Supplementary Information for the article "A decentralized approach to integrate national and global food and land use modelling"

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1 Overview of the Scenathon reporting template

The Scenathon report template is an Excel file that needs to be filled for each country and region, each pathway and each iteration, before it is uploaded to the scenathon web platform and can be used to feed the global database.

Table S1: Information required at the national level for each five year time step between 2000 and 2050

Macro	Food consumption	Biodiversity	Land area& Land cover change	GHG	Water
• Population • GDP	• Targeted calorie intake (kcal/c/d) • Feasible calorie intake (kcal/c/d) • MDER (kcal/c/d) • Fat intake (g/c/d) • Protein intake (g/c/d)	• Share of land where LNPP[1] (%) • Forests in PA[2] (1000ha) • Other natural land in PA2 (1000ha) • Other land in PA2 (1000ha)	• Cropland (1000ha) • Pasture (1000ha) • Forest (1000ha) • New Forest (1000ha) • Urban and settlements (1000ha) • Other land (1000ha) • Forest loss (1000ha/5 years) • Forest gain (1000ha/5 years)	• CO_2, N_2O, CH_4 and total GHG from crops (Mt) • CO_2, N_2O, CH_4 and total GHG from livestock (Mt) • CO_2 from deforestation (Mt) • CO_2 emissions from other land use change (Mt/year) • CO_2 removals from passive natural vegetation regrowth on agricultural land abandonment (Mt/year) • CO_2 removals from active re-or afforestation (Mt/year) • CO_2 savings from fossil fuel substitution by biofuels (Mt)	• Green consumptive water use for crops (Mln m3) • Blue consumptive water use for crops (Mln m^3) • Grey consumptive water use for crops (Mln m^3)

[1] LNPP = Land where Natural Processes Predominate; [2] PA=Protected Areas.

Table S2: Information required at the national level, for each five year time step between 2000 and 2050, for each product

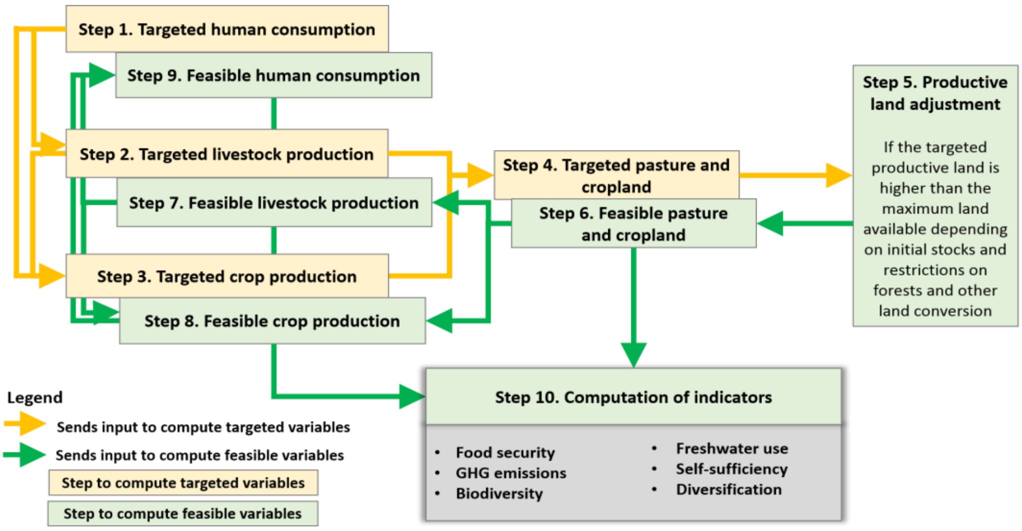
Trade	Demand	Production	Loss and waste	Nutrition
• Exports (1000t) • Imports (1000t)	• Food consumption (1000t) • Animal feed (1000t) • Input for bioenergy (1000t) • Input to other processing (1000t) • Non-food human consumption (1000t)	• Production (1000t) • Stock variation (1000t) • Harvested area (1000ha) • Planted area (1000ha) • Crop yield (t/ha) • Number of animals (1000TLU)	• Post-harvest losses (1000t) • Food waste (1000t)	• Calorie intake (kcal/c/d) • Protein intake (g/c/d) • Fat intake (g/c/d)

2 The FABLE Calculator: how does it work?

Text from this section is adapted from (Mosnier et al., 2020).

The principle of the FABLE Calculator is to define several steps of calculation where, except for the first step, all steps are dependent on one or several variable(s) that are computed in the previous steps. This is represented by the arrows in Figure S1. For instance, we first need to compute the targeted human consumption as this will be used to compute the targeted livestock production and the targeted crop production. The numbering of the calculation worksheets in the FABLE Calculator reflects the sequence of the calculation steps that is required, e.g., 1_calc_human_demand, 2_calc_livestock, 3_calc_crops, etc.

Figure S1: Sequence of the calculation steps in the FABLE Calculator



Source: Mosnier et al., 2020

By default, the FABLE Calculator has 16 parameters that can be modified through scenarios, each of which has between 2 to 17 possible alternative values (Figure S2). The user can select pre-defined scenarios or add new scenarios. There are, therefore, millions of possible combinations of scenarios that lead to different pathways. The FABLE Calculator's computation steps are automatically updated with the parameter values corresponding to the selected scenarios and the results are updated in a less than one minute.

Figure S2: Example of a pathway definition in the FABLE Calculator

Scenario on GDP	Scenario on Population	Scenario on Diet	Scenario on Food Waste Share	Scenario on Import Share	Scenario on Exports	Scenario on Livestock Productivity	Scenario on Crop Productivity
SSP2	SSP1	EATLancetAverage	Current	I2	E1	BAUGrowth	HighGrowth
Scenario on Agricultural Land Expansion	Scenario on Afforestation	Scenario on Trade Adjustment	Scenario on Population Activity	Scenario on Climate Change	Scenario on Protected Areas	Scenario on Post-Harvest Loss	Scenario on Biofuels
FreeExpansion	NoAffor	No	Middle	rcp6p0_hadgem2-es_n_GEPIC	NoChange	Reduced	OECD_AGLINK

Note: The parameters that can be changed through scenarios are listed in purple, the selected scenarios are in green.

The computation of the annual human demand for food and non-food human consumption is the first step of the FABLE Calculator and has three components: food, biofuels, and other non-food consumption. Food and non-food demand per product per capita for the historical years is computed based on the commodity balance of the FAOSTAT. The evolution of food consumption per capita depends on the scenario on the evolution of the average kilocalorie consumption per food group per capita per time step. By-default, the other non-food demand per capita is fixed at the 2010 level but this can easily be changed by the user. The final demand per capita per year per product is computed as the sum of non-food consumption per capita plus food consumption per capita augmented by the share of consumption which is wasted at retail and household level. Finally, the total demand is computed by multiplying average demand per capita by total population plus the demand to produce biofuels. Targeted production is computed as the human consumption including waste, increased by the share of the production which is lost after harvests. For crops, demand for animal feed is added to human consumption. Imports depend on computed internal demand and the assumption on the share of this consumption that needs to be imported. Exports are exogenously driven.

Livestock production systems, input, output, and emission factors are taken from Herrero et al. (2013). We differentiate between *dairy* cattle and *other* cattle, *dairy* sheep and goats and *other* sheep and goats, *laying hens*, *chicken broilers*, and *poultry mixed*, and there is only one production system for pigs. The number of animals is computed as the projected domestic production level, multiplied by the contribution of each animal type and production system in the total production by animal product in 2000 as reported by Herrero et al. (2013). Finally, the production per animal type and production system is divided by the average productivity per Tropical Livestock Unit (TLU). Animal productivity depends on the level in the year 2000 and the productivity shifter which is calibrated using FAOSTAT until 2010 and the selected animal productivity scenario after 2010. We use the feed requirements per TLU computed by Herrero et al. (2013) for corn, wheat, sorghum, rice, barley, other cereals, and soybean, for each animal type and production system. The current assumption is that these feed requirements are proportionally adjusted with changes in animal productivity. This assumption might lead to an overestimation of the increase in animal feed demand over time when productivity gains are high while improved breeding and animal health could also play an important role in reality. We then divide the number of ruminants by the average ruminant density per hectare to obtain the targeted pasture area. By default, historical ruminant density is computed using FAOSTAT's ruminant numbers divided by the grassland area for 2000, 2005, and 2010 and kept constant at 2010 levels over 2015-2050 but an optional update package for implementing alternative scenarios on the evolution of the ruminant density is available.

For crops, an additional demand comes from processing. This is related to the human and feed demand of processed commodities such as vegetable oils or refined sugar. Harvested area is computed as the total targeted production divided by the average annual yield in ton per hectare. This productivity is taken from FAOSTAT for 2000, 2005, and 2010 and depends on the productivity scenario which is selected for the period 2015-2050. In some countries, several harvests are possible during the year resulting in lower cropland area than the total harvested area per year. The planted area is obtained by dividing the harvested area by the harvesting coefficient. We compute the average harvesting coefficient as the sum of all harvested area per crop divided by the total cropland area using historical FAO data. If the total harvested area is lower than cropland area, the harvesting coefficient is set to 1. This can be explained by missing crops in the FAO database but also because arable land includes "temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years)" (FAOSTAT, 2020), which are not yet explicitly considered in the FABLE Calculator. The difference is allocated to "other crops" and this area is set constant at 2000 levels for the whole period of simulation.

We represent 6 land cover types in the FABLE Calculator: pasture, cropland, urban area, forest, new forest, and other natural land. The initial other natural land category in 2000 is computed as the difference between the total land area of the country/region minus pasture used for livestock, cropland, forest, and urban areas. It can thus include quite heterogeneous land types and degree of wilderness. Computed changes in area of pasture, cropland, urban, and new forest induce changes in forest and other natural land as the total land area cannot expand. For each land cover type, we first compute the initial area at the beginning of the period using 2000 historical data as the base year and the feasible computed area at the end of the previous period for the other time steps. In case the targeted expansion is higher than the maximum expansion (because of expansion constraints from scenarios or land scarcity), the maximum value is used to compute the feasible productive land area. The adjustment factor for pasture and cropland is computed as the maximum feasible pasture area over the targeted pasture area and the maximum feasible cropland area over the targeted cropland area. Urban and afforested area are excluded from the adjustment.

Any discrepancy between targeted and feasible pasture area and/or cropland area is channelled back through the causality chain up to the consumption level (Figure S1). The feed demand for all crops and processed products from crops is multiplied by the cropland adjustment ratio and ruminant herd number is recomputed based on the feasible pasture area and feed. For crops, targeted planted area for all the is reduced proportionally to the total cropland reduction. Feasible production is computed as the feasible planted area by crop times the average number of harvests per year times the productivity per hectare. Feasible feed is taken from the previous step. Feasible final human demand, feasible exports, and feasible processed demand are adjusted to compensate for the remaining production reduction so that market balance is ensured. If the scenario *Fixed trade* is selected, exports are not adjusted proportionally to the production reduction resulting from the land constraint and the reduction is distributed to the internal demand only. In a final step, the Calculator computes key indicators using as an input the feasible variables computed during the last steps.

3 GHG coverage in the FABLE Calculator and in MAgPIE

We cover emissions from agriculture, land use change, and carbon sequestration from passive natural vegetation regrowth on abandoned agricultural land and active afforestation. Computed CO_2 removals are substantially lower in our calculations compared to official GHG inventories because CO_2 accounting for the categories “forest land remaining forest”, “grassland remaining grassland”, and “woody products” are not represented in our modeling framework (or only partially represented in MAgPIE) (Table S). Moreover, within the represented categories some products and processes are not accounted for. For example, our pathways only consider deforestation that occurs to produce the commodities included in the models and ignores deforestation due to land speculation or driven by products not covered in the FAO statistics. Finally, the FABLE Calculator does not account for all carbon pools: only emissions from biomass change are included, leaving aside emissions/sequestration from changes in dead organic matter and soil carbon.

Table S3 - Coverage of the UNFCCC categories in the FABLE Calculator and MAgPIE

GHG reporting category	Coverage[1]	FABLE Calculator coverage	MAgPIE coverage
Agriculture			
Enteric fermentation	CH_4 production from herbivores during the digestive process. Animal categories include Cattle, Buffalo, Sheep, Goats, Camels and Lamas, Horses, Mules and Asses, Swine, Poultry, and Other.	CH_4 emissions from cattle (dairy and non-dairy), sheep, and goats	Included for all FAO ruminant livestock categories
Manure management	CH_4 and N_2O produced from the decomposition of manure under low oxygen or anaerobic conditions (i.e. often when large numbers of animals are managed in a confined area).	CH_4 and N_2O emissions from cattle (dairy and non-dairy), sheep, goats, poultry, and swine	Included for all ruminants (dairy and non-dairy), poultry, and swine
Rice cultivation	CH_4 emissions from anaerobic decomposition of organic material in flooded rice fields.	CH_4 emissions	Included
Agricultural soils	CH4 and N2O emissions and removals from agricultural soil/land and Non-methane volatile organic compounds (NMVOCs) from crops (includes the biological nitrogen fixation, and return of crop residues to the field or to animal production)	N_2O emissions from synthetic fertilizers and return of crop residues to the field	Emissions from organic and inorganic fertilizers, return of crop residues to the field and to the animals, nitrogen fixation, and atmospheric deposition
Other	Field burning of agricultural residues, liming, urea application, other carbon-containing fertilizers, other. Burning of savannas is not included in the inventory total.	CO_2, CH_4, and N_2O emissions from energy use in agriculture and direct emission savings due to the replacement of fuel with biofuels	Field burning of agricultural residues
Land use, Land Use Change, and Forestry (LULUCF)			
Annex 1 parties			
Cropland	Changes in carbon in cropland remaining cropland include changes in biomass in monoculture tree plantations, fruit and nut orchards, and polycultures such as agroforestry systems, changes in soil carbon due to management practices, and burning of agricultural residues	Not included	Not included

[1] Coverage outlines the current coverage under the UNFCCC.

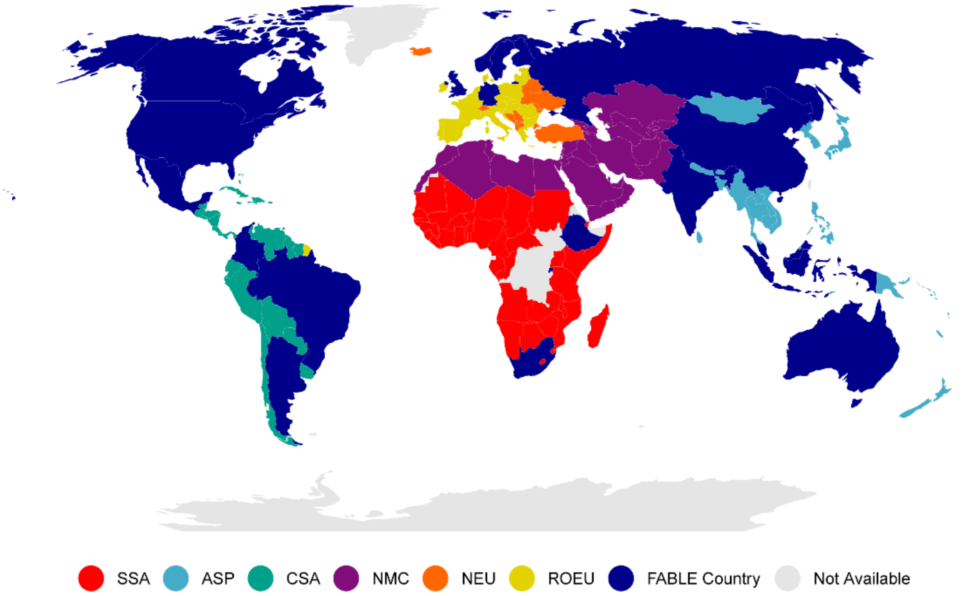
	Carbon stock change due to the conversion of land from natural conditions and other uses to cropland includes biomass, dead organic matter, soil carbon, and non-CO_2 emissions from biomass burning	CO_2 emissions due to changes in biomass stock due to the conversion of forest and other natural land to cropland	Changes in carbon stocks including biomass, dead organic matter and soil carbon due to the conversion of forests, pastures and other natural land to cropland
Grassland	Changes in carbon in grassland remaining grassland include variations in cover of woody vegetation, effects of organic matter additions, effects of management and liming, and non-CO_2 emissions from incomplete combustion of biomass in managed grassland	Not included	Not included
	Carbon stock change due to the conversion of land from natural conditions and other uses to grassland includes i) biomass, ii) dead organic matter, iii) soil carbon, iv) non-CO_2emissions from biomass burning	CO_2 emissions due to changes in biomass stock due to the conversion of forest and other natural land to grassland	Changes in carbon stocks including biomass, dead organic matter and soil carbon due to the conversion of forests, cropland and other natural land to pasture
Forest Land	Changes in carbon in forest remaining forest include gains from total biomass growth, biomass losses from roundwood removal, fuelwood removal, and from disturbances by fire, insects, diseases, and other disturbances, and non-CO_2 emissions from biomass burning	Not included	Changes in biomass carbon stocks due to climate change.
	Carbon stock change through afforestation and reforestation either by natural or artificial regeneration (including plantations and abandoned productive lands)	CO_2 removals due to changes in biomass dues to active afforestation (e.g. through plantations) CO_2 removals due to changes in biomass (due to biomass regrowth) after grassland and cropland abandonment are accounted for in Other Natural Land category	Changes in biomass due to active afforestation (e.g. through plantations) Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment are accounted for in Other Natural Land category
Settlements	Changes in biomass, dead organic matter (DOM), and soil carbon on lands classified as settlements	Not included	Not included
	Carbon stock change due to the conversion of Forest Land, Cropland, Grassland etc. to Settlements	CO_2 removals due to changes in biomass stock due to the conversion of forest and other natural land to urban area	Not included
Wetlands	Emissions from managed wetlands e.g. any land that is covered or saturated by water for all or part of the year, that does not fall into the Forest Land, Cropland, or Grassland categories, and where the water table is artificially changed (e.g., drained or raised)	Managed wetlands other than for cropland and grassland are included under other natural land	Not included

	or those created through human activity (e.g., damming a river)		
Other Land	Other land (includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories) remaining other land	CO_2 removals due to changes in biomass (due to biomass regrowth) after grassland and cropland abandonment	Changes in biomass (due to biomass regrowth) after grassland and cropland abandonment
	Carbon stock change due to the conversion of land to Other land	Not included	Not included
Harvested Wood Products	Includes carbon stored in all wood material (including bark) that leaves harvest sites from Forest Land, Cropland and other types of land use and remains in products for differing lengths of time	Not included	Not included
Non-Annex 1 Parties			
CO_2 emissions and removals from soils	Emissions and removals from i) cultivation of mineral soils, ii) cultivation of organic soils, and iii) liming of agricultural soils	CO_2 emissions from the cultivation of organic soils (only included in Finland and Indonesia)	Not included
Changes in forests and other woody biomass stocks	Commercial management, harvest of industrial roundwood (logs) and fuelwood, production and use of wood commodities, and establishment and operation of forest plantations as well as planting of trees in urban, village and other non-forest locations	Not included	Not included
Forest and Grassland conversion	Conversion of forests and grasslands to pasture, cropland or other managed uses	CO_2 emissions due to changes in biomass stock due to the conversion of forest to cropland and grassland	CO_2 emissions due to changes in carbon stocks including biomass, dead organic matter, and soil carbon due to the conversion of forest and other natural vegetation to cropland and grassland
Abandonment of managed lands	Lands that regrow into their prior natural grassland or forest condition	CO_2 removals due to changes in biomass (due to biomass regrowth) after grassland and cropland abandonment (allocated to the Other natural Land category)	CO_2 removals due to changes in biomass (due to biomass regrowth) after grassland and cropland abandonment (allocated to the Other natural Land category)

Source: FABLE 2020

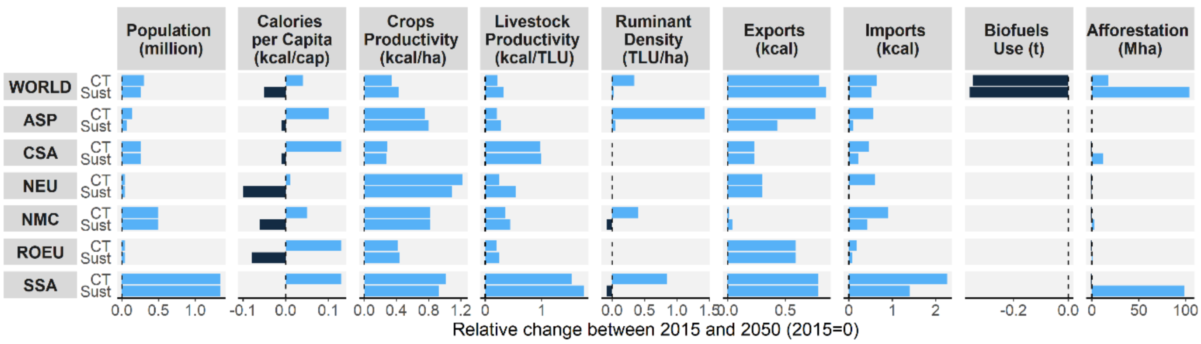
4 The rest-of-the-world regions

Map S1: Overview of FABLE countries and Rest of the World regions in FABLE



Notes: ASP = Rest of Asia and Pacific, CSA = Rest of Central and South America, ROEU = Rest of European Union, NEU = Rest of Europe non EU27, NMC = Rest of North Africa, Middle East, and Central Asia, Middle East and Central Asia, SSA = Rest of Sub-Saharan Africa. The following countries are excluded from our analysis because of missing data in the FAO database: Andorra, Antigua and Barbuda, Barbados, Burundi, Comoros, the Democratic Republic of the Congo, Dominica, Equatorial Guinea, Grenada, Kiribati, Liechtenstein, Maldives, Marshall Islands, Micronesia, Monaco, Nauru, Palau, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, San Marino, Sao Tome and Principe, Seychelles, South Sudan, Tonga and Tuvalu.

Figure S3 - Overview of scenarios for the Rest of the World regions for the Current Trends and Sustainable Pathways



Notes: ASP: Rest of Asia and Pacific; CSA: Rest of Central and South America; NEU: of Europe (non EU27); NMC: Rest of North Africa, Middle East and Central Asia; ROEU: Rest of European Union; SSA: Rest of Sub-Saharan Africa.

Population is measured in million people. Calories per capita is measured in average daily kilocalorie intake. Crop productivity is measured in average kilocalorie output per hectare of cropland. It results from the combination of the assumption on the evolution of crop yield growth and climate change impacts. Livestock productivity is measured in average kilocalorie per Tropical Livestock Unit (TLU – one unit is equivalent to 250 kg animal weight). Ruminant density is measured in TLU per hectare of pasture. Biofuel consumption is measured in metric tons of biofuels used. Exports and imports are measured in kilocalories. Afforestation is measured in absolute million hectare change between 2015 and 2050. Total afforestation goes up to 206 million ha by 2050. In the first stage, each country develops its trade assumptions without consultation of the modeling teams in the other countries (in the FABLE Calculator, trade projections are exogenous while in MAgPIE they are endogenous).

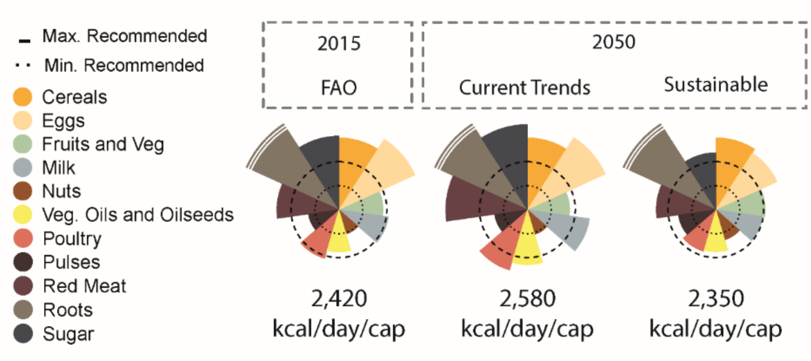
For the rest of the world regions, we define alternative productivity scenarios based on the historical productivity growth over the period 2000-2010 and the yield potential per crop per biome. Each country was allocated a biome using the dominant biome in current cropland area using ESA 2010 data. We define the yield potential as the maximum value between the Global Yield Gap Atlas (GYGA; (Grassini & van Ittersum, 2020)) yield potential data and the FAO 2019 maximum country average crop productivity in each biome. GYGA has values for 9 crops (barley, corn, millet, potato, rice, sorghum, soyabean, sugarcane, wheat) with values for 3 to 54 countries for each crop. We have differentiated three cases depending on the historical productivity change rate between 2000 and 2010 (negative, medium and high**Error! Reference source not found.**), that are combined with tailored yield potential gap closure scenarios.

In the FABLE calculator, the average ruminant density per hectare of pasture is an important driver of the land system e.g., if the current average density is very low and is not assumed to increase over time, this will drive large pasture expansion to satisfy even slight increase of domestic production of beef, milk or mutton-goat. For the rest of the world regions with currently very low average ruminant density per ha (SSA and NMC) the model was designed so that demand for ruminant products would not impact pasture area and would remain at FAO 2010 levels.

5 Further analysis of diet, productivity, and trade assumptions

Diet scenarios - Compared to the EAT-Lancet recommendations for a healthy diet, the *Sustainable* pathway reduces the world average kilocalorie intake close to the upper intake threshold for animal-based products and sugar, and within the recommended range for vegetable fats, milk and dairy, and poultry meat (Figure S).

Figure S4. World average diet composition and kilocalorie input

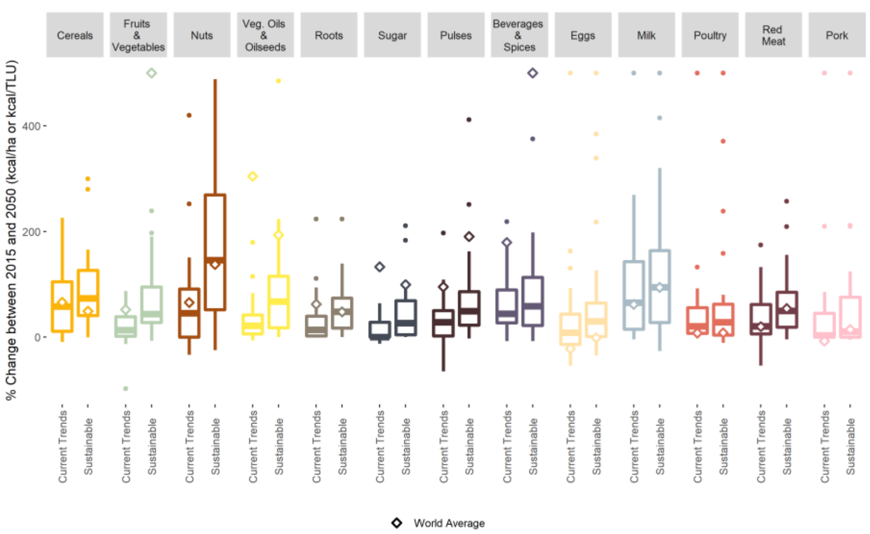


Notes: These figures are computed using the relative distances to the minimum and maximum recommended levels (i.e. the rings), therefore, different kilocalorie consumption levels correspond to each circle depending on the food group. The EAT-Lancet Commission does not provide minimum and maximum recommended values for cereals: when the kcal intake is lower than the average recommendation it is displayed on the minimum ring and if it is higher, it is displayed on the maximum ring. The discontinuous lines that appear at the outer edge indicate that the average kilocalorie consumption of these food categories is significantly higher than the maximum recommended.

Source: FAOSTAT(2020) for 2015; Willett et al. (2019) for EAT Lancet minimum, average and maximum recommendations and FABLE pathways for the 2050 projections.

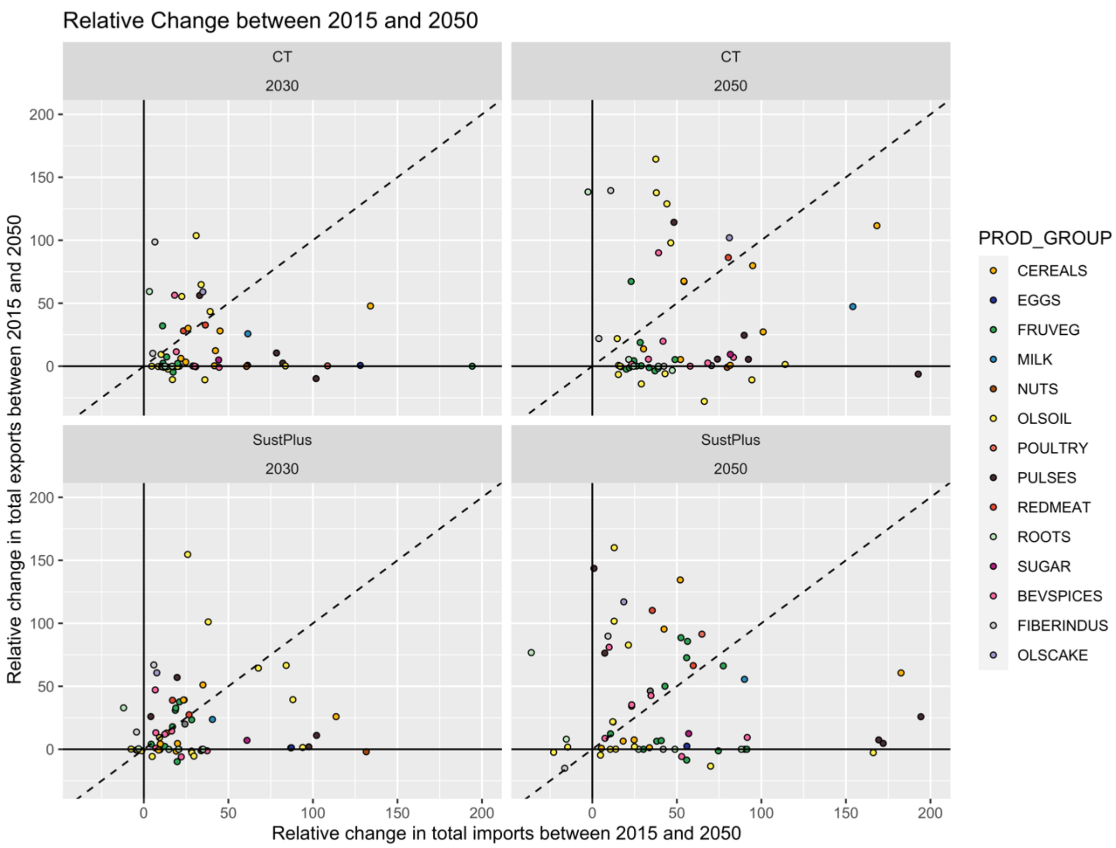
Productivity scenarios

Figure S5. Assumptions on the relative productivity change by product group between 2015 and 2050 in the Current Trends and Sustainable pathways across countries and regions



Trade - Except Finland, Norway and the UK, all FABLE countries have assumed an increase in their aggregated agricultural exports in calories equivalent between 2015 and 2050 and except a few countries in the Sustainable pathway, all countries and regions assume increased imports in calories (Figure S). Figure S compares the relative change in total imports with the relative change in exports quantities by product between 2010 and 2050 that result from this first round of trade assumptions. We can see that 1) in the CT pathway we assume an increase in total imports between 2015 and 2050 for all products except for cassava, 2) projected imports are higher than projected exports for most of the products, 3) the Sustainable pathway leads to a reduction in total imports for some products and an increase of the products for which trade is imbalanced with exports well above imports by 2030 and 2050 e.g. cereals such as barley, corn and wheat, almost all vegetable oils, soybean, and meat.

Figure S6. Assumed total imports and exports relative change between 2010 and 2050 before trade harmonization



Note: the dashed line indicates a similar relative change of total imports and exports. For 2050 CT pathway, total imports for chicken, date and eggs have higher relative changes than 200%; for 2050 Sustainable pathway, date, nuts, and rapeseed oil have higher relative changes than 200%, and rapeseed and soybean oil have higher relative change of total exports than 200%. A reduction of total exports between 2015 and 2050 might occur despite assumptions of export growth if there is not enough land available in exporting countries to satisfy both the targeted internal demand and the targeted exports.

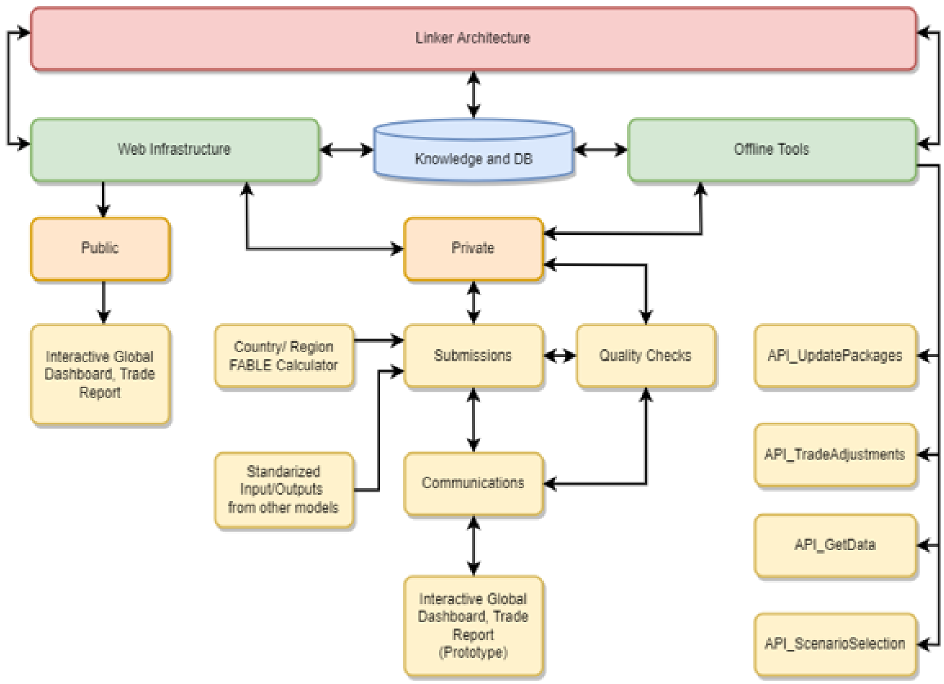
6 High-performance computing for the FABLE-Scenathon

The FABLE-Scenathon process, because of its distributed dynamic process, requires the use of High-performance computing. The output from twenty-six models is used to compare global projections against global targets defined by the FABLE consortium through one or several iterations for each individual model. The system becomes heavy to process by computing updates for the models, making trade adjustments, experimenting with new pathways and scenarios for each iteration, and doing it for all the countries.

The FABLE-Scenathon architecture to compute all the required iteration tasks use a High-performance server and seven client computers to support the process. The client computers work in parallel doing the previously mentioned tasks, making the process faster. Other methods are computed by the online server aiming to support the submission of the models using the website scenathon.org. The page includes the private section, which allows the user to submit their country model and then see the model output contributing to the global targets, and the public section. Before seeing the country's contribution to achieving the global target, the backend applications compute a set of review quality processes to ensure the quality of the data given by the models. Finally, the consortium decides if a new iteration is required after all the countries have submitted their projections, and all the quality processes are satisfactory. If so, the process is restarted until a final iteration. After the last iteration, the public dashboard is released. Thanks to high-performance computing, FABLE-Scenathons can be run with several iterations in a few days.

Figure S7 describes the computing architecture developed to support the FABLE Computing System. There are five elements: the FABLE Calculator, The Linker Architecture, the DataBase (DB); the Web Infrastructure, and the OutLine Tools; those elements are relevant to support the Scenathon iteration process.

Figure S7 - FABLE-Scenathon Computing System



Notes:
DB: Database stores the outputs of the models, such as the Trade values and indicators.
FABLE Calculator: the used model; each country could adapt the model according to the country's needs. But all of their reports are according to a predefined format called Scenathon_Report.
The API Tools are used during the process to facilitate and optimize the work time used to update the model.
The API_UpdatePackages aims to implement changes in current formulas or to introduce new formulas or tables to the model.
The API_TradeAdjusment updates the trade values for imports and exports for each commodity and year.
The API_GetData extracts the Information of any table from the model.

The API_ScenarioSeleciton helps the user model to implement automatic changes on the scenarios selected. It also helps build new sustainable pathways based on the new Scenarios.