World Health Organization

European Region

The Diet Impact Assessment model: a tool for analyzing the health, environmental and affordability implications of dietary change

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Abstract

This manual describes the Diet Impact Assessment (DIA) model – a new interactive modelling tool for analysing the health, environmental and affordability implications of diets and dietary change. The tool enables countries to analyse user-specific scenarios of dietary change, and to estimate the health, environmental and cost burden of each scenario in terms of diet costs, avoidable deaths, changes in resource use and compatibility with global environmental targets, including those associated with food-related greenhouse gas emissions, land use, water use and fertilizer application. The tool was commissioned by the WHO Regional Office for Europe and is based on analytical frameworks developed by Marco Springmann and colleagues. This manual outlines use of the tool and its scientific basis.

Keywords: HEALTH, ENVIRONMENT, NUTRITION, DIET

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Designed by: PELLEGRINI

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Abbreviations

CH_4	methane
CO_2	carbon dioxide
DIA	Diet Impact Assessment [model]
FAO	Food and Agriculture Organization of the United Nations
GBR	United Kingdom
GDP	gross domestic product
GHG	greenhouse gas
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
NCD	noncommunicable disease
N_2O	nitrous oxide
OECD	Organisation for Economic Co-operation and Development
PIF	population impact fraction
SDG	Sustainable Development Goal

1. Introduction

This manual describes a new modelling tool for analysing the health, environmental and affordability implications of diets and dietary change. In many regions, diets and the food systems underpinning those are neither healthy nor sustainable *(1)*. Unhealthy diets are a leading risk factor for noncommunicable diseases and are responsible for 1 in 5 deaths globally *(2,3)*. In addition, about 2 billion people are overweight and obese, 2 billion have nutritional deficiencies, and affording healthy diets continues to be a persistent challenge for households on low incomes *(4,5)*.

The environmental impacts of food production are similarly daunting. Agriculture is responsible for about a quarter of all greenhouse gas (GHG) emissions *(6)*, occupies about 40% of the Earth's surface *(7)*, uses 70% of all freshwater resources *(8)*, and over-application of fertilizers in some regions has led to pollution of surface and groundwater, and to dead zones in oceans *(9)*. As a result, the global food system has contributed to the crossing of several of the proposed planetary boundaries that attempt to define a safe operating space for humanity on a stable Earth system *(1,10,11)*.

Many of these health and environmental impacts are expected to intensify as the global population is projected to grow from the current 7 billion to close to 10 billion by mid-century *(10)*. This growing population is also expected to increasingly demand foods with greater health and environmental impact, such as meat, dairy products and processed foods. Without dedicated food-system changes, including the adoption of healthier and more plant-based diets, there is little chance of avoiding dangerous levels of climate change and staying within key planetary boundaries *(1,10)*.

Commissioned by the WHO Regional Office for Europe, the Diet Impact Assessment (DIA) model is intended to help devise pathways towards healthy and sustainable diets at a country level. Based on research published in the academic literature *(10,12–15)*, DIA enables countries to analyse user-specific scenarios of dietary change, and to estimate the health, environmental and cost burden of each scenario in terms of diet costs, avoidable deaths, changes in resource use and compatibility with global environmental targets – including those associated with food-related GHG emissions, land use, water use and fertilizer application. This manual outlines how DIA can be used and its scientific basis.

2. Running the tool

The modelling tool can be run online from the **WHO NCD Modelling Platform:**

https://gams.ncd.digital/

To start the modelling tool, select

"The Diet Impact Assessment (DIA) model"

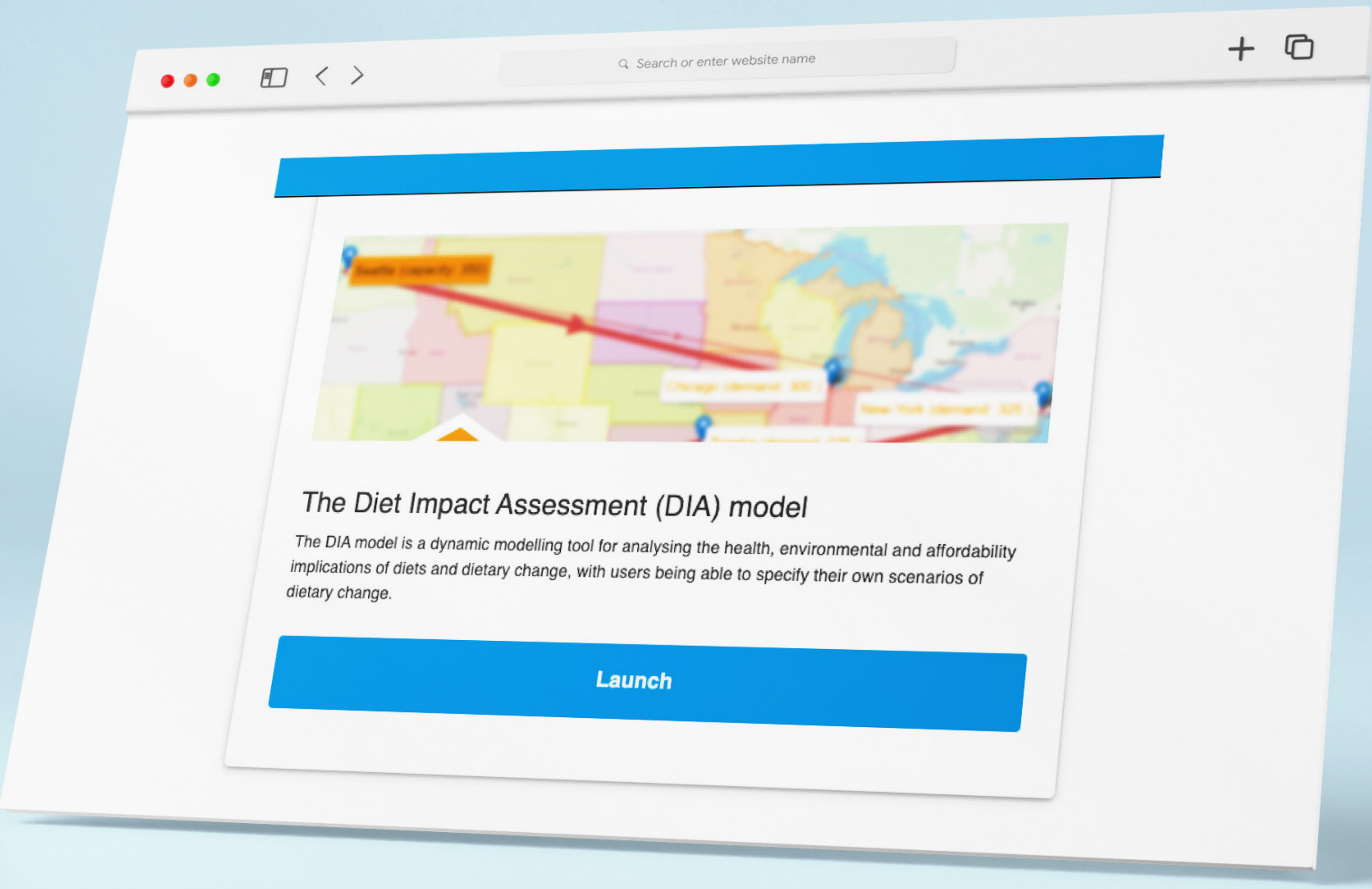
and click

"launch"

(See Fig. 1).

This opens an instance of the deployment interface of the model. You will see a pre-formatted pivot table without entries.

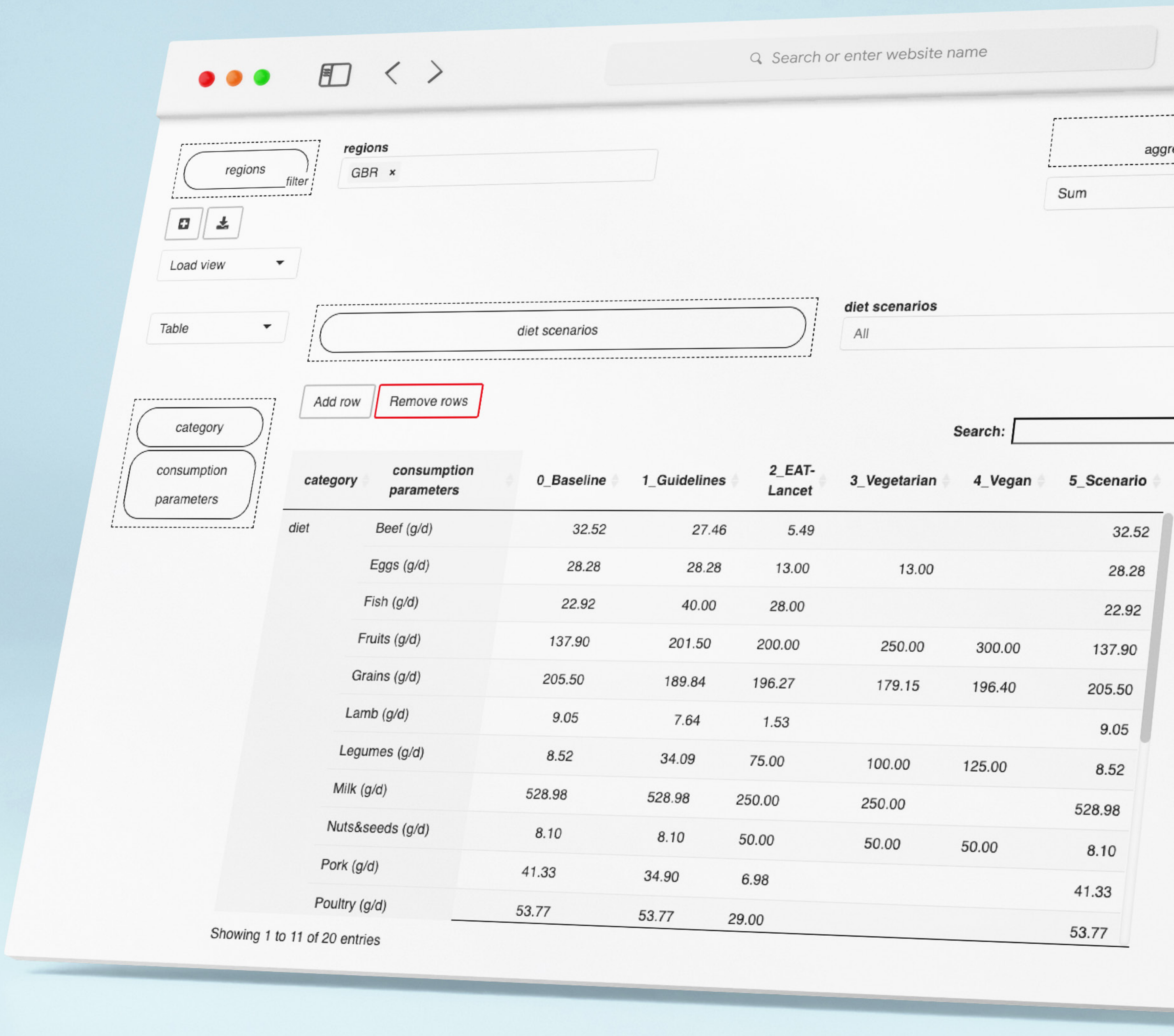
Fig. 1. Window for launching the modelling tool



2.1 Initializing the model

Please load the model data by clicking **"Load data"** on the left, then select the last run/scenario, usually denoted **"default"**, and click **"import"**
The pivot table for the input parameters should now be populated (see Fig. 2).

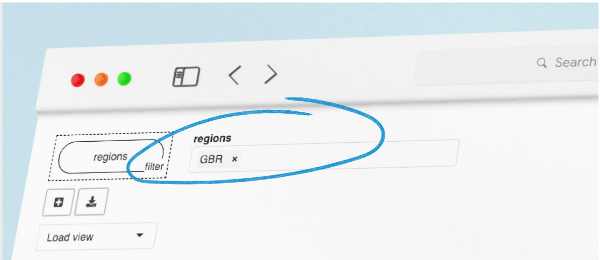
Fig. 2. Example of input field



2.2 Inspecting the input parameters

The input table allows you to inspect the data on diet and weight used as input to the analysis. It also allows you to specify the scenarios of dietary change that you would like to analyse. This manual first describes the input and output parameters and then provides detail on how to specify and run new scenarios (under "2.4 Specifying new diet scenarios").

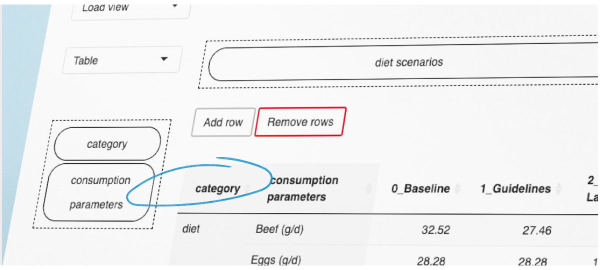
At the top of the pivot table of inputs, you can select the "**region**" in which you are interested. This is done by typing in or selecting the ISO3 code of the country.



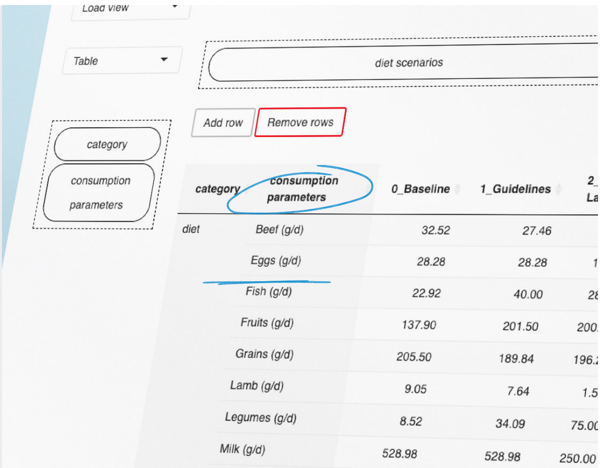
As an illustration, the United Kingdom has been chosen by selecting its ISO3 code "GBR" (Fig. 2).

The actual table allows you to inspect and specify the consumption and weight levels in the selected region:

The column "**category**" specifies whether the input data are related to dietary intake ("**diet**") or to weight levels ("**weight**").



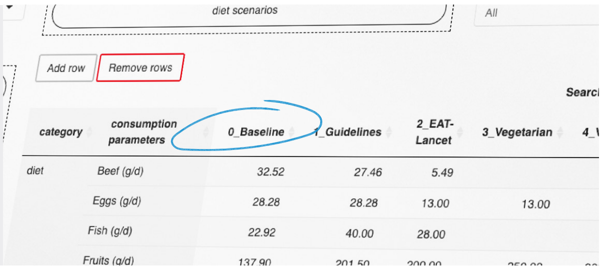
The column "**consumption parameters**" lists the food groups specified in the diets and their unit (e.g. intake of vegetables in grams per day per person, "**vegetables (g/d)**") and the weight categories with which the weight distribution is specified (e.g. the percentage of the population that is overweight, "**overweight (%)**").



The subsequent columns contain the consumption and weight-related values for different dietary scenarios:

“0_Baseline”:

current dietary intake and weight levels

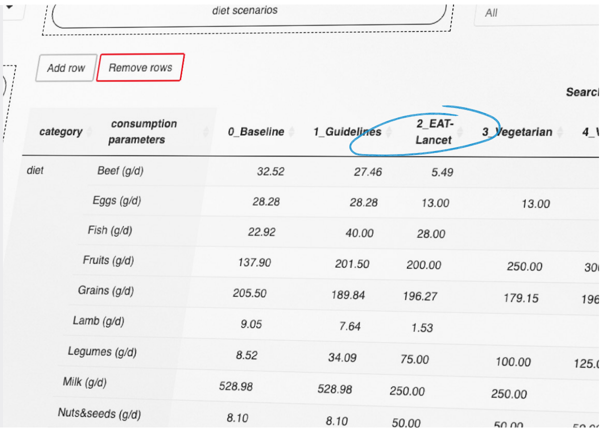


“1_Guidelines”:

dietary intake and weight levels recommended by the country’s national dietary guidelines (see Springmann et al (12) for a description of how this was quantified)

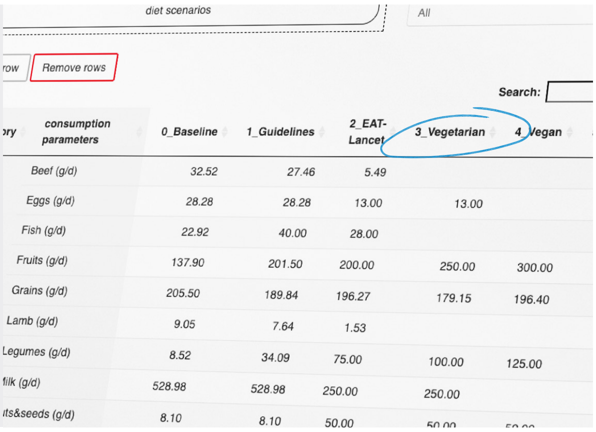
“2_EAT-Lancet”:

dietary intake and weight levels as recommended by the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems (1), in particular the main recommendations for healthy flexitarian diets



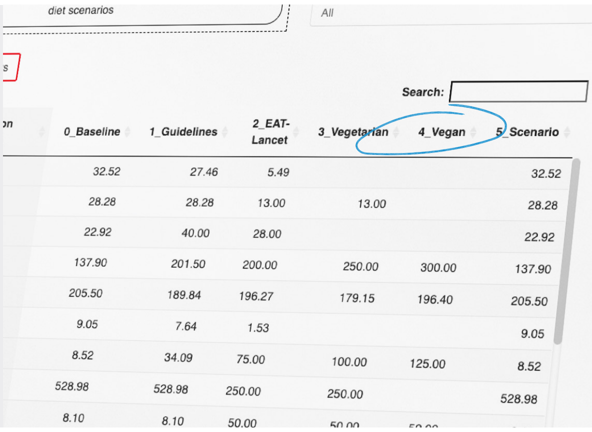
“3_Vegetarian”:

dietary intake and weight levels based on the EAT-Lancet flexitarian diets but which, instead of meat, contain more legumes, fruits and vegetables



"**4_Vegan**":

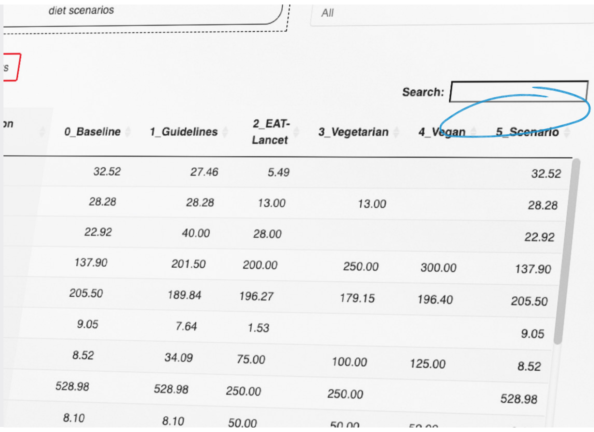
dietary intake and weight levels based on the EAT-Lancet flexitarian diets but which, instead of animal products, contain more legumes, fruits and vegetables



0_Baseline	1_Guidelines	2_EAT-Lancet	3_Vegetarian	4_Vegan	5_Scenario
32.52	27.46	5.49			32.52
28.28	28.28	13.00	13.00		28.28
22.92	40.00	28.00			22.92
137.90	201.50	200.00	250.00	300.00	137.90
205.50	189.84	196.27	179.15	196.40	205.50
9.05	7.64	1.53			9.05
8.52	34.09	75.00	100.00	125.00	8.52
528.98	528.98	250.00	250.00		528.98
8.10	8.10	50.00			

"**5_Scenario**":

modifiable dietary intake and weight levels, initially set to baseline values



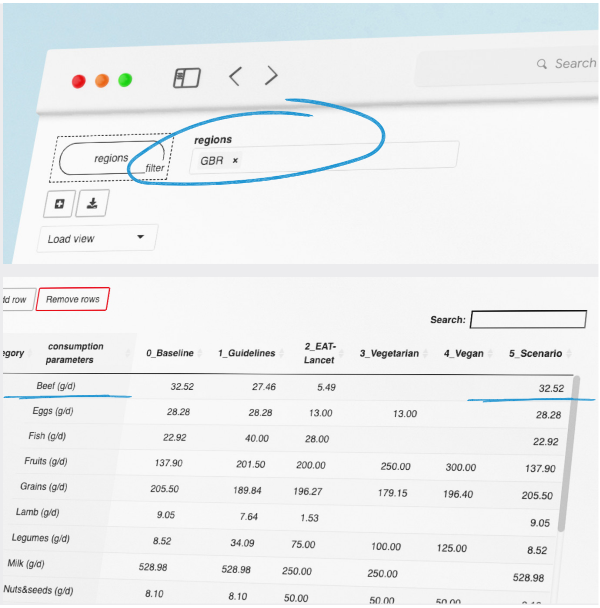
0_Baseline	1_Guidelines	2_EAT-Lancet	3_Vegetarian	4_Vegan	5_Scenario
32.52	27.46	5.49			32.52
28.28	28.28	13.00	13.00		28.28
22.92	40.00	28.00			22.92
137.90	201.50	200.00	250.00	300.00	137.90
205.50	189.84	196.27	179.15	196.40	205.50
9.05	7.64	1.53			9.05
8.52	34.09	75.00	100.00	125.00	8.52
528.98	528.98	250.00	250.00		528.98
8.10	8.10	50.00			

The detailed description of methods in **Chapter 3** provides the data sources for each parameter. Briefly, food intake in the tool is derived from data on the amount of food available in a country minus the amount wasted at the household level. This way of accounting for food intake allows for a consistent, comparable analysis that is easy to update and covers multiple domains, including health, environment and affordability.

2.3 Inspecting the model outputs

You can see an overview of the model results by clicking on "**Output**" in the menu on the left. Initially, there are no data for display, but the tabs will be populated once you run a scenario. You can modify any value in the open scenario "**5_Scenario**" (or other scenarios) in the input table, and click "**Solve model**" on the left. The model will solve all scenarios in the country for which data have been modified and will display the output of the analysis in the output section.

As an example, the United Kingdom ("**GBR**") has been selected as the region, and beef intake reduced in the open scenario "**5_Scenario**" by a few grams to let the model solve the United Kingdom-specific scenarios (Fig. 2). In the following sub-sections, the focus is mostly on the pre-specified scenarios.



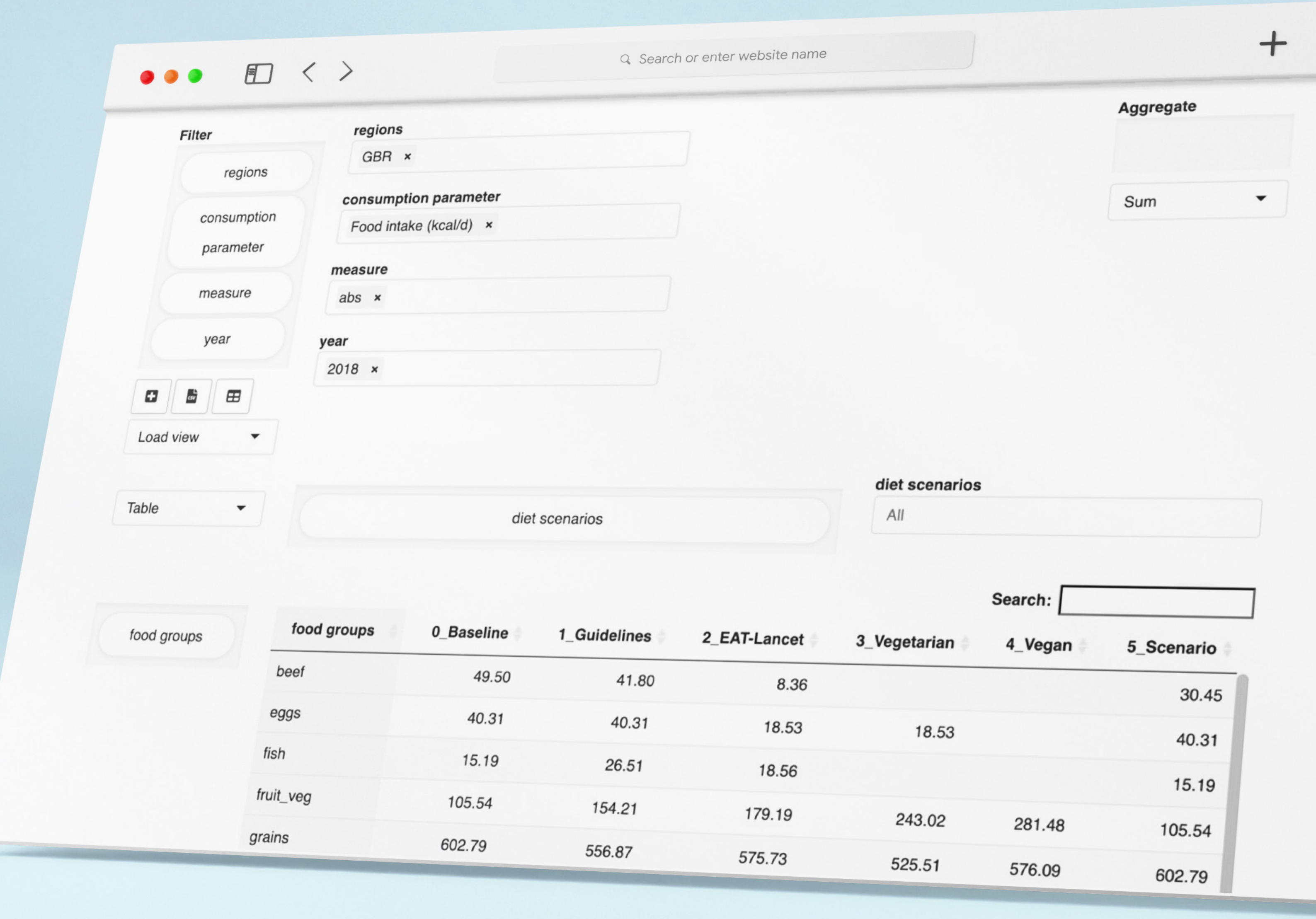
The output section contains several tabs: consumption analysis; health analysis; environmental analysis; planetary boundary analysis; cost-of-diet analysis; valuation of health impacts; and nutritional analysis. These are explained in greater detail in the subsections that follow (2.3.1–2.3.7).

2.3.1 Consumption analysis

This tab contains the results of the consumption analysis. The parameters are estimates of "**food intake**", with and without food waste, in grams per person per day (**g/d**) and kilocalories per person per day (**kcal/d**). In the "**measure**" field, the analysis can be selected to be displayed in absolute values ("**abs**", i.e. in g/d or kcal/d), as absolute changes from the baseline scenario ("**chg**", again in g/d or kcal/d) or as percentage changes from the baseline ("**pct**").

As an example, the United Kingdom ("**GBR**") has been selected as the region (in line with the changes in the input tab) and food intake (g/d) displayed for the different scenarios (Fig. 3). The field "**consumption parameter**" has been completed to also check the equivalent values of food intake in terms of kilocalories per person per day (kcal/d). For that, the new parameter "**Food intake (kcal/d)**" has been selected, and the pre-selected parameter "**Food intake (g/d)**" de-selected by clicking the "**x**" symbol on it. The table now displays food intake in terms of kilocalories per person per day by food group and diet scenario.

Fig. 3. Overview of consumption analysis in terms of food intake in kilocalories per person per day in the United Kingdom by food group and diet scenario



food groups	0_Baseline	1_Guidelines	2_EAT-Lancet	3_Vegetarian	4_Vegan	5_Scenario
beef	49.50	41.80	8.36			30.45
eggs	40.31	40.31	18.53	18.53		40.31
fish	15.19	26.51	18.56			15.19
fruit_veg	105.54	154.21	179.19	243.02	281.48	105.54
grains	602.79	556.87	575.73	525.51	576.09	602.79

2.3.2 Health analysis

This tab contains the results of the health analysis. The parameters include estimates of the “**numbers of avoided deaths**”, “**premature deaths**” (i.e. between the ages 30 and 70 years), “**percentage reductions in all-cause and premature mortality**” and “**avoided deaths per 1000 people**” – in each case for changes from baseline diets to the different diet scenarios by risk factor and cause of death.

The “**risk factors**” are reductions in the consumption of fruits, vegetables, legumes, nuts, seeds and whole grains; increases in the consumption of red meat and processed meat; and being underweight, overweight or obese. The risk-factor selection also contains summary estimates of all diet-related risks (“**diet**”), all weight-related risks (“**weight**”) and all diet- and weight-related risk factors (“**all-rf**”). The summary estimates are lower than the sum of the individual risk factors because they account for co-exposure to multiple risks.

The “**causes of death**” include coronary heart disease (“CHD”), stroke (“**Stroke**”), cancer (“**Cancer**”), type 2 diabetes (“**T2DM**”), respiratory disease (“**Resp_Dis**”) and the sum of all causes (“**all-c**”).

As an example, the United Kingdom (“**GBR**”) has been selected as the region, and the “**number of avoided deaths**” as the health parameter to be displayed, with a focus on all causes of death (“**all-c**”) and the “**mean**” values of the uncertainty interval. The pivot chart with this selection (Fig. 4) displays the number of avoided deaths for the different dietary scenarios by risk factor.

Different graphical representations of the health estimates can be selected by clicking on the current display configuration (“**Stacked bar chart**”) and selecting, for example, “**Table**” as the display option.

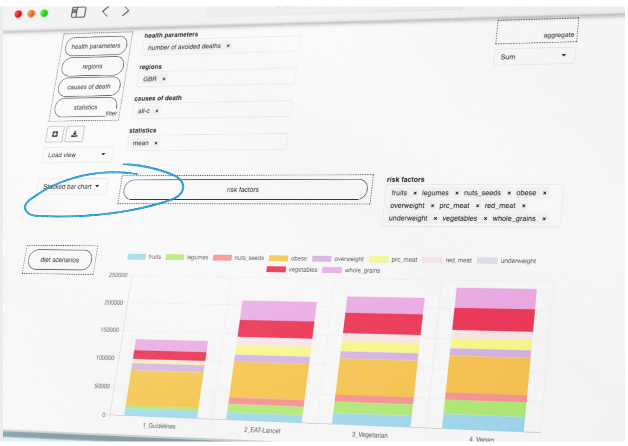
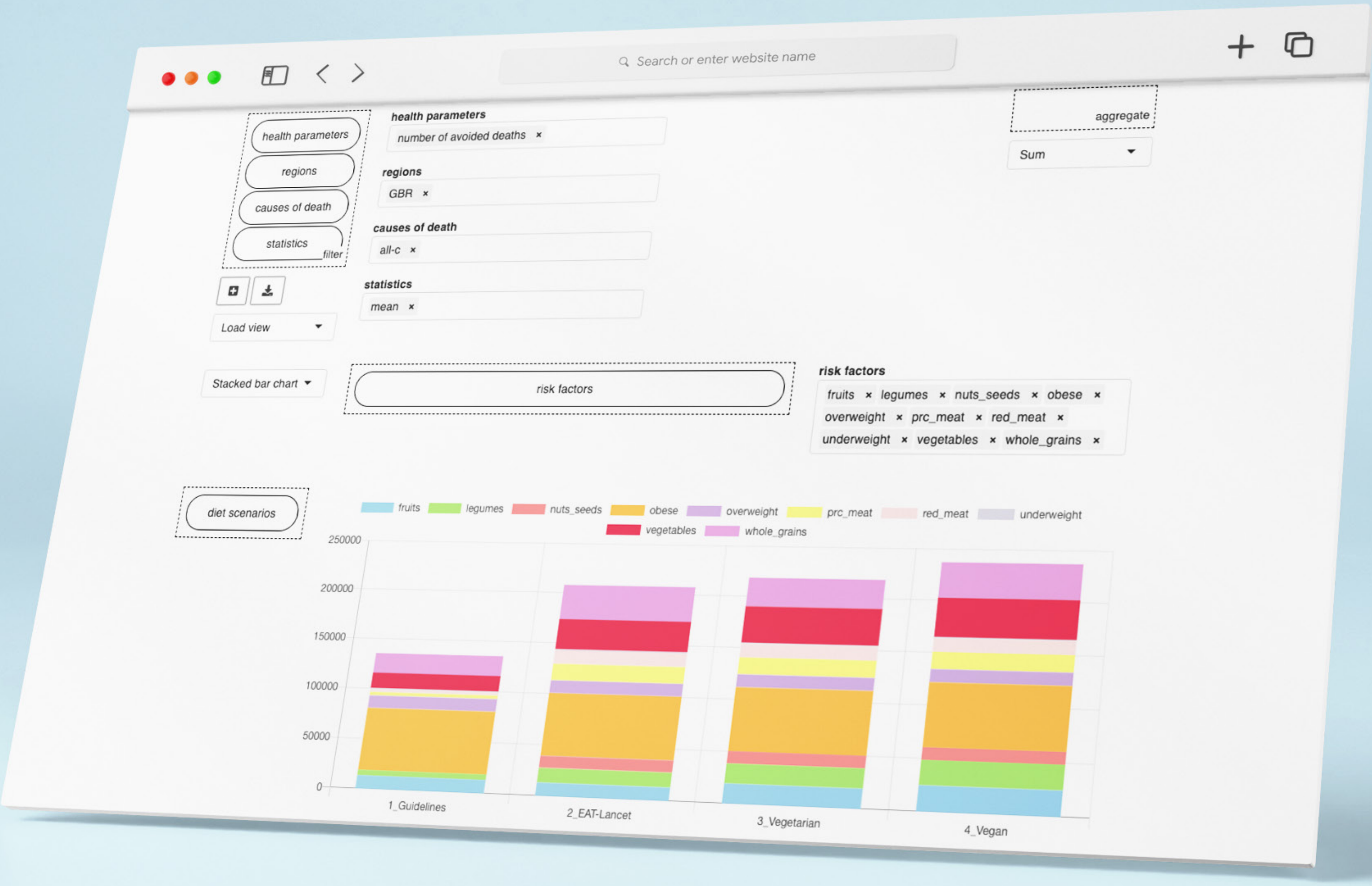


Fig. 4. Overview of the health analysis in terms of avoided deaths associated with dietary changes in the United Kingdom by risk factor and diet scenario



2.3.3 Environmental analysis

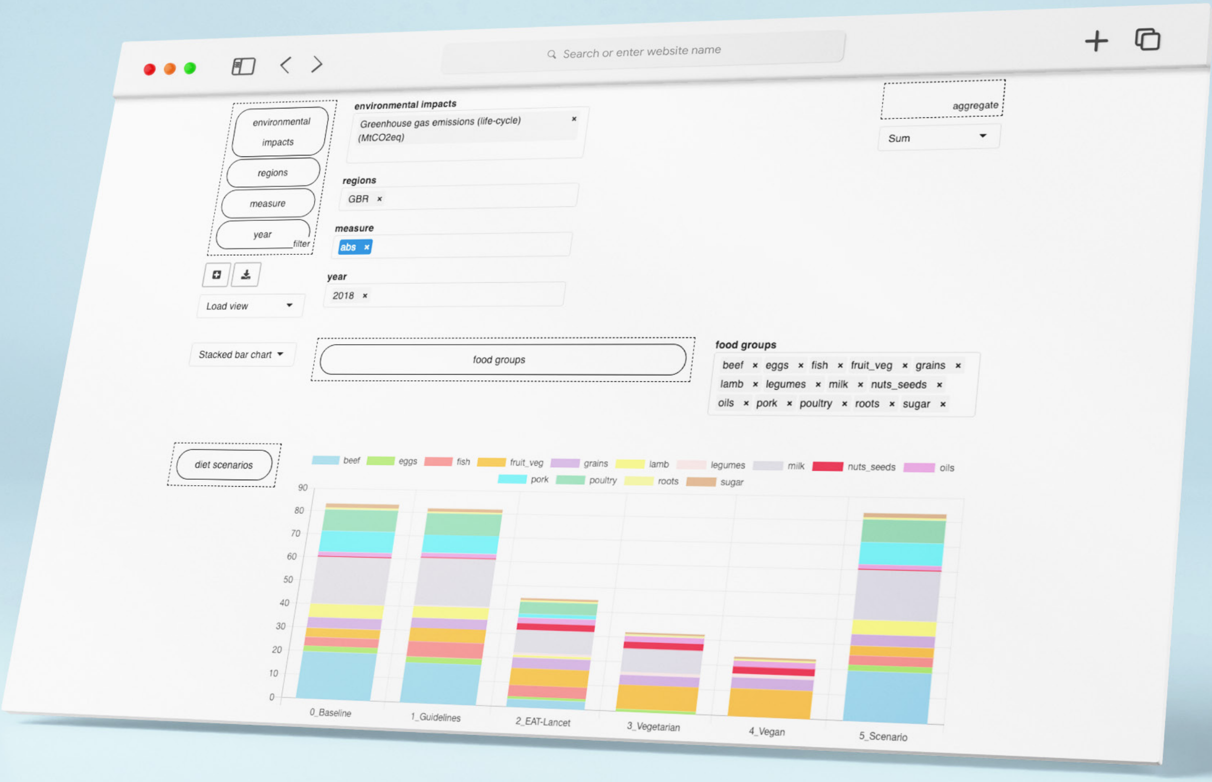
This tab contains the results of the environmental analysis. The parameters include estimates of "**greenhouse gas emissions**", covering either processed-based emissions of methane (CH_4) and nitrous oxide (N_2O) or all gases (including carbon dioxide (CO_2)) as measured by "**life-cycle analyses**"; "**cropland use**"; "**freshwater use**"; "**nitrogen application**" and "**phosphorus application**" for each diet scenario by food group and in total.

Different options for "**measure**", including absolute and percentage changes from baseline diets ("**chg**" and "**pct**") can be selected.

As an example, the absolute impacts have been selected of United Kingdom ("**GBR**") diets (including those of baseline diets) in terms of GHG emissions from a life-cycle perspective (Fig. 5).

As before, different graphical representations of the health estimates can be selected by clicking on the current display configuration ("**Stacked bar chart**") and selecting, for example, "**Table**" as the display option.

Fig. 5. Overview of an environmental analysis in terms of GHG emissions associated with United Kingdom diets by food group



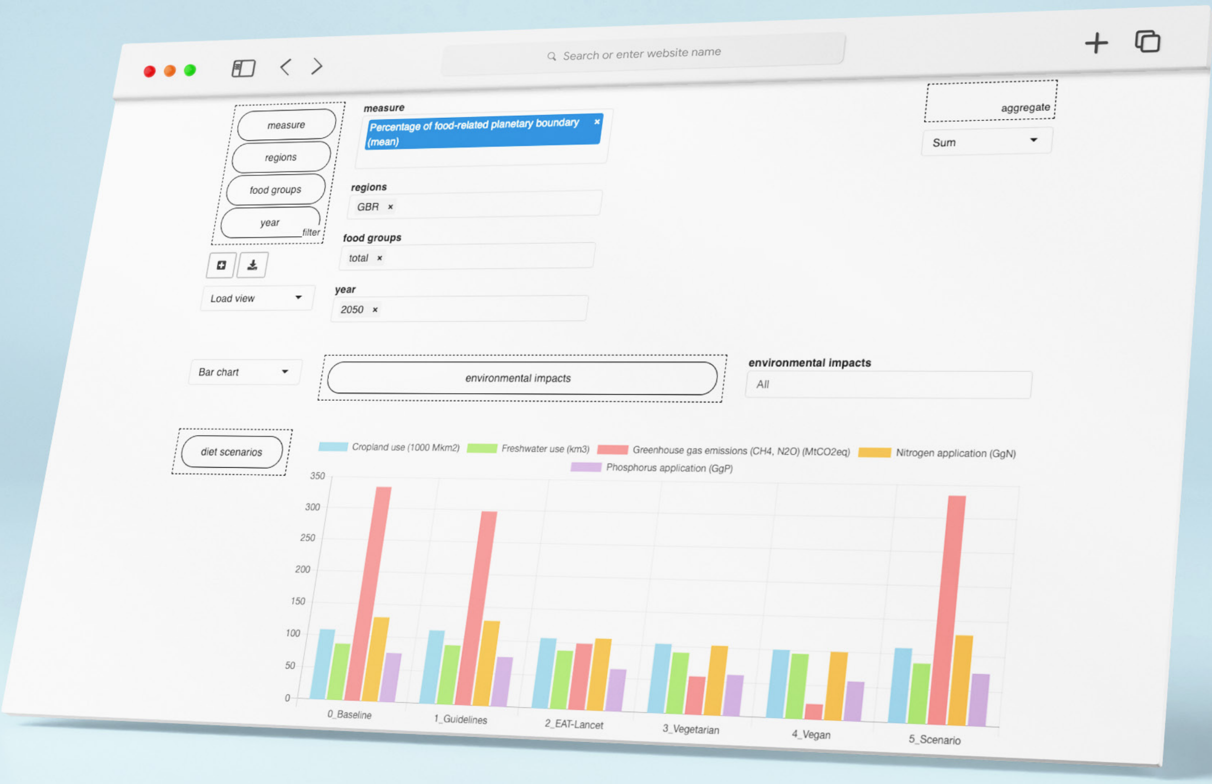
2.3.4 Planetary boundary analysis

This tab contains the results of the planetary boundary analysis. The results of the analysis answer the question of whether the different diet scenarios, if adopted globally, would be compatible with global environmental limits on the food system as specified by planetary boundary values and by the Sustainable Development Goals (SDGs).

The parameters are the "**global environmental impacts**" in absolute values and the impacts in terms of "**percentage of the mean and low and high values of the food-related planetary boundaries**". The boundaries comprise "**Greenhouse gas emissions**", "**Cropland use**", "**Freshwater use**", "**Nitrogen application**" and "**Phosphorus application**".

As an example, the following selection shows what the impacts would be of universal adoption of United Kingdom ("**GBR**") diets and the country-specific diet scenarios in terms of food-related planetary boundaries. These are expressed as percentages, summed over all food groups and for the year 2050 (Fig. 6).

Fig. 6. Overview of a planetary boundary analysis for United Kingdom diets and diet scenarios



2.3.5 Cost-of-diet analysis

This tab contains the results of the cost-of-diet analysis. The parameters include the cost of diet in 2017 in United States dollars per person per day (“**cost (USD/d)**”), absolute and percentage changes over the baseline scenario (“**change in cost (USD/d)**”, “**change in cost (%)**”) and the relative composition of costs by food group (“**composition of costs**”). The cost analysis can be specified to include food that is wasted at the household level (“**full_waste**”) or to omit these (“**no_waste**”). The statistics are “**mean**”, “**low**” and “**high**” values in relation to the standard deviation of food prices within each food group.

As an example, the cost of diets per person per day (“**cost (USD/d)**”) was selected in the United Kingdom (“**GBR**”), including food waste (“**full_waste**”) (Fig. 7).

Fig. 7. Overview of the cost of United Kingdom diets by food group and diet scenario

2.3.6 Valuation of health impacts

This tab contains the results of the valuation of health impacts based on pairing the number of avoided deaths with country-specific values of statistical life, which is a measure of the willingness to pay for a small reduction in mortality risk summed statistically to prevent one death *(16)*. The unit of the parameter can be selected as US dollar million or percentage of gross domestic product (GDP). As in the health analysis, risk factors can be selected individually for each scenario. The statistics are the "**mean**", "**low**" and "**high**" values of the base value of statistical life and the "**mean**", "**low**" and "**high**" values of the elasticity used to transfer the base value to different countries.

As an example, the health-related value of dietary changes in the United Kingdom ("**GBR**") as a percentage of GDP ("**value (% of GDP)**") has been selected for the different risk factors and scenarios of dietary change (Fig. 8).

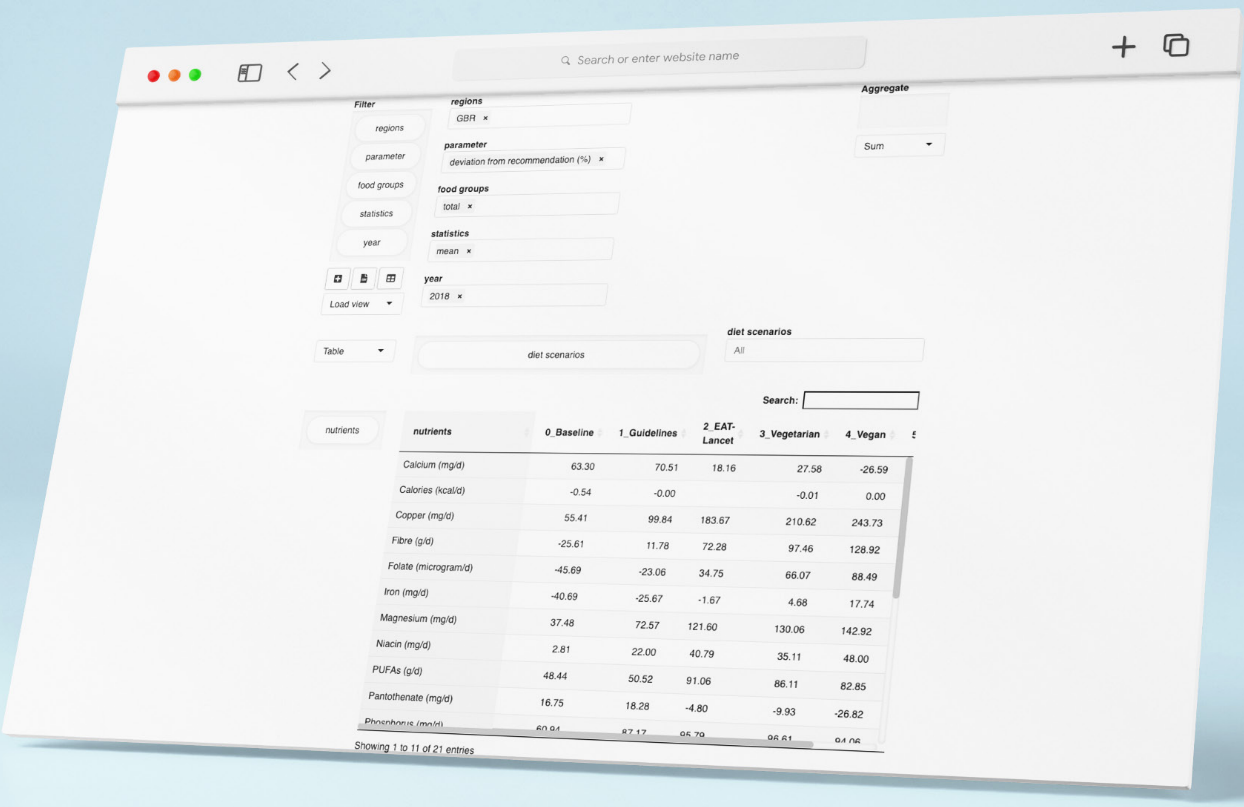
Fig. 8. Overview of the health-related value of dietary changes in the United Kingdom by risk factor and diet scenario

2.3.7 Nutritional analysis

This tab provides the results of the nutritional analysis. The parameters are the nutrient content of diets ("**nutrient content**") in the units given after the name of each nutrient, percentage changes in nutrient content over the baseline diet ("**change in nutrients (%)**"), the recommended intake of each nutrient ("**recommended intake**") and the percentage deviation from those recommendations ("**deviation from recommendation (%)**") by diet scenario. The statistics field gives the "**mean**" values and the "**low**" and "**high**" limits of the 95% confidence intervals of the nutrient contents of foods.

As an example, the percentage deviation from the recommended nutrient values ("**deviation from recommendation (%)**") of diet scenarios in the United Kingdom ("**GBR**") has been selected (Fig. 9).

Fig. 9. Overview of nutritional analysis of diet scenarios in the United Kingdom



2.4 Specifying new diet scenarios

The modelling tool allows users to define and analyse diet scenarios. New scenarios can be specified by going back to the "**Input**" data and changing the values for dietary and weight exposures in the scenario column ("**5_Scenario**"). New values can be inserted by double-clicking on a value and overwriting the existing entry. The initial values mirror the baseline values, such that modifying one entry (or a set of entries) will create a diet scenario in which everything is the same as in the baseline except for the modified entry (or set of entries).

Once the exposures of interest have been changed, the new diet scenario can be analysed by clicking "**Solve model**" on the left. After the model has been solved, the output parameters are updated and can be inspected as described in the previous section. Scenarios can be saved by clicking on "**Scenario**" in the top right corner, and they can be compared interactively by clicking on "**Compare scenarios**".

The input data can be updated similarly. In general, any field in the input table is modifiable. Thus, for example, as new data on dietary intake in the baseline become available, they can be inserted in the inputs table by modifying the related value and re-running (solving) the model. Likewise, each of the pre-specified dietary patterns can be changed to suit the desired analysis.

3. Detailed description of the model

The scientific basis of the modelling tool is published in a series of articles by Springmann et al. *(10,12–15)*. The methods used for the different analyses are summarized in this section. Additional details are available in the supplementary data in the published articles.

3.1 Analysis of consumption

Baseline food consumption was estimated by adopting estimates of food availability from the food balance sheets of the Food and Agriculture Organization of the United Nations (FAO) and adjusting those estimates for the amount of food wasted at the point of consumption *(17,18)*.

An alternative would have been to rely on consumption estimates from a variety of sources, including dietary surveys, household budget and expenditure surveys, and food availability data (19,20). For some countries, the use of dietary surveys would have been an alternative; however, underreporting is a persistent problem in dietary surveys *(21,22)*, and regional differences in survey methods would have meant that the results would not be comparable among countries. In contrast to dietary surveys, estimates of waste-adjusted food availability indicate levels of energy intake per region, which reflect regional differences in the prevalence of overweight and obesity *(23)*.

Food balance sheets indicate the amount of food available for human consumption *(18)*. They reflect the quantities that reach the consumer, but not the waste of both edible and inedible parts of the food commodity in households. The amount of food actually consumed may therefore be lower than that shown on the food balance sheet, depending on the degree of loss of edible food in the household (e.g. during storage, in preparation and cooking, as plate-waste, as quantities fed to domestic animals and pets or thrown away).

The model incorporates the waste-accounting method developed by the FAO to account for the amount of food wasted at household level that was not accounted for in estimates of food availability *(17)*. For each commodity and region, food consumption was estimated by multiplying food availability by conversion factors *(cf)* that represent the amount of edible food (e.g. after peeling) and the percentage of food wasted during consumption *(1-wp(cns))*. For roots and tubers, fruits and vegetables, and fish and seafood, the estimate also accounts for differences in wastage between the proportion that is used fresh (pct_{frsh}) and the proportion that is used in processed form (pct_{prcd}). The equation used for each food commodity and region was:

$$Consumption = Availability \cdot \frac{pct_{frsh}}{100} \cdot cf_{frsh} \cdot \left(1 - \frac{wp(cns_{frsh})}{100}\right) + Availability \cdot \frac{pct_{prcd}}{100} \cdot cf_{prcd} \cdot \left(1 - \frac{wp(cns_{prcd})}{100}\right)$$

Table 1 lists the parameters used in the calculation and Table 2 the baseline consumption data calculated in that way. The differences in energy intake reflect differences in the prevalence of overweight and obesity among regions *(23)*.

Food balance sheets list food availability in terms of primary commodity equivalents and therefore do not include estimates of processed foods, such as whole grains and processed meat. To code recommendations on whole grains and processed meat, the consumption estimates (based on waste-adjusted food availability) were supplemented by estimates from a regionally adjusted set of dietary surveys *(20)*. For processed meat, the survey estimates for red and processed meat were used to estimate the ratio of processed meat to the sum of red and processed meat, and that ratio was applied to the estimates of total red meat intake. As no equivalent comparison was available for whole grains, the estimates for differences in energy intake between the survey results and the obtained estimates were used and divided by the estimates of total grain intake to obtain the ratio of whole grain intake.

Table 1. Percentage of food wasted during consumption (wp(cns)) and percentage of use of processed food (pct_{prcd})

Food group	Item	Region						
		Europe	USA, Canada, Oceania	Industrialized Asia	Sub-Saharan Africa	North Africa, west and central Asia	South and south-east Asia	Latin America
cereals	wp(cns)	25	27	20	1	12	3	10
roots and tubers	pct_{prcd}	73	73	15	50	19	10	80
	wp(cns)	17	30	10	2	6	3	4
	$wp(cns_{prcd})$	12	12	12	1	3	5	2
oilseeds and pulses	cns	4	4	4	1	2	1	2
fruits and vegetables	pct_{prcd}	60	60	4	1	50	5	50
	wp(cns)	19	28	15	5	12	7	10
	$wp(cns_{prcd})$	15	10	8	1	1	1	1
milk and dairy	wp(cns)	7	15	5	0.1	2	1	4
eggs	wp(cns)	8	15	5	1	12	2	4
meat	wp(cns)	11	11	8	2	8	4	6
fish and seafood	pct_{prcd}	40% for low-income countries and 96% for all others						
	wp(cns)	11	33	8	2	4	2	4
	$wp(cns_{prcd})$	10	10	7	1	2	1	2

Conversion factors: maize, millet, sorghum: 0.69; wheat, rye, other grains: 0.78; rice: 1; roots: 0.74 (0.9 for industrial processing); nuts and seeds: 0.79; oils: 1; vegetables: 0.8 (0.75 for industrial processing); fruits: 0.8 (0.75 for industrial processing); beef: 0.715; lamb: 0.71; pork: 0.68; poultry: 0.71; other meat: 0.7; milk and dairy: 1; fish and seafood: 0.5; other crops: 0.78.

Note: The percentage use of fresh food is calculated as 1-pct_{prcd}.

Table 2. Baseline consumption data by region and food group (in g/day for each food group and in kcal/day for total energy intake)

Food group	Region						
	all-NDG	EURO	LACA	ASPA	AFRI	NEEA	NOAM
wheat	112	182	97	100	66	280	126
rice	149	11	56	209	68	64	14
maize	26	13	83	15	93	4	18
other grains	14	14	5	11	73	2	9
roots	116	140	114	91	380	96	115
legumes	17	10	31	16	26	24	12
soybeans	5	1	4	6	4	0	0
nuts and seeds	9	13	3	8	15	26	17
vegetables	281	231	111	331	118	442	207
fruits (temperate)	77	109	73	73	35	166	87
fruits (tropical)	51	64	110	36	46	101	80
fruits (starchy)	28	14	53	27	34	20	20
vegetable oil	25	45	30	16	13	32	77
palm oil	7	7	7	7	18	1	1
sugar	46	61	90	33	34	57	94
other crops	87	182	125	55	123	18	176
milk	229	581	328	131	88	161	577
eggs	26	29	29	26	10	15	32
beef	19	28	55	8	14	14	66
lamb	5	9	3	4	8	8	2
pork	33	60	22	31	4	0	46
poultry	28	37	60	16	16	48	87
shellfish	8	7	2	9	0	1	12
fish (freshwater)	10	4	3	13	4	5	5
fish (pelagic)	5	6	4	5	6	5	4
fish (demersal)	5	8	3	4	7	2	5
processed meat	13	31	23	6	4	2	49
whole grains	43	56	24	39	63	35	72
energy intake	2245	2428	2335	2174	2134	2334	2563

Notes: The regions include all countries with food-based dietary guidelines (all-NDG) and countries with guidelines in Europe (EURO), Latin America and the Caribbean (LACA), Asia and the Pacific (ASPA), Africa (AFRI), the Near East (NEEA) and North America (NOAM). The estimates for grains (wheat, maize, rice, other grains) and red meat (beef, lamb, pork) are not differentiated by the degree of processing and therefore implicitly include whole grains and processed meat. Explicit estimates of the latter are listed separately.

3.2 Diet scenarios

The model contains a set of predefined dietary scenarios and also allows users to specify their own scenarios. The predefined scenarios include diets based on national food-based dietary guidelines *(12)* and also diets that meet the recommendations of the EAT-Lancet Commission *(1)*, in particular flexitarian, vegetarian and vegan dietary patterns.

The dietary guideline scenarios were constructed in a number of steps, described in detail in the published literature *(12)*. First, existing food-based dietary guidelines were reviewed, and the recommendations for a set of food groups relevant for health and environmental impacts were extracted. The recommendations – some of which were qualitative and some quantitative – were converted into purely quantitative representations of suggested intake or change in intake for each food group. Then, full diet scenarios were constructed by applying the quantitative recommendations from food-based dietary guidelines to estimates of current intake per food group and country.

The online repository of food-based dietary guidelines maintained by the FAO *(24)* was used to access national dietary guidelines. From each source document, verbatim key messages were extracted for 12 food groups that are commonly present in dietary guidelines and for body weight. The food groups were fruits, vegetables, whole grains, red meat, processed meat, poultry, fish, milk (including dairy products), eggs, legumes, nuts and seeds, and sugar. Recommendations on balancing energy intake were included by adjusting the consumption of staple foods, such as grains and potatoes, in order to increase or decrease energy intake (while maintaining recommendations for whole grains).

As previously estimated *(14)* and used by the EAT-Lancet Commission *(1)*, the average calorie requirements differ by region according to its age composition. For the calculations – which are based on estimates of healthy body weight (or body mass index), physical activity level and height – it was assumed that the body mass index was in line with WHO recommendations *(25)*, and moderate physical activity levels were maintained as recommended. In addition, the characteristics for height in the United States of America were used *(26)*, which may be considered an upper bound that does not penalize future growth in populations. According to the estimates, calorie requirements reach a maximum of 2500 kcal/d for people aged 20–24 (average for men and women), but are reduced to 2000 kcal/d for those aged ≥ 65; the population-level average was about 2100 kcal/d.

The flexitarian, vegetarian and vegan dietary patterns were constructed as defined by the EAT-Lancet Commission (1). The flexitarian diets contained at least 500 g/d of fruits and vegetables of different colours and groups (the composition of which is determined by regional preferences), at least 100 g/d of plant-based protein sources (legumes, soya beans, nuts), a focus on whole grains, modest amounts of animal-based proteins such as poultry, fish, milk and eggs, and limited amounts of red meat (one portion per week), refined sugar (< 5% of total energy), vegetable oils that are high in saturated fat (in particular palm oil), and starchy foods with a relatively high glycaemic index. Table 3 lists the food-based recommendations used to construct the flexitarian-diet scenario.

More specialized diets were also constructed, including vegetarian and vegan diets, which are in line with dietary guidelines and observed dietary patterns in dedicated cohorts in epidemiological studies *(27,28)*. For the vegetarian diets, up to three quarters of meat-based protein sources in the flexitarian diets were replaced by plant-based proteins and one quarter by either fruit or vegetables. For the vegan diets, up to three quarters of all animal-based protein sources were replaced by plant proteins and one quarter by fruits and vegetables. To preserve the regional character of dietary patterns, the calculation maintained the regional composition of some foods within broader categories, such as preferences for specific staple crops (e.g. wheat, maize, rice) and fruits (temperate, tropical).

Table 3. Food-based dietary recommendations for healthy, more plant-based (flexitarian) diets

Food item	minimum level		maximum level	
	g/d	serving	g/d	serving
wheat	–	–	A total of up to 860 kcal/d for energy balance for all staple crops	3–4 (1/3 of energy)
rice	–	–		
maize	–	–		
other grains	–	–		
roots	–	–		
legumes	50	1/2	–	–
soybeans	25	1/4	–	–
nuts & seeds	50	2	–	–
vegetables	300	3–4	–	–
fruits	200	2–3	–	–
sugar	–	–	31	5% of energy
palm oil	–	–	6.8	1
vegetable oil	–	–	80	1/3 of energy
beef	–	–	A total of 14 g/d for all red meat	1/7
lamb	–	–		
pork	–	–		
poultry	–	–	29	1/2
eggs	–	–	13	1/5
milk	–	–	250	1
shellfish	A total of 28 g/d for all fish and seafood	1/2	–	–
fish (freshwater)			–	–
fish (demersal)			–	–
fish (pelagic)			–	–

Note: The recommendations include recommended minimum and maximum intake expressed by weight or calories and servings. Fish and seafood can be substituted for plant-based foods (legumes, soya beans, nuts and seeds, fruit and vegetables) in vegetarian diets.

3.3 Health analysis

The model estimates the mortality and morbidity attributable to dietary and weight-related risk factors by calculating population impact fractions (PIFs), which represent the proportions of disease cases that would be avoided by changing the risk exposure from the baseline situation to a counterfactual situation. To calculate PIFs, the following general formula was used *(29–31)*:

$$PIF = \frac{\int RR(x)P(x)dx - \int RR(x)P'(x)dx}{\int RR(x)P(x)dx}$$

where ***RR (x)*** is the relative risk of disease for risk factor level ***x***, ***P(x)*** is the number of people in the population with risk factor level ***x*** in the baseline scenario, and ***P' (x)*** is the number of people in the population with risk factor level ***x*** in the counterfactual scenario. It was assumed that changes in relative risks follow a dose–response relationship *(30)* and that PIFs combine multiplicatively (i.e. $PIF = 1 - \prod_i (1 - PIF_i)$, where i denotes independent risk factors) *(30,32)*.

The number of deaths avoided by the change in exposure to risk i, $\Delta deaths_i$, was calculated by multiplying the associated PIF by the disease-specific death rate, ***DR***, and by the number of people alive in a population, ***P***:

$$\Delta deaths_i(r,a,d) = PIF_i(r,d) \cdot DR(r,a,d) \cdot P(r,a),$$

where PIFs are differentiated by region, r, and disease or cause of death, d; the death rates are differentiated by region, age group, a, and disease; the population groups are differentiated by region and age group; and the change in the number of deaths is differentiated by region, age group and disease.

Publicly available data sources were used as parameters in the comparative risk assessment. Mortality data were adopted from the Global Burden of Disease project *(33)*. Baseline weight distribution in each country was adopted from a pooled analysis of population-based measurements undertaken by the NCD Risk Factor Collaboration *(23)*.

The relative risk estimates that relate the risk factors to the disease endpoints were adopted from meta-analyses of prospective cohort studies for dietary and weight-related risks *(34–42)*. In line with the meta-analyses, non-linear dose–response relationships were included for fruits and vegetables, and nuts and seeds, and linear dose–response relationships for the remaining risk factors. As the analysis focused primarily on mortality from chronic diseases, the model focused on adults aged ≥ 20 years. The estimated relative risks were adjusted for attenuation with age based on a pooled analysis of cohort studies on metabolic risk factors *(43)*, in line with other assessments *(31,44)*.

Table 4 lists the relative-risk parameters used. Each risk factor is discussed in the supplementary information of Springmann et al *(14)*. To ensure that the relative risks are well defined for the entire range of exposures considered in the diet scenarios, the maximum exposure and potential risk reductions were capped at the maximum values included in the meta-analyses (800 g/d of fruit or vegetables, 28 g/d of nuts). For whole grains, a maximum exposure of 125 g/d was used, in line with the value for the theoretical minimum-risk exposure level suggested by the Global Burden of Disease project and the Nutrition and Chronic Diseases Expert Group *(44)*. The linear dose–response functions (for legumes, red meat and processed meat) are unconstrained.

Table 4. Relative risk parameters (mean and low and high limits of 95% confidence intervals) for dietary risks and weight-related risks

Food group	Endpoint	Unit	RR mean	RR low	RR high	Reference
Processed meat	CHD	50 g/d	1.27	1.09	1.49	Bechthold et al *(37)*
	Stroke	50 g/d	1.17	1.02	1.34	Bechthold et al *(37)*
	Colorectal cancer	50 g/d	1.17	1.10	1.23	Schwingshackl et al *(39)*
	Type 2 diabetes	50 g/d	1.37	1.22	1.55	Schwingshackl et al *(38)*
Red meat	CHD	100 g/d	1.15	1.08	1.23	Bechthold et al *(37)*
	Stroke	100 g/d	1.12	1.06	1.17	Bechthold et al *(37)*
	Colorectal cancer	100 g/d	1.12	1.06	1.19	Schwingshackl et al *(39)*
	Type 2 diabetes	100 g/d	1.17	1.08	1.26	Schwingshackl et al *(38)*
Fruits	CHD	100 g/d	0.95	0.92	0.99	Aune et al *(36)*
	Stroke	100 g/d	0.77	0.70	0.84	Aune et al *(36)*
	Cancer	100 g/d	0.94	0.91	0.97	Aune et al *(36)*
Vegetables	CHD	100 g/d	0.84	0.80	0.88	Aune et al *(36)*
	Cancer	100 g/d	0.93	0.91	0.95	Aune et al *(36)*
Legumes	CHD	57 g/d	0.86	0.78	0.94	Afshin et al *(34)*
Nuts	CHD	28 g/d	0.71	0.63	0.80	Aune et al *(35)*
Whole grains	CHD	30 g/d	0.87	0.85	0.90	Aune et al *(42)*
	Cancer	30 g/d	0.95	0.93	0.97	Aune et al *(42)*
	Type 2 diabetes	30 g/d	0.65	0.61	0.70	Aune et al *(42)*

Table 4. contd

Food group	Endpoint	Unit	RR mean	RR low	RR high	Reference
Underweight	CHD	15<BMI<18.5	1.17	1.09	1.24	Global BMI Collab *(41)*
	Stroke	15<BMI<18.5	1.37	1.23	1.53	Global BMI Collab *(41)*
	Cancer	15<BMI<18.5	1.10	1.05	1.16	Global BMI Collab *(41)*
	Respiratory disease	15<BMI<18.5	2.73	2.31	3.23	Global BMI Collab *(41)*
Overweight	CHD	25<BMI<30	1.34	1.32	1.35	Global BMI Collab *(41)*
	Stroke	25<BMI<30	1.11	1.09	1.14	Global BMI Collab *(41)*
	Cancer	25<BMI<30	1.10	1.09	1.12	Global BMI Collab *(41)*
	Respiratory disease	25<BMI<30	0.90	0.87	0.94	Global BMI Collab *(41)*
	Type 2 diabetes	25<BMI<30	1.88	1.56	2.11	Prosp Studies Collab *(45)*
Obesity (grade 1)	CHD	30<BMI<35	2.02	1.91	2.13	Global BMI Collab *(41)*
	Stroke	30<BMI<35	1.46	1.39	1.54	Global BMI Collab *(41)*
	Cancer	30<BMI<35	1.31	1.28	1.34	Global BMI Collab *(41)*
	Respiratory disease	30<BMI<35	1.16	1.08	1.24	Global BMI Collab *(41)*
	Type 2 diabetes	30<BMI<35	3.53	2.43	4.45	Prosp Studies Collab *(45)*
Obesity (grade 2)	CHD	30<BMI<35	2.81	2.63	3.01	Global BMI Collab *(41)*
	Stroke	30<BMI<35	2.11	1.93	2.30	Global BMI Collab *(41)*
	Cancer	30<BMI<35	1.57	1.50	1.63	Global BMI Collab *(41)*
	Respiratory disease	30<BMI<35	1.79	1.60	1.99	Global BMI Collab *(41)*
	Type 2 diabetes	30<BMI<35	6.64	3.80	9.39	Prosp Studies Collab *(45)*
Obesity (grade 3)	CHD	30<BMI<35	3.81	3.47	4.17	Global BMI Collab *(41)*
	Stroke	30<BMI<35	2.33	2.05	2.65	Global BMI Collab *(41)*
	Cancer	30<BMI<35	1.96	1.83	2.09	Global BMI Collab *(41)*
	Respiratory disease	30<BMI<35	2.85	2.43	3.34	Global BMI Collab *(41)*
	Type 2 diabetes	30<BMI<35	12.49	5.92	19.82	Prosp Studies Collab *(45)*

CHD: coronary heart disease; RR: relative risk.

Note. Non-linear dose–response relationships were used for fruits, vegetables, and nuts and seeds, as specified in the references. Linear dose–response relationships were used for the remaining risk factors.

The selection of risk–disease associations used in the health analysis was based on criteria used to judge the certainty of evidence, such as the Bradford-Hill criteria used by the Nutrition and Chronic Diseases Expert Group *(44)*, and the criteria of the World Cancer Research Fund used in the Global Burden of Disease project *(2)* and NutriGrade *(46)* (Table 5). The quality of evidence in meta-analyses that covered the same risk–disease associations as used here was graded with NutriGrade as moderate or high for all risk–disease pairs included in the analysis *(37–39)*. In addition, the Nutrition and Chronic Diseases Expert Group graded the evidence for a causal association of 10 of the 14 cardiometabolic risk associations included in the analysis as probable or convincing *(44)*, and the World Cancer Research Fund graded all five of the associations with cancer as probable or convincing *(47)*. The grading of the certainty of the evidence in each case was based on the general relationship between a risk factor and a health outcome, and not on a specific value for relative risk.

The analysis does not include all the risk–disease associations that were graded as having evidence of moderate certainty *(37–39)* because, for some associations, such as with milk and fish, more detailed meta-analyses (with more sensitivity analyses) were available that indicated potential confounding by other major dietary risks or health status at baseline *(48–50)*. Such sensitivity analyses were not available for the meta-analyses included in the NutriGrade assessments, but they are important for health assessments of changes in multiple risk factors.

For each diet scenario, the model calculates the uncertainty intervals associated with changes in mortality based on standard methods of error propagation and the confidence intervals of the relative risk parameters. For error propagation, the error distribution of the relative risks is approximated by a normal distribution, and the largest deviations from the mean are used. This method results in conservative, potentially larger uncertainty intervals than probabilistic methods such as Monte Carlo sampling, but it has significant computational advantages and is justified by the magnitude of the errors dealt with here (< 50%) (see for example Intergovernmental Panel on Climate Change (IPCC) uncertainty guidelines *(51)*).

Table 5. Ratings of the certainty of evidence for a statistically significant association between a risk factor and a disease endpoint

Food group	Endpoint	Association	Certainty of evidence
Fruits	CHD	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
	Stroke	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
	Cancer	reduction	WCRF: strong evidence (probable) for some cancers NutriGrade: moderate quality of meta-evidence for colorectal cancer
Vegetables	CHD	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
	Cancer	reduction	WCRF: strong evidence (probable) for non-starchy vegetables and some cancers NutriGrade: moderate quality of meta-evidence for colorectal cancer
Legumes	CHD	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
Nuts and seeds	CHD	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
Whole grains	CHD	reduction	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
	Cancer	reduction	WCRF: strong evidence (probable) for colorectal cancer NutriGrade: moderate quality of meta-evidence for colorectal cancer
	Type 2 diabetes	reduction	NutriCoDE: probable or convincing NutriGrade: high quality of meta-evidence
Red meat	CHD	increase	NutriGrade: moderate quality of meta-evidence
	Stroke	increase	NutriGrade: moderate quality of meta-evidence
	Cancer	increase	WCRF: strong evidence (probable) for colorectal cancer NutriGrade: moderate quality of meta-evidence for colorectal cancer
	Type 2 diabetes	increase	NutriCoDE: probable or convincing NutriGrade: high quality of meta-evidence
Processed meat	CHD	increase	NutriCoDE: probable or convincing NutriGrade: moderate quality of meta-evidence
	Stroke	increase	NutriGrade: moderate quality of meta-evidence
	Cancer	increase	WCRF: strong evidence (convincing) for colorectal cancer NutriGrade: moderate quality of meta-evidence for colorectal cancer
	Type 2 diabetes	increase	NutriGrade: high quality of meta-evidence

NutriCoDE: Nutrition and Chronic Diseases Expert Group; NutriGrade: Grading of Recommendations Assessment, Development and Evaluation; WCRF: World Cancer Research Fund.

Note: The ratings include those of NutriCoDE *(44)*, the WCRF *(47)* and NutriGrade *(37–39)*. The ratings refer to risk–disease associations in general and not to the specific relative-risk factor used for the associations in this analysis.

3.4 Environmental analysis

The environmental impacts of dietary change are estimated by using a global dataset of country- and crop-specific environmental footprints for GHG emissions, cropland use, freshwater use and nitrogen and phosphorus application. The footprints are based on global datasets on environmental resource use in the producing region, which have been converted to consumption-related footprints by using a food systems model that connects food production and consumption across regions *(10)*. The model distinguishes several steps along the food chain: primary production; trade in primary commodities; processing to oils, oil cakes and refined sugar; use of feed for animals; and trade in processed commodities and animals. The parameters were taken from estimates of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) *(52)* on current and future food production, processing factors and feed requirements for 62 agricultural commodities and 159 countries. Table 6 lists the footprints for 2010 and 2050. Those for 2050 are used in calculating planetary boundaries, as described in the next section.

For GHG emissions, the model contains two sets of footprints. One is based on process-related emissions and on non-CO_2 emissions of agriculture, in particular CH_4 and N_2O, in line with the method used by the IPCC. Data on GHG emissions were adopted from country-specific analyses of GHG emissions from crops *(53)* and livestock *(54)*. Non-CO_2 emissions of fish and seafood were calculated on the basis of feed requirements and feed-related emissions of aquaculture *(55)* and on projections of the ratio between wild-caught and farmed fish production *(56,57)*. The other set of footprints is based on estimates from life-cycle analyses and includes not only CH_4 and N_2O, but also CO_2 emissions *(58)*. The estimates for future years incorporate the mitigation potential of bottom-up changes in management practices and technologies by using marginal abatement cost curves *(59)*, in line with the projected value of the social cost of carbon in that year *(60)*. The mitigation options include changes in irrigation, cropping and fertilization that reduce CH_4 and N_2O emissions from rice and other crops, and changes in manure management, feed conversion and feed additives that reduce enteric fermentation in livestock.

Data on cropland and use of surface and groundwater (also termed “blue water”) were adopted from the IMPACT model for various socioeconomic pathways *(52)*. To derive commodity-specific footprints, the use data were divided by data on primary production, and the footprints of processed goods (vegetable oils, refined sugar) were calculated by using country-specific conversion ratios *(52)* and categorizing co-products (oils and oil meals) by economic value to avoid double counting. The estimation included country-specific feed requirements for terrestrial animals *(52)* to derive the cropland and freshwater footprints of meat and dairy products. It used global feed requirements for aquaculture *(55)* and projections of the ratio between wild-caught and farmed fish production *(56,57)* to derive the cropland and freshwater footprints for fish and seafood. For future years, the model includes efficiency gains in agricultural yields, water management and feed conversion based on IMPACT projections *(52)*.

Data on the application rates of nitrogen and phosphorous fertilizers were adopted from the International Fertilizer Industry Association *(61)*. For future years, the estimates include efficiency gains in nitrogen and phosphorus application by rebalancing fertilizer application rates between regions with over- and under-application, in line with closing yield gaps *(62)*. In addition, they include improvements in nitrogen use efficiency of 15% by 2030 and 30% by 2050, in line with the targets suggested in the International Nitrogen Assessment *(63)*. They also include rates of recycling of phosphorus of 25% by 2030 and 50% by 2050 *(64)*.

Table 6. Environmental footprints of food commodities (per kg of product; global averages) for 2010 and 2050

Food group	GHG emissions ($kgCO_2eq/kg$)		Cropland use (m_2/kg)		Freshwater use (m_2/kg)		Nitrogen use (kgN/t)		Phosphorus use (kgP/t)	
	2010	2050	2010	2050	2010	2050	2010	2050	2010	2050
wheat	0.23	0.21	3.36	2.46	0.49	0.37	28.73	19.78	4.39	2.01
rice	1.18	0.90	3.51	2.78	1.07	0.89	36.64	25.07	5.20	2.28
maize	0.19	0.17	1.98	1.40	0.15	0.12	22.77	14.36	3.57	1.55
other grains	0.29	0.22	6.17	4.43	0.17	0.14	16.39	9.82	2.72	0.97
roots	0.07	0.06	0.69	0.52	0.04	0.04	3.60	2.07	0.71	0.30
legumes	0.23	0.19	11.11	6.89	0.94	0.61	0.00	0.00	0.00	0.00
soybeans	0.12	0.09	3.95	3.14	0.14	0.15	2.75	1.75	5.88	3.17
nuts and seeds	0.69	0.65	6.39	5.13	0.43	0.33	14.16	10.84	2.10	1.17
vegetables	0.06	0.07	0.49	0.34	0.09	0.06	9.55	6.32	1.67	0.81
oil crops	0.70	0.64	3.12	2.37	0.22	0.19	13.33	8.50	2.86	1.32
fruits (temperate)	0.08	0.08	1.18	0.97	0.33	0.28	12.73	8.57	1.91	0.92
fruits (tropical)	0.09	0.10	0.94	0.62	0.32	0.23	10.27	6.10	1.58	0.70
fruits (starchy)	0.11	0.10	0.88	0.59	0.11	0.08	6.15	3.76	1.05	0.48
sugar	0.19	0.19	1.67	1.35	1.22	0.88	22.34	15.26	3.84	1.86
palm oil	1.85	2.03	3.10	2.39	0.00	0.00	22.34	16.29	3.57	1.85
vegetable oil	0.67	0.63	10.31	8.46	0.47	0.45	42.73	28.19	11.47	5.66
beef	36.78	40.36	4.21	2.78	0.22	0.17	27.29	17.16	5.36	2.29
lamb	36.73	37.21	6.24	4.48	0.49	0.42	27.52	21.82	4.94	2.47
pork	3.14	3.25	6.08	4.90	0.35	0.29	51.52	34.19	8.87	4.05
poultry	1.45	1.39	6.59	5.18	0.40	0.36	50.20	36.00	9.02	4.35
eggs	1.61	1.48	6.86	5.19	0.44	0.39	51.22	35.09	8.81	4.18
milk	1.28	1.39	1.34	1.01	0.08	0.08	6.32	4.63	1.58	0.78
shellfish	0.03	0.04	0.36	0.46	0.03	0.04	2.19	2.39	0.50	0.40
fish (freshwater)	0.12	0.12	1.51	1.37	0.10	0.10	11.26	8.39	2.37	1.29
fish (pelagic)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
fish (demersal	0.01	0.01	0.13	0.20	0.01	0.01	0.75	0.99	0.19	0.18

Notes: Footprints for animal products represent feed-related impacts, except for GHG emissions of livestock, which also have a direct component. Footprints for fish and seafood represent feed-related impacts of aquaculture production weighted by total production volumes. The global averages account for expected improvements in efficiency, such as improved feed for livestock, and changes in production by 2050, such as increases in extensive beef production in middle-income countries. The analysis is based on country-specific values.

3.5 Analysis of planetary boundaries

The model includes analyses of whether the diet scenarios are in line with global health and environment targets by modelling their adoption by all countries. With the exception of the proportional target for noncommunicable diseases (NCDs), all the targets were expressed in absolute terms (e.g. not exceeding global GHG emissions (related to food consumption) by a certain amount). In the context of these absolute targets, the rationale for this global sustainability test is to determine whether global targets can be met without imposing exceptions for one country or group of countries. From this perspective of equity, a country with food-based dietary guidelines (or a food scenario) that fails the test is, in effect, outsourcing its responsibility to fulfilling the target, as other countries would have to divert from their food-based dietary guidelines to meet it.

The targets included are the SDG of reducing premature mortality from NCDs by a third, the Paris Agreement to limit global warming to below 2 °C, the Aichi Biodiversity Target of limiting the rate of land-use change, and the SDGs and planetary boundaries related to freshwater use and nitrogen and phosphorus pollution (Table 7).

To derive target values, the analysis isolates the diet-related portions of the health and environmental targets, such as the emissions budget allocated to food production under a climate stabilization pathway that is in line with fulfilling the Paris Climate Agreement *(66)*, which mirrors how the planetary boundaries for the food system are derived from the overall boundary values *(10)*. For NCD risks, the analysis takes into account the proportion of NCD risks that are due to the diet *(65)*. When targets were expressed for future years, the analysis included projections of environmental footprints such as improvements in technologies and management practices, including reductions in food loss and waste, along a middle-of-the-road socioeconomic development pathway *(10)*. Derivation of the target values is summarized in Table 7.

Table 7. Global health and environmental targets and their derivation

Global targets	Comment	Implementation
NCD Agenda	SDG 3.4 is to "reduce by one third premature mortality from non-communicable diseases through prevention and treatment, and promote mental health and wellbeing", which builds on the WHO "25×25" NCD target.	According to the Global Burden of Disease project *(65)*, imbalanced diets and weight contribute more than half to preventable causes of NCD deaths (the rest is due to tobacco, alcohol and insufficient physical activity). Application of this proportion to overall reduction target yields a target for diet-related reductions of around 18.5%.
Paris Climate Agreement	The Paris Agreement's long-term goal is to keep the increase in global average temperature to well below 2 °C above pre-industrial levels and to limit the increase to 1.5 °C, as this would substantially reduce the risks and effects of climate change. The goal is reflected in SDG 13 and in the planetary boundary for climate change.	The target for agricultural emissions in line with the 2 °C target was calculated as 4.7 (4.3–5.3) $GtCO_2$-eq *(10,66)*. This value was adjusted for the proportion of emissions related specifically to food consumption (92% of emissions of the whole food system, according to Springmann et al.*(10)*).
Aichi Biodiversity Targets	Target 5: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation are significantly reduced. The target is related to SDG 15 and the planetary boundary for land-system change.	The target can be fulfilled by not increasing pressure to convert natural land into cropland (or pastures), in line with the food-related planetary boundary for land-systems change *(10,67)*. The planetary boundary value was set to the extent of current cropland (+/- 16%). The value was internally recalculated for consistency with the baseline parameters and the focus on food available for consumption (9.9 Mkm^2, 8.3–11.5).
SDG target on water withdrawals	SDG 6.4: By 2030, substantially increase water-use efficiency in all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. The goal is in line with the planetary boundary for freshwater use.	The food-related planetary-boundary target of maintaining environmental flow requirements is in line with limiting agricultural freshwater use to below 2000 km^3, with a range of 800–3350 km^3 *(10)*. The value was adjusted for the proportion of the food system attributed to current diets (1600 km^3, 640–2600).
SDG target on nutrient pollution	SDG 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution. The goal is in line with the planetary boundary for biogeochemical flows of nitrogen and phosphorus.	The food-related planetary-boundary target for nitrogen and phosphorus application is in line with limiting eutrophication risk *(10,68)*. The value was recalculated for the focus on consumption-related impacts by applying the original risk fractions to estimates of baseline use, which yielded target values of 51 TgN (38–83) and 11 TgP (5.6–12.9).

TgP: terra grams of phosphorus; TgN: terra grams of nitrogen.

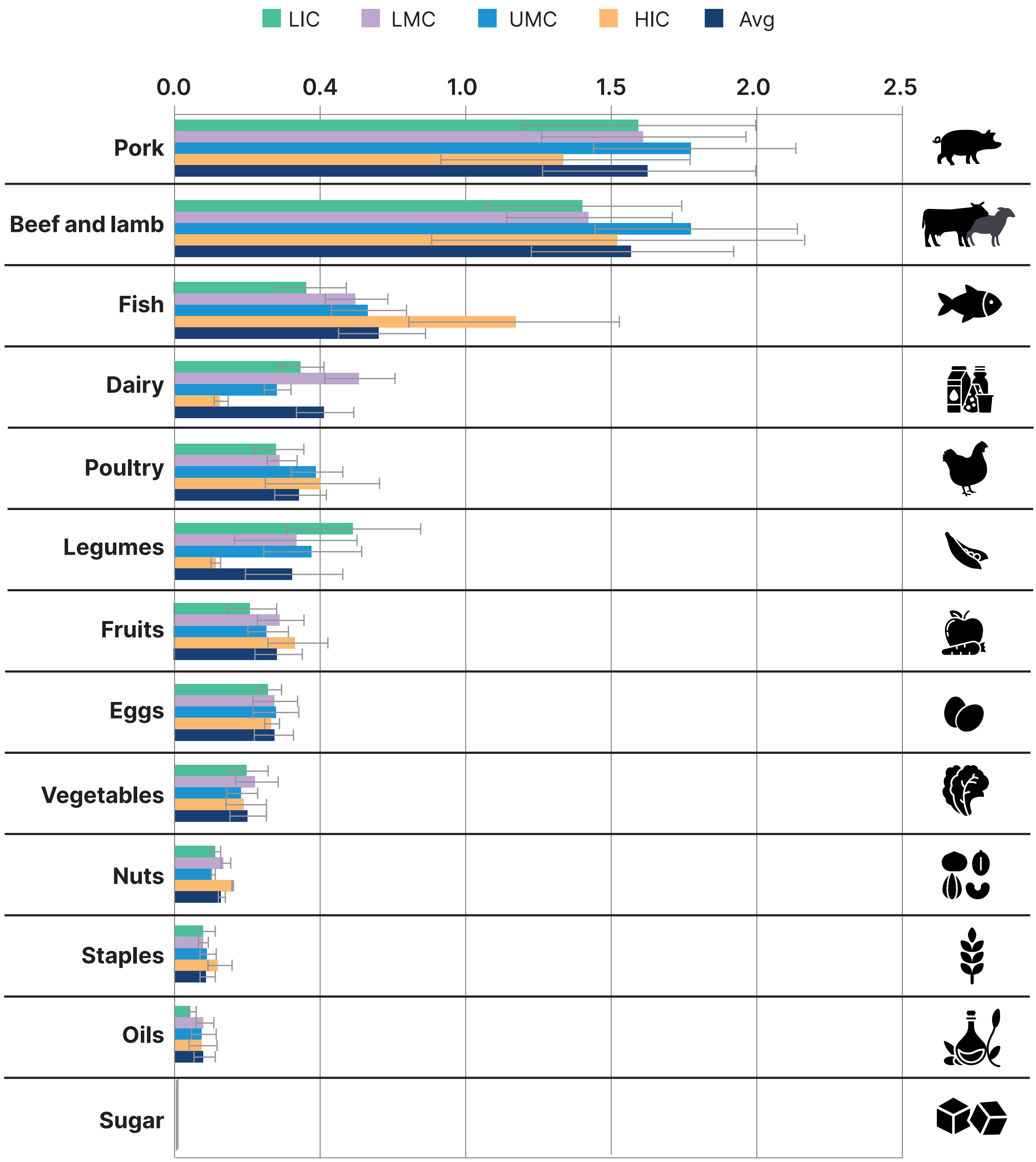
3.6 Analysis of cost of diets

The model calculates the costs of diets per country by pairing estimates of food demand in the different diet scenarios with estimates of commodity prices *(13)*. The price data were based on a detailed list of commodity prices collected by statistical offices for 2017 as part of the International Comparison Program led by the World Bank *(69)*.

This analysis used 20 666 estimates of annual average prices in 179 countries, covering 463 food items. The analysis focuses on those commodities that are related to foods, can be expressed in primary commodity equivalents and do not include beverages, except for milk. The food items included 319 items from regional lists that are representative of the consumption pattern in the region and 144 items from a global core list developed for the specific purpose of linking regional results to a global set of results by including products that can be priced in most regions.

The detailed list of food items was aggregated into a list of 31 food groups, which were used to construct the diet scenarios. For the aggregation, each item was paired with its caloric content (to control for difference in processing and edible fractions), and averaged prices were converted from local currency to US dollars. For the calorie conversion, calorie data from the FoodData Central database maintained by the US Department of Agriculture were used. The price conversion was based on the application of purchasing-power parity rates to control for differences in prices among countries. Fig. 10 provides an overview for general food groups.

Fig. 10. Prices per serving of food groups in 2017 by world region, differentiated by income group



Avg: global average; HIC: high-income countries; LIC: low-income countries; LMC: lower middle-income countries; UMC: upper middle-income countries.

3.7 Economic valuation of health impacts

The economic valuation follows standard methods of cost-benefit analysis *(15)*

To estimate the value of health impacts, estimates of diet-related mortality are combined with estimates of the value of statistical life *(15)*, which is a measure of the willingness to pay for a reduction in mortality risk defined as the marginal rate of substitution between money and mortality risk in a defined period *(16)*. The value of statistical life does not represent the value of life itself but rather the value of small risks to life, which can be estimated from either market decisions that reveal the implicit values reflected in behaviour (revealed preference studies) or surveys that elicit respondents' willingness to pay directly for small reductions in mortality risks (stated preference studies).

The values of statistical life used for the analysis are based on a comprehensive global meta-analysis of stated preference surveys of mortality risk valuation undertaken for the Organisation for Economic Co-operation and Development (OECD) *(70)*. According to OECD recommendations, the analysis starts with the base value of statistical life of the European Union (US$ 3.5 million, US$ 1.75–5.25 million) and then uses a benefit-transfer method to calculate the values of statistical life in other regions *(16)*. In the benefit-transfer method, the base value of statistical life is adjusted by income, Y, subject to an elasticity of substitution, β:

$$VSL_r = VSL_{base}\left(\frac{Y_r}{Y_{base}}\right)^{\beta},$$

where VSL is the value of statistical life.

According to OECD recommendations, GDP per capita adjusted for purchasing power parity is used as a proxy for income, with an elasticity of 0.8 for benefit transfers to high-income countries and an elasticity of 1.0 for benefit transfers to low- and middle-income countries *(16)*. Baseline data on GDP per capita were derived from the World Bank Development Indicators database. Countries were classified by income in line with World Bank methods and according to their GDP per capita, adjusted for purchasing power parity.

3.8 Nutritional analysis

In the model, the nutrient adequacy of the diet scenarios is analysed by calculating their nutrient content and comparing it with international recommendations *(14)*. To calculate the nutrient content, the consumption of each food group is paired with its nutrient density as reported in the Global Expanded Nutrient Supply dataset, which provides estimates of the supply of 23 nutrients in 225 food categories in over 150 countries *(71)*. For the analysis, the nutrient dataset was aggregated into more general food groups (e.g. all green-leafy vegetables instead of spinach, kale, etc), and calorie densities were normalized to those of the FAO for consistency with the diet scenarios.

The model allows comparison of the calculated nutrient content of the diet scenarios to WHO recommendations. Because the recommendations differ by age and sex, population-level average values were calculated for each nutrient by using the age and sex structure for the year of analysis based on data from the Global Burden of Disease project.

The estimates of recommended energy intake account for the age- and sex-specific energy requirements for a moderately active population of US height as an upper bound, and include the energy costs of pregnancy and lactation *(25)*. The estimates of calcium intake include accounting for the average calcium content of drinking-water, in line with previous assessments *(72)*. As WHO has not set guidelines for phosphorus or copper, the recommended intakes of these elements were adopted from those of the US Institute of Medicine.

To analyse the effects of changing to greater intake of whole grains, the nutrient content of whole wheat from the Harvard Nutrient Database was used and paired with the extent of whole-grain consumption specified in the diet scenarios. In line with the EAT-Lancet recommendations *(1)*, the nutrient contents of a colour-defined mix of vegetables were used to calculate the nutrient contents of the related scenarios, including the flexitarian, vegetarian and vegan dietary patterns.

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