Documentation
FABLE Calculator
2020 update

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Acknowledgements

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1 Introduction

1.1 What is the FABLE Calculator?

The FABLE Calculator ("the Calculator") is an Excel accounting tool used to study the potential evolution of food and land-use systems over the period 2000-2050. It focuses on agriculture as the main driver of land-use change and tests the impact of different policies and changes in the drivers of these systems through the combination of a large number of scenarios. It includes 76 raw and processed agricultural products from the crop and livestock sectors (Appendix 1) and relies extensively on the FAOSTAT (2020) database for input data. For every 5-year time step over the period 2000-2050, the Calculator computes the level of agricultural activity, land use change, food consumption, trade, greenhouse gas (GHG) emissions, water use, and biodiversity conservation according to selected scenarios. Users can replace data from global databases with national or subnational data.

1.2 Why did we develop the FABLE Calculator?

We developed the FABLE Calculator because we are convinced models can help frame better policies. Models describe and explain in a simplified framework how things work. By integrating various sources of existing information, they highlight information gaps and inconsistencies as well as the connections between different parts of complex systems. Models also explore the potential impact of policy options or of future changes. Specifically, scenarios test for the consequences of a wide range of "if" assumptions and their most important dependencies.

The FABLE Calculator is an accounting tool built in Excel in order to allow a wide range of users, modelers or non-modelers alike, to explore future land-use and food-systems change. This includes policymakers, researchers, or even students who develop more complex tools on food and land-use systems. Compared to more complex models, the Calculator has several advantages. It can identify major imbalances in, and threats to, national food and land-use systems without complex optimization algorithms. It can run on almost any computer since Excel is one of the most widely used programs in the world and newer versions are backwards-compatible with older Excel files. Because all the data is visible and the structure of the Excel functions is clear, the Calculator contains no hidden "black-box" to hide its weaknesses. Moreover, users can quickly select alternative combinations of scenarios and see the impacts on the main indicators. This is an advantage when interacting with stakeholders, as assumptions can be changed easily and transparently.

However, there are tradeoffs to these advantages, so users should keep in mind the Calculator's shortcomings and limitations when conducting any analyses:

1) The Calculator is not an optimization tool and prices are only used ex-post to compute production and trade values. Therefore, prices do not influence the results and results do not influence commodity prices, contrary to economic models.

2) There is no detailed representation of production practices and/or technologies. This means that neither the technical feasibility nor the economic feasibility of the pathway is evaluated within the FABLE Calculator. This should be assessed through complementary analysis.

3) The forestry sector is not yet considered. This means that parts of AFOLU GHG emissions/sequestration are not covered i.e., GHG emission/sequestration in managed forests and woody products are not represented.

4) The emissions from agriculture can only be reduced by lowering production volumes or increasing productivity. Other mitigation options for agriculture, such as improved rice management, animal feed supplements, fertilization techniques or anaerobic digesters are not yet represented.

5) Water availability constraints are not represented.

6) Even though the Calculator is an Excel file and the formulas are transparent, fully understanding the computations and being able to make changes require some time. Training materials are under development and will be progressively added online.

The tool has been developed within the framework of the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium, a collaborative initiative, operating as part of the Food and Land Use (FOLU) Coalition, working to understand how countries can transition towards sustainable land-use and food systems. Before joining the Consortium, very few country teams had access to models or accounting tools that covered both food and land systems. Therefore, the FABLE Calculator was initially developed with the objective of providing a model to each country team as quickly as possible to allow them to make initial projections of their food and land-use systems up to 2050. The FABLE Consortium played a key role in identifying problems and mistakes in the Calculator and in suggesting improvements.

1.1 What is new compared to the previous version?

Compared to the 2019 version, updates to the documentation include the improvements that have been made to the FABLE Calculator during the course of the past year, 2020, and which are accessible in the Open FABLE Calculator 2020. These are related to:
- Improvements to the scenarios for protected areas (cf. Section 3.9)
- New indicator on the share of land where natural processes predominate (cf. Section 5.5.2)
- New scenarios on alternative climate change impacts for selected crops (cf. Section 3.8)
- New representation of crop demand for biofuels and alternative scenarios on biofuel demand (cf. Section 3.11)

- New indicators on protein and fat intake (cf. Section 5.1)
- Improvements to the representation of food waste (cf. Section 3.3)
- New scenarios on alternative levels of post-harvest losses in the future (cf. Post-harvest loss)
- Separated food group for nuts (Appendix 1: List of product groups and products)

2 Structure of the FABLE Calculator and conventions

The current version of the FABLE Calculator is a light Excel file (less than 6 MB) that contains country or regional historical data in the grey "DATA" sheets, the calculation formulas for the calculation in the green "CALCULATION" sheets, the definition and selection of scenarios definition and selection in the light red "SCENARIOS" sheets, and the visualization of the main results in the yellow "INDICATORS" sheets (Figure 1). The worksheet called "SCENATHON_report" contains all the parameters and variables that are uploaded during a Scenathon.

The worksheet called "CHANGE LOG" is used to document the changes which are made to the Calculator over time by one or different users. This is useful for the user to avoid forgetting what has changed and, in the case of multiple people working with the same Calculator, to ensure that all users know which changes have been made. We recommend that the FABLE Calculator be saved under a different version name after a change or a series of changes have been implemented.

Figure 1. Overview of the FABLE Calculator Excel workbook
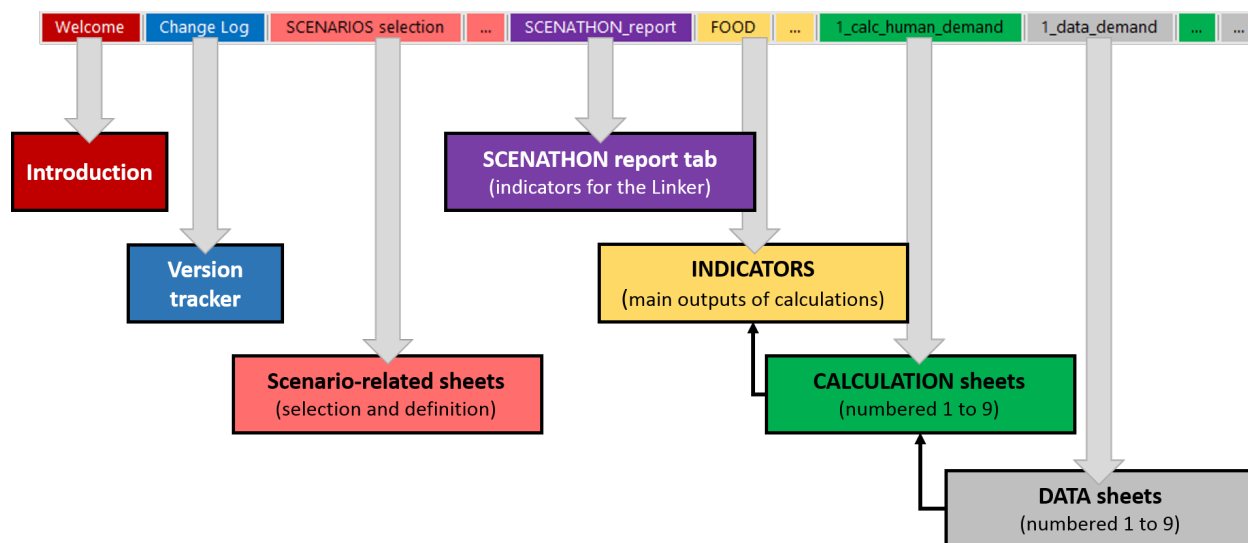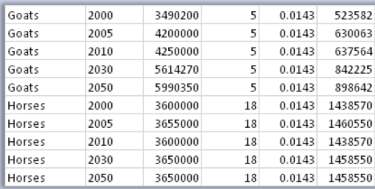
Each worksheet usually contains several tables. Each table is formatted as an Excel object called "Table" (Figure 2). This feature makes it possible to:

- give a name to a table which can be directly used in calculations,
- automatically recognize all column names which can be used in calculations as an attribute of the table name,
- automatically copy the calculation entered in the first row to all the other rows or lines of the table in the same column,
- better understand the formula when table names are used instead of cell numbers, and
- avoid mistakes in the formulas when rows/columns number of a table are changed.

Figure 2. Format as table in Excel
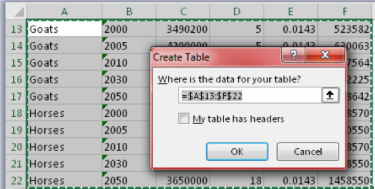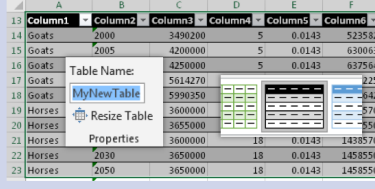
Each table uses the following conventions summarized in Figure 3:
- The name of the Table which is recognized as an object by Excel should be written on the top of the table.
- The table should be numbered and described by clear text (potentially dividing the table into several sections if it facilitates understanding).
- Each column of the table should use the legend presented in Figure 4 to allow the user to quickly identify the type of information that is used in a column: a parameter defined by a scenario ("SCEN"), a parameter that comes from certain input data tables ("DATA"), a variable that results from a computation in the column ("CALC"), a variable computed in another calculation table or another column of the same calculation table ("OUTPUT"), a variable computed to do some verification e.g. to compare computation with historical data ("CHECK"), or a parameter that has been entered manually i.e., which is not related to any other table or column (DIRECT).
- **Each column should be described with clear text and the unit should be specified**.

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Figure 3. Information displayed in each table
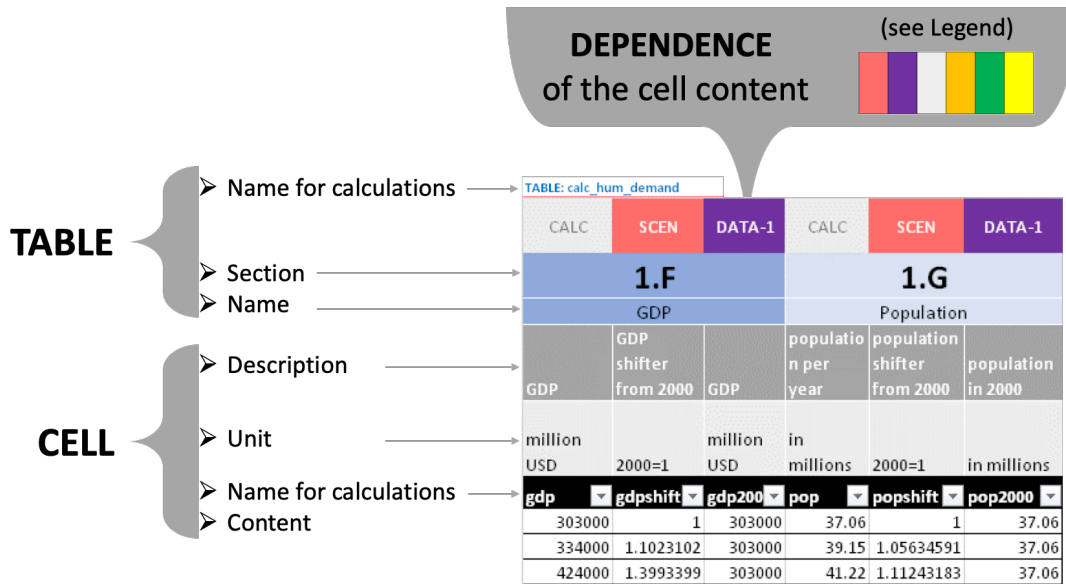
Figure 4. Legend for table columns

SCEN	The cell content depends on the selection of a SCENARIO.
DATA-n	The cell content is taken from a table in a DATA sheet (**n** indicates the number of the data sheet).
CALC	The cell content is calculated based on cells in the SAME sheet.
CHECK	The cell serves as data verification.
OUTPUT-n	The cell content represents an output result obtained within a table in a CALCULATION sheet (**n** indicates the number of calculation sheet).
DIRECT	The cell content is filled directly (and not linked to anything).

We define a pathway as a combination of scenarios that represents the coherent development of a system along a certain trajectory. Scenarios are the suite of possible actions that set a pathway on a certain trajectory. Assumptions are the conditions that a modeler establishes before the model is run to make predictions on, for example, causality chains and changes in specific parameters of the model according to the selected scenarios. A parameter is a constant in model simulations except when it is changed for a specific scenario (i.e. the modeler decides on its value before running the model) - this is an input of the model. A variable represents a model state and results from the model's computations (i.e. the modeler does not decide on its value before the model is run) - this is an outcome of the model.

3 Scenarios

We have established a list of parameters that can be changed through the selection of different scenarios. Each parameter and corresponding alternative scenarios are grouped by tables. By default, the Open Calculator has 16 parameters that can be modified through scenarios, each of which has between 2 to 17 possible alternative values. There are, therefore, millions of possible combinations of scenarios that lead to different pathways (Table 1). The user can select pre-defined scenarios or add new scenarios, but the latter requires a good understanding of the Calculator.

Table 1. 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.

To select a scenario, the user simply needs to **enter "x"** next to the scenario that they want to test (Table 2). There can be **only one scenario selected per table**. The FABLE Calculator's computation steps are automatically updated with the parameter values corresponding to the selected scenarios[1], using SUMIFS and VLOOKUP Excel (Appendix 2), respectively.

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[1] Excel tip: if you have a laptop / PC with limited computational power, you should turn off auto calculation while making changes (go to Formulas/Calculation options/ and select Manual), and just manually run the calculation (go to Formulas and select Calculate now) when you want to see the impact on the results. It is also recommended to turn the option back to Automatic when you have finished making changes, so that all the steps are considered in the final results.

Table 2. Example of scenario selection

TABLE: Pop_Scen				
S.2	**Alternative population projections**			
SELECTION	POP_SCEN	DESCRIPTION	Population variation 2000-2050	USED in
	SSP1	"*Sustainability* " - Low to medium fertility, low mortality, medium migration, high education. Fast urbanization.	1.32	
x	SSP2	"*Middle of the Road* " - Medium fertility, medium mortality, medium migration, medium education. Extension of current trends in urbanization.	1.43	
	SSP3	"*Fragmentation* "- High fertility, high mortality, low migration, low education. High rural population growth.	1.59	
	SSP4	"*Inequality* " - High fertility, high mortality, medium migration, very low education. Fast urbanization.	1.47	calc_hum_demand;
	SSP5	"*Conventional Development* " - Low fertility, low mortality, high migration, high education. Fast urbanization.	1.30	
	UN_medium	Medium growth	1.48	
	UN_high	High growth	1.65	
	UN_low	Low growth	1.32	
	UN_constantfertility	Constant fertility	1.64	
	UN_instantreplacement	Instant replacement	1.48	
	UN_momentum		1.47	
	UN_zeromigration	Zero migration	1.52	
	UN_constantmortality	Constant mortality	1.41	
	UN_nochange	No change in fertility, mortality, replacement, and migration	1.57	

Note: "x" indicates which scenario is selected in the first column; the second column indicates the short name of the scenario that will appear in the different tables of the Calculator; the third column describes the scenario; the fourth column summarizes the quantitative change introduced by each scenario; the fifth column lists the tables where the scenario is used.

A key concept for implementing the scenarios are shifters, or time-step-specific relative changes applied to a parameter's initial value, that introduce parameter time variation. Some shifters are created based on historical values or trajectories. The combination of final targeted values for 2050 defined by the user and an implementation rate of the target between 2010 and 2050 is also used to compute the evolution of some parameters for every time step for different scenarios. The implementation rate parameter is used to translate targeted values for 2050 as targeted values for each time step between 2015 and 2050 (Figure 5). The implementation coefficient is the share of the difference between the current situation and the 2050 target that is assumed to be achieved in each time-step.

Figure 5. Definition of alternative implementation rates for scenarios
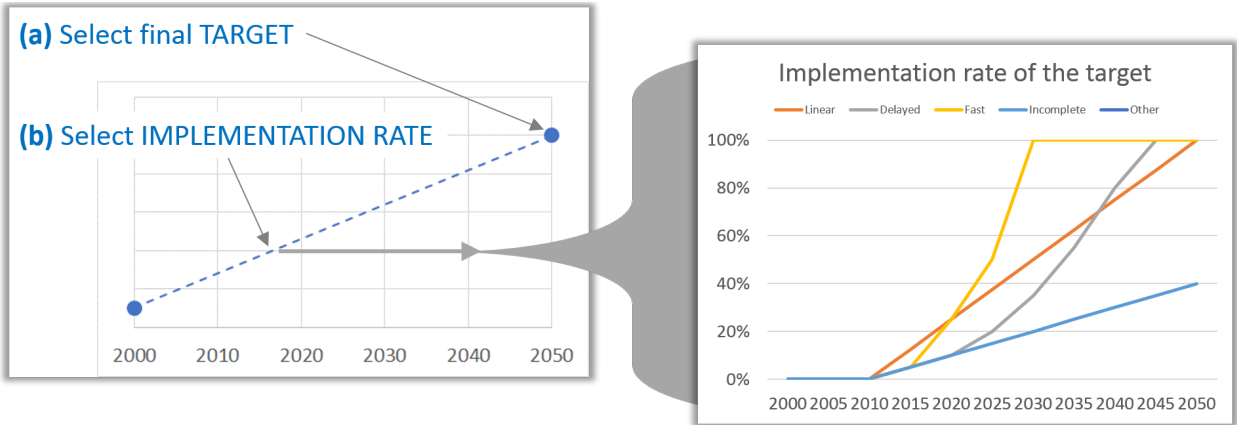
Below we describe the various parameters that can be changed by selecting different scenarios.

3.1 Population

Population growth is a key parameter as it is used to compute the evolution of the targeted demand together with the diet assumption. Nine population projections are taken from the United Nations DESA population division prospects: low, medium, high, constant fertility, instant replacement, momentum, zero migration, constant mortality and no change (UNDESA, 2017). Five population projections are taken from the SSP database developed at IIASA: SSP1 to SSP5 (KC & Lutz, 2017). Historical data for 2000, 2005, 2010, and 2015 are taken from UN DESA (UNDESA, 2017). Shifters are computed as the ratio between the projected population in each time step and the population reported in 2015 in each database. The shifters corresponding to the selected population scenario are applied to the 2015 historical population level from UN DESA as well as its growth projections regarding age group and sex to derive the evolution of the average Minimum Dietary Energy Requirement (MDER) (cf. Section 4.1). One problem is that the historical population value for 2015 is inconsistent across the UN and SSP databases.

The average activity level of a nation's population affects its minimum dietary energy requirement (MDER) against which the FABLE Calculator compares feasible consumption. By default, three activity-level scenarios are defined in accordance with USDA (Institute of Medicine, 2002): *low*, *middle*, and *high*. *Low* corresponds to the USDA's definition of a mostly sedentary lifestyle "that includes only the physical activity of independent living". *Middle* corresponds to a moderately active lifestyle, "including physical activity equivalent to walking about 1.5 to 3 miles per day at 3 to 4 miles per hour, in addition to the activities of independent living". *High* activity corresponds to USDA's active lifestyle, including "physical activity equivalent to walking more than 3 miles per day at 3 to 4 miles per hour, in addition to the activities of independent living". Daily calorie needs increase with higher activity: for instance, an adult male's minimum needs are 2,600 kcal per day with low activity but 3,200 kcal per day with high activity.

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Table 3. List of tables related to the population scenarios

Worksheet	Table name	Table description
Scenarios Selection	Pop_scen	Alternative population projections
	PopActivity_Scen	Alternative level of activity of the population
Scenario Definition	GdpPopTarget	Alternative projections of population and GDP between 2015 and 2050
	Def_dmer	Calorie requirement by age, sex and activity level
1_data_demand	gdp_pop_hist	Historical evolution of GDP and population between 2000 and 2016
	UNPopSexAge	Population projections by sex and age class
1_calc_human_demand	calc_hum_demand	Human food and non-food demand for agricultural products
	Calc_dmer_Activitylevel	Minimum calorie consumption per capita per day by sex and age class
	Calc_min_daily_kcal	Average Minimum Daily Energy Requirement (MDER) per capita at the national level

3.2 Diets

Three scenarios are defined in the Calculator by default: No change, Healthy diet, and Fat diet2. No change corresponds to the 2010 consumption profile taken from the FAO. Healthy diet corresponds to an average of the range indicated by the EAT-Lancet report for each food group (Willett et al., 2019). The EAT-Lancet report quantitatively describes a universal healthy reference diet for an average adult with a total daily energy intake of about 2,500 kcal per capita. In order to take the structure of the population into account, we have multiplied the EAT-Lancet recommendations by the ratio between the average national MDER (Lupton et al, 2002) and the total kilocalories in the EAT-Lancet diet. We have defined the Fat Diet as a high share of meat products, oil, and sugar in the total food intake (Table 4). We compute the difference between the kilocalorie consumption per food group in the selected diet and the consumption level observed in 2010. This difference is then progressively reduced over time starting in 2015 in order to match the selected diet in 2050. Corresponding shifters are computed for each time step, depending on the chosen implementation rate. The shifters are the same for all the products within a certain food group (Appendix 1).

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[2] *Or a diet high in fat, sugar, and meat.*

Table 4. Definition of healthy diet and fat diet scenarios in average kilocalorie per capita per day

PROD_GROUP	EAT Lancet	Fat_diet
ALCOHOL	0	119
ANIMALFAT	96	58
BEVSPICES	0	35
CEREALS	811	786
EGGS	19	54
FISH	40	31
FRUVEG	204	187
MILK	153	382
NUTS	291	20
OLSOIL	354	632
PORK	15	151
POULTRY	62	200
PULSES	284	39
REDMEAT	15	111
ROOTS	39	93
SUGAR	120	297

Note: *For the description of the acronyms for the food groups, see Appendix 1. The products grouped in the table above as ALCOHOL (wine, beer and other alcoholic beverages) and BEVSPICES (cacao, beverages, spices and tobacco) are not included in the EAT-Lancet guidelines and hence are equal to zero. The table also does not include the food groups categories of OLSCAKE and OTHER. These are the values before adjustment of the average diets to reflect the population structure.*

Table 5. List of tables related to the diet scenarios

Worksheet	Table name	Table description
Scenarios Selection	Diet_scen	Alternative diets
Scenario Definition	DietImplRates	Alternative diets implementation rates
	Diet_target	Definition of shifters by food group to match targeted diets
1_data_demand	EATLancet_rec	Dietary recommendations from the EAT-Lancet report
	OtherDiets	Other diets used for scenarios
1_calc_human_demand	calc_hum_demand	Human food and non-food demand for agricultural products

3.3 Food waste

In the FABLE Calculator, we account for food losses at the consumption level that include losses during distribution (e.g. supermarket retail) and at the household level. Food waste is represented as a share of total food available. For instance, if the targeted food consumption is 2,500 kilocalories per capita per day and the food waste at the household level represents 10%, the total market supply needs correspond to an average consumption level of 2,777 kilocalories per capita per day, i.e. target /(1 - share of losses). The calorie, protein, and fat intake is thus computed on the basis of food consumption minus consumption losses. This can explain some

deviations with the reported statistics on food consumption by the FAO, which does not take into account these losses at the consumption level.

In the previous version of the Calculator, it was assumed that food losses represented 10% of total consumption. The new version represents shares of specific consumption losses by food group and by region using FAO reported values for large regions (Gustavsson et al., 2011). Three scenarios are available: a constant share of food waste over time, increased food waste over time, and reduced food waste over time. Specific relative changes and implementation rates per food group can be defined.

Table 6. List of tables related to the food waste scenarios

Worksheet	Table name	Table description
Scenarios Selection	Scen_foodloss	Alternative shares of food waste
Scenario Definition	FLScenTarget	Targeted food loss shares in 2050 by food group
	FoodLossTarget	Share of the food consumption which is wasted by year and by food group in the selected scenario
1_data_demand	FoodLossByGroup	Estimated/assumed waste % of each commodity group in each step of the food supply chain
1_calc_human_demand	calc_hum_demand	Human food and non-food demand for agricultural products

3.4 Trade

Imports are computed based on total consumption including food and non-food human consumption, food waste, and feed consumption. The parameter which allows the computation of future imports is the share of the total consumption which is satisfied by imports. Exports are computed differently: targeted exports are purely exogenous and expressed in 1,000 tons because the determinants of the demand outside the country are not represented in the model. The final exports can be reduced if there is not enough land (cf. Feasible production, trade and consumption). The default assumption is that the share of the total consumption which is imported, and the level of exports, remain constant at the 2010 level, as reported by the FAO in the Commodity Balances (FAOSTAT, 2020). The "Exports" and "Imports" scenarios make it possible to change this assumption but only for the products which are selected in the export and import scenarios tables (Tables *product_impscen* and *product_exports*; Appendix 4). Users can specify by how much the 2010 exports or the 2010 share of consumption which is imported will vary by 2050 for each selected product using a shifter (2010=1) and the implementation rate of the target. By-default, three scenarios are defined for the imports (I1, I2, and I3) and 3 scenarios

are defined for the exports (E1, E2, E3) with no change, reduced, and increased trade assumptions.

One scenario makes it possible to fix trade to certain values i.e. overwriting the previous imports and exports scenarios and impeding trade adjustment due to the land constraint (*Fix Trade* scenario). This scenario is used during the global trade harmonization stage during the Scenathon, after the national and regional net trade have been adjusted to solve global trade imbalances. By-default, this scenario should be "No", trade is not adjusted.

Table 7. List of tables related to the exports and imports scenarios

Worksheet	Table name	Table description
Scenarios Selection	Scen_imports	Alternative shares of domestic consumption which is imported for selected products
	Scen_exports	Alternative exports evolution for selected products
	FixTrade_scen	Choose if trade is being adjusted to ensure global trade balance
Scenario Definition	Product_impscen	Selected products for scenarios on imports
	IMPScenTarget	Targeted share of domestic consumption which will be imported in 2050 for selected products
	ImportDef	Share of domestic consumption which is imported in each time-step for selected products
	Product_Exports	Selected products for scenarios on exports
	EXPScenTarget	Exports quantity targeted for 2050 for selected products
	ExportDef	Exports quantity targeted for each time-step and for selected products
	FinalTradeAdj	Imports and exports quantities after global trade adjustment
1_data_demand	Prod_balance	Commodity balance for historical period 2000-2015
2_calc_livestock	calc_livestocknb	Computation of targeted livestock herd
3_calc_crops	calc_crops	Computation of the targeted production and harvested area by crop
5_feas_livestock	Calc_FeasFeed	Computation of feed needed by the feasible ruminant herds
	Calc_FeasProdLivestock	Livestock products: trade and internal use, adjusted for the feasible herd sizes
6_feas_crops	Calc_FeasCrops	Computation of feasible crop production, consumption and trade

3.5 Productivity

Because of the large number of products, the design of the scenarios on productivity relies on very simplistic assumptions: the starting point is always historical productivity growth from 2000-2010 which is computed based on FAOSTAT production data (FAOSTAT, 2020). The default assumption in the *High* productivity growth scenario is that the historical growth rate will be multiplied by -1 if it was negative, by 2 if it was below 1%, and by 0.7 if it was above 1%. For the *Low* productivity growth scenario, the historical growth rate is multiplied by -0.5 if the historical growth rate was negative, by 0.5 if it was lower than 1%, and by 0.1 if it was higher than 1%. Two additional alternative scenarios are available: *NoChange* which fixes the crop productivity to the 2010 level, and *BAUGrowth* which uses the same crop productivity growth as observed during 2000-2010. We have added a condition so that productivity cannot drop below 50% of the reported yield in 2010. In the future, we plan to add maximum productivity values to avoid unrealistic productivity projections. This is a priority for improving the tool.

Table 8. List of tables related to the productivity scenarios

Worksheet	Table name	Table description
Scenarios Selection	Live_scen	Alternative scenarios on livestock productivity
	Crop_scen	Alternative scenarios on crop productivity
Scenario Definition	LivePdtyTarget	Livestock historical annual productivity rate change in 2050 compared to 2000-2010
	LivePdtyDef	Livestock historical productivity shifter in 2050 compared to 2000
	CropPdtyTarget	Crop historical annual productivity rate change in 2050 compared to 2000-2010
	CropPdtyDef	Crop historical productivity shifter in 2050 compared to 2000
2_data_livestock	FAOLivePdty	Historical animal productivity
3_data_crops	FAOCropPdty	Historical crop productivity growth
2_calc_livestock	calc_livestocknb	Computation of targeted livestock herd
	calc_feed	Computation of livestock feed requirements
	calc_pasture	Computation of pasture needed for livestock and emissions related to livestock
3_calc_crops	calc_crops	Computation of the targeted production and harvested area by crop
8_calc_emissions	calc_rumemis	Computation of emissions from ruminants
	calc_monogemis	Computation of emissions from monogastric animals
	calc_cropemis	Emissions from cultivated land

3.6 Land availability

This scenario makes it possible to restrict agricultural expansion even when there is still some land available. There are three default scenarios: *No expansion,* which does not allow the expansion of agricultural land beyond 2010 agricultural land area; *NoDefor2030,* which forbids agricultural expansion on forest land after 2030; and *Free expansion,* which allows for agricultural expansion of natural land up to the limit of the natural land area which is under protection.

Table 9. List of tables related to the land availability scenarios

Worksheet	Table name	Table description
Scenarios Selection	Land_scen	Alternative scenarios on land available for agricultural expansion
Scenario Definition	LandScenTarget	Alternative maximum area of cropland and grassland by year
4_data_land	CalcHistLand	Historical land use changes
4_calc_land	calc_land_cor	Computed area by land cover type

3.7 Afforestation/reforestation

Afforestation (or reforestation) is exogenously driven in the FABLE Calculator. Afforestation (or reforestation) is represented as a separate land cover class ("New forest") and this scenario fixes the total targeted afforested area by 2050 and the share of the total afforested area which is planned on each land cover type (i.e. cropland, pasture, and other natural land), then selects and applies the implementation rate to distribute the afforestation target over the period. There are two alternative scenarios by default: *No afforestation* and *BonnChallenge,* where the target should correspond to the commitments which have been made under the Bonn Challenge.

Table 10. List of tables related to the afforestation scenarios

Worksheet	Table name	Table description
Scenarios Selection	Affor_scen	Alternative scenarios on afforestation target
Scenario Definition	AfforTarget	Alternative targets for afforestation/reforestation by land cover type by 2050
	AfforScenDef	Alternative afforested/reforested area by land cover type and by year
4_data_land	CalcHistLand	Historical land use changes
4_calc_land	calc_land_cor	Computed area by land cover type

3.8 Climate change

Climate change impacts are introduced as shifters applied to crop yields, crop water requirements, and fertilizer use for each time step between 2015 and 2050. We use climate change impact data for both irrigated and rain-fed crops, based on two crop models, GEPIC and LPJmL, for four and

twelve crops respectively[3] from the ISIMIP database (Arneth et al., 2017). The impact estimates are modeled for combinations of four different representative concentration pathways (RCPs; 2.6, 4.5, 6.0, and 8.5), five global climate models (GCMs; GFDL-ESN2N, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M), and the fertilization effect of increased atmospheric carbon dioxide concentration on plants either turned on or off (on for 40 scenarios, off for 24). This results in sixty-four climate change scenarios. Crop yields, crop water requirements, and fertilizer use remain the same as without climate change for the crops not included in GEPIC or LPJmL, respectively.

Table 11. List of tables related to climate change impacts

Worksheet	Table name	Table description
Scenarios Selection	ClimateChange_scen	Alternative combinations of RCP, climate model and crop models, with or without CO2 fertilization effect
Scenario Definition	CCshifters	Climate change impacts on crop yields and input use
3_calc_crops	Calc_crops	Computation of the targeted production and harvested area by crop
8_calc_emissions	Calc_cropemis	Emissions from cultivated land
9_calc_water	calc_crop_wf	Computation of production water footprint

3.9 Protected area

This scenario defines the targeted protected share of natural land in each ecoregion by 2050. Depending on the historical distribution, this results in specifically defined amounts of protected forest and other natural land, which cannot be changed to another land type in the calculation process. By default, two scenarios are defined: *no change* and *PA expansion*. *No change* keeps the protected area share constant at 2010 levels, based on the WDPA database. By-default, *PA expansion* targets a protected share of at least 17% for each ecoregion by 2050. Ecoregions with a higher protected share in 2010 as well as ecoregions with a protected share below 5% are kept constant at 2010 levels. Using the resulting 2050 protected areas targets, targets for each time step are calculated depending on the selected implementation rate (cf. Implementation Rate).

Table 12. List of tables related to protected areas scenarios

Worksheet	Table name	Table description
Scenarios Selection	PA_scen	Alternative evolutions of protected areas
Scenario Definition	PAparameters	Minimum and targeted shares of natural land under protection by ecoregion
	PAtarget	Targeted protected areas in 2050 by ecoregion and land cover type

---

[3] *Corn, rice, soy, and wheat for GEPIC; cassava, field pea, groundnut, maize, millet, rapeseed, rice, soy, sugarbeet, sugarcane, sunflower, and wheat for LPJmL.*

	Patarget_def	Targeted protected areas by year by land cover type at the national level
4_data_land	PAIntactLandEcoregion	Protected and intact areas by land cover type and ecoregion in 2010
4_calc_land	Calc_cropemis	Computed area by land cover type

3.10 Post-harvest loss

In the FABLE Calculator, post-harvest loss is applied as a share of crop and livestock products availability i.e. production plus imports plus stock withdrawals. This share can change over time, depending on the selected post-harvest-loss scenario. Following the FAO definition, losses occurring before and during harvest are excluded, quantities lost during the transformation of primary commodities into processed products are taken into account in the assessment of respective extraction/conversion rates, and waste from both edible and inedible parts of the commodity occurring in the household is included in food waste (cf. Food waste). Post-harvest losses mostly include losses during storage and transportation. By default, two scenarios are defined: *no change* and *reduced*. *No change* uses historical data and keeps this share constant for all time steps. *Reduced* defines relative reduction targets of the shares of post-harvest-loss by 2050, independently for crop and livestock products. Depending on the defined implementation rate, this reduction target is translated into partial reduction levels for each time step.

Table 13. List of tables related to post-harvest loss scenarios

Worksheet	Table name	Table description
Scenarios Selection	PostHarvestLoss_Scen	Alternative shares of the supply which is lost between production and distribution
Scenario Definition	PHLoss_target	Post-harvest loss target in 2050
	PHLossTarget_def	Post-harvest loss relative change by year
1_data_demand	Prod_balance	Commodity balance for historical period 2000-2015
2_calc_livestock	calc_livestocknb	Computation of targeted livestock herd
3_calc_crops	Calc_crops	Computation of the targeted production and harvested area by crop

3.11 Biofuel

In the FABLE Calculator, besides food and feed, crops and vegetable oils can also be used for biofuel production. This additional demand for biofuel production affects the calculated cropland and associated sustainability indicators. At the same time, biofuels replacing petrol-based fuels have a positive effect on GHG emissions, estimated in the FABLE Calculator by comparing emission factors for gasoline and diesel oil (IPCC) with ethanol and biodiesel (US-RFA 2008), respectively. By default, two biofuel scenarios are defined: stable biofuel demand on 2010 levels and OECD-FAO projections until 2028 (OECD-FAO, 2019), with stable levels afterwards. In the OECD-FAO scenario, shifters for each time step are calculated by dividing the respective time

step's projected biofuel use by the 2010 level. In the stable scenario, all shifters are 1. It should be noted that there are projections for future biofuel demand only for a few countries and regions in the OECD-FAO report. The other countries and/or regions would need to look for alternative biofuel projections.

Table 14. List of tables related to biofuel scenarios

Worksheet	Table name	Table description
Scenarios Selection	Biofuel_Scen	Alternative biofuel demand scenarios
Scenario Definition	BiofuelScen_def	Scenario on future demand by commodity for biofuel use
1_data_demand	BiofuelDataOECD	Commodity biofuel use and biofuel production 2000-2028
1_calc_human_demand	calc_hum_demand	Human food and non-food demand for agricultural products

4 Calculation steps

The principle of the FABLE Calculator is to define several steps of calculation where, with the exception of 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 6. 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:
- 1_calc_human_demand (Step 1 in Figure 6)
- 2_calc_livestock (Step 2),
- 3_calc_crops (Step 3),
- 4_calc_land (steps 4, 5 and 6),
- 5_feas_livestock (step 7),
- 6_feas_crops (step 8),
- 7_feas_consohum (step 9),
- 8_calc_emissions (step 10),
- 9_calc_water (step 10).

In each calculation worksheet, there are several tables which use data input and calculation results from previous steps and which themselves can be referenced in the formulas of the tables defined in next steps.

Figure 6. Sequence of the calculation steps in the FABLE Calculator
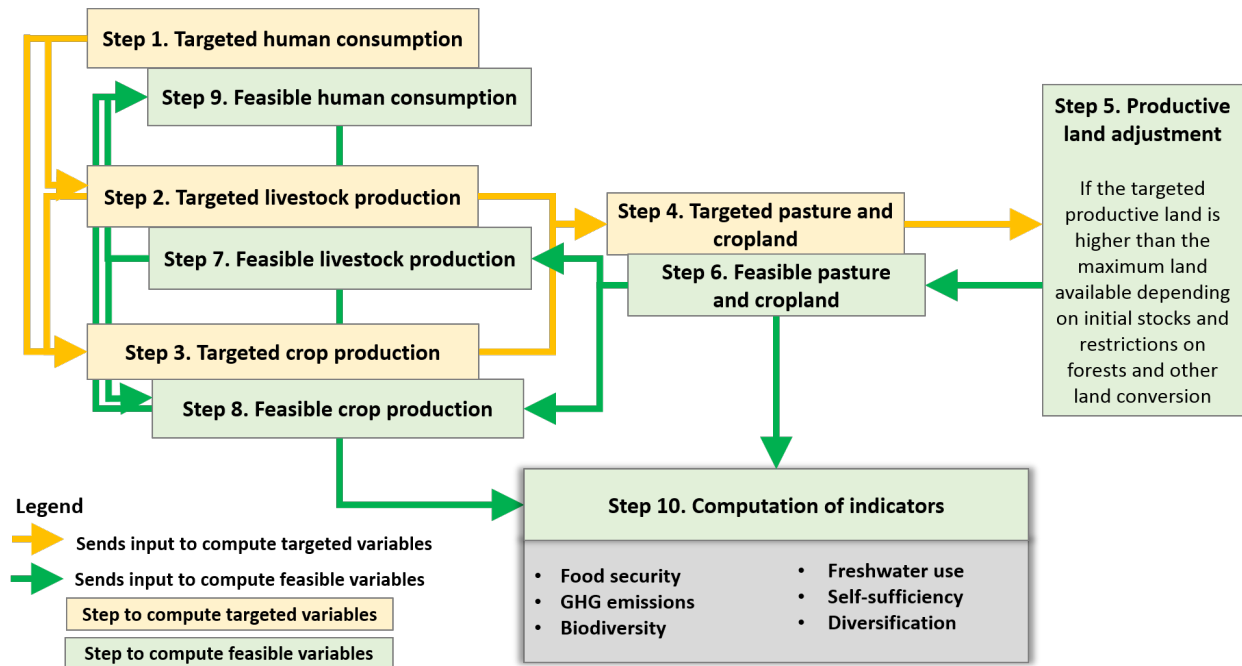
4.1 Step 1: computation of the targeted human demand

Worksheets in the FABLE Calculator:
⇒ 1_calc_human_demand
⇒ 1_data_demand

The computation of the annual demand for food and non-food human consumption is the first step of the FABLE Calculator. This means that all computed changes in the food and land-use systems modeled in the FABLE Calculator are caused by human demand (i.e. the underlying
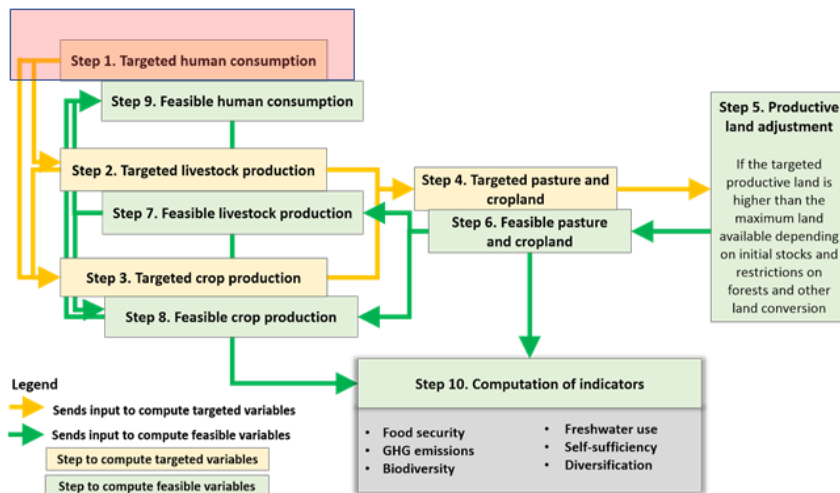
assumption is that human demand is the key driver of change in food and land-use systems). Human demand has three components: food, biofuels, and other non-food consumption (Figure 7). Most of the agricultural products in the FABLE Calculator are food products but can also be used for other purposes and some agricultural products are not fit for human consumption (e.g. fiber crops). Food and non-food demand per product per capita for the historical years is computed based on the commodity balance of the FAOSTAT.

Figure 7. Computation of the targeted human demand
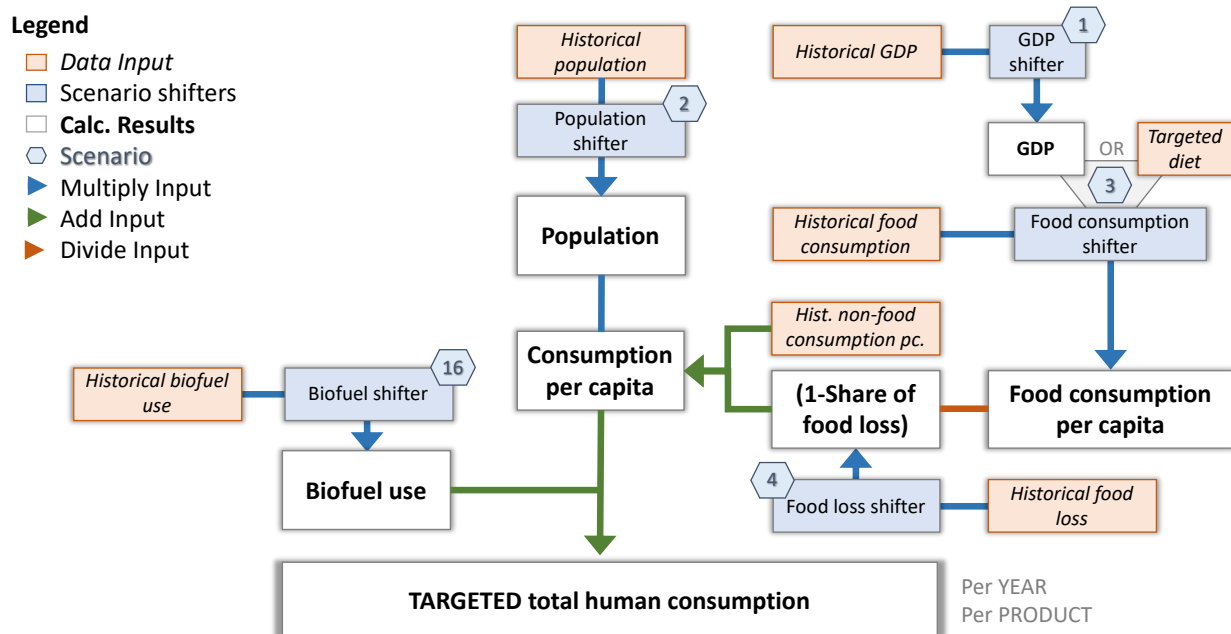
Note: *When an arrow passes through a box or is sourced from more than one, it means that two parameters are used together in order to compute the next parameter e.g. population shifter times historical population equals the population and population times consumption per capita plus biofuel use equals the targeted total human consumption. The numbers within the blue hexagons refer to the scenario table numbers in the worksheet Scenarios Selection, as labeled in the Open FABLE Calculator 2020 (e.g. 1 for Table S.1). The numbers may differ in other versions of the FABLE Calculator.*

The evolution of food consumption per capita depends on which scenario is selected. It is computed as the historical food demand in 2010 (without food waste) times the shifter corresponding to the selected scenario (cf. Diets). The evolution of biofuels does not depend on the population but is solely driven by the biofuel scenario that is selected. In Open FABLE Calculator 2020, the other non-food demand per capita is fixed at the 2010 level. 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 (cf. Food waste). Finally, the total demand is computed by multiplying average demand per capita

by total population (cf. Population) plus the demand to produce biofuels. Historical consumption levels are directly taken from the FAOSTAT for 2000, 2005, and 2010 and future demand is computed for each 5-year time step over 2015-2050 for each of the 76 raw and processed agricultural products (cf. Appendix 1).

4.2 Step 2: computation of the targeted livestock production

Worksheets in the FABLE Calculator:

⇒ 2_calc_livestock

⇒ 2_data_livestock
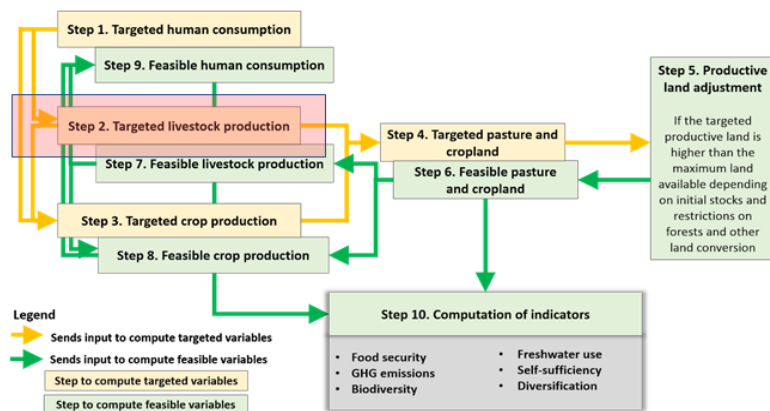
The computation of the production from the livestock sector is the second step in the FABLE Calculator. The livestock sector supplies animal food products (cf. Appendix 1) and consumes other agricultural products for animal feed. This explains why we need to compute the production of the livestock sector before the production of the crop sector. The objective of this calculation step is to compute the evolution of the livestock herd which then determines the feed demand and the pasture area which are used in the calculation steps that follow.

Figure 8. Computation of the targeted livestock herd, feed demand, and pasture area
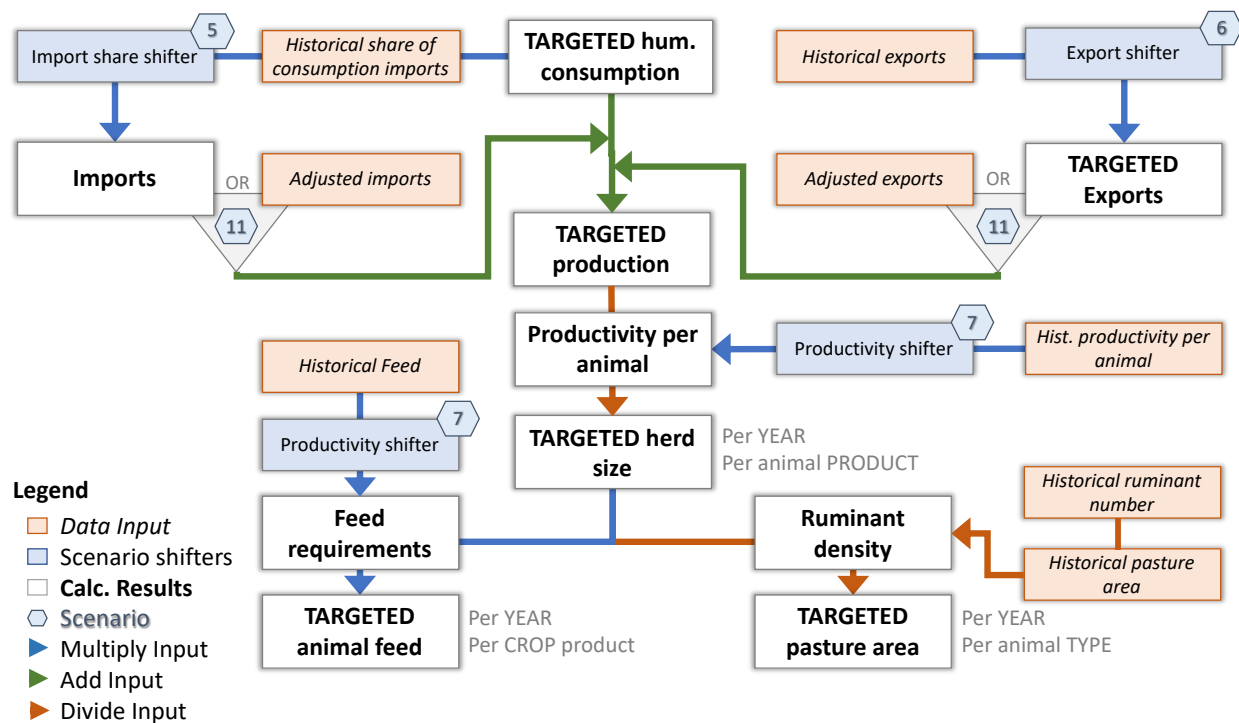
Note: When an arrow passes through a box or is sourced from more than one, it means that two parameters are used together in order to compute the next parameter e.g. historical exports times export shifter equals to the targeted exports. The numbers within the blue hexagons refer to the scenario table numbers in the worksheet Scenarios Selection, as labeled in the Open FABLE Calculator 2020 (e.g. 5 for Table S.5). The numbers may differ in other versions of the FABLE Calculator.

4.2.1 Herd

The demand for livestock products which has been defined in Step 1 (cf. Human demand) is the starting point of the calculation (Figure 8). Next, imports are computed as the share of total consumption which is imported times the consumption for each product and time step. The exported quantity is taken from the selected scenario (cf. Trade). Consumption minus imports plus exports increased by the share of the production which is lost gives the production which is required domestically by animal product and time step. Production loss is product specific. It is computed based on FAO's Commodity Balance (FAOSTAT, 2020) and is kept constant at 2010 levels over 2010-2050. 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. Livestock production systems, input, output, and emission factors are taken from Herrero et al. (2013).

One difficulty in modelling the livestock sector is the fact that some animal products, such as milk, can be produced by different animals and across different production systems. In order to compute the number of animals which are required to reach the projected domestic production level, we multiply total domestic production by animal product 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). This parameter is constant but should be made dependent on scenarios in the future to allow for testing of structural changes in the livestock sector. Finally, the production per animal type and production system is divided by the average productivity per Tropical Livestock Unit (TLU) to compute the herd in 1,000 TLUs for each animal type, production system, and time-step. Animal productivity depends on the level in the year 2000 as reported by Herrero et al. (2013) and the productivity shifter in the selected animal productivity scenario (cf. Productivity).

4.2.2 Feed

The herd number by animal type and production system which is computed during the previous computing step is the starting point for the calculation of feed demand (cf. Herd; Figure 8). 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 (cf. Productivity). In reality, several factors could explain a lower increase in animal feed compared to animal productivity so this assumption might lead to overestimation of the increase in animal feed demand over time when productivity gains are high.

4.2.3 Pasture

The total herd number for ruminants (cattle, sheep, and goats) is the starting point for the calculation of the pasture area (cf. Herd; Figure 8). 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. However, an optional update package for implementing alternative scenarios on the evolution of the ruminant density is available.

4.3 Step 3: computation of the targeted crop production

Worksheets in the FABLE Calculator:
⇒ 3_calc_crops
⇒ 3_data_crops
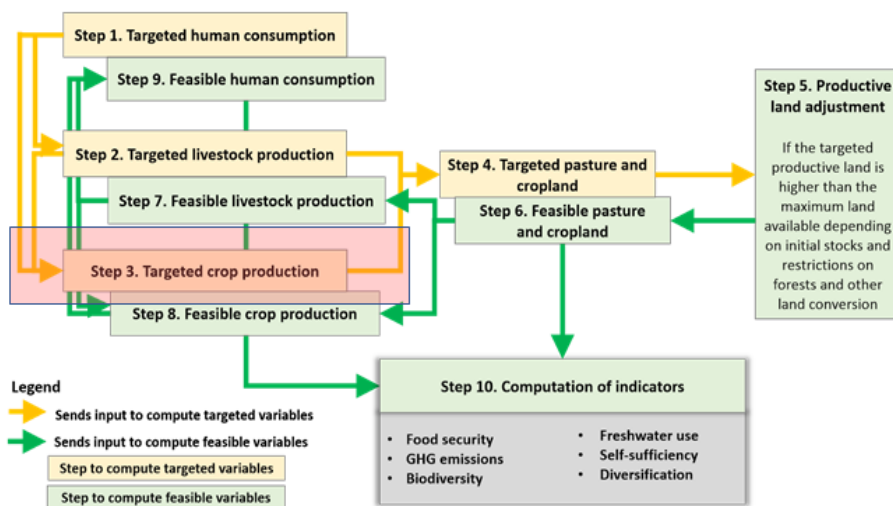
For crops, the starting points are human and feed demand which have been computed during the previous steps (cf. Human demand and Feed) (Figure 9). Then we compute imports by multiplying the sum of human demand and feed demand with the share of the consumption which is imported according to the selected import scenario, and exported quantity is taken from the selected export scenario (cf. Trade).

According to the FAOSTAT Commodity Balance (FAOSTAT, 2020), post-harvest losses include "waste during the year at all stages between the level at which production is recorded and the household" (i.e. storage and transportation); in the FABLE Calculator, losses in retail are considered as part of food waste (c.f. Food Waste). We compute the share of losses for each commodity in each country as the quantity of historical losses over production plus imports plus stock withdrawals, based on historical data from the FAO Commodity Balance. By default, depending on the selected scenario (cf. Post-Harvest Loss), we either keep the share constant at 2010 levels for the rest of the period 2015-2050 or reduce it by a target percentage by 2050, where the time steps are defined through the set implementation speed. Stock variation is only included for historical years using FAO statistics and assumed null for the rest of the period. Targeted production is computed as targeted human consumption, plus targeted feed consumption, plus targeted exports, minus imports, plus losses, minus stock variation.

Figure 9. Computation of the targeted crop production, harvested area, and planted area
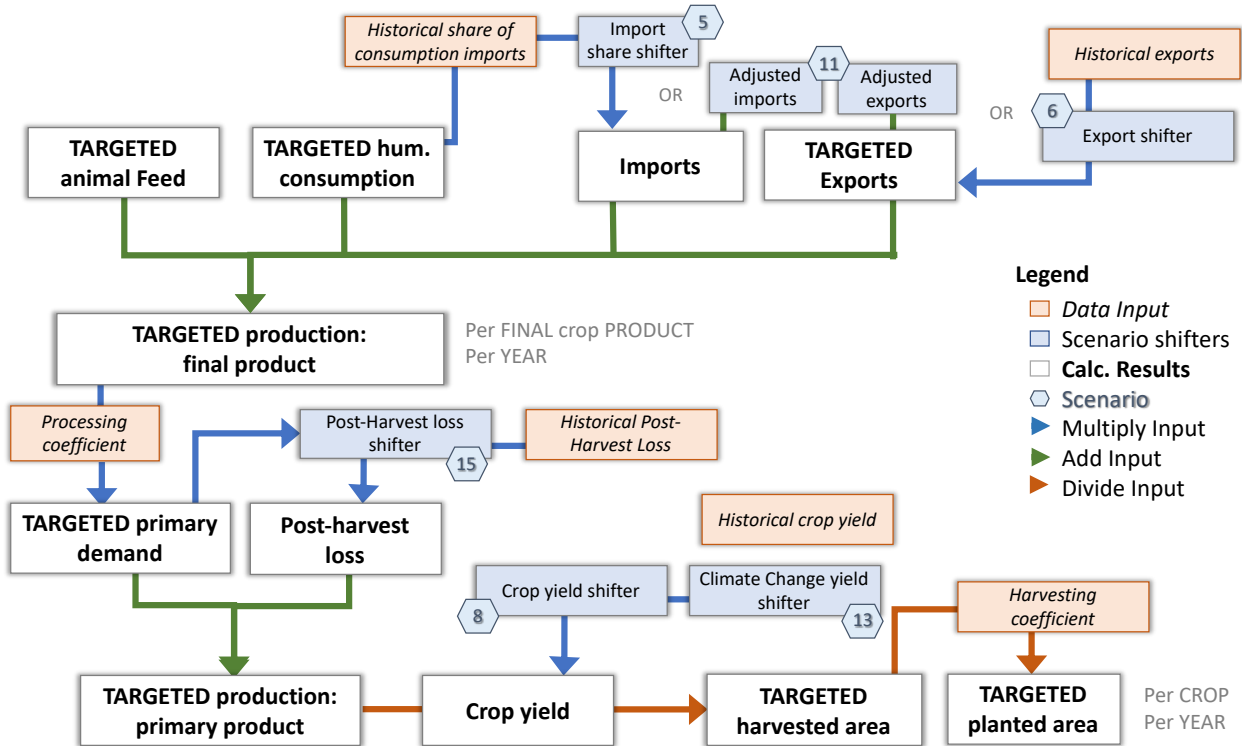
Note: *When an arrow passes through a box or is sourced from more than one, it means that two parameters are used together in order to compute the next parameter e.g. historical exports times export shifter equals to the targeted exports. The numbers within the blue hexagons refer to the scenario table numbers in the worksheet Scenarios Selection, as labeled in the Open FABLE Calculator 2020 (e.g. 5 for Table S.5). The numbers may differ in other versions of the FABLE Calculator.*

An additional demand for crops comes from processing. This is related to the human and feed demand of processed commodities such as vegetable oils or refined sugar. Targeted production or processed commodities is computed as described in the previous paragraph, but an additional computation step is required to compute the quantity of raw product (crop) which is needed to produce the targeted production of the final product. We compute the processing coefficient as the reported production level of a processed product divided by the reported processed quantity of the raw product which is used as input in 2010 according to FAO Commodity Balance (e.g. the production of sunflower oil divided by the sunflower quantity which is reported as processed). Targeted production is the sum of the targeted production of a crop which is used as the final product and the targeted production of a crop which is used for processing. In fact, several products can result from the processing of the same input (e.g. after extracting the oil from oilseeds, oilseed cakes which are left over can be used for animal feed). In order to convert the targeted production into harvested areas, we need to select the targeted input production for the production of a single final processed product to avoid double-counting.

Harvested area is computed as the total targeted production of a crop 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 (cf. Productivity). In some countries, several harvests are possible during the year resulting in lower cropland area than the total harvested area per year. 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. The planted area is obtained by dividing the harvested area by the harvesting coefficient.

4.4 Steps 4 to 6: computation of the targeted productive land, land adjustment coefficient and feasible productive land

Worksheets in the FABLE Calculator:
⇒ 4_calc_land
⇒ 4_data_land
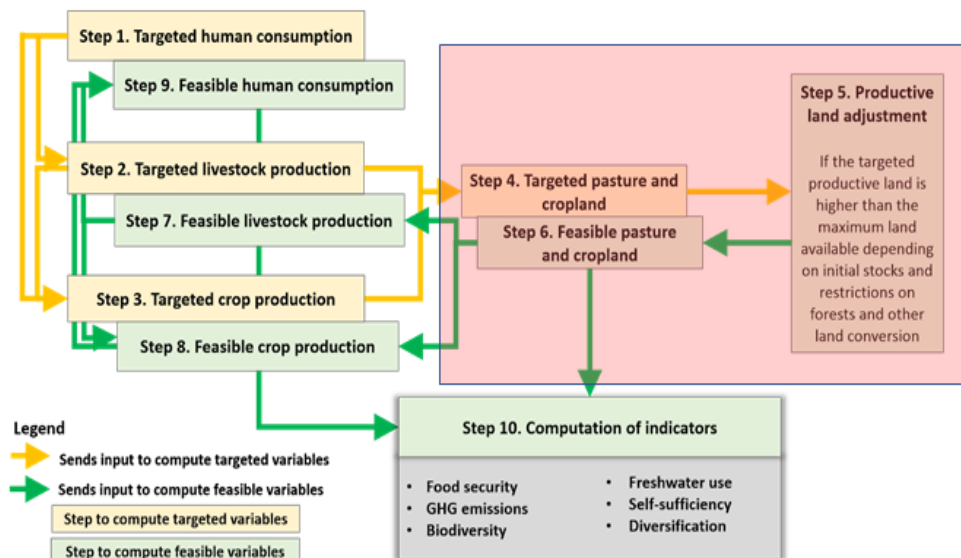
We represent **6 land cover types** in the FABLE Calculator: pasture, cropland, urban area, forest, new forest, and other natural land. Computed changes in area of pasture, cropland, urban, and new forest induce changes in the area of forest and other natural land as the total land area cannot expand. 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.

1. Pasture area - The difference between the targeted pasture area for each time step which is computed in the previous steps (cf. Pasture) and the initial pasture area at the beginning of the time step corresponds to the targeted pasture area change (expansion or reduction) (Figure 8;

Figure 10). The targeted pasture change is compared with the maximum pasture expansion which depends on the selected land scenario (cf. Land availability) e.g. in the *No Expansion* scenario, there is no pasture expansion possible after 2015. In case the targeted expansion is higher than the maximum expansion, the maximum value is used to compute the feasible pasture area.

2. Cropland area - The same is done for cropland. The targeted cropland area is computed as the sum of computed harvested area by crop in previous steps (cf. Crops; Figure 9) plus the area for "other crops" which results from the difference of cropland area in 2000 and the sum of harvested area by crop in the FAO database. The discrepancy between reported cropland and the sum of harvested area 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 taken into account in the FABLE Calculator. The area under "other crops" is set constant at 2000 levels for the whole period of simulation.

3. Urban area - Targeted urban area is computed based on historical expansion rates computed based on ESA-CCI land cover maps from 2000 and 2005 but capped at 3.5% of total land area maximum.

4. Afforested area - Depending on the Afforestation scenario which is selected (cf. Afforestation), there might be some land which is taken out of pasture, cropland and/or other natural land to be converted into new forest (afforested area). In this case, the afforested area is removed from the initial land area before the land expansion/reduction is computed.

5. Forest - Targeted deforestation is computed as the share of the total expansion which occurs at the expense of forests and the total targeted expansion which is computed by adding cropland, pasture, and urban area expansion. The share of the expansion which occurs on forest is based on FAO data over 2000-2005 but can also be changed through land scenario (cf. Land availability) e.g. in the *No deforestation* scenario, the share is set to zero. This targeted deforestation is compared with the maximum deforestation which is computed as the initial forest area at the beginning of the period minus the forest within protected areas. The targeted deforestation cannot be higher than the maximum deforestation.

6. 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. The maximum other natural land which is available for conversion to productive land use is computed as the initial other natural land at the beginning of the period minus the area within protected areas and minus the area which is targeted for afforestation. The targeted other natural land change is the sum of the targeted productive land expansion minus the targeted productive land expansion that occurs on forest land or the targeted reduction of productive land area, and the targeted afforestation on other natural land. The computed other natural land change cannot be higher than the maximum available other natural land area outside protected areas.

Figure 10. Computation of targeted expansion of agricultural land and urban area with a focus on pasture and feasible deforestation and other natural land change
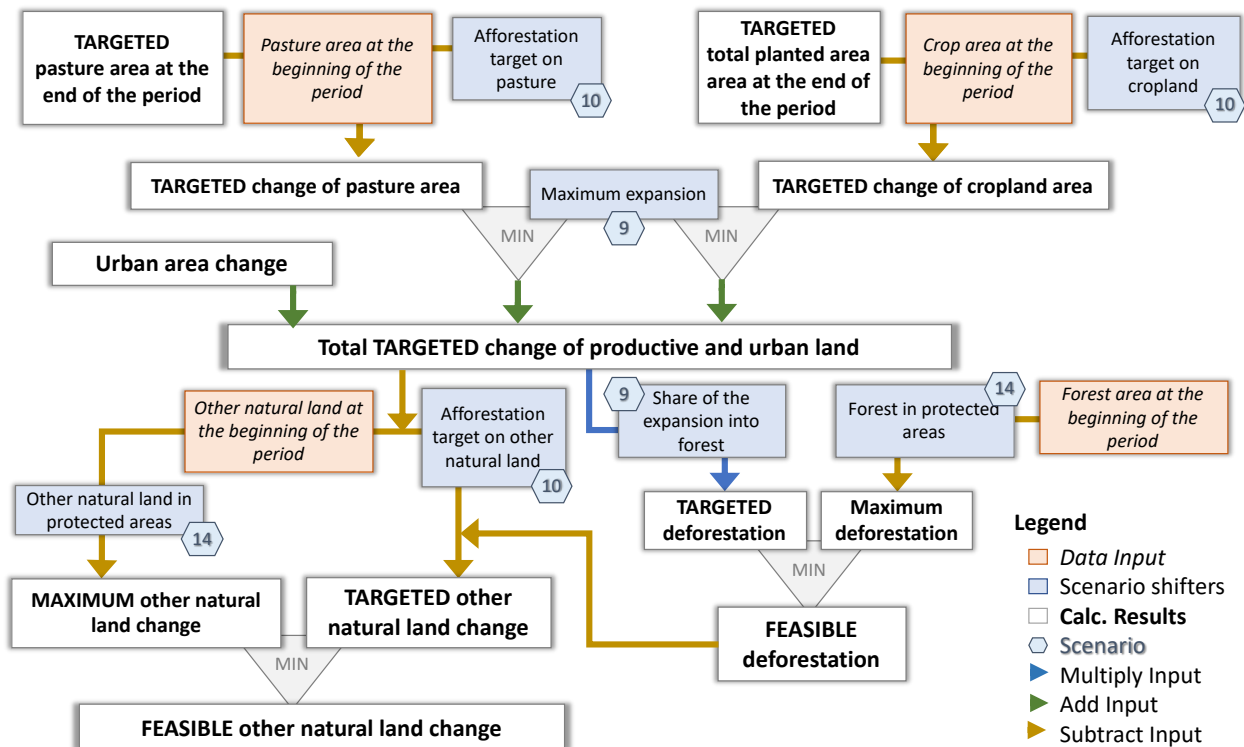
Note: *When an arrow passes through a box or is sourced from more than one, it means that two parameters are used together in order to compute the next parameter. The numbers within the blue hexagons refer to the scenario table numbers in the worksheet Scenarios Selection, as labeled in the Open FABLE Calculator 2020. The numbers may differ in other versions of the FABLE Calculator.*

If the targeted expansion of productive land (i.e. the sum of pasture, cropland, and urban area) is higher than the feasible expansion, we call the difference the "excess expansion" (Figure 11). Pasture and cropland targeted areas are then proportionally reduced according to their share in the total targeted expansion of agricultural land. 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.

Figure 11. Computation of the excess expansion and resulting cropland and pasture adjustment factors
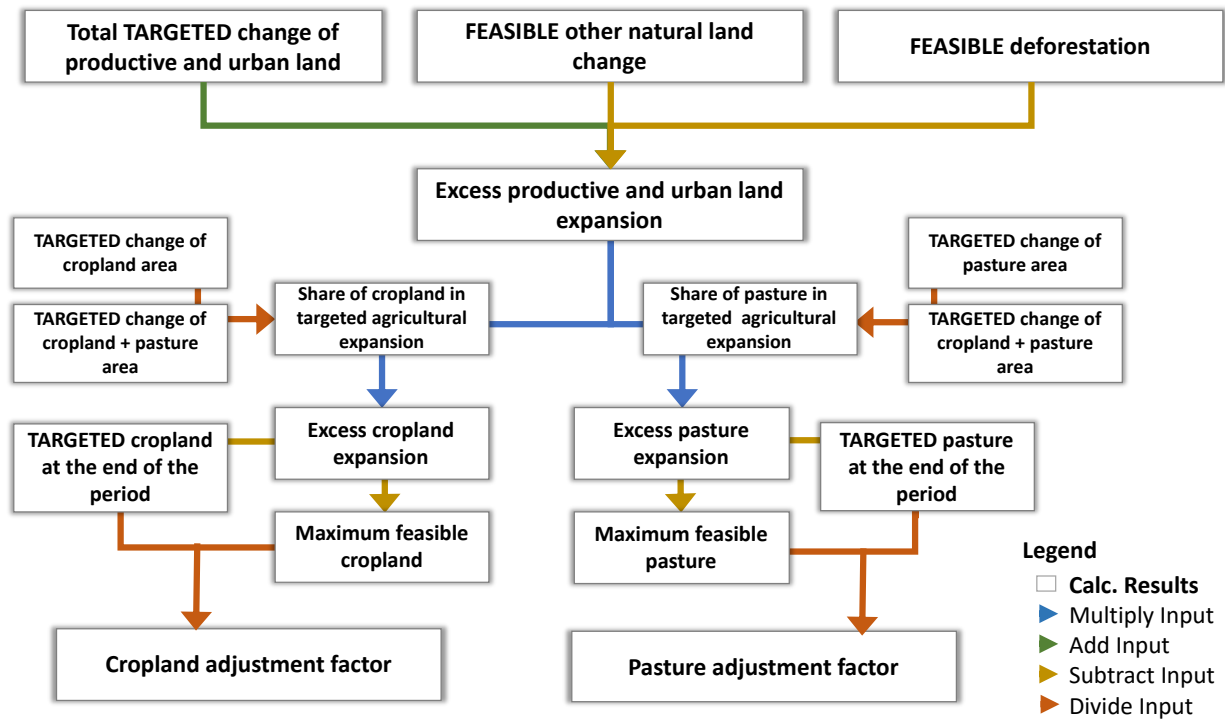
Note: *When an arrow passes through a box or is sourced from more than one, it means that two parameters are used together in order to compute the next parameter.*

4.5 Steps 7 to 9: computation of the feasible production, trade, and consumption

Worksheets in the FABLE Calculator:

⇒ 5_feas_livestock

⇒ 6_feas_crops

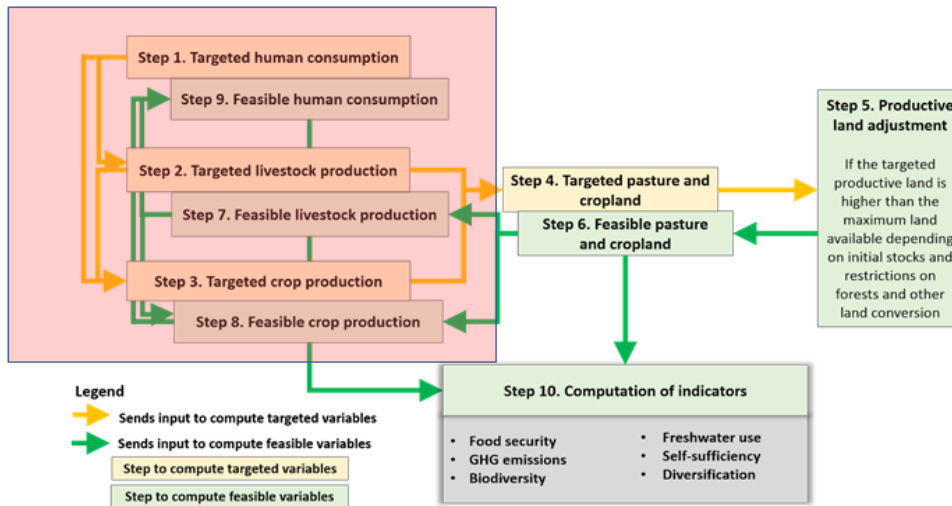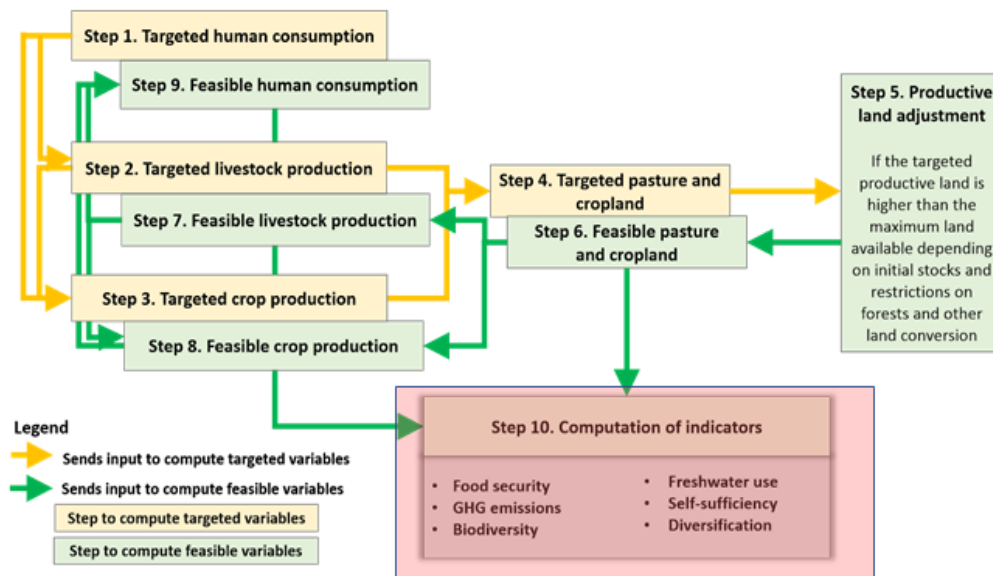Any discrepancy between targeted and feasible pasture area and/or cropland area needs to be channeled back through the causality chain up to the consumption level (Figure 6). Livestock is the first sector that should be adjusted. The targeted pasture area (cf. Pasture) is first multiplied with the pasture adjustment ratio. This affects the ruminant herd number (cf. Herd) which is recomputed as the feasible pasture area times the ruminant density. The feed demand for all crops and processed products from crops (cf. Feed) is first multiplied by the cropland adjustment ratio. Then, the new feed demand based on the feasible ruminant herd number is computed using feed requirements. The feasible feed demand is the minimum value between the new feed demand based on the adjusted herd and the adjusted feed demand based on the cropland adjustment ratio. The feasible herd is finally computed as the feasible feed divided by the feed requirement. Exports and final human consumption of livestock products are proportionally reduced using the ratio of the feasible herd compared to the targeted herd. If the scenario Fixed trade is selected, exports are not adjusted proportionally to the production reduction resulting from the land constraint: the reduction is distributed between feed demand and final human consumption only.

For crops, targeted planted area for all the crops (cf. Crops) is multiplied by the cropland adjustment factor (i.e. planted area by crop 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 and imports are fixed. Feasible final human demand, feasible exports, and feasible processed demand are adjusted to compensate for the remaining crop production reduction so that market balance is ensured.

5 Results indicators

Step 1. Targeted human consumption

Step 9. Feasible human consumption

Step 2. Targeted livestock production

Step 7. Feasible livestock production

Step 3. Targeted crop production

Step 8. Feasible crop production

Step 4. Targeted pasture and cropland

Step 6. Feasible pasture and cropland

Step 5. Productive land adjustment

If the targeted productive land is higher than the maximum land available depending on initial stocks and restrictions on forests and other land conversion

Step 10. Computation of indicators

- Food security
- GHG emissions
- Biodiversity
- Freshwater use
- Self-sufficiency
- Diversification

Legend
➜ Sends input to compute targeted variables
➜ Sends input to compute feasible variables
▭ Step to compute targeted variables
▭ Step to compute feasible variables

In a final step, the Calculator computes key indicators using as an input the feasible variables computed during the last steps. These include daily kilocalorie, protein, and fat consumption per capita; production value and trade balance; greenhouse gas emissions from land-use change and agriculture; the share of total land area used for biodiversity conservation, the share of total land where natural processes predominate, and the share of each land cover type within protected areas; water footprint from crops and livestock production. This list of computed indicators will be expanded in the future.

5.1 Food

Worksheets in the FABLE Calculator:
⇒ FOOD
⇒ 7_feas_consohum
⇒ 1_data_demand

The main food indicator is the average calorie consumption per capita per day (kcal/cap/day). We also compute protein and fat consumption in grams per capita per day. We start from the feasible total consumption for each product (cf. Feasible consumption), multiply it by the share of the total consumption that is for food, subtract food waste at the household level, divide by the population to get the average per capita consumption and by the number of days per year to

get the average daily consumption (cf. Human demand). Finally, we multiply the average daily consumption per capita by the calorie content of each product. Kilocalorie content per product per country is taken from the FAO Food Balance Sheets for the year 2000.

In the FABLE Calculator, the main results related to food are presented in the FOOD worksheet. In the first figure (Figure 12), we display the evolution of the total kcal/cap/day both for the targeted and the feasible levels. The targeted consumption should be equal to the FAO consumption for the historical years[4]. A difference between the targeted and the feasible food consumption can be due to two reasons: there is not enough land available or production is not represented for some of the products included in the demand (cf. Appendix 1) because there is no data on production in the FABLE Calculator. In this case, a lower feasible consumption than the targeted consumption should be observed for the historical period. If the gap between the targeted and the feasible consumption increases over time, the missing products on the production side are expected to represent a larger share of total consumption and/or the targeted production cannot be met because of land constraints (cf. Land scenarios and Land calculation).

We compare our results on calorie consumption with the historical consumption level according to FAO and the Minimum Daily Energy Requirement (MDER). The daily MDER is computed following FAO guidelines (Cafiero, 2014) using data on the structure of the population by age and sex and the dietary recommendations by age and sex for a certain level of activity. The average MDER at the national level is the sum of the MDER by population group multiplied by the population number in each group ("age-bracket") divided by the total population[5]. The dietary requirements are taken from the National Academy of Medicine (formerly the Institute of Medicine) for three different activity levels, low, medium, and high (Institute of Medicine, 2002), and the population structure is taken from the UN DESA medium estimate scenario (2017). The user is free to select the level of preferred activity as part of the scenario selection (cf. Population). An average feasible consumption level below, or just at, the MDER level could be worrying as it would mean that each individual in a given country would have just enough food to cover the minimum requirements if the available food were equally shared across the population.

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[4] *The calorie intake is computed on the basis of food consumption minus food waste. This can explain some deviations with the reported statistics on food consumption by the FAO which does not take into account these losses at the consumption level.*

[5] *Because the population level can also depend on a separate growth scenario determined by the user, the number of people in each age-bracket is scaled accordingly. Scaling of populations in age-brackets is simple and linear, meaning that there is no effect on the population age structure across age-brackets (i.e. selecting different population growth scenarios in the Open FABLE Calculator 2020 changes only the number of individuals represented in each age-bracket, not the structure across age-brackets).*

Figure 12. Average daily food intake per capita at the national level
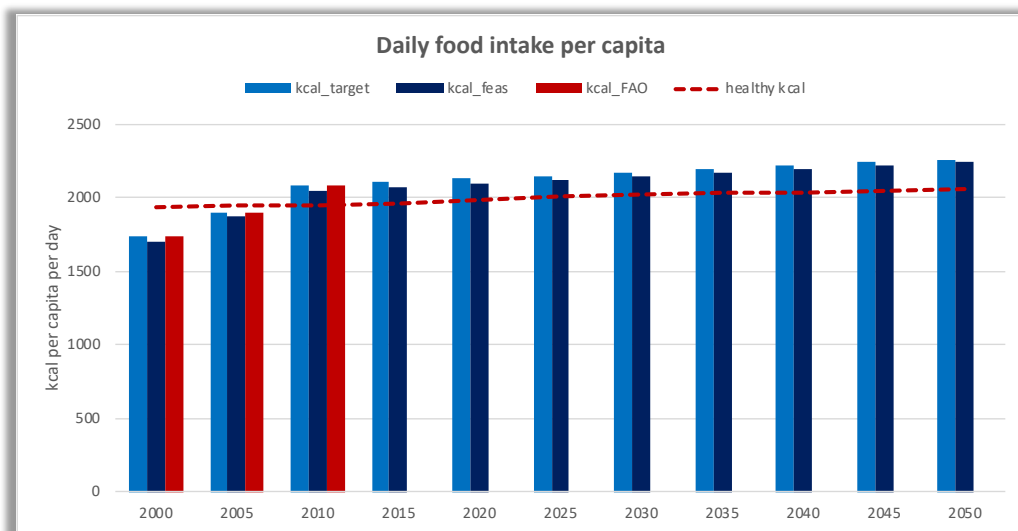
The evolution of protein and fat intake, in total or by food group, is also monitored in the FABLE Calculator using average protein and fat content by product from FAOSTAT and the average consumption per capita. We notice that the average protein and fat content per product might vary significantly across countries and even for one country across different years. Some of our products are aggregates of several products with different protein and fat content and the weight of each product in the aggregated production might vary over time. There are also different nutrition properties per product variety and different countries might use different varieties of the same product. We compare the computed level with the recommended intake of proteins and fats. For fats the dietary reference intake is 20% to 30% of kilocalorie consumption and for proteins it is 10% to 35% of kilocalorie consumption.

Another figure of the FOOD worksheet presents the average daily kilocalorie consumption per capita per food group (Figure 13). The correspondence between product and food groups is presented in Appendix 1. The results are presented for feasible consumption only. The comparison between the computed feasible consumption by food group and the historical data from the FAO can help identify where a large gap between computed and historical consumption could come from and what should be corrected in the Calculator.

Figure 13. Average daily food intake per capita per food group at the national level
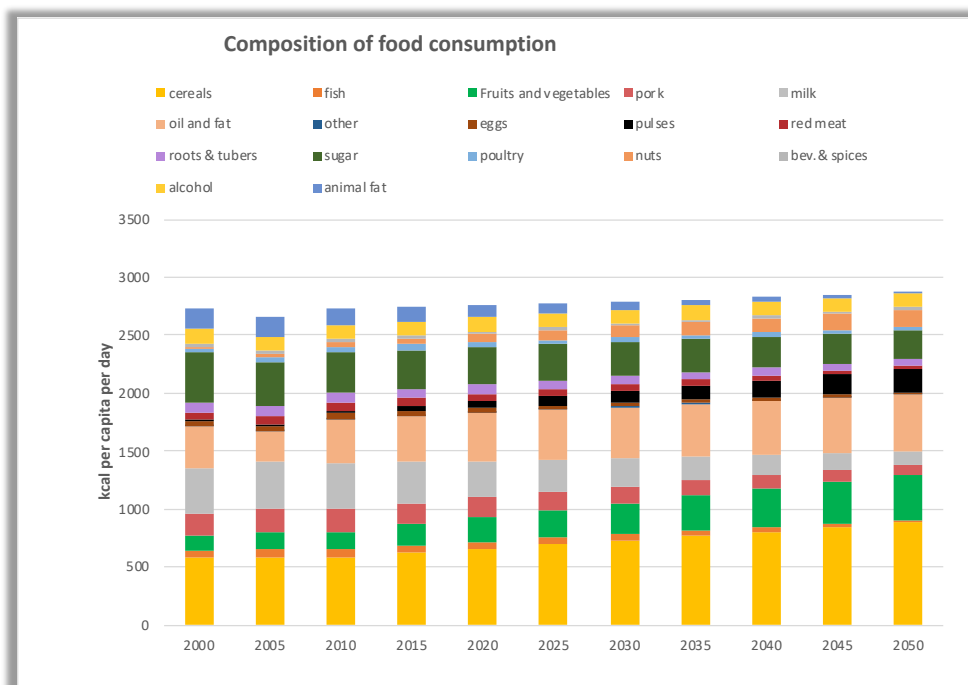
5.2 Production and trade

Worksheet(s) in the FABLE Calculator:

⇒ PRODUCTION

⇒ TRADE

⇒ 5_feas_livestock

⇒ 6_feascrops

The main indicator related to production is the total production value of the agricultural sector in local currency and US dollars in 2000. Prices are not generated by the FABLE Calculator. Historical producer prices from FAOSTAT are currently used to compute future production value. With constant prices over time, variation of the total production value over time is only caused by changes in the production quantities and changes in the share of products of different prices in the total production (composition effect). Targeted, feasible, and historical production values are displayed on the figure.

The main indicator related to trade is the net trade balance of the agricultural sector. It is computed as the sum of all exported quantities times historical export prices minus the sum of all imported quantities times historical import prices. It generally does not match national statistics on the value of the agricultural trade balance; it includes more processed products with a usually

higher unit price. This indicator is very coarse, but it still gives an idea of the evolution of the trade balance over time (i.e. if the agricultural trade balance deteriorates or improves). An agricultural trade deficit is not necessarily negative, but it can lead to a broader discussion about how the deficit is compensated by either the trade surplus in other sectors, increased debt, or increased foreign investment in a given country.

5.3 Land

Worksheet(s) in the FABLE Calculator:
⇒ LAND
⇒ 4_calc_land

5.3.1 Area in each land cover type

Our main indicator related to land is the evolution of the area of each land cover type (Figure 14). It shows the feasible area in each land cover class (cf. Land) and the historical data. FAOSTAT is used as the default reference. The results of the FABLE Calculator should mimic the historical evolution of land as closely as possible. Discrepancies highlight some potential problems, for instance some problems related to the evolution of the different demand components. Currently, the FABLE Calculator only includes a limited set of products in the animal feed requirements (i.e. the feed demand for some products is not represented, leading to an underestimation of the total demand for these products). For human demand and trade, estimates should be very close to the FAO values as historical data has been used to initialize key parameters (cf. Human demand, Trade). Another known problem is related to the production of by-products during the processing stage that could be used in animal feed, potentially substituting other crops and feedstock.

Figure 14. Area by land cover by year
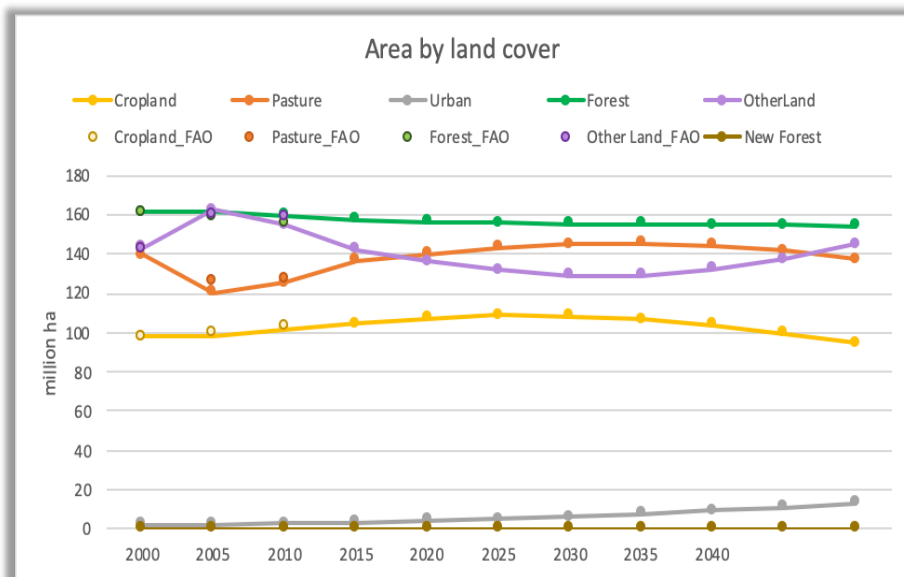
5.3.2 Deforestation

The second indicator is the evolution of forest loss and forest gain by 5 year-time step and the comparison with historical deforestation. By default, historical deforestation is computed from FAOSTAT land cover data. Net forest cover change is the sum of forest loss and forest gain.

Figure 15. Evolution of forest loss and forest gain
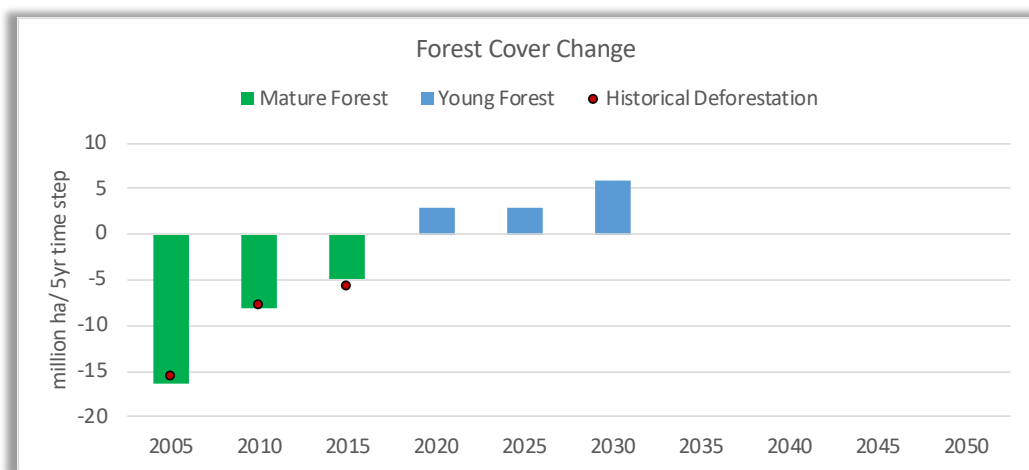
5.4 GHG

Worksheet(s) in the FABLE Calculator:
⇒ GHG
⇒ 8_calc_emissions
⇒ 8_data_emissions

In the GHG worksheet of the Calculator, GHG emissions are expressed in $MtCO_2e$ per year per 5-year time-step (Figure 16). GHG emissions are grouped into four categories: emissions from crops, emissions from livestock, net emissions from land-use change, and GHG savings from biofuels replacing fossil fuel. Total emissions from the year 2000 cannot be directly compared with the other time-steps as it does not include emissions from land-use change. Historical emissions from agriculture (crops and livestock) and projected emissions from agriculture according to FAOSTAT are also displayed for comparison. Historical emissions from land-use change according to FAOSTAT are not displayed as they are not directly comparable with emissions from land-use change computed in the Calculator.

Figure 16. GHG emissions from agriculture and land use change
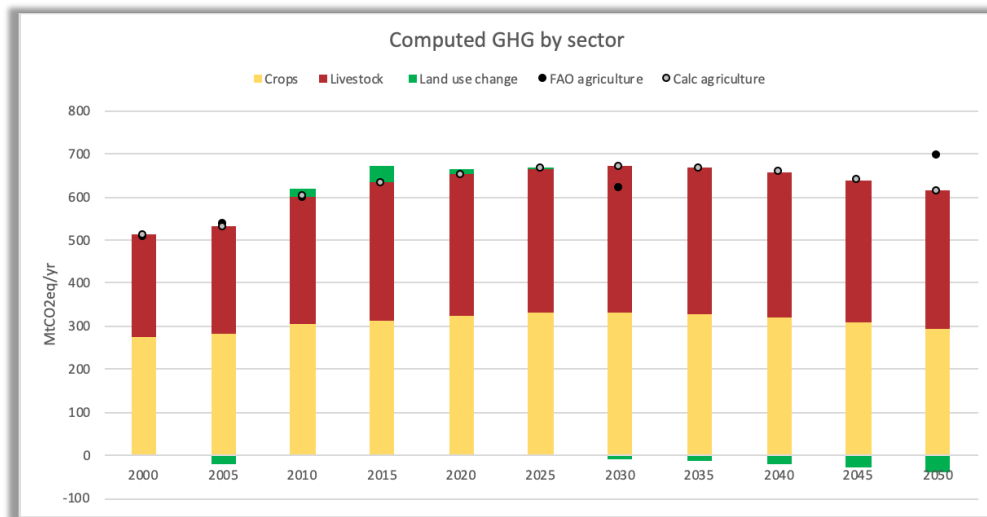
5.4.1 GHG from crops

There are three sources of emissions related to crop cultivation in the FABLE Calculator: methane emissions from rice cultivation, nitrogen emissions from synthetic fertilizers, and emissions related to energy use in crop fields. Emission factors are computed based on, or taken directly from, FAOSTAT for the year 2010. For rice cultivation, the emission factor is country specific and is expressed in tCO_2e per hectare of harvested rice. Total emissions are computed as the total harvested rice area (cf. Crops and Feasible production) times the emission factor per hectare. For emissions from fertilizer use, without detailed data on fertilizer use per crop, we compute the emission factor as total emissions from fertilizer use divided by total harvested area (i.e. the same emission factor per hectare for all the crops). Finally, the emission factor for energy use for crops is also not specific by crop because of the lack of more detailed information on the energy use by crop in the FAOSTAT database. We have three emission factors for energy: one for methane emissions, one for nitrogen emissions, and one for carbon emissions, but all are expressed in tCO_2e per hectare of harvested area.

5.4.2 GHG from livestock

There are two sources of emissions related to livestock production in the FABLE Calculator: methane emissions from ruminant enteric fermentation and methane and nitrogen emissions from manure. Emission factors per TLU per animal and production system come from the Herrero et al. (2013) database which has been calibrated on FAOSTAT for the year 2000. Total emissions are computed by multiplying the emission factor by TLU with the total herd in 1,000 TLU per animal type and production system (cf. Herd).

5.4.3 GHG from land

There are two sources of carbon sequestration and three sources of emissions from land use and land-use change in the FABLE Calculator: carbon sequestration in afforested land and in abandoned agricultural land, emissions due to the expansion of cropland, pasture, and urban areas into forests and other natural land. There is also an optional feature for computing emissions from peatland drainage (cf. Appendix 5).

Emissions from land-use change are computed based on the land-use change matrix of each time-step as the number of hectares of forest and other natural land which have been converted to cropland, to pasture, and to urban areas, multiplied by the emission factor which depends on the land-cover class which is converted and the land cover class which expands. Land-use change emission factors are computed as the difference between the carbon stock per hectare in the initial land cover and the carbon stock per hectare of the land cover class at the end of the period. In the FABLE Calculator, emissions from land-use change include conversion of forests and other natural land to cropland, pasture, and urban area. The FAOSTAT database only provides carbon stock of forest land. Carbon stock in other natural land is assumed to be 30% of the forest carbon stock, carbon stock in pastureland 10% of forest carbon stock, and cropland 5%. Carbon stock in urban areas is assumed to be null. **These are very rough assumptions, and each user is strongly encouraged to replace these assumptions by statistics on average carbon stock by land-cover class based on domestic biomass measurements**.

Carbon sequestration in afforested land is computed as the cumulative afforested land since 2000 and the sequestration rate is computed as the initial forest carbon stock divided by 50. This is also a rough assumption which implies linear growth of biomass and a 50-year period to reconstitute forest biomass. Carbon sequestration in abandoned agricultural land is assumed to be passive (i.e. without human action), which is why we assume a slower rate of carbon sequestration than on afforested land as we compute the annual sequestration rate by dividing the forest carbon stock by 80 instead of 50 for afforested land. Sequestration through passive regeneration is computed as the cumulative abandoned cropland and pasture times the sequestration rate.

5.4.4 GHG savings from biofuels

Based on the selected biofuel scenario, defining for each time step the amount of any possible commodity to be used as biofuel feedstock, GHG emissions savings due to biofuel replacing fossil fuels are calculated. Annual savings are calculated per feedstock, taking into account the conversion efficiency of each feedstock into biofuel, the biofuel energy density, and the CO_2 savings per energy unit of fossil fuel and added up for the total annual saving.

5.5 Biodiversity

Worksheet(s) in the FABLE Calculator:

⇒ BIODIVERSITY

⇒ 4_calc_land

5.5.1 Land which could support biodiversity conservation

The first indicator related to biodiversity is the share of the total land which could support biodiversity conservation (Figure 17). This indicator is the proportion of total land which is covered by forest, other non-agricultural land, and non-urban land areas to the country or region's total land area. It includes new forest as well as land converted from other uses. By default, the target is set at 50% share of total land area.

Figure 17. Share of total land which could support biodiversity conservation
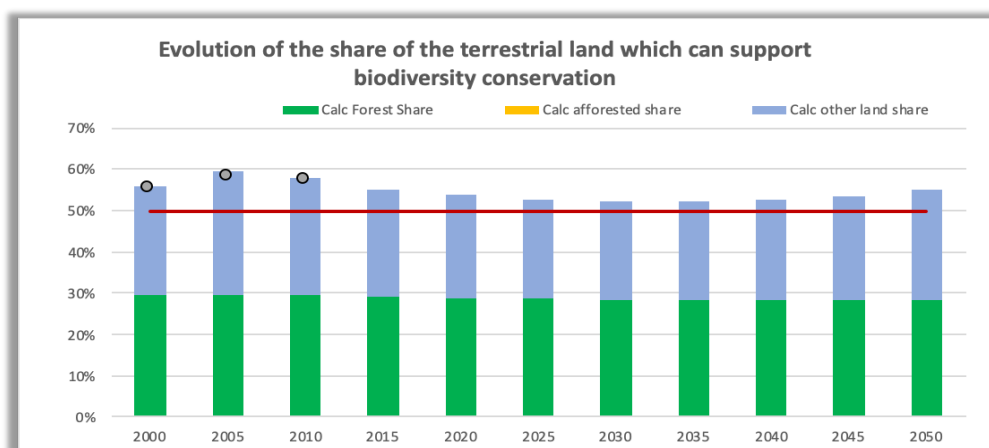
5.5.2 Land where natural processes predominate

The other indicator related to biodiversity is the share of the total land where natural processes predominate (Figure 18). The term is taken from Jacobson et al. (2019) who describe low-impact areas as "areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes, or faunal assemblages". There are many different spatial datasets that can be used as indicators of areas where natural processes predominate to monitor progress towards this target. By default, we use a combination of key biodiversity areas (BirdLife International, 2019), intact forest landscapes (Potapov et al., 2008), and Low Impact Areas (Jacobson et al., 2019). Starting from the historical area where natural processes predominate, we remove the converted area of natural land (forest or other natural land) times the historical share of area where natural processes predominate per land cover type, times 80%, assuming that the first 20% of the conversion would occur in non-intact area.

Figure 18. Share of total land where natural processes predominate
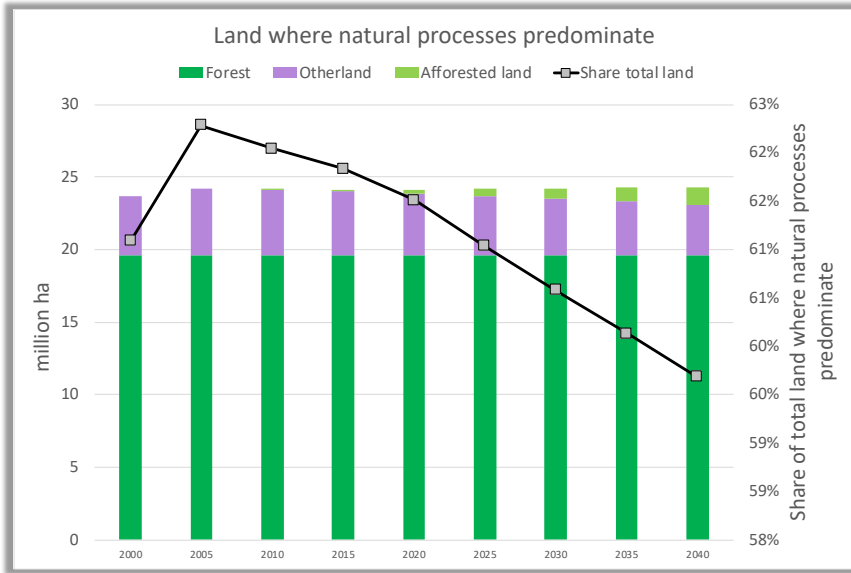
5.5.3 Protected areas

Finally, we compute the share of the total land in protected areas by 2050. For each unique ecoregion in a country, a specific share of protected land is targeted and implemented. Summing over the resulting protected areas gives the total protected area and the share of total protected land. The annual values per time step are broken down by land type (Figure 19).

Figure 19. Evolution of the land within protected areas
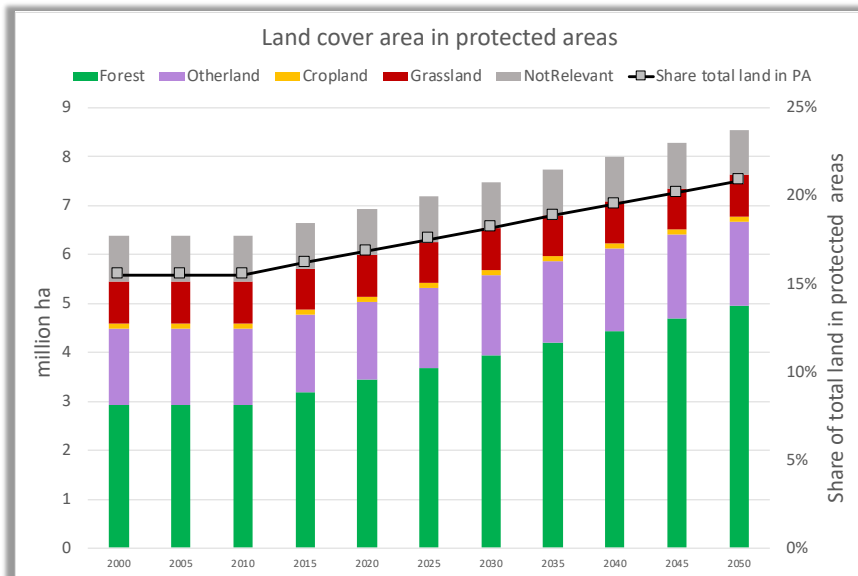
5.6 Water

Worksheet(s) in the FABLE Calculator:
⇒ WATER
⇒ 9_calc_water

In the Water sheet of the FABLE Calculator, the total blue, green, and grey water use for domestic agricultural production is computed and compared to historical values, given in Mm³ per year per five-year time step (Figure 20). The calculations are based on water-use data per product tonne from Mekonnen and Hoekstra (2010a, 2010b, 2011). Blue water refers to surface and groundwater, green water to rainwater if it hasn't become runoff. These two footprints describe water consumption instead of withdrawal. Consumed water is lost in the catchment area as it is incorporated in the product or evaporates to another catchment area. Water withdrawal, on the other hand, describes the total amount of water withdrawn from a source, including consumed water as well as withdrawals that are later returned to the source. Grey water refers to freshwater necessary to reduce pollution concentration to natural background levels.

The final overall water footprint for livestock products is calculated per five-year time step by summing over the feasible production quantity times the respective water fraction per tonne. Similarly, for crops, green and grey water use are calculated directly from the feasible production quantity times the respective footprint data. The blue-water footprint for some crops can also be affected by the climate change scenario (cf. Climate change).

In the FABLE Calculator, the crop footprint and the livestock footprint should not be added to compute the total water footprint of the production in a country! This would lead to a problem of double-counting since the livestock product footprint includes the footprint from crops used for animal feed and this is by far the most important aspect of the water footprint for livestock (Mekonnen and Hoekstra, 2010b). Consequently, only the crop footprint is taken into account in the domestic water footprint of agricultural production. Further work is required to split the different components of the livestock water footprint in the Calculator to be able to compute the full water use from domestic agricultural production, including on pastureland.

Figure 20. Evolution of water footprint for crops
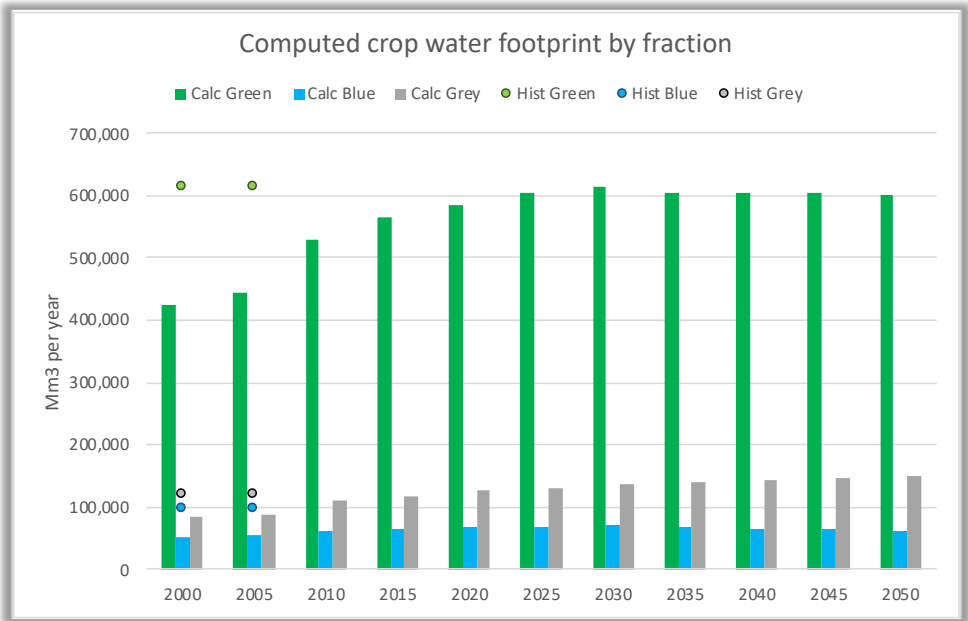
Estimated blue and green water footprints from Mekonnen and Hoekstra are based on daily soil water balance, crop water requirements, actual crop water use, and actual yields on global scale in 5 by 5 arc minute spatial resolution in rainfed and irrigated systems. To estimate actual crop water use, actual evapotranspiration is calculated, depending on climate parameters, soil water availability, and crop characteristics, where the latter depend on crop growth. Actual yield is estimated in response to computed water stress. Grey water is quantified considering nitrogen run offs and the difference between maximum acceptable concentration and the natural concentration (Mekonnen and Hoekstra, 2010a).

For animal products, Mekonnen and Hoekstra (2010b) consider water consumption for feed, animal drinking, and service water (water used for cleaning the animal and its environment). These footprints depend on the animal, the country of production and the farm system (grazing, industrial, mixed). When calculating the water footprint of feed, they use the national average footprints of the crop products described above, considering import shares from different countries, and combine those with a feed-mixing water footprint. Feed conversion efficiencies and feed concentrate shares are estimated based largely on FAOSTAT data and other sources. Finally, for each country and animal product a weighted average between the farming systems is calculated to get national average blue, green, and grey water footprints.

6 Conclusion

The FABLE Calculator is a recent tool that has been developed over the past three years (2018-2020). It has been used to produce pathways at the country level and for the rest of the world regions, as described in the FABLE 2019 Report (FABLE, 2019) and the FABLE 2020 Report (FABLE, 2020). There are country teams using and developing a FABLE Calculator in the following countries: Argentina, Australia, Brazil, Canada, China, Colombia, Ethiopia, Finland, Germany, India, Indonesia, Malaysia, Mexico, New Zealand, Norway, Russia, Rwanda, South Africa, Sweden, the UK, and the USA. If you would be interested in working on one of these Calculators or would like to adapt the tool to your country, or another jurisdiction, and would need some advice, please send an email to info.fable@unsdsn.org.

All users are welcome to report problems and suggestions for improvements to the forum dedicated to the FABLE Calculator or send an email to info.fable@unsdsn.org. You can also visit the FABLE page on the FOLU website for more information on the FABLE Consortium, as well as the FABLE Calculator training website where you can find more training materials and the latest updates of the Calculator.

An online version of the FABLE Calculator documentation is currently under development on GitHub in order to facilitate navigation across the document. We also acknowledge that this documentation does not provide sufficient guidance on many aspects. This will be the focus of dedicated, additional online training materials.

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3 Appendix 1: List of product groups and products

Short product group name	Full group name	PRODUCT
ALCOHOL	alcoholic beverages	beer, wine, fermented beverage, alcoholic beverage
BEVSPICES	beverages, spices and tobacco	clove, cocoa, coffee, pepper, piment, other spices, tea, tobacco
CEREALS	cereals	barley, corn, millet, oats, rice, rye, sorghum, wheat, other cereals
FIBERINDUS	fiber & industrial crops	abaca, jute, rubber, sisal, other hard fibers, other soft fibers, cotton lint
FRUVEG	fruits & vegetables	apple, banana, coconut, date, grape, grapefruit, lemon, onion, orange, pineapple, plantain, tomato, nuts, other citrus, other fruits, other vegetables
NUTS	nuts	nuts
OLSOIL	oilseeds and veg. oils	cotton, oil palm fruit, olive, rapeseed, sesame, sunflower, soybean oil, coconut oil, cotton oil, groundnut oil, olive oil, palm oil, palm kernel oil, rapeseed oil, sesame oil, sunflower oil, other oils
OLSCAKE	oil cakes	cotton cake, groundnut cake, palm kernel cake, rapeseed cake, soybean cake, sunflower cake, other oilseed cake
PULSES	pulses	beans, groundnut, peas, soybean, other pulses
ROOTS	roots and tubers	cassava, potato, sweet potato, yams, other tubers
SUGAR	sugar and sugar crops	sugarbeet, sugarcane, sugar raw
FISH	fish	fish
ANIMFAT	animal fat	butter ghee, cream, raw animal fat
EGGS	eggs	eggs
MILK	milk and dairy products	milk
OTHER	other livestock products	offal
PORK	pork	pork
POULTRY	poultry meat	poultry meat
REDMEAT	red meat	beef, goat & lamb

4 Appendix 2: Most used Excel features and formulas

If you click on the cell AA28 in the worksheet 1_calc_hum_demand you see that the value of this cell is equal to the column "Pop_shift" of the table called "gdp_pop_hist" when the year is lower or equal to 2015 and to the column "pop_shift_2000" from the table GdpPopTarget when the year is higher than 2015:
=IF([@year]<=2015,SUMIF(gdp_pop_hist[YEAR],[@year],gdp_pop_hist[POP_shift]),SUMIFS(GdpPopTarget[POP_shift_2000],GdpPopTarget[SCEN],[@[POP_scen]],GdpPopTarget[YEAR],[@year]))

You can easily find the table called gdp_pop_hist if you do an advanced search in the whole workbook looking for gdp_pop_hist in values. You will be directed to the cell where the name gdp_pop_hist appears which is at the top of the worksheet where the table is introduced, and above the table. Or you can go to the worksheet Index Tables and look for the table name in the first column. If you click on it, you will be also directed to the table.

The most used formulas in the FABLE Calculator are:
- **IF** - e.g. in the table called calc_hum_demand, in the column popshift (calc_hum_demand[popshift]).
- **IFERROR** - e.g. in calc_crops[PlantArea]
- **AND** - e.g. in calc_livestocknb[FinalExports]
- **SUMIF** - e.g. in calc_hum_demand[popshift])
- **SUMIFS** - e.g. in calc_hum_demand[popshift])
- **VLOOKUP** - e.g. in calc_crops[Crop_scen]
- **OFFSET** - e.g. in calc_land_cor[Initpasture]

We encourage users who are not yet familiar with these formulas to look at the help within Excel and explanations in several forums and online Excel tutorials.