega tons of oil equivalent per real GDP. This reflects the assumption of strongly increasing carbon taxes over time which provoked additional energy savings in SSP1. In this scenario and SSP3, the target proposed by ICSU and ISSC [1] of improving energy intensity of GDP by at least 2.9 % annually would be met by four countries over the 36 years.

Urban area expands over time in all countries and SSPs, with some countries doubling urban area until 2050 (see Fig. 5) due to the projected exogenous GDP and population growth, and the rising share of urban population projected for all SSPs. However, the urban area grows generally less than overall population growth (Indicator 11.3.1, SDG11 'Sustainable Cities and Communities'), both until 2030 and 2050, representing higher population densities in cities. In particular, under SSP1 assumptions, since here, none of the countries shows a contra-trend.

3.3. Economy results

Fig. 6 summarizes the SDG indicators linked to the economic layer of the 'wedding cake'. Following the exogenous SSP projections, real GDP per capita and per employed person rise over time, indicating progress towards SDG8 'Decent Work and Economic Growth'. However, Target 8.1 states that in LDCs real GDP per capita should grow by at least 7 % annually through 2030, which none of the SSPs would accomplish, although SSP1 is closest to the target. GDP growth is accompanied by at least half of the countries in all SSPs by a decreasing share of total agricultural labor, which is associated with economic development and depicts technological progress. Furthermore, decoupling GHG emissions growth (included in Target 8.4) from economic growth in 2050 for six countries in SSP1 and SSP2 adds a further positive dimension to this development. Nevertheless, for the others, we observe substantial intensification in terms of GHG emissions. In SSP3, none of the countries decouples economic growth from emissions, which generally matches the results of SDG13 in Subchapter 3.1.

The targets of SDG9 ('Industry, Innovation and Infrastructure') indicators "manufacturing value added as a proportion of real GDP and per capita" and "manufacturing employment as a proportion of total employment", are to increase the shares substantially and to double them in LDCs by 2030. In all three baselines, both the shares of manufacturing on GDP and total employment regress from these targets over time in all countries. Since, in general, the service sectors, the grains and crops sectors, and the meat and livestock sectors contribute, on average, larger shares to the total value-added. In turn, the manufacturing value added per capita shows a positive trend in all countries and SSPs (most in SSP1) up to 2050, reaching the target for all three LDCs in SSP1 and SSP2 albeit not by 2030.

We observe from Fig. 6 that countries mostly become more equal over time (focused on SDG10: 'Reduced Equality'). For example, a lower share of the people lives below 50 % of the median income in 2050 for all countries but Nigeria in all SSPs, both until 2030 and 2050, with Bolivia improving only until 2050. A strong outlier is Ghana in SSP1 and 2050 only. Given this strong regression in Ghana in SSP1, here the Palma Index (i.e., the share of income owned by the bottom 40 % relative to the one owned by the upper 10 %) also worsens over time until 2050, while in the other two SSPs a rising Palma index is projected. Improvements are generally highest in SSP3 per country, with the lowest changes being projected for SSP1. Until 2030, considerably more countries show a higher Palma Index. Despite the improvements observed in most countries until 2050, none reaches the target value set by Sachs et al. [52] of a Palma index of 0.9. Similarly, the Gini coefficient also improves over time for most countries, with none reaching the optimal value for this indicator set by Sachs et al. [52] to 27.5 neither in 2030 nor in 2050. In fact, under some SSPs in Bolivia, Indonesia and Nigeria, the Gini index even worsens until 2050. Similar countries already develop away from the target until 2030 (Figure B.3). Target 10.1 addresses household expenditure growth rates and aims to achieve higher growth for the bottom 40 % of the population compared to the national average through 2030, which in all three scenarios, shows positive trends for five countries until 2050. Nevertheless, some countries with a reduction in this ratio still realize faster expenditure growth of the bottom 40 % of the population by 2050. Consequently, several countries achieve this target, while until 2030 this is the case for fewer countries only. In SSP3, the indicator outcome is worse with only five countries succeeding. In summary, SSP2 and SSP3 generally show the lowest Gini and Palma values, which contrasts with higher inequality in terms of expenditure growth also observed in both SSPs. Thus, the strongest increase in per capita income under SSP1 projections would worsen inequality. This is also reflected by a decline in the labor income share on GDP over time in all SSPs and countries, especially in SSP2 and SSP1, which disadvantages households mainly depending on labor income. In contrast, factor returns to land grow substantially in all countries (particularly in SSP1) to the benefit of households with larger property rights to land. The related income distribution graphs are in the annex (Figure B.13).

Production increases over time are found in all SSPs, however, at different magnitudes, and increase the domestic extraction of natural resources, linked to SDG12 'Responsible Consumption and Production', also at a per capita level. Thus, the so-called material footprints widen, especially in SSP1, except for Ghana which shows a per capita reduction in SSP1. However, GDP creation relies less on the exploitation of natural resources for most countries. As no quantitative target exists for SDG12, the improvement cannot be further evaluated.

This overall production increase comes with higher global

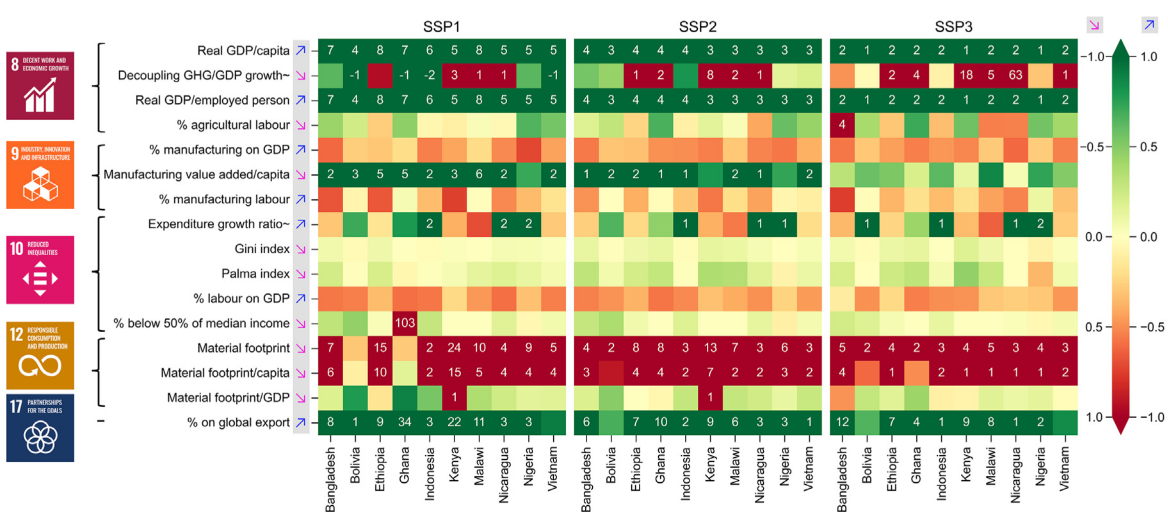

Fig. 6. Heatmaps of Sustainable Development Goal indicators quantified in the economy layer in terms of the relative change to 2050. Indicators are abbreviated for better readability; complete full information can be found in Table A.3 in the annex. The color bar is fixed to values between 1 and -1; exceeding values are shown as numbers in the respective cell. All indicators show improvements as green and regressions as red, while the pink and blue arrows indicate the desired direction. Source: model results.

market integration for the focus countries, linked to Target 17.11 of SDG17 'Partnership for the Goals', which aims to double the LDCs' share on global exports and to significantly increase developing countries' share by 2020. All countries in all SSPs expand their export shares with most countries even more than doubling it by 2050. Except for Bangladesh, SSP1 has the highest trade participation for the countries. Already, by 2030, the three LDCs (Bangladesh, Ethiopia and Malawi) double their export shares (see Figure B.1), indicating that these countries could achieve the goal (at least) by 2030 under the baseline assumptions.

3.4. Aggregated results

The aggregated summary graph (Fig. 7) shows the unweighted average effect per SDG and SSP. It confirms again that general trends for the SDGs are similar across SSPs. Nevertheless, when findings for each SSP are ranked by the number of countries that show the highest relative change in the underlying indicators per SDG compared to the other SSPs, differences in magnitude and sometimes also in direction become visible. SSP1 tends to have the highest number of countries with the highest changes over time compared to the other SSPs, with only three cases of the largest adverse developments. This implies that no SSP outperforms the other SSP in all SDGs without further weighting.

Summarizing the detailed description in Subchapter 3.1–3.3, we observe predominantly positive developments for several SDGs under the Economy and the Society layer, with negative trade-offs to the Biosphere layer where either all indicators or some show adverse developments. Positive trends associated with SDG6 'Clean Water and Sanitation' and SDG13 'Climate Action' in the Biosphere layer relate to per capita or GDP indicators, while total demand for irrigation water and total GHG emissions continue to rise.

Trade-offs are also found inside the Economy and the Society layer, based on unsustainable energy generation (SDG7, Society Layer), stronger air pollution (SDG3, Society Layer) and the increasing material footprint (SDG12, Economy Layer). However, SDG8, SDG10, and SDG17, relating to economy, income equality, and trade integration in the Economic Layer, show a synergetic development funneled by economic growth. Similarly, primarily positive improvements for SDG1, SDG2, and SDG5, relating to reduced poverty, eradication of hunger and increases in gender equality in the Society Layer benefit from overall economic growth, and thus show synergies with positive trends for SDG8, SDG10, and SDG17 under the Economic Layer.

4. Discussion

The 68 indicators in the framework allow for a detailed assessment, depicting heterogeneity in response to the three pathways, both at country and household level. Regardless of the differences between the SSP scenarios, none of them is able to achieve the SDGs in unison by 2030 or 2050. While no clearly dominant scenario emerges here due to trade-offs between underlying model assumptions, we often find the best results projected under SSP1 assumptions. This fits to the results of previous studies, which find even most optimistic SSP1 scenarios to be not fully sustainable according to the SDGs by 2030 [13,49,56].

Generally, our projected SDG developments between the SSPs are similar, while they differ in magnitude and sometimes directions of trends depending on the layer of the 'wedding cake' and single SDGs or indicators. Confirming existing literature, in all SSPs, the prevalence of undernourishment or risk of hunger relating to SDG2 decreases [13,56]. With the microsimulation applied here, however, we observe partly lower calorie intake for the households that already consumed the lowest amount in 2014. Even if food consumption increases for all, trends still imply higher inequality in 2050. Philippidis et al. [12] also found average improved calorie availability, but our results differ from theirs in other aspects: for instance, we find manufacturing shares of employment to decrease against the desired development, while they determine increasing shares. Campagnolo et al. [11] and Philippidis et al. [12] also confirm the general improvements in social indicators found in the underlying study.

Addressing the three layers of the 'wedding cake', trade-offs within the SSPs emerge between Society and Economic SDGs, which improve towards or even reach the target, and adverse developments for the Biosphere layer. We thus confirm trade-offs between environmental and economic goals found in previous studies [11,12] and determine them for societal SDGs and the Biosphere [5]. The relevance of these trade-offs is underlined by the findings of Campagnolo et al. [11], as their composite indicator suggests that these conflicts could even reduce the overall sustainability at global level.

What interactions a study can highlight depends on the included indicators and SDGs [57]. While our developed indicator framework quantifies many indicators and SDG, beyond what previous CGE modelling approaches provide, it still lacks indicators for SDG4 and SDG16. Assumptions on SDG4 ('Quality Education') are currently taken as exogenous and drive the development of the labor force by skill level. Interlinkages between SDG4 and others are hence not endogenously modelled, while they have been analyzed previously using other methodologies [3,58]. Changes in education could be treated as endogenous in follow-up work, for instance, driven by the development of spending on education as in Roson [59], an approach partly already incorporated in the latest version of the CGEBox modelling framework. Endogenous indicators relating to SDG16 'Peace, Justice and Strong Institutions' are challenging, while its basal for the achievement of the SDGs [60]. Numerous synergies and trade-offs were found among SDGs, also supporting other literature, such as trade-offs among parts of the biosphere SDGs [12] or trade-offs for economic growth (SDG8), industry (SDG9), consumption and production (SDG12) and terrestrial resources (SDG15) with other SDGs [3].

For SDGs for which indicators are available in the framework, the CGE model cannot address all aspects. SDG14 'Life on Land' is quantified here only by assessing fish extractions from the sea and

Fig. 7. Simplified unweighted summary over indicators per Sustainable Development Goal in the three Shared Socioeconomic Pathways (SSP), grouped by the three layers Biosphere, Society, and Economy. Shared Socioeconomic Pathways are ranked by the numbers of countries with the largest relative change compared to the other Shared Socioeconomic Pathways. Green square = only/predominantly positive trends, red square = only/predominantly negative trends, divided squares = half of the indicators show positive/negative trend, darkest color = highest number of countries with strongest positive/negative change. Source: model results.

the economic importance of the fishery sectors, while other issues, such as lowering plastic exposure under Target 14.1 and reducing ocean acidification under Target 14.3, are not covered. Similarly, for SDG3 air pollution risks to human health are captured; however, other SDG3 targets, such as relating to maternal mortality (Target 3.1), or road injuries and deaths (Target 3.6), remain unexplored. Rather, demography and thus birth and death rates are exogenous and their development is thus not further described here in detail. SDG3 is highlighted to have synergetic relationships with many other SDGs and is therefore a strong determinant of development processes [61] which we could not show. Similarly, we find smaller intra-SDG8 'Decent Work and Economic Growth' trade-offs in contrast to Pradhan et al. [3] since the indicators of 'Material Footprint' are double assigned in the UN Indicator framework (both to SDG8 and SDG12) and were here only considered under SDG12. Nevertheless, we confirm intra-SDG trade-offs for SDG7 [3] since rising biomass use in the energy sectors under SDG7 'Clean Water and Sanitation' develop in tandem with increasing calorie shares flowing into these sectors. In addition, several indicators provided context for other indicators and allowed for further evaluation of the developments. For example, the undesired development of increasing irrigation water use (SDG6, 'Clear Water and Sanitation') is put into context as its increase is below production growth in sector using irrigation. In fact, exclusively positive trends in the depicted indicators were observed for 'No Poverty' (SDG1) and 'Partnership for the Goals' (SDG17) alone, underling the complexity of achieving sustainability both among and within SDG.

Most omitted indicators in this study are 'non-marketed', reflecting the limits of economic modelling. Here, linkages with other models or incorporating equations capturing relationships of non-marketed indicators to economic variables could help [62], as often done in Integrated Assessment Models. However, as Zimm et al. [56] discussed, comparing different SDG indicator frameworks of models that exploit their respective strengths might be more fruitful than continuously increasing the model boundaries.

The discussion of the 68 indicators covered in the study underlines the challenges of analyzing and presenting findings of detailed indicator frameworks. Composite indicator development, such as in Campagnolo et al. [11], could condense the information of our framework but implies a loss of information and asks for sensitive decisions on indicator normalization and their weighting [63]. Especially synergies and trade-offs among different SDGs, indicators and households remain visible when the full set of indicators is used. As Philippidis et al. [12], we refrain therefore from weighting indicators, SDGs or layers. Finding a comprehensive set of SDG indictors that is both manageable and detailed enough is thus crucial [56].

The graphs showing distributions based on the micro-simulation provide further insights beyond average effects. They reveal that most indicators grow unevenly among the population, leading to higher inequality (e.g., income per capita), while others converge (e.g., energy budget shares). For some indicators, parts of the population even develop in opposite directions (such as increases in food diversity in terms of expenditure against the average negative trend), rendering such an assessment crucial for sustainability analysis. Findings on distributional impacts are not reported in the existing literature and underline the study's novelty. Regarding SDG10 'Reduced Inequality', generally higher equality is projected for all indicators under all SSPs. Compared to the empirical analysis of the Gini index for the SSPs [64], we did not always find the lowest Gini values under SSP1 assumptions due to the uneven increase in income among the population.

The described effects are generally similar for the ten countries, with some country-specific differences. As we focus here on low- and lower-middle income countries, which are found to have the highest trade-offs and distances to targets [6,11,48,65], an assessment of middle- and high-income countries could reveal whether our methodological approach also determines a lower sustainability gap for the latter two country categories.

Our results suggest that many SDGs would not be reached in 2030 and 2050 in the assessed countries under the given SSP-specific exogenous projections of economic growth and demography, complemented by own assumptions. Thus, additional societal action is needed to meet the SDGs as the projected economic growth and slowing population increases are insufficient. Trade-offs and synergies within and among SDGs are transformative processes that can switch over time due to changing conditions [50,65]. Changing governance is essential for SDG achievement [2,58], as improving institutions and other dimensions of governance can boost SDG progress and determine positive or negative linkages between goals and targets. Given the trade-offs with the Biosphere layer and resource extractions, stronger food consumption shifts and lower household waste rates [66] could play an essential role in achieving economic growth that does not compromise environmental boundaries, as do higher sustainability in production techniques through higher circularity in the bioeconomy [67,68]. Also, further increasing land productivity could alleviate pressures from population growth [12]. Policies can foster these developments when taking current lock-in relation among SDGs into account [2,3] by targeted subsidization or taxation and support to develop more sustainable technologies, also taking the social dimension of political change into account [69]. However, Biermann et al. [70] found that, to date, the impact of SDGs on profound changes in policies is limited and that they mainly have changed political institutions and raised discussions. The required investments toward achieving the SDGs are probably large for some SDGs [71], such that finding and exploiting synergies between SDGs is crucial [72].

The indicator framework can be directly applied to counterfactual scenarios against any of the developed (or other) baselines, for instance, to analyze actions that tackle the determined trade-offs. All indicators used and discussed are linked to endogenous variables via the model results and thus change also in counterfactual scenarios. In this regard, the only exception is SDG8 'Decent Work and Economic Growth' which mainly depicts GDP developments exogenously provided by the SSP database during baseline generation. This changes in counterfactual runs where GDP turns endogenous. Counterfactuals could also assess options for global burden sharing, where especially high-income countries contribute to reduced resource extractions and lower emissions.

A drawback of the methodological approach is the missing feedback of induced environmental impacts on economic performance. As climate change damages can exacerbate conflicting targets and destroy or weaken synergies [3], they could be integrated into counterfactual runs to depict sector-differentiated impacts and results on the SDG indicator framework. For instance, climate change induced yield changes led to quite differentiated impacts for household aggregates with the same model as used here [45]. Additional channels of damages are, for instance, found in Ref. [73].

Assuming fixed emission factors, our study might overestimate the link between output increases and emissions. While the model considers different power generation technologies that reduce emissions per unit of electricity produced, such differentiation is missing for other sectors, such as transport, where low-emission technologies exist today. Moreover, future technologies might allow to reduce emission factors. Equally, while we consider future carbon tax increases that generate incentives to reduce GHG emissions, such an instrument is missing for health-relevant air emissions.

Using a recursive dynamic CGE model allows the depiction of long-term structural change. However, it requires exogenously projected changes in income and demography for baseline construction, which are surrounded by uncertainties [74]. This is partially addressed by applying three different sets of projections. Inevitably, however, parameterization and other decisions in setting up the model introduce further uncertainties. Following the categories of Allen et al. [75] specifying models suitable for SDG analysis, CGEBox fulfils several of their prerequisites. As a simulation model, it allows to generate long-term scenarios up to 2030 or 2050 at a flexible geographical coverage, including single countries (or even the option to disaggregate to NUTS2-level) and their global feedbacks building on a highly disaggregated database. They also found social dimensions to be least addressed by models, which find the largest coverage compared to the other two layers in our framework.

The extension of the CGE with a post-model micro-simulation allows for a rich assessment of distributional effects at the household level. Yet, the methodology also comes with some weaknesses. The model addresses only two of three channels of adjustment proposed by van Ruijven et al. [43]: heterogeneous factor endowments, heterogeneous preferences and savings. Unemployment or leisure categories for labor or different labor markets as the third channel are not captured. However, wages are differentiated by the disaggregated labor categories, namely skilled and unskilled labor, as well as gender categories. Furthermore, the average of the micro-simulation results does not always perfectly resemble the model average due to the nonlinearity of the demand function. As a result, for a few indicators, both averages showed opposite trends over time. For consistency, therefore, all results for average indicators, for which household-level results exists, are taken from the micro-simulation. The heatmap with the model averages can be found in Figure B.14-B.16 for comparison. Lastly, the quality of the micro-simulation results strongly relies on the underlying data. The FAO [14] data set mainly focuses on farming households, and in Ethiopia, predominantly rural households are represented due to missing data from surveys. Repeating the assessment, thus, with household data with other focus could provide further insights, also how the already now differentiated income growth, being most pronounced for large land lords, would evolve and affect equality.

Previous work that used similar micro-macro linkage approaches with GTAP models applied these for other contexts. While the general idea is the same, the design and focus of the micro-simulations differs among these assessments. For example, compared to Bussolo et al. [76], and Laborde et al. [77], the update mechanisms for income per capita level applied at household-level reflect differences in data availability and methodological choices. While these two papers focus on a larger data set, assessing global income distribution, we selected here ten countries to assess the full set of SDG indicators. A key addition of our approach lies on the expenditure side, where we model explicitly a demand system for each household to better depict changes in the demand structure across countries at household level as relevant for several SDGs. Drawing on the employed MAIDADS demand system and the extended database, a special focus lies on depicting food consumption and related realistic nutrient intakes at household level as well as on differences in energy expenditures in the long run.

The SSP projections were published in 2017 [10], so that underlying data are by now almost a decade old. An update of the SSP data is currently in process and will reflect besides newer data the likely consequences of shocks such as the global COVID-19 crisis. These shocks probably imply less optimistic projections of economic growth, which shape many of the indicators discussed here. Moreover, we observe currently that advances towards SDG targets, for instance, regarding poverty or hunger reduction or health, have stalled or even been eroded by recent developments [78–81]. Furthermore, the pandemic entailed a decline in life expectancy for many countries [82]. Thus, repeating the assessment with the updated SSP and updated GTAP data could reveal new information on the sustainability issues of recent developments.

Beyond the SSPs, Sustainable Development Pathways are required to extend the narratives of SSPs to derive scenarios capable of reaching the SDGs. Not at least because even the most optimistic scenario of the SSPs does not reach all SDGs, it is clear that we need a set of projections and narratives that are more comprehensive than what is captured to study climate change scenarios. Soergel et al. [48] provide a first quantification of Sustainable Development Pathways that add different narratives to the set of SSP1 in an Integrated Assessment Model. Their study shows that the additional interventions enable improvements in different dimensions while sustainability gaps remain. Thus, the findings of the study at hand contribute to this field of research and highlight the need to incorporate distributional effects in narratives to analyze the required redistribution of wealth but also governance.

5. Conclusions

Economic modelling frameworks linked to further accounting, such as on emissions, land use or nutrition, can provide information on synergies and trade-offs between SDGs from policy changes and socioeconomic developments. However, most SDG-related CGE analysis have been based on aggregate household effects, missing distributional aspects, and using rather aggregated agri-food sectors. This limited the details in related SDG indicators. Therefore, this study extends existing SDG indicator frameworks for recursive dynamic CGE models by adding, among other things, distributional effects through a post-model micro-simulation linked to different SDGs and great detail for the agri-food sector. The framework is then applied to three different SSP baselines up to the year 2050 to provide an assessment for the years 2030 and 2050 for the different dimensions of sustainability, grouped by the three layers of the wedding cake (i.e., Economy, Biosphere, and Social). Drawing on 68 indicators, trade-offs both between and within SDGs can be determined. The combination of long-term CGE analysis and the sustainability indicator framework introduced in this study proofs beneficial for a multifaceted comparison of scenario outcomes. In particular, the integration of micro-simulation allows the quantification of indicators associated with distributional aspects that remain otherwise hidden behind average effects.

Of the three scenarios assessed here, none outperforms the others, preventing a clear ranking and emphasizing the complexity of sustainable development. None of the scenarios improve indicators fast enough to reach goals in their targeted timeframe (mostly by 2020 or 2030), and goals for many SDGs might not even be reached by 2050. Consequently, counterfactual analyses, incorporating policies that tackle remaining challenges and trade-offs, could help determine decisive action points. Our analysis found negative trends mainly in the Biosphere layer for resource extraction and emissions. Accordingly, policies and technologies should target a decoupling of economic growth from environmental pollution and exploitation of natural resources, for example, by providing sustainable energy resources that do not compromise food production. The results suggest the importance of incorporating distributional aspects in policy-making to initiate socially just transitions when solving the trade-offs. The indicator framework can hence serve as a toolbox to study specific effects of novel policies and socio-economic developments on SDG targets and beyond. Furthermore, the results of this study can be used for the further scenario development process of Sustainable Development Pathways.

Follow-up work could perform such counterfactual analysis. It might also add indicators for SDG4 'Quality Education' and SDG16 'Peace, Justice and Strong Institutions' and broaden the indicators coverage of some SDGs where currently only some dimensions are addressed. Moreover, climate change damages and technological progress linked to update of emissions factors could be integrated into such analysis.

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CRediT authorship contribution statement

Rienne Wilts: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Wolfgang Britz:** Writing – review & editing, Supervision, Software, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.glt.2024.06.004.

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