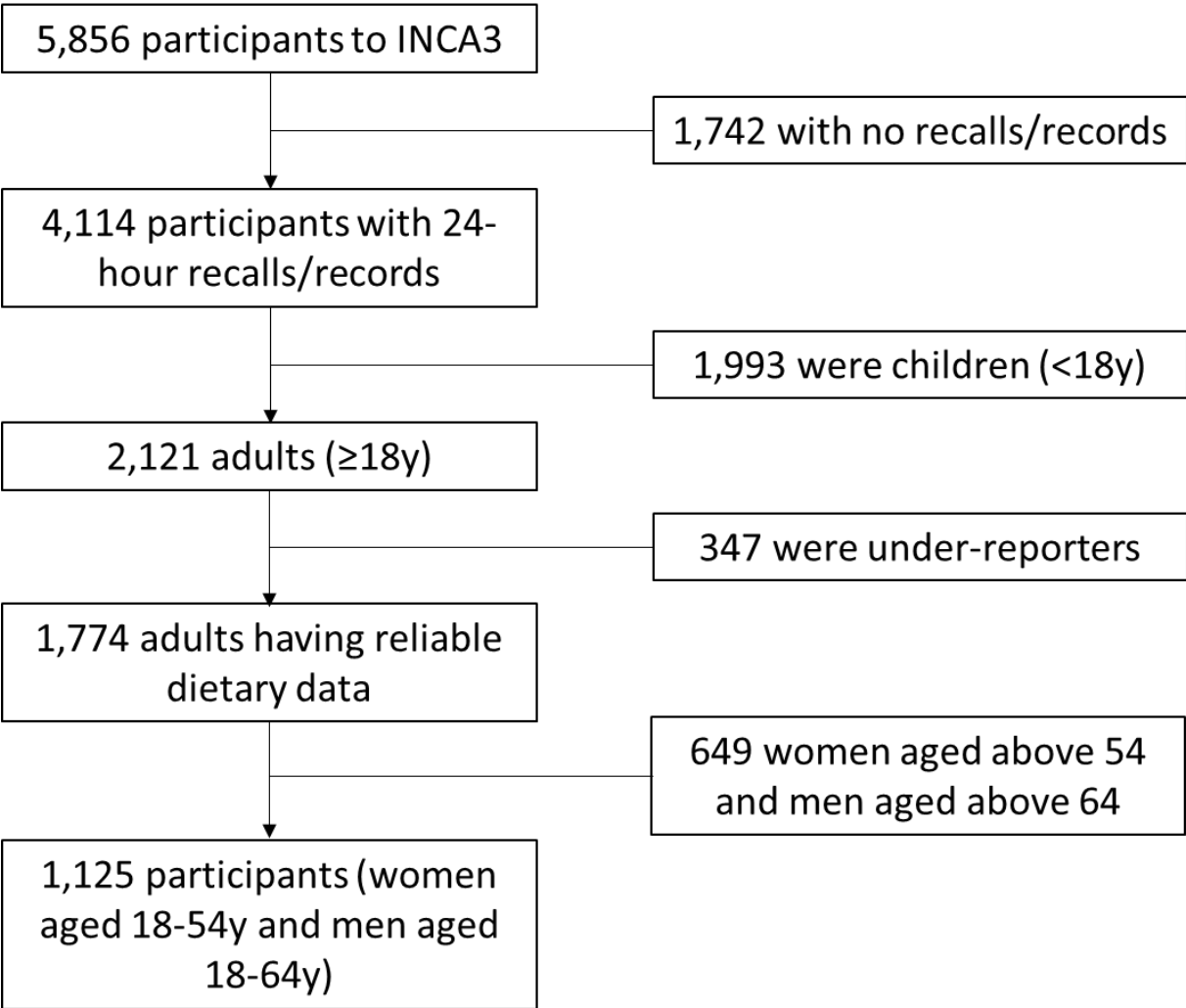


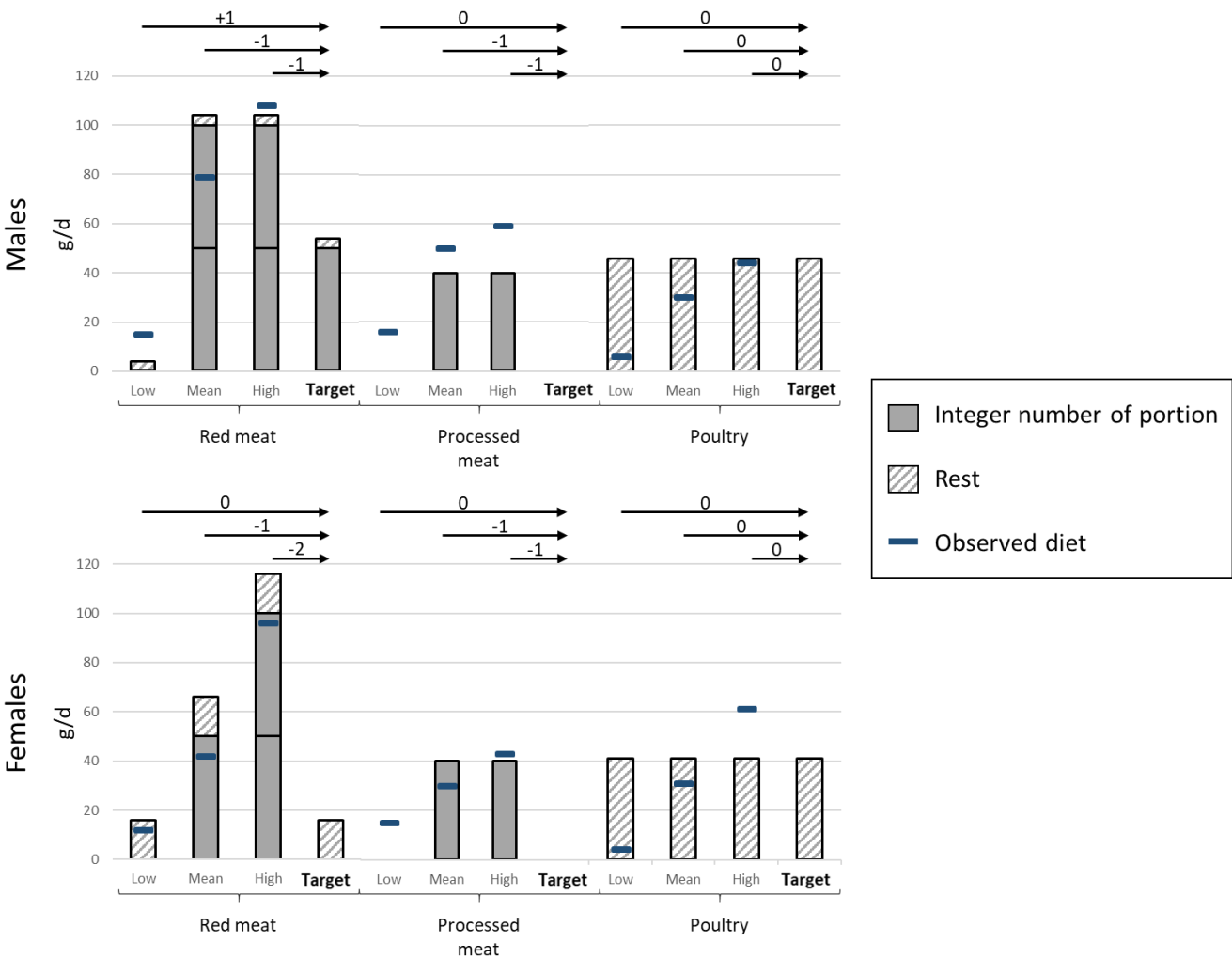
# **Supplemental material: In a trajectory toward a healthy diet, meat consumption reduction needs specific diet changes: a graph-based analyses optimization study**

Elie Perraud, Juhui Wang, H  l  ne Fouillet, Fran  ois Mariotti

Supplemental Figure 1 Flow chart explaining the sampling of French participants from the third Individual and National Study on Food Consumption Survey (INCA3)

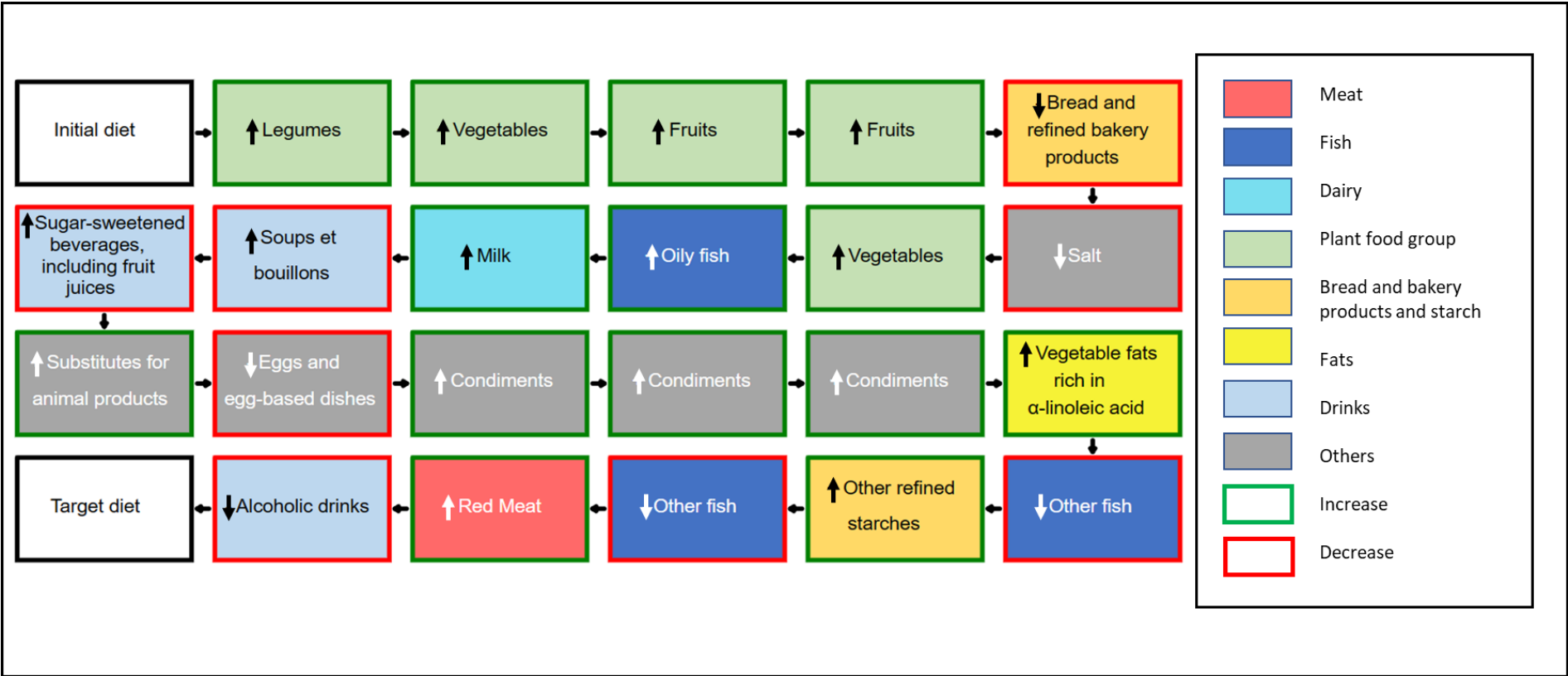


Supplemental Figure 2 Consumption of each type of meat in the target and initial diets by sex and considered population. Three different initial diets are considered by sex, corresponding to Low (first quintile), Mean, and High (fifth quintile) consumption of meat, with all initial consumptions adjusted to differ from target consumption by an integer number of portions (see Supplemental Method 2). The blue lines show the meat consumption observed in the population. Rather than adjusting the target diets, which could have altered their full nutritional adequacy, we rounded the difference between the initial and target diets and slightly adjusted the initial diets so that they differ from the target diets by the integer number of portions. Each histogram bar thus describes the adjusted meat consumption for each diet. They are composed of zero, one, or two portion (full-colored rectangle) step sizes (50 grams for red meat and poultry and 40 grams for processed meat) and the common remainder (hatched). Above the graphs are the number of portion increases or decreases needed to reach the target diet (i.e., a -1 means a decrease of one portion is needed).



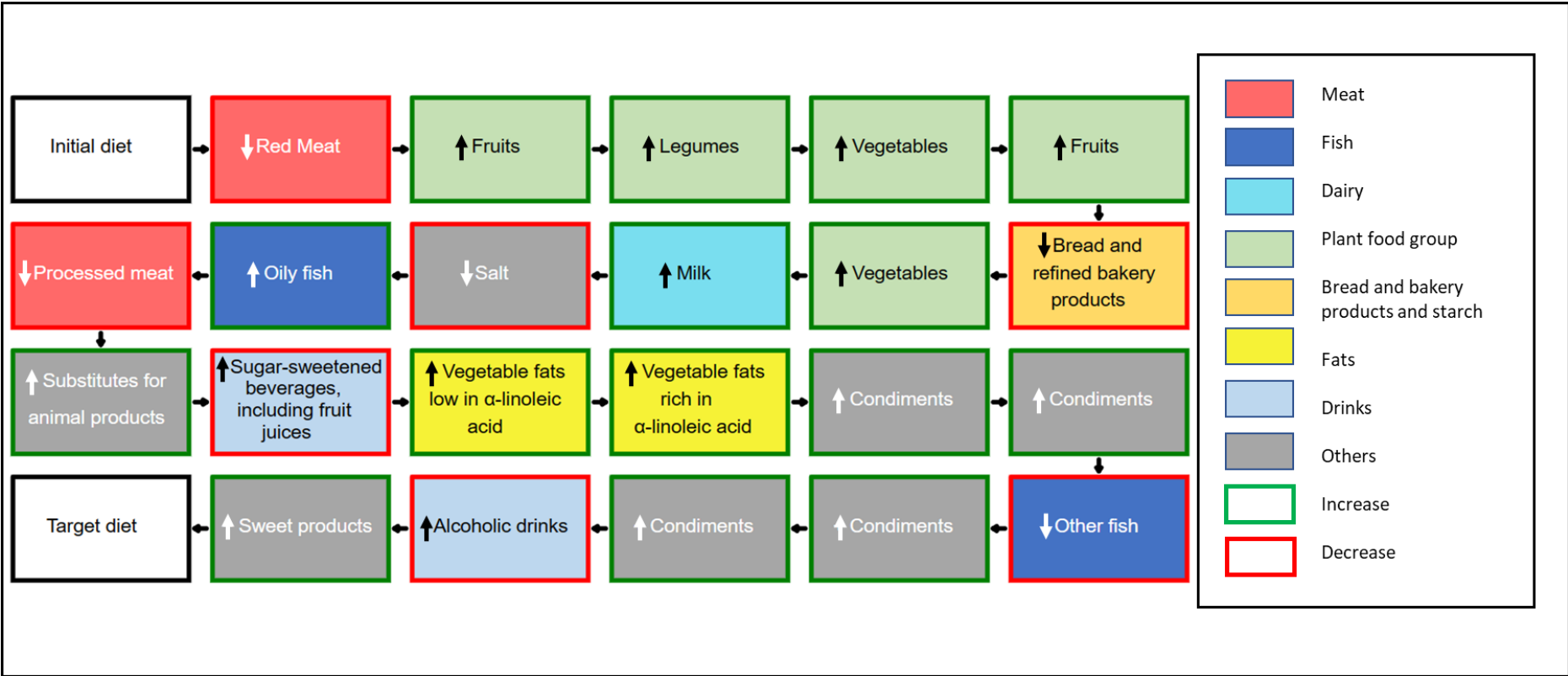
Supplemental Figure 3 Best pathway identified for males based on their first quintile of meat dietary intake.

Best pathway is identified using an optimization criteria combining the total meat intake and the Health Risk Criterion, with prioritization of the former over the latter.



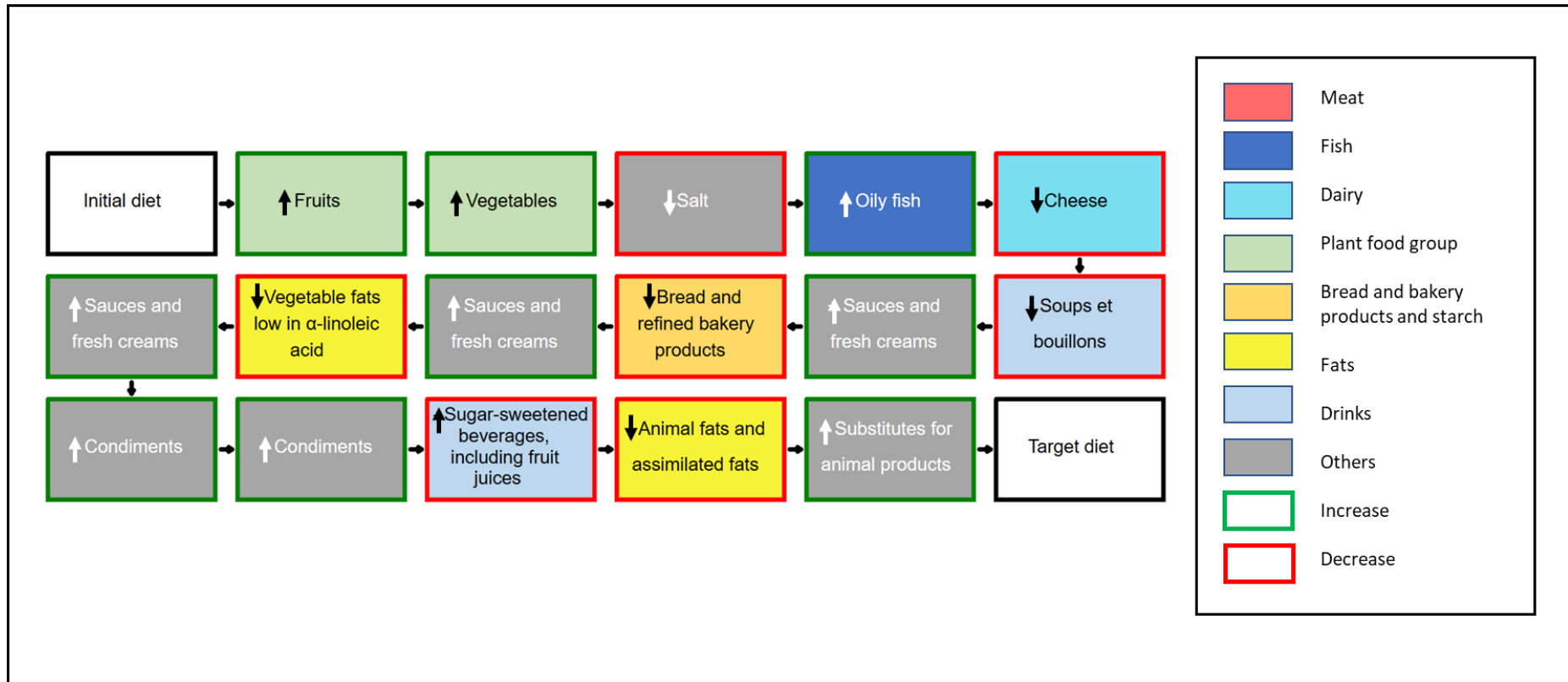
Supplemental Figure 4 Best pathway identified for males based on their fifth quintile of meat dietary intake.

Best pathway is identified using an optimization criteria combining the total meat intake and the Health Risk Criterion, with prioritization of the former over the latter.



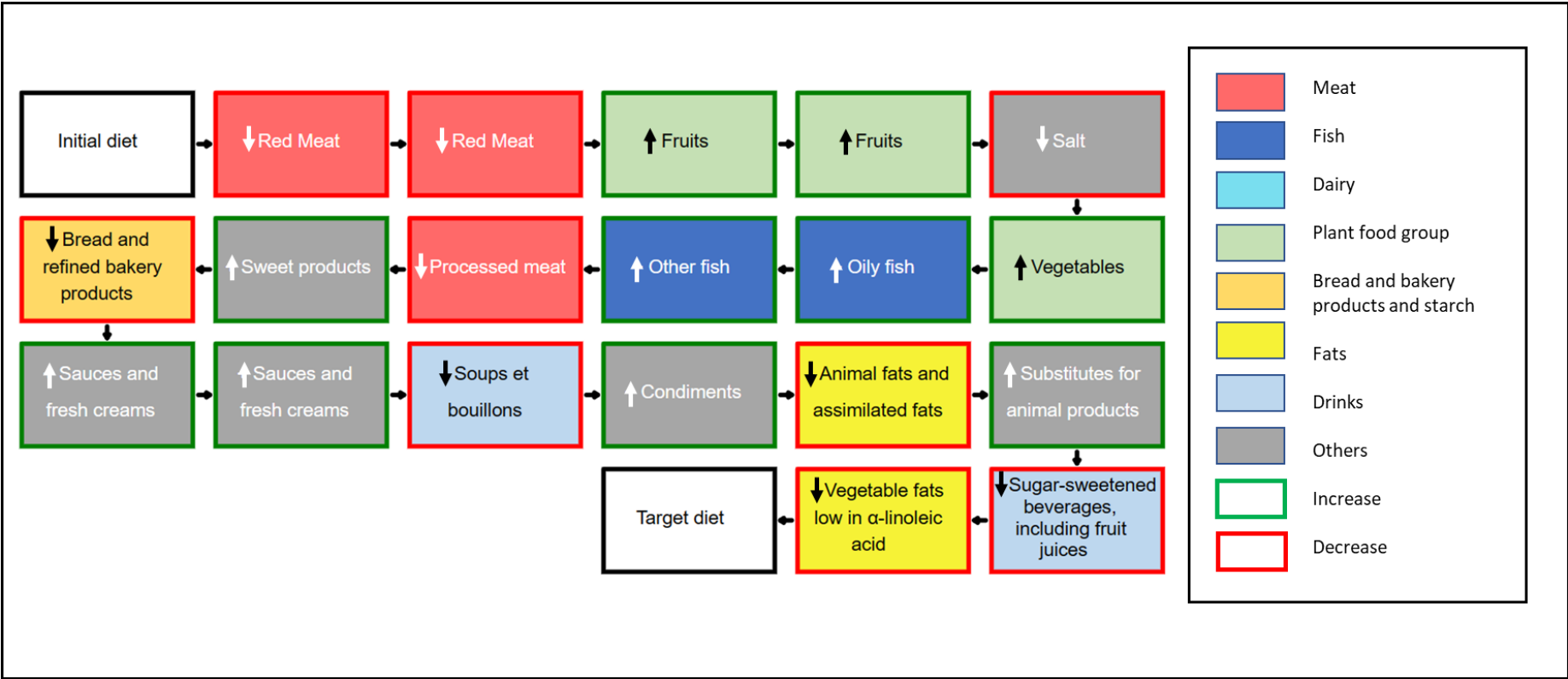
Supplemental Figure 5 Best pathway identified for females based on their first quintile of meat dietary intake.

Best pathway is identified using an optimization criteria combining the total meat intake and the Health Risk Criterion, with prioritization of the former over the latter.



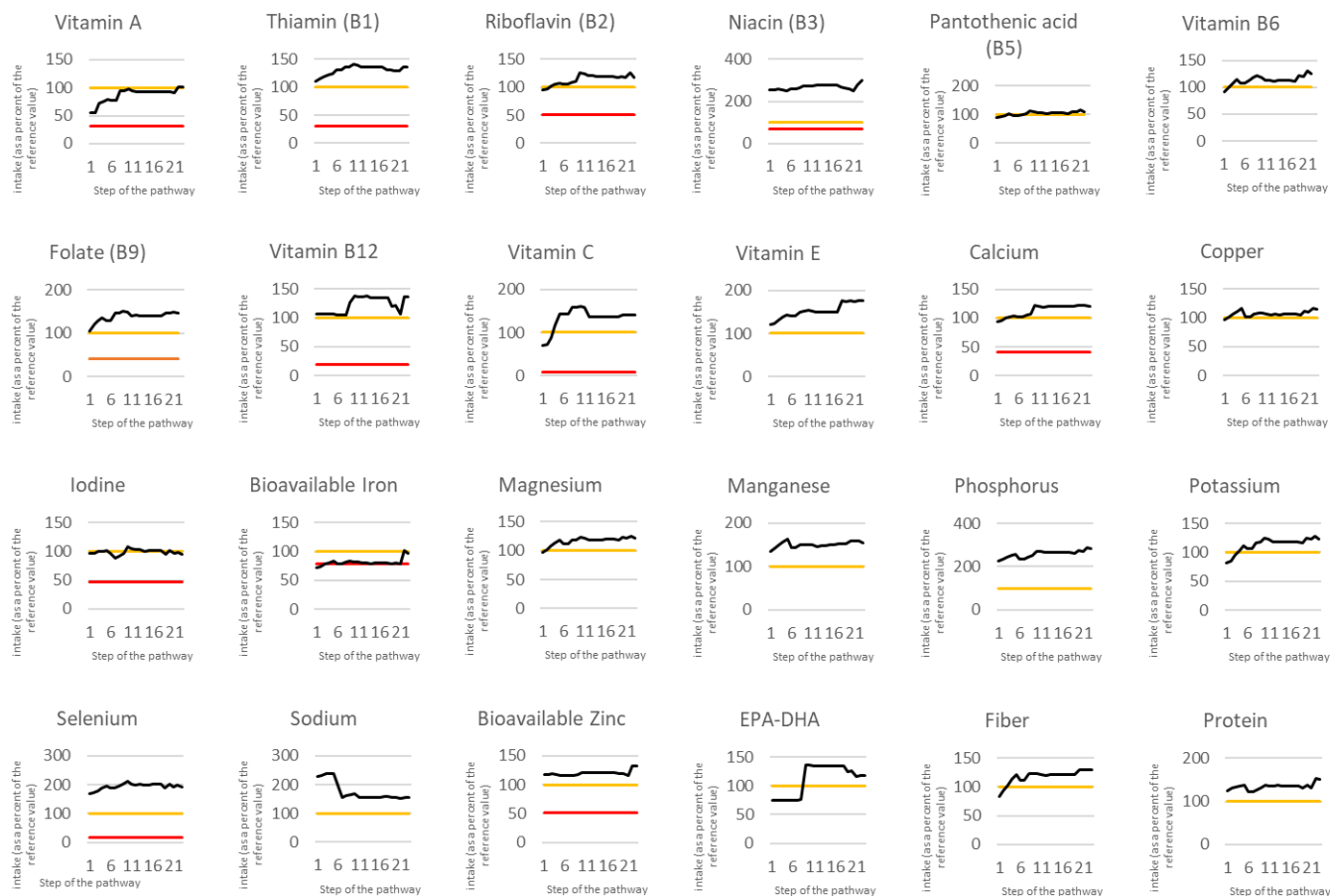
Supplemental Figure 6 Best pathway identified for females based on their fifth quintile of meat dietary intake.

Best pathway is identified using an optimization criteria combining the total meat intake and the Health Risk Criterion, with prioritization of the former over the latter.



**Supplemental Figure 7 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for males based on their first quintile of meat dietary intake**

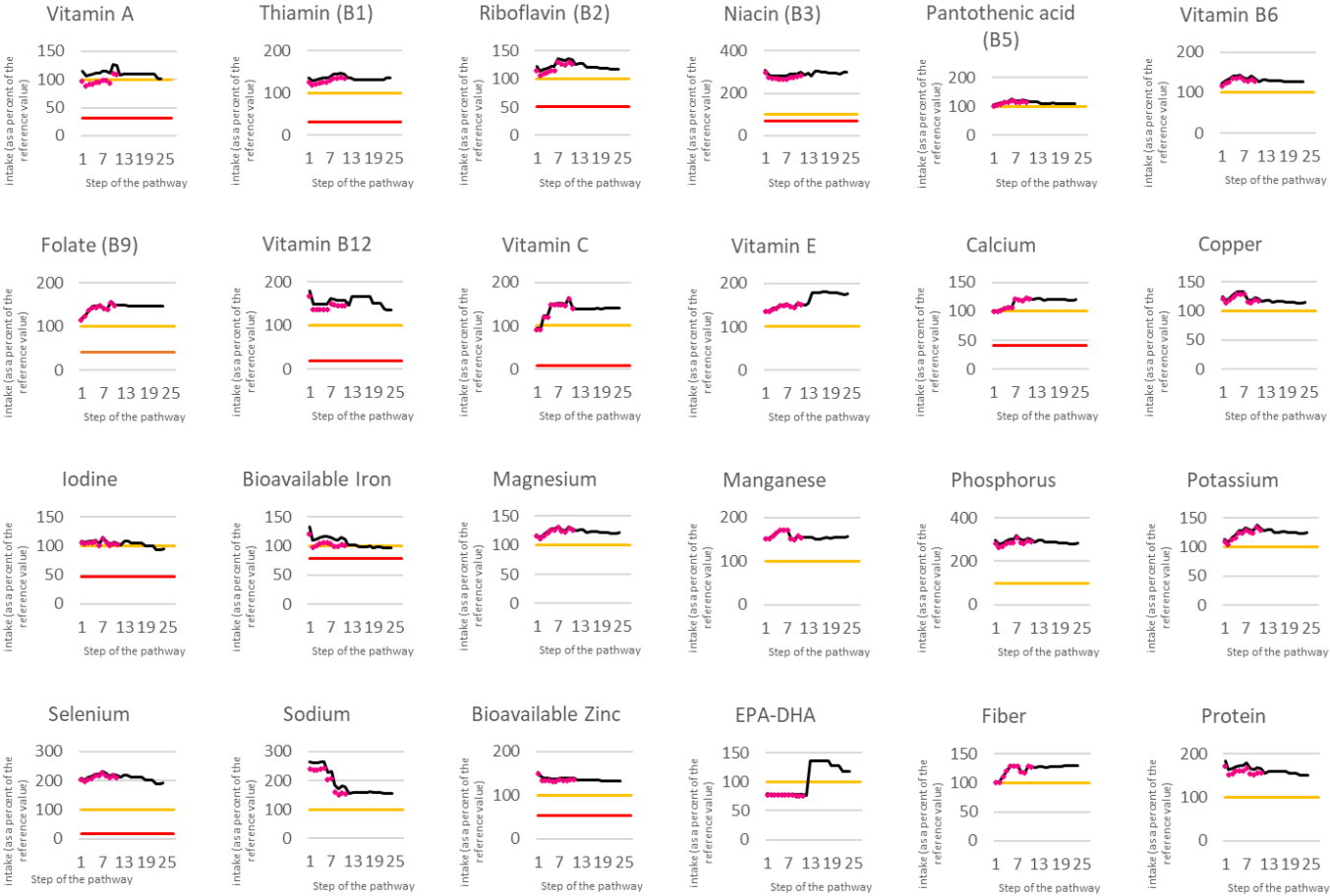
**Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively.**





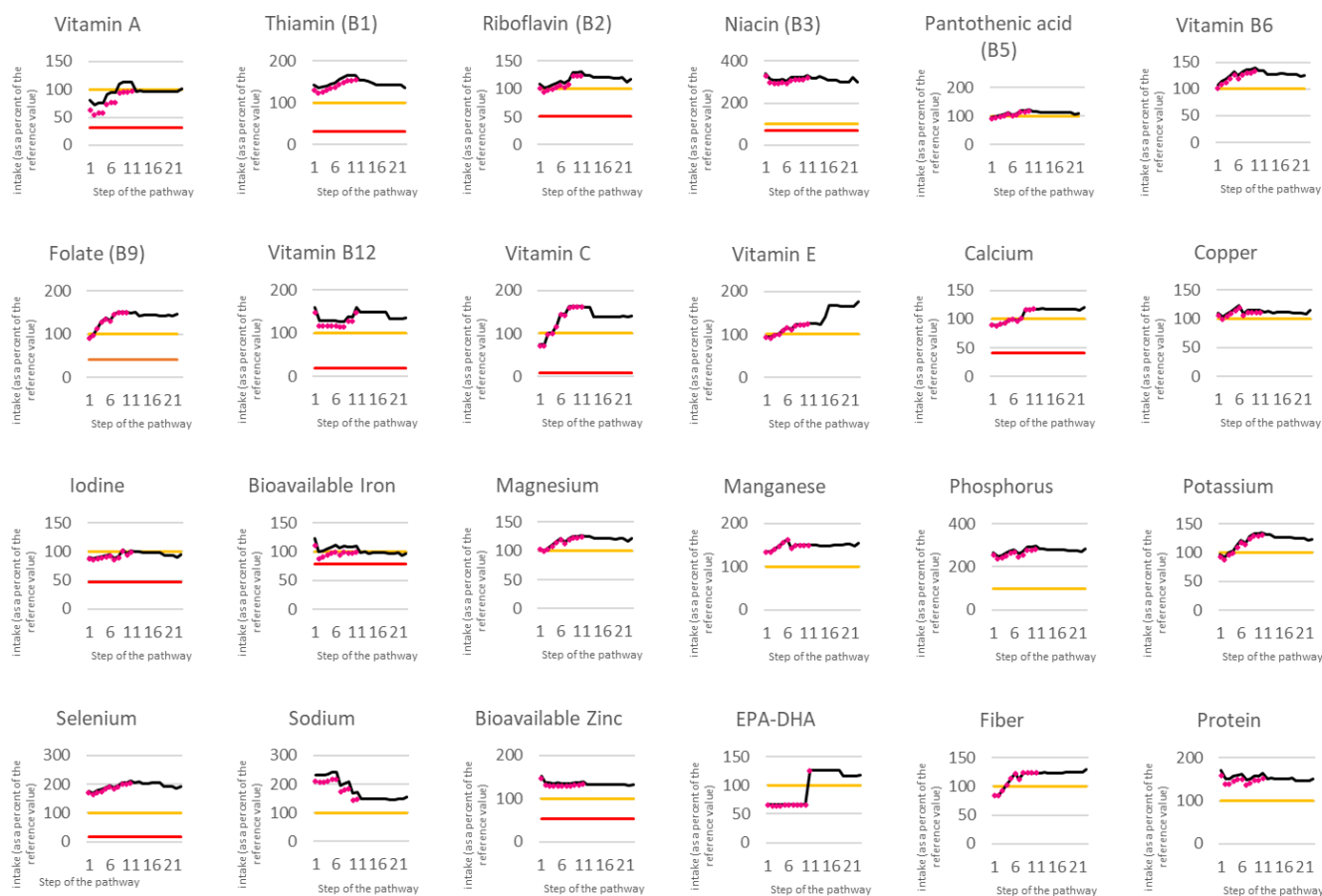
**Supplemental Figure 8 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for males based on their mean dietary intake**

Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively. The symbols show what would have happened if red meat (red triangle) or processed meat (pink diamond) had been reduced.



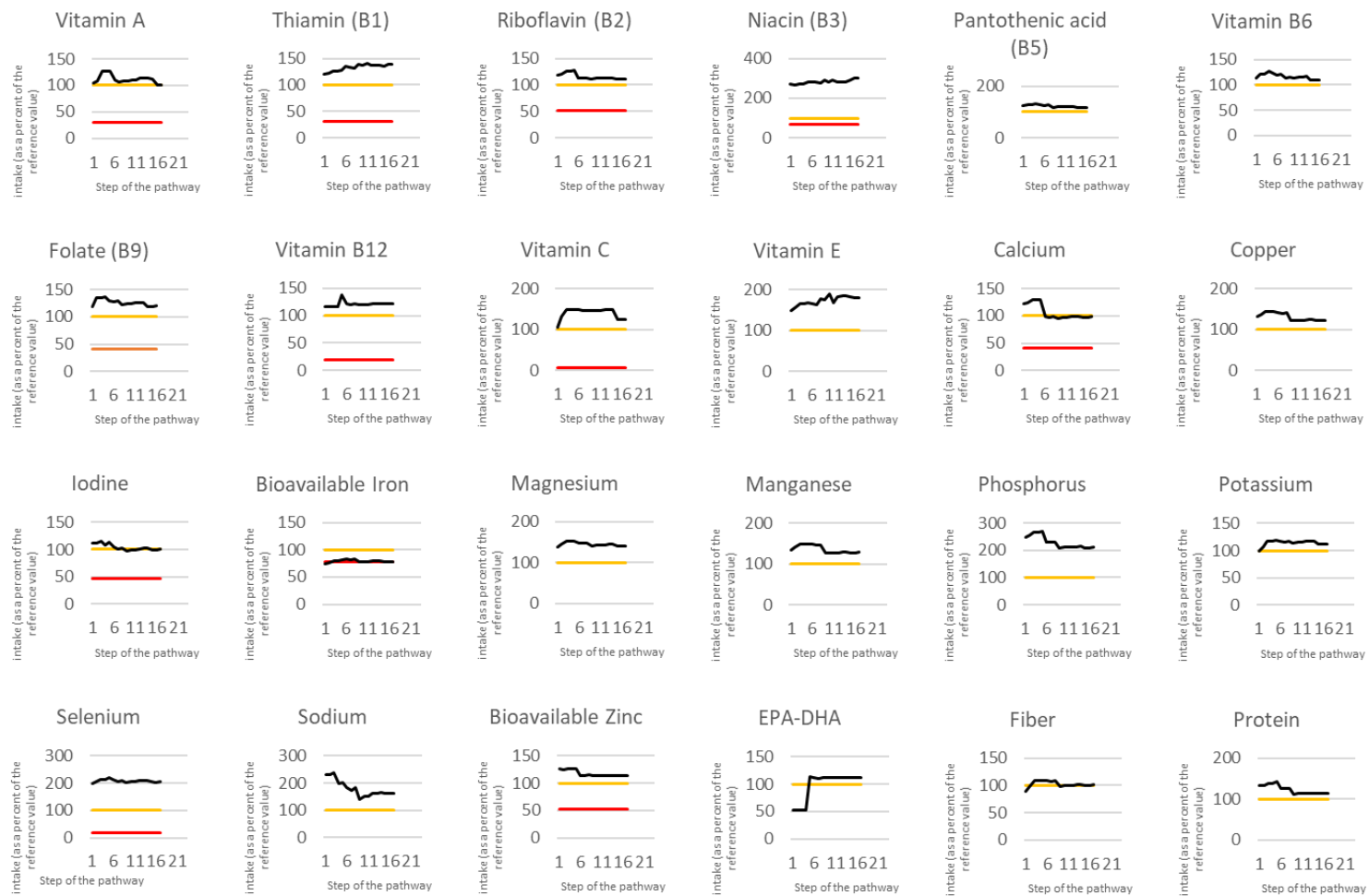
## Supplemental Figure 9 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for males based on their fifth quintile of meat dietary intake

Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively. The symbols show what would have happened if red meat (red triangle) or processed meat (pink diamond) had been reduced.



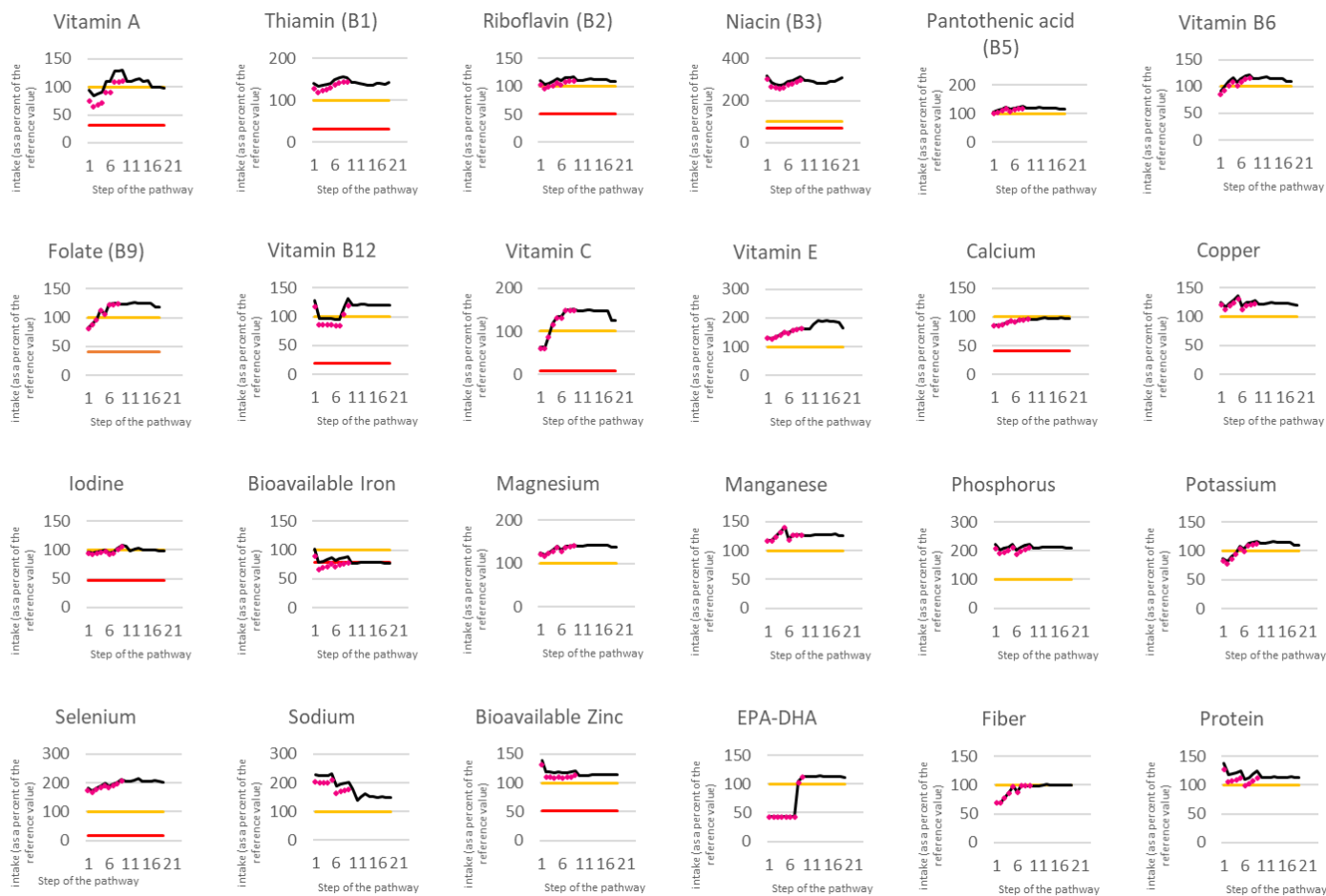
**Supplemental Figure 10 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for females based on their first quintile of meat dietary intake**

Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively.



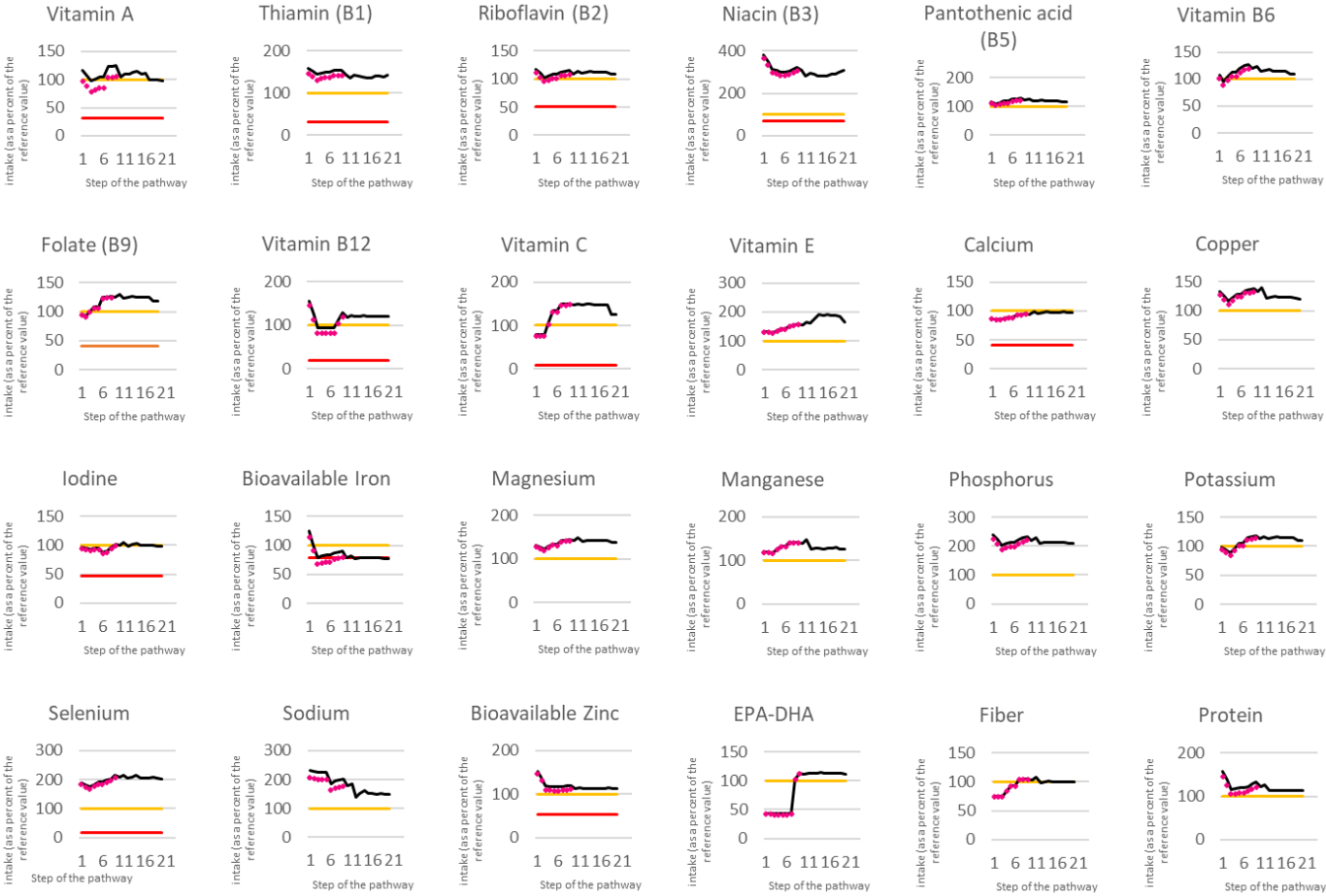
**Supplemental Figure 11 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for females based on their mean dietary intake**

Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively. The symbols show what would have happened if red meat (red triangle) or processed meat (pink diamond) had been reduced.

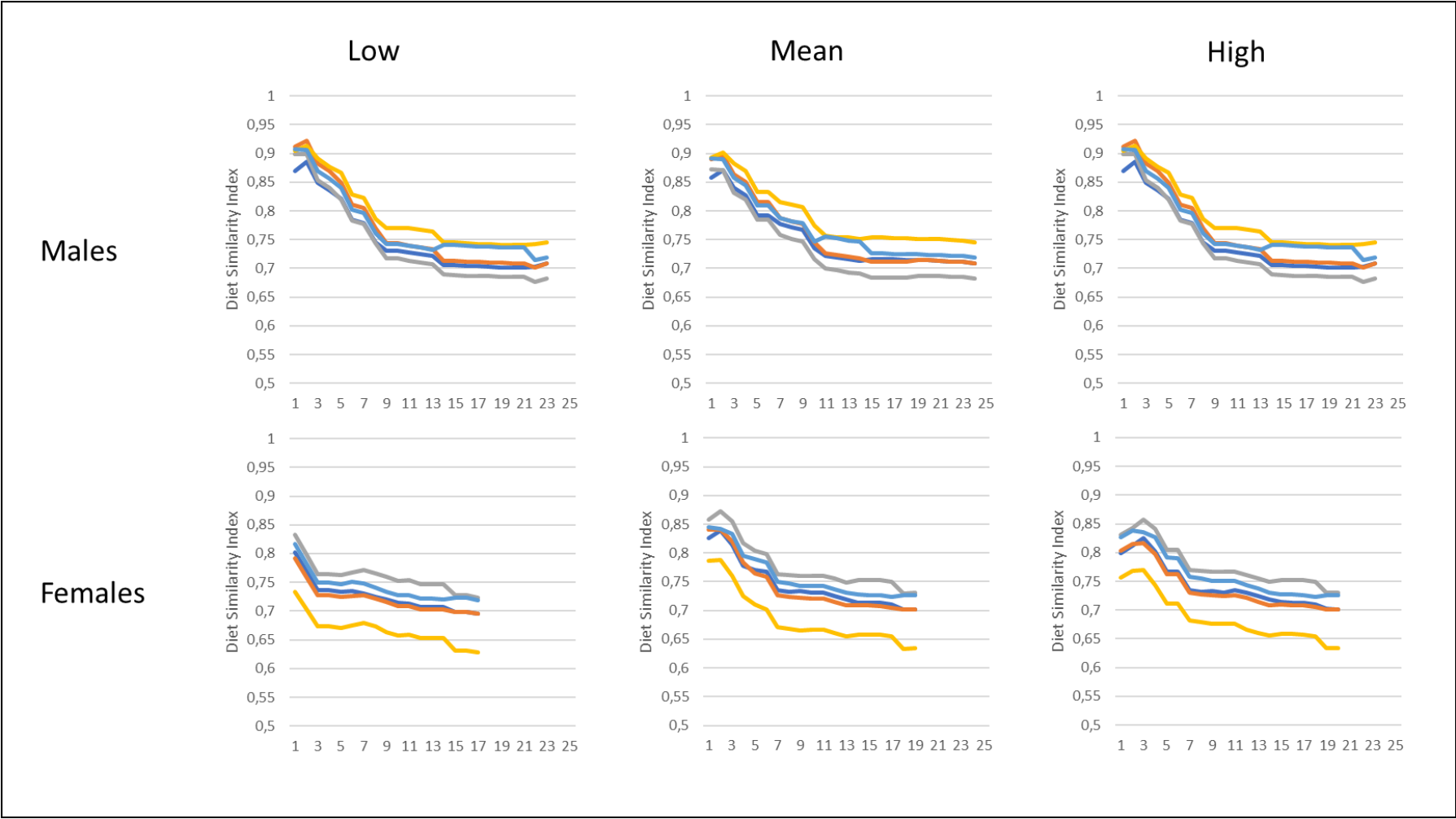


**Supplemental Figure 12 Changes in nutrient (as a percentage of the reference value) along the pathway from initial to target diets for females based on their fifth quintile of meat dietary intake**

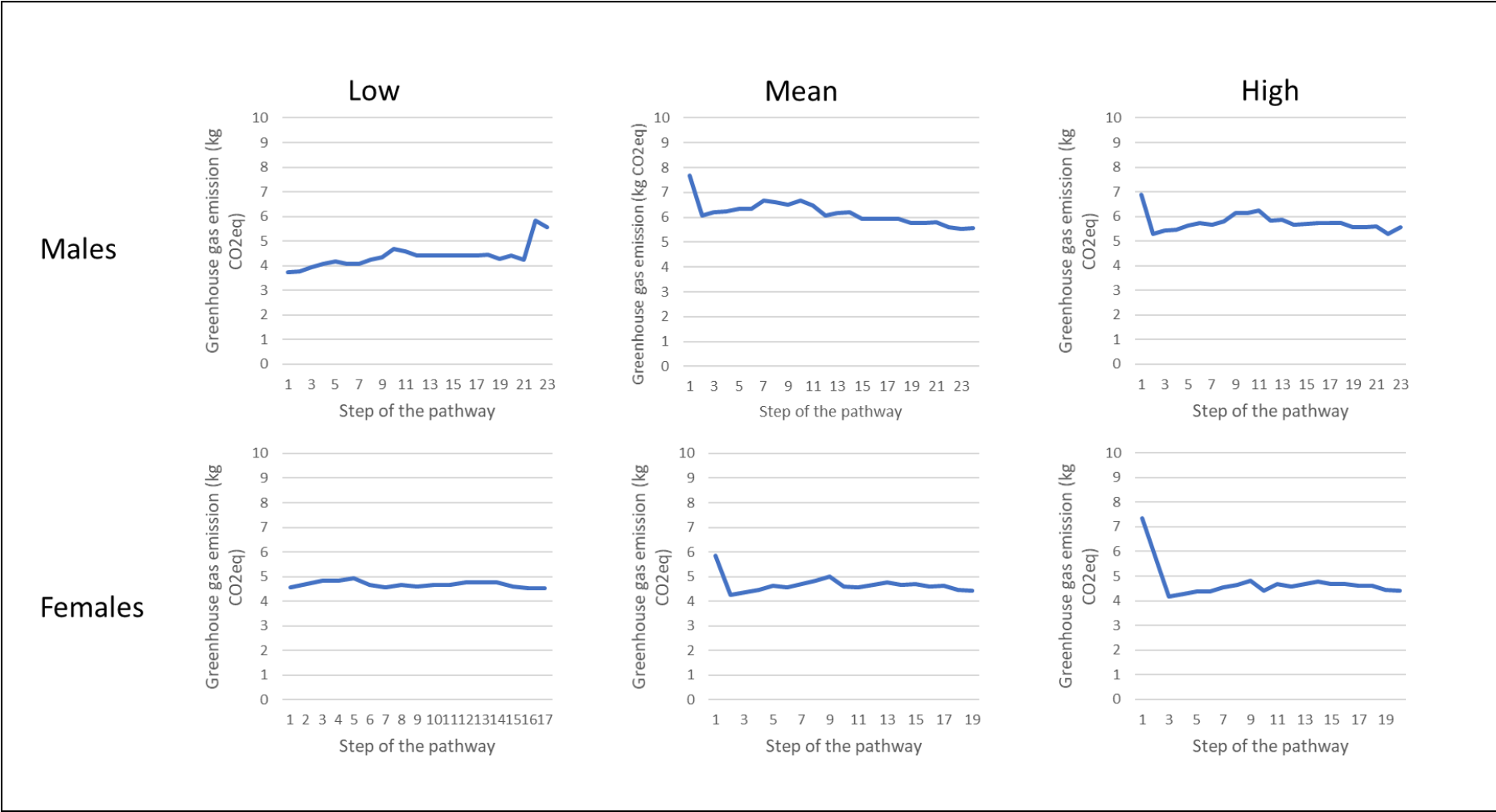
Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and the lower threshold of overt deficiency, ensuring  $\leq 5\%$  prevalence of iron-deficiency anemia, respectively. The symbols show what would have happened if red meat (red triangle) or processed meat (pink diamond) had been reduced.



**Supplemental Figure 13 Similarity between the consumption profiles as defined using the hierarchical classification of the food groups consumed by the INCA3 individual participants and the diets throughout the trajectory, as assessed using the Diet Similarity Index (Mertens et al., 2021, 2020) with the first quintile of meat consumption as initial diet for male**



**Supplemental Figure 14 Changes in the Greenhouse gas emissions (CO<sub>2</sub>eq) along the pathway from initial to target diets by sex and considered population. Three different initial diets are considered by sex: Low (first quintile), Mean, and High (fifth quintile) meat-eaters.**









**Supplemental Table 1 Food group consumptions (g/d) by sex in the observed diets (Low (first quintile), Mean, and High (fifth quintile) meat-eaters) and target diets**

	Observed diet						Target diet	
	Male			Female			Male	Female
	Low	Mean	High	Low	Mean	High		
Vegetables	156	176	147	201	160	185	400	387
Fruit	146	142	101	136	124	133	419	360
Nuts	4	3	1	4	2	1	11	12
Refined bread	125	168	101	106	115	84	27	10
Whole bread	15	11	8	23	15	13	99	62
Other refined starches	116	177	153	113	121	136	193	98
Other whole starches	5	4	3	9	4	3	5	9
Processed products	18	24	16	25	21	19	0	14
Legumes	4	13	8	6	6	4	86	16
Poultry	6	30	44	4	31	61	46	41
Red Meat	15	79	108	12	42	96	54	16
Processed meat	16	50	59	15	30	43	0	0
Oily fish	10	8	6	12	6	6	26	20

Other fish	27	27	9	33	19	14	1	31
Eggs	16	14	11	16	14	15	11	18
Milk	60	84	55	77	75	59	190	114
Fresh dairy products	60	81	63	77	81	97	28	72
Sweet milky desserts	10	19	14	17	16	16	0	14
Cheese	43	49	33	43	36	34	48	12
Animal fats	9	11	5	9	10	7	4	0
ALA vegetable fats	0	0	1	0	0	0	16	5
Other vegetable fats	11	12	9	12	10	11	15	4
Sauces	28	35	28	26	32	31	35	100
Sweet products	87	103	60	93	83	57	103	100
Drinking water	1008	1007	1034	857	929	917	878	1141
SSB	194	221	155	185	208	177	0	0
Hot drinks	397	494	371	559	507	575	379	507
Salt	1	1	1	1	1	2	0	0
Condiments	7	6	4	3	4	4	13	6

Soups	63	76	29	80	79	93	0	27
Substitutes	5	3	2	7	5	6	29	27
Other foods	3	4	3	2	2	3	4	2
Alcoholic drinks	183	216	162	89	59	84	0	43

Nuts: Nuts and seeds, Refined bread: Bread and refined bakery products, Whole bread: Whole meal and semi-refined bread and bakery products, Other whole starches: Other whole and semi-refined starches, Processed products: Processed starch-based products, Eggs: Eggs and egg-based dishes, Animal fats: Animal fats and assimilated fats, ALA vegetable fats: Vegetable fats rich in  $\alpha$ -linoleic acid, Other Vegetable fats: Vegetable fats low in  $\alpha$ -linoleic acid, Sauces: Sauces and fresh creams, SSB: Sugar-sweetened beverages, including fruit juices, Soups: Soups and bouillons, Substitutes: Substitutes for animal products

**Supplemental Table 2 Food group consumption (g/d) for each consumption profile coming from the hierarchical classification of the food groups consumed by the INCA3 individual participants.**

	Males					Females				
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
Number of individuals	123	119	92	68	162	85	112	95	109	160
Vegetables	180	167	163	197	179	179	136	163	141	183
Fruit	145	140	107	191	144	109	120	137	90	158
Nuts	7	2	3	2	2	3	2	2	2	2
Refined bread	171	163	163	147	181	99	102	134	116	117
Whole bread	15	10	11	7	9	14	18	21	9	15
Other refined starches	157	174	173	189	191	107	133	105	136	117
Other whole starches	4	4	4	3	5	14	1	5	4	2
Processed products	22	27	39	27	20	30	22	19	20	18
Legumes	7	19	10	23	12	9	5	2	8	6
Poultry	36	64	8	16	26	7	6	68	51	21
Red Meat	11	72	100	73	119	8	54	7	50	70
Processed meat	44	48	60	41	54	37	34	28	25	30
Oily fish	9	5	4	20	8	7	7	8	4	5
Other fish	29	15	15	57	29	30	19	22	15	15
Eggs	15	13	16	16	11	19	13	11	13	14
Milk	108	59	61	107	90	66	81	78	83	67
Fresh dairy products	67	80	69	99	91	83	79	79	82	83
Sweet milky desserts	14	22	19	21	20	15	22	14	13	15
Cheese	47	46	64	37	48	44	42	31	29	36
Animal fats	11	13	11	13	9	8	10	8	8	13
ALA vegetable fats	0	0	0	0	0	0	1	0	0	1

Other vegetable fats	10	12	9	12	15	12	11	9	10	10
Sauces	40	33	42	39	26	24	36	43	31	26
Sweet products	105	119	96	96	100	97	89	84	75	79
Drinking water	917	1119	1032	971	992	899	1001	951	851	951
SSB	229	265	236	259	158	205	187	251	233	171
Hot drinks	529	403	498	461	544	635	439	569	388	560
Salt	1	1	1	2	1	2	1	1	1	2
Condiments	7	3	8	5	4	4	4	5	5	4
Soups	79	90	67	62	77	152	68	58	56	82
Substitutes	1	3	5	1	2	8	2	5	2	7
Other foods	3	4	5	3	3	1	2	2	1	2
Alcoholic drinks	171	198	194	180	290	62	55	66	43	72

Nuts: Nuts and seeds, Refined bread: Bread and refined bakery products, Whole bread: Whole meal and semi-refined bread and bakery products, Other whole starches: Other whole and semi-refined starches, Processed products: Processed starch-based products, Eggs: Eggs and egg-based dishes, Animal fats: Animal fats and assimilated fats, ALA vegetable fats: Vegetable fats rich in  $\alpha$ -linoleic acid, Other Vegetable fats: Vegetable fats low in  $\alpha$ -linoleic acid, Sauces: Sauces and fresh creams, SSB: Sugar-sweetened beverages, including fruit juices, Soups: Soups and bouillons, Substitutes: Substitutes for animal products

## Supplemental method 1 Target diet

### Multi-criteria diet optimization under constraints

Target diets were identified using a multi-criteria optimization approach previously developed by our group (Dussiot et al., 2022a; Fouillet et al., 2022). We thus identified modeled target diets (i.e., modeled consumptions of 33 food groups) with minimal long-term health risk and a minimal departure from the observed diet (to consider cultural acceptability and inertia), under constraints to ensure adequate nutrient intakes and remain within current consumption limits.

This non-linear optimization problem was performed using the NLP solver of the OPTMODEL procedure of SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA.). Optimization was implemented at the population level but in males and females, separately.

### Constraints

During diet optimization, the total energy intake was constrained to stay within  $\pm 5\%$  of its observed value. Thirty-five nutritional constraints were applied to ensure adequate nutrient intake in the male and female populations (Method Table 1), based on the most recent reference values from the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) (ANSES, 2021b). We did not consider any constraints for vitamin D because its reference value is known to be much too high to be reached by a non-fortified diet alone (Dussiot et al., 2022b; Mariotti et al., 2021). As the absorption of iron and zinc is dependent on dietary factors, the requirements were based on bioavailable iron and zinc calculated from the dietary intake using equations that predict their absorption (Armah et al., 2013; Hallberg and Hulthén, 2000; Miller et al., 2007; “Scientific Opinion on Dietary Reference Values for zinc,” n.d.), as detailed in a previous study by our group (Dussiot et al., 2022b). This previous study demonstrated that current recommendations regarding bioavailable iron and zinc are very constraining when trying to model healthier diets, these recommendations being much higher than current intakes (e.g., there is a current iron-deficiency anemia prevalence of 4.1% in French female) (Dussiot et al., 2022b). Therefore, like in this previous study, we used threshold values lower than current reference values. They correspond to a deficiency prevalence of 5% because such flexibility enables the identification of diets that are apparently healthier overall, with a better balance in disability-adjusted life-years (DALYs) due to less cardiometabolic disease, despite a higher prevalence of iron-deficiency anemia (Dussiot et al., 2022b). In addition, to take into account the slightly lower digestibility of plant vs. animal proteins regarding the nutritional constraint on protein requirement, a 5% penalty was applied to protein intake from plant protein food items, as previously described (De Gavelle et al., 2018). As the intake of individual amino acids is generally adequate when the protein intake is sufficient in a varied diet (de Gavelle et al., 2017), only protein requirements were considered in the model constraints. However, we have *a posteriori* verified that modeled diets also contained adequate intakes of indispensable amino acids by using a database of the amino acid composition of food groups.

Moreover, some acceptability constraints were applied to the food group consumption (Method Table 2). Acceptability constraints aimed to keep the food group intakes within the range of observed intakes by bounding each food group intake between its 5<sup>th</sup> and 95<sup>th</sup> percentile of observed consumption in males and females separately. For the unhealthy food groups (red meat, processed meat and sweetened beverages), more restrictive upper limits were defined as dietary constraints according to the French dietary guidelines. Another exception was made for some healthy food groups (legumes and milk) that had 95<sup>th</sup> percentile values slightly lower than TMREL values, and for which the upper limit has thus been raised to their TMREL values.

### Objectives

The main optimization objective was to minimize the long-term health risk of the modeled diet, as assessed by the *HR* criterion. The *HR* criterion was set to target the dietary recommendations from the Global Burden of Diseases (GBD) based on epidemiological studies about the associations between the consumption of different food groups and the risk of chronic diseases (Murray et al., 2020). The *HR* criterion thus aimed to limit the consumption of three unhealthy food groups or categories (red meat, processed meat and sweetened beverages), while promoting six healthy food groups or categories (whole grain products, fruits, vegetables, legumes, nuts and seeds, and milk) until their TMREL values were reached. According to the most recent (2019) estimates from the GBD, TMREL values were 0 g/d for red meat, processed meat and sweetened beverages, and 150, 325, 300, 95, 14.5 and 430 g/d, respectively, for whole grain products, fruits, vegetables, legumes, nuts and seeds, and milk (Murray et al., 2020). According to the most recent (2019) estimates from the GBD, TMREL values were 3 mg/d for sodium, and 21.5 g/d, 1080 mg/d, 0.45 g/d and 8 % of total energy intake, respectively, for fibers, calcium, EPA/DHA and PUFA (Murray et al., 2020). In our study, the *HR* criterion was thus expressed and minimized as:

$$\begin{aligned} \text{Min } HR = & \sum_{i=1}^3 \left( \frac{\text{Opt}(i)}{\text{Max}(i)} \times \frac{\text{DALYs}(i)}{\text{DALYs}(\text{all})} \right) + \sum_{j=1}^6 \left( \max \left[ \frac{\text{TMREL}(j) - \text{Opt}(j)}{\text{TMREL}(j)}; 0 \right] \times \frac{\text{DALYs}(j)}{\text{DALYs}(\text{all})} \right) \\ & + \sum_{n=1}^4 \left( \max \left[ \frac{\text{TMREL}(n) - \text{Opt}(n)}{\text{TMREL}(n)}; 0 \right] \times \frac{\text{DALYs}(n)}{\text{DALYs}(\text{all})} \right) \\ & + \left( \max \left[ \frac{\text{Opt}(\text{Na}) - \text{TMREL}(\text{Na})}{\text{TMREL}(\text{Na})}; 0 \right] \times \frac{\text{DALYs}(\text{Na})}{\text{DALYs}(\text{all})} \right) \end{aligned}$$

Where *i* denotes the food groups to be decreased (red meat, processed meat and sweetened beverages), *j* denotes the food groups to be increased (whole grain products, fruits, vegetables, legumes, nuts and seeds, and milk), *n* denotes the nutrients to be increased (fibers, calcium, EPA/DHA, PUFA), *Opt*(*i*), *Opt*(*j*), *Opt*(*n*), and *Opt*(*Na*) are the optimized consumptions of food groups *i* and *j* and nutrients *n* and sodium (*Na*), respectively, *Max*(*i*) is the upper limit of consumption of food group *i* (in g/d), *TMREL*(*j*), *TMREL*(*n*), and *TMREL*(*Na*) are the TMREL values of food group *j* and nutrients *n* and *Na*, respectively (in g/d), *DALYs*(*i*), *DALYs*(*j*), *DALYs*(*n*), and *DALYs*(*Na*) are the disability-adjusted life-years associated with excessive or insufficient consumptions of food groups *i* and *j* and nutrients *n* and *Na*, respectively (in y), and *DALYs*(*all*) is the sum of all *DALYs*(*i*), *DALYs*(*j*), *DALYs*(*n*) and *DALYs*(*Na*). The *Max*(*i*) values used were the maximal recommended consumption of unhealthy foods in line with the French dietary guidelines (Mariotti et al., 2021): 71g/d for red meat, 25g/d for processed meat and 263 g/d (corresponding to the average portion size) for sweetened beverages intake. The TMREL and DALYs values used were issued from the most recent (2019) estimates from the GBD (Murray et al., 2020) adapted to our study context (by using sex-specific and French DALYs values, Method Table 3).

We also evaluated how the modeled diets deviated from current diets (*DD* criterion), in order to consider inertia to changes in food consumption, which is one way to account for social/cultural acceptability. The *DD* criterion was defined as the sum of the squares of the differences between observed and optimized food group consumption, standardized by their observed standard deviations, as previously explained (Dussiot et al., 2022b). *DD* was thus expressed and minimized as:

$$\text{Min } DD = \sum_{k=1}^n \left[ \frac{\text{Obs}(k) - \text{Opt}(k)}{\text{SD}(k)} \right]^2$$

Where *k* is the number of food groups (*n*=45), *Obs*(*k*) and *Opt*(*k*) are respectively the observed and optimized consumption of food group *k* (in g/d) and *SD*(*k*) is the current standard deviation of the consumption of food group *k*.





**Supplemental Method 1, Table 1.** Nutritional constraints applied in the optimization model in French males and females<sup>1</sup>.

Nutrients	Units (/day)	Lower bounds <sup>2</sup>		Upper bounds <sup>3</sup>	
		Males	Females	Males	Females
Energy intake <sup>4</sup>	kcal	2 470	1 995	2 730	2 205
Retinol	µg	-	-	3 000	3 000
Vitamin A	µg	750	650	-	-
Vitamin B1 (Thiamin)	µg/kcal	0.418	0.418	-	-
Vitamin B2 (Riboflavin)	mg	1.6	1.6	-	-
Vitamin B3 (Niacin) <sup>5</sup>	mg NE/kcal	0.0067	0.0067	900	900
Vitamin B5 (Pantothenic acid)	mg	3.77	3.22	-	-
Vitamin B6	mg	1.7	1.6	25	25
Vitamin B9 (Folate)	µg	330	330	-	-
Vitamin B12	µg	4	4	-	-
Vitamin C	mg	110	110	-	-
Vitamin D <sup>6</sup>	µg	-	-	100	100
Vitamin E	mg	5.28	4.37	-	-
Vitamin K1	µg	39.47	34.48	-	-
Calcium	mg	950	950	2 500	2 500
Copper	mg	1.07	0.89	5	5
Bioavailable iron <sup>7</sup>	mg	1.10 (1.40)	1.16 (1.49)	-	-
Iodine	µg	150	150	600	600
Magnesium	mg	253.5	194.6	-	-
Manganese	mg	1.99	1.52	-	-
Phosphorus	mg	550	550	-	-
Potassium	mg	3 500	3 500	-	-
Selenium	µg	70	70	300	300
Sodium	mg	1 500	1 500	2 300	2 300
Bioavailable zinc <sup>7</sup>	mg	2.06 (2.35)	1.61 (1.82)	25	25
Water	g	2 500	2 000	-	-
Saturated fatty acids	% EI	-	-	12%	12%
Atherogenic fatty acids	% EI	-	-	8%	8%
Linoleic acid	% EI	4%	4%	-	-
α-linolenic acid	% EI	1%	1%	-	-
Linoleic acid / alpha-linolenic acid ratio	-	-	-	5	5
EPA+DHA	g	0.5	0.5	-	-
Sugar (excluding lactose)	g	-	-	100	100
Protein <sup>8</sup>	g/kg bw	0.83	0.83	2.3	2.3
Fiber	g	30	30	-	-

<sup>1</sup>Lower and upper bounds of the nutritional constraints are based on the most recent nutrient reference values from the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) (ANSES, 2021b).

<sup>2</sup>Lower bounds correspond to the Population Reference Intake (PRI) or lowest value of the macronutrient reference intake range. For vitamins B5, E, K1, copper, magnesium and manganese, lower bounds correspond to the 5<sup>th</sup> percentile of consumption.

<sup>3</sup>Upper bounds correspond to the Tolerable Upper Intake Level (UL) or highest value of the macronutrient reference intake range.

<sup>4</sup>Total energy intake was constrained to stay within ±5% of the current energy intake (2600 kcal for males and 2100 kcal for females).

<sup>5</sup>1 mg niacin equivalent (NE) is equal to 1 mg niacin or 60 mg tryptophan

<sup>6</sup>For vitamin D, a lower bound was not applied as the current reference value is too high to be reached through food intake alone.

<sup>7</sup>For bioavailable iron and zinc, lower bounds were not based on current reference values but on lower threshold values ensuring ≤5% deficiency prevalence. During sensitivity analysis, we also used the values shown in parentheses, which consider more demanding requirements thus ensuring ≤1% deficiency prevalence. These latter values are closer to current reference values, although still lower (but nevertheless higher than the currently observed values for bioavailable iron in females).

<sup>8</sup>To account for the slightly lower average digestibility of plant protein, protein intake from plants was reduced by 5% when calculating total protein intake.

Atherogenic fatty acids, lauric and myristic and palmitic acids; DHA, docosahexaenoic acid; EI, energy intake; EPA, eicosapentaenoic acid.

**Supplemental Method 1, Table 2.** Dietary and acceptability constraints applied for the consumption of each food group in the optimization model in French males and females.

Food groups	Males			Females		
	Lower consumption limit (g/d)	Prevailing diet (g/d)	Upper consumption limit (g/d)	Lower consumption limit (g/d) <sup>1</sup>	Prevailing diet (g/d)	Upper consumption limit (g/d)
<u>Unhealthy food groups (dietary constraints)<sup>1</sup></u>						
Beef and veal	0	48	71*	0	28	71*
Pork and other meats	0	27	71*	0	13	71*
Offal	0	4		0	1	
Processed meats	0	50	25	0	30	25
Sweetened soda type beverages	0	141	263*	0	140	263*
Fruit juices	0	80		0	67	
<u>Other food groups (acceptability constraints)<sup>2</sup></u>						
Vegetables	20	176	400	18	160	387
Fresh fruits	0	128		0	107	
Dried fruits	0	1	453*	0	1	359*
Processed fruits: compotes and cooked fruits	0	13		0	15	
Nuts, seeds and oleaginous fruits	0	3	20	0	2	14
Bread and refined bakery products	28	168	354*	19	115	316*
Whole and semi-refined bread and bakery products		11			15	
Other refined starches	0	98	276*	0	72	188*
Other whole and semi-refined starches	0	4		0	4	
Starch-based products, sweet/fat processed	0	22	97	0	19	82
Salt/fat processed starch products	0	4	21	0	2	14
Potatoes and other tubers	0	79	264	0	49	196
Legumes <sup>3</sup>	0	13	107	0	6	87
Poultry	0	30	108	0	31	109
Oily fishes <sup>4</sup>	0	8	39*	0	6	39*
Other fishes <sup>4</sup>	0	22	(26 for oily)	0	15	(26 for oily)
Mollusks and crustaceans	0	5	28	0	4	26
Eggs and egg-based dishes	0	14	61	0	14	70
Milk <sup>3</sup>	0	84	486	0	75	393
Fresh natural dairy products	0	31	138	0	33	143
Fresh sweetened dairy products	0	50	179	0	48	168
Sweet milky desserts	0	19	93	0	16	73
Cheeses	0	49	131	0	36	94
Animal fats and assimilated fats <sup>5</sup>	1	1	1	0	0	0
Butters and light butters	0	10	33	0	10	30
Vegetable fats rich in $\alpha$ -linolenic acid	0	0	32*	0	0	32*
Vegetable fats low in $\alpha$ -linolenic acid	0	12		0	10	
Sauces and fresh creams	0	35	118	0	32	100
Sweet products or Sweet and fatty products	9	103	251	9	83	215
Salt	0	1	4	0	1	4
Condiments	0	4	29	0	3	21
Aromatic herbs, Spices except salt	0	2	7	0	2	6
Soups	0	71	434	0	75	381
Bouillons	0	5	21	0	4	25
Other foods <sup>5</sup>	4	4	4	2	2	2
Substitutes of animal products <sup>6</sup>	3	0	29	5	0	29
Drinking waters	182	1 007	-	75	929	-
Hot drinks <sup>7</sup>	0	494	494	0	507	507
Alcoholic drinks <sup>7</sup>	0	216	216	0	59	59
Liquids (sum of Milk, Drinking waters, Sweetened soda type drinks, Fruit juices, Hot drinks, Soups and Bouillons)	1 061	2 098	3 777	738	1857	3 087

\*These upper consumption limits correspond to coupled constraints for the groups mentioned (e.g., 71 g/d is the maximum intake for beef and veal, pork and other meats and offal grouped together).

<sup>1</sup>In the dietary constraints, upper bounds were applied to the food groups for which the consumption needed to be limited, in line with the French dietary guidelines (Mariotti et al., 2021).

<sup>2</sup>In the acceptability constraints, lower and upper consumption limits generally represented the 5<sup>th</sup> and 95<sup>th</sup> percentiles of consumption, respectively, of the food group in males and females, calculated using data from the third Individual and National Study on Food Consumption French Survey (INCA3), n=1125 (564 males, 561 females).

<sup>3</sup>For legumes and milk, the upper consumption limits in each sex were raised to their theoretical minimum-risk exposure level (TMREL) values as their 95<sup>th</sup> percentiles of consumption values were slightly lower (86 g/day and 43 g/day for legumes and 343 g/day and 322 g/day for milk in males and females, respectively).

<sup>4</sup>For fish, in order to take account of sustainable fish consumption and to limit exposure to contaminants, and in line with the French dietary guidelines on fish consumption (ANSES, 2008), total fish consumption was limited to 39 g/day and oily fish consumption was limited to 26 g/day.

<sup>5</sup>For animal fats and assimilated fats and other foods, consumptions have been imposed constant and equal to the observed intakes in the modeled diets.

<sup>6</sup>For animal product substitutes, due to the very low value of the 95<sup>th</sup> percentile of consumption in male, their upper bound was set to the corresponding value in females.

<sup>7</sup>For hot and alcoholic drinks, the upper bound was set at the prevailing consumption.

**Supplemental Method 1, Table 3.** Theoretical minimum-risk exposure level (TMREL) and disability-adjusted life-years (DALYs) values used in the optimization model in French males and females.

		TMREL <sup>1</sup> (g/d)		DALYs <sup>2</sup> (y)	
		Males	Females	Males	Females
Unhealthy foods	Red meat	0	0	28 562	20 824
	Processed meat	0	0	14 346	6 288
	Sweetened beverages	0	0	4 105	1 791
Healthy foods	Whole grains	170	137	31 405	10 987
	Fruit	367	297	20 130	9 512
	Legumes	107	87	17 103	3 386
	Vegetables	339	274	9 342	3 090
	Nuts & seeds	16	13	6 531	1 355
	Milk	486	393	3 521	2 727
Sum				135 045	59 961

<sup>1</sup>According to the most recent (2019) estimates from the GBD, the TMREL values are 0 g/d for red meat, processed meat and sweetened beverages, and 150, 325, 95, 300, 14.5 and 430 g/d, respectively, for whole cereal products, fruits, legumes, vegetables, nuts and seeds, and milk (Murray et al., 2020). As these TMREL values are overall estimates corresponding to a mean energy intake of 2300 kcal (Murray et al., 2020), we used sex-specific values adapted to the particular energy intake of males and females in our French adult population (centered around 2600 kcal and 2100 kcal in males and females, respectively).

<sup>2</sup>We used the most recent (2019) French sex-specific DALYs values associated with excessive/insufficient consumption of unhealthy/healthy foods, available from the Global Health Data Exchange website (<http://ghdx.healthdata.org/gbd-results-tool>).

## Supplemental method 2 Rounding of the initial diet

For a portion size of  $x_{ps}$ , a target consumption of  $y_t$ , and a quantity  $q$  in the observed diet, the number of portions between the observed and target diet was calculated as follows:

$$\text{number of portions} = \text{round\_down} \left( \frac{q - \text{rest} \left( \frac{y_t}{x_{ps}} \right)}{x_{ps}} \right)$$

Round\_down is the function rounding a number down to the closest integer.

If the number of portions was negative, it was rounded to 0. This method sets an integer number of portions to be modified (between observed and target), and so finally enables the construction of a graph with each node differing by one portion size, connecting observed and target diet.

For example, red meat portion size is 50 g/d and there is 54 g/d in the target diet for male. The high red meat intake for male is 108 g/d. Thus, the number of portions is:

$$\begin{aligned} \text{number of portions} &= \text{round\_down} \left( \frac{108 - \text{remainder} \left( \frac{54}{50} \right)}{50} \right) \\ &= \text{round\_down} \left( \frac{108 - 4}{50} \right) \\ &= \text{round\_down} \left( \frac{104}{50} \right) \\ &= 2 \end{aligned}$$

After adjustment, the quantity for the high meat intake initial diet of male is 104g/d ( $50 \times 2 + 4$ ), and the difference to the target diet is one portion ( $104 - 50 = 54$ g).

### Supplemental Method 3: Calculation of the SecDiet

The SecDiet has been designed to assess the risk of nutrient deficiency due to insufficient intake of nutrients for an adult population. This score computes the probability for each nutrient of having a sufficient intake to avoid nutrient deficiency. This is calculated using the standard normal distribution of nutrient requirements, and taking into account the mean intake  $y$ , the day-to-day variability of intake  $SDy^2$ , the number of days of dietary record  $n$ , the inter-individual variability  $SDr^2$  and the nutrient reference value  $r$ , as follows:

$$F\left(\frac{y - r}{\sqrt{SDr^2 + \frac{SDy^2}{n}}}\right)$$

$F(x)$  is the function returning the probability that an observation from the standard normal distribution is lower than  $x$ . The probability for a nutrient ranges from 0 to 1, where 1 represents a 100 % probability that the usual intake is adequate.

The nutrients included as components in the SecDiet score and the associated threshold values are described in the table below

Nutrient	Threshold	CV(%)
Vitamin A	300 µg RE or 270 µg RE	15
Thiamin	0.18 mg/4 .184 MJ	20
Riboflavin	1.0 mg	10
Niacin	4.35 mg NE/4.184 MJ	10
Folate	175 µg	15
Vitamin B12	1 µg	15
Vitamin C	10 mg	10
Iodine	150 µg	20
Selenium	21 µg or 16 µg	15
Bioavailable Fe	1.74 mg	40
Bioavailable Zn	1.6 mg or 1.3 mg	15
Calcium	500 mg	15

An extended description of the method is presented in Salomé et al. (Salomé et al., 2021b).

#### Supplemental Method 4: Agribalyse database

The environmental pressures associated with diets were estimated by matching INCA3 consumption data with the French database Agribalyse® 3.0.1 developed by the French Agency for the Environment and Energy Management (ADEME). This allowed for a connection to be made between the environmental and nutritional properties of foods for 2497 foods consumed in France (Colomb et al., 2015).

Environmental indicator estimations are based on the method of Life Cycle Assessment (LCA), whose scope is "from field to plate." The perimeter of the indicators covers each process of the value chain: production of raw materials, transport, transformation, packaging, distribution and retailing, food preparation by the consumer, and disposal of packaging. These processes are split into two phases 1) production and 2) post-farm. Of note for Agribalyse, losses and wastes (other than non-edible parts) at home, as well as transport from the retail to the household are not considered.

Overall, Agribalyse construction is based on the international LCA standards: ISO 14040 ("ISO 14040:2006(fr), Management environnemental — Analyse du cycle de vie — Principes et cadre," n.d.) and ISO 14044("ISO 14044:2006(fr), Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices," n.d., p. 14044), LEAP guidelines ("Livestock Environmental Assessment and Performance (LEAP) Partnership - Food and Agriculture Organization of the United Nations," n.d.), and PEF (European Commission, 2018). The finalized indicators are provided per kg of product and are detailed per process.

For the agricultural phase of plant products, all upstream processes (notably input production), excluding storage or drying, are included except for ingredients in processed food. In the case of animal products, all operations including the phases of production, transport and storage of feed, fattening of animals, milking, construction and maintenance of buildings and machinery, have been considered. The scope chosen is consistent with those defined in GESTIM (Gac et al., 2011) and ecoinvent® (Nemecek and Kägi, 2007).

The LCI (life cycle inventory) data of AGRIBALYSE v3.0.1 covered the period 2005-2009, except for perennial crops (2000-2010). The variety of production systems was considered by applying coefficients based on the share of systems in national production. Imported products were also considered by applying coefficients. The allocation rules are varied and are based on international recommendations as described by the ISO 14040/14044 standards ("ISO 14040:2006(fr), Management environnemental — Analyse du cycle de vie — Principes et cadre," n.d.; "ISO 14044:2006(fr), Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices," n.d.). In particular, allocations have been developed in order to distribute organic nitrogen fertilizers and mineral fertilizers (P and K) between crop sequences. Biophysical allocations were used for animal production (milk versus meat). The biophysical models used for animal production and allocations by type of productions are presented in the full report (Koch and Salou, 2020) according to the reference AFNOR-BPX 30-323 ("BP X30-323-5," n.d.)(AFNOR, 2011) and in compliance with the ISO 14044 standard ("ISO 14044:2006(fr), Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices," n.d.) according to three rules in descending order: 1) allocation avoidance, 2) : biophysic allocation and 3) economic allocation.

A characterization method recommended by the European Commission (Environmental Footprint 3.0) translates the input and output flows of the inventory into impacts. For the background data (inputs in construction, raw materials, etc.) the ecoinvent® database is used to assess the indirect emissions (off-field emissions). The full methodology and methodological choices for the use of the ecoinvent® database have been described elsewhere (Koch and Salou, 2020).

The transition from commodities to consumed food results in two coefficients related to the edible food part, and economic allocations between co-products. The recipes are then disaggregated into ingredients. For feasibility reasons, a threshold of 95% of the ingredients covered was used. Similarly, for the origin of the ingredients, a threshold of 70% coverage was used followed by a standardization step. See (Asselin-Balençon et al., 2020) for the entire description of the methodology and methodological adoptions. Post-farm estimations are based on the PEF guidelines (European Commission, 2018)

A total of 14 midpoint indicators are available in Agribalyse: climate change, ozone depletion, particulate matters, ionizing radiation (effect on human health), ecotoxicity, photochemical ozone formation (effect on human health), acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, land use, water use, minerals and metals use, and fossil resources use.



*Description of the environmental indicators*

Environmental indicator	Description	Unit
Greenhouse gas emission	Linked to the increase in the average global temperatures	Carbon dioxide equivalent (kg CO <sub>2</sub> eq)
Exposure ionizing radiation	The impact on human health due to emissions of radiation under normal operating conditions	Equivalent of kilobecquerels of Uranium 235 (kg U <sub>235</sub> eq)
Photochemical ozone (O <sub>3</sub> ) formation	Ozone on the ground has a deleterious impact on organic compounds including animals and plants. It increases for example the frequency of respiratory problems for humans	Equivalent of kilograms of non-methane volatile organic compounds (kg NMVOC eq)
Ozone depletion	Stratospheric ozone protects the earth from hazardous ultraviolet radiation. Its depletion increases the rate of skin cancer in humans, can damage some plants, and may play a role in global warming	Equivalent of kilograms of trichlorofluoromethane (Freon-11)
Emission of particulate matter	Airborne particulate matter is responsible mostly for respiratory problems in humans and animals and can cause a considerable amount of damage to plants	Change in mortality due to particulate matter emissions
Acidification	The acidification contributes to a decline of plant species like coniferous forests and increases fish mortality	Equivalent of moles hydron (mol H <sup>+</sup> eq)
Terrestrial eutrophication	Terrestrial eutrophication affects all ecosystems. For example, it impacts strongly the lichen communities or forest tree health	Equivalent of moles of nitrogen (mol N eq)
Freshwater eutrophication	Freshwater eutrophication causes algae proliferation reducing the oxygen content in water. This reduced oxygen concentration can cause fish deaths. It also increases the drinking water treatment costs, reduces the recreational value of water bodies, and is a source of greenhouse gases	Equivalent of kilograms of phosphorus (kg P eq)
Marine eutrophication	Marine eutrophication causes algae proliferation. It affects the physiology and growth of marine organisms which has a cascading effect on the ecosystem functioning	Equivalent of kilograms of nitrogen (kg N eq)
Freshwater ecotoxicity	It refers to the potential toxic impacts on an ecosystem.	Comparative Toxic Unit for ecosystems (CTU <sub>e</sub> ) a score based on a model called USEtox
Water use	The water use is related to the local scarcity of water	Cubic meters of water

Land use	Land use refers to the use and transformation of land	Loss of soil organic matter content in kilograms of carbon deficit (kg C deficit)
Fossils resource use	Use of non-renewable resources such as coal, oil, and gas expressed	MJ
Metals and minerals resource use	Use of metals and minerals resource	Equivalent of kilograms of antimony (kg Sb eq)

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