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1 **In healthy pathways of dietary changes, a very rapid reduction of**
2 **red meat is possible, but specific diet changes are required for full**
3 **reduction – a graph-based analysis.**

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5

6 Abbreviations used: DALYs: Disability Adjusted Life Years; DHA: DocosaHexaenoic Acid;
7 EPA: EicosaPentaenoic Acid; GBD: Global Burden of Diseases; GHGe: greenhouse gas
8 emissions; HAC: Hierarchical Ascendant Classification; HR: Health Risk; INCA3: third
9 individual and national study on food consumption survey; PUFA: PolyUnsaturated Fatty
10 Acid; RACC: Reference Amount Customarily Consumed; TMREL: theoretical minimum-risk
11 exposure levels

Data sharing: Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval.

Keywords: graph theory, pathway optimization, diet optimization, dietary transition, plant-based diet, meat reduction pathways, long-term morbidity and mortality, bioavailable iron

12 **Abstract**

13 **Background:** Although reducing meat consumption is becoming increasingly popular in
14 Western countries, such a transition to a sustainable diet can pose some nutritional risks.

15 **Objective:** We aim to analyze the pathways for reaching a low-meat healthy diet and the
16 changes in other food categories needed to rapidly decrease total red meat consumption.

17 **Methods:** We used a recently developed method based on graph theory to represent all
18 possible pathways of stepwise changes that avoid nutritional deficiencies toward a target
19 healthy diet. Initial and target diets were defined as the daily consumption of 33 food groups.
20 For each sex, three initial diets were taken from the French representative survey INCA3 as
21 the mean observed diet and low (first quintile) and high (fifth quintile) meat consumption.
22 Target diets were identified using multi-criteria optimization to minimize the long-term health
23 risk of chronic diseases while ensuring nutritional adequacy. The Dijkstra algorithm was used
24 to identify the optimal pathways between the initial and target diets, with the aim of reducing
25 meat consumption as quickly as possible and thus minimizing long-term health risks.

26 **Results:** Unprocessed red meat was easily minimized in the first steps of the pathways
27 regardless of sex and initial level of meat consumption. However, processed meat could only
28 be decreased later and required prior changes such as increases in fruit, vegetables, and oily
29 fish. During total red meat minimization in females, securing adequate intakes of bioavailable
30 iron had the most substantial impact on the other dietary changes needed.

31 **Conclusions:** Immediate reduction of red meat consumption is possible on the pathway to a
32 healthy diet that avoids any nutrient deficiency. However, early increases in fruit, vegetables,
33 and fish are required before minimizing total red meat early in the diet.

34 **Introduction**

35 It is generally accepted among scientists that red meat has negative health and environmental
36 effects as well as debatable ethical implications. Many studies have shown a higher long-term
37 health risk with the consumption of red and processed meat (1–6), with the lowest
38 consumption often considered as the lowest risk. Stronger evidence of adverse health
39 associations has been reported for processed red meat than for unprocessed red meat (7–10). It
40 should, however, be noted that the effect of meat reduction may depend on what is being
41 replaced (11). Total red meat (i.e., red and processed meat) consumption has also been
42 pointed out as a significant contributor to several environmental pressures (12,13). For
43 example, the diets of French adults with the highest amount of red meat had the highest
44 greenhouse gas emissions (GHGe), and meat consumption accounted for about 50% of the
45 diet-related GHGe (14). This result is in line with numerous studies (12,15,16). Meat
46 consumption is also questioned from an ethical point of view, with the rise of animal welfare
47 concerns in Western societies (17). These concerns are prompting a significant number of the
48 population to adopt flexitarian or vegetarian diets (18).

49 Although plant-based diets have been associated with a lower risk of long-term disease,
50 several authors also point out the importance of meat in compliance with nutrient
51 recommendations (19). Even though the risks of deficiency for protein and amino acids are
52 small to inexistent in vegetarians (20), some studies have shown some risk of insufficient
53 intake and deficiency for some vitamins and minerals (e.g., bioavailable iron, vitamin B12).
54 This risk is related to the type of plant-based diet, i.e., factors beyond meat exclusion (21–24).
55 Furthermore, although healthy, nutrient-adequate diets with less or no meat have been
56 identified (25,26), these diets, which could be proposed target diets, are much different from
57 current diets. Even if many people were willing to reduce meat consumption in the ways that
58 these diets suggest, such a significant diet modification is only readily attainable for a small

59 percentage of them. Thus, in the context of a possible rapid transition to less meat, we need to
60 understand if there is a risk of deficiency directly linked with meat reduction and if other
61 dietary changes should parallel meat reduction to secure a healthy diet transition.
62 Our recent publication shows that graph-based analysis of diet trajectories offers a unique
63 opportunity to identify the critical first small steps on the best pathway towards an objective
64 diet (27). Using this same approach, this paper analyzes the different pathways for reaching a
65 low-meat healthy diet and the changes in other food categories needed to rapidly decrease
66 total red meat consumption. Compared to traditional optimization methods, which identify
67 optimal diet resulting from changes in all food group consumption at the same time, the
68 present approach is unique in that it reveals unit changes in consumption of one food group,
69 highlighting critical early changes that are required alongside or prior to the gradual meat
70 reduction. Based on portion sizes, those pathways are interpretable in terms of changes that
71 could be implemented as food choice options while also being integrated into a more long-
72 term transition with the complete dynamics of change. Like other optimization methods,
73 although based on different mathematical foundations, the method also identifies the critical
74 nutrients for enabling the changes.

75 **Methods**

76 **Studied population and dietary data**

77 This study used data from the third individual and national study on food consumption survey
78 (INCA3) performed in France between 2014 and 2015 (28,29). The INCA3 survey received
79 the ‘public interest and statistical quality’ seal of approval from French National Council for
80 Statistical Information and the mandatory authorization from the French Data Protection
81 Authority. The oral consent for participation had to be obtained directly from each individual
82 (29). The participant selection process for this study involved a three-stage random sampling
83 design conducted by the National Institute of Statistics and Economic Studies (INSEE) based

84 on the 2011 annual population census. Ineligible individuals included institutionalized
85 individuals, those planning to move out of their homes within the next two months, and those
86 who could not be interviewed. A further description of the method is provided in (29).

87 Participants identified as under-reporters were excluded using the basal metabolic rate as
88 estimated by the Henry equation (30), using the cutoff values recommended by Black (31).
89 Older adults (above 54 years old for females and 64 years old for males (32)) were excluded,
90 as their risk of long-term morbidity and mortality differed from younger adults. The final
91 sample contained 1125 adults (Supplemental Figure 1).

92 Dietary data was collected by professional investigators assisted by dietary software from
93 three unplanned, non-consecutive, 24-hour dietary recalls spread over three weeks (two
94 during the week and one at the weekend). Portion sizes were estimated using validated
95 photographs (29). The nutrient content values of the food were extracted from the 2016
96 database of the French Centre d'Information sur la Qualité des Aliments (CIQUAL) (33).
97 Mixed foods were divided into ingredients and then gathered into 33 food groups (27). The
98 nutrient content of each food group was calculated as the mean nutrient content of food items
99 constituting the food group weighted by their mean intake, as previously described (34).

100 **Initial diets**

101 A sex-specific average diet was calculated using the data from the 564 males and the 561
102 females and used as initial diets for defining the pathways. To account for the variability in
103 meat consumption as well as the mean diet observed in the entire population, the mean diets
104 of the first and last quintiles of meat consumption were also used as alternative initial diets. In
105 this work, the first quintile will be named low-meat eaters, and the fifth quintile will be named
106 high-meat eaters. A graph was created for each initial diet considered, resulting in three
107 graphs per sex. The low meat eaters of both sexes did not need to decrease their total red meat
108 consumption to reach the target diet and can be considered as comparison points.

109 **Target diet**

110 Using the same approach of multi-criteria diet optimization under constraints as in our
111 previous works (27,34,35), a target diet was identified for each sex that minimized the long-
112 term health risk and the departure from the observed diet while ensuring adequate nutrient
113 intakes and remaining within current consumption limits. Notably, compared to our previous
114 works, this study places a greater emphasis on health risk reduction than diet proximity in
115 selecting the trade-off between them. However, it still means that the diet with minimal
116 departure from the observed diet will be selected at a given level of health risk reduction. This
117 choice was made on account of our goal of identifying target diets that were more distant
118 from the initial observed diets and, in particular, lower in total red meat. For more details on
119 the method used for identifying the target diets, see Supplemental Method 1.

120 **Graph construction**

121 We used graph theory as previously detailed (27). A graph is a pair $G = (N, E)$ of nodes (N)
122 and edges (E) (36). When modeling dietary changes (27), nodes represent diets, and edges
123 correspond to elementary dietary changes such that if an edge connects two nodes, it is
124 possible to transition from one diet to the other.

125 All foods consumed in the INCA3 survey have been classified into 33 food groups according
126 to their nutritional and usage characteristics. A node was thus a vector of 33 components, one
127 for each food group expressed in portions. To simplify the graph, only dietary changes
128 corresponding to an integer number of portions were considered, with an edge corresponding
129 to a change of one portion unit of one food group. Portion sizes are useful for a standardized
130 representation of dietary consumption, were needed to avoid overly detailed pathways (e.g.
131 using grams), and finally, changes as portion steps provide a simple view of feasible changes
132 that could be understood by readers.

133 We defined the portion sizes for each food group, which were taken as either the distribution
134 mode, the average difference between multiple modes in the distribution, or as the labeled

135 portion size for portioned food. For example, since observed amounts of red meat consumed
136 per occasion were often a multiple of 50g, portion size was set at 50g. The group "fresh dairy
137 product" portion size was 125g, as is conventional for individual yogurt portions sold in
138 French supermarkets. We also adapted the portion sizes so that food groups with a similar role
139 in the dietary pattern have the same portion size, e.g. poultry and red meat. Table 1 presents
140 the portion size for each food groups.

141 Each edge of the graph corresponds to an integer portion change. Rather than adjusting the
142 target diets, which could have altered to their full nutritional adequacy, we rounded the
143 difference between the initial and target diets and slightly adjusted the initial diets to differ
144 from the target diets by the integer number of portions. Thus, to calculate the quantity in
145 grams, the number of portions needs to be multiplied by the portion size and added to the
146 remainder. More details of the method are in Supplemental Method 2.

147 Graphs were created in a similar way as previously described (27). All nodes/diets were
148 created by proximity until the graph was connected. An additional extension was then added
149 to ensure that the graph had no bottleneck. During the extension process, some constraints and
150 limits were added to ensure the nutritional adequacy and cultural acceptability of all the
151 nodes/diets added to the graph. The nodes/diets that did not meet the following constraints
152 were censured from the graph:

- 153 (i) For each food group, the number of portions should remain between 0 and the maximum
154 value observed in the INCA3 population.
- 155 (ii) The total energy should remain between 80% and 120% of that of the initial diet.
- 156 (iii) The SecDiet, a score of the overall risk of overt deficiency (37) (Supplemental Method 3),
157 should be >99% of that of the initial diet to ensure no increase in the risk of overt
158 deficiency.
- 159 (iv) The iron intake should be greater than or equal to the deficiency threshold or its initial
160 value when lower than the deficiency threshold.

161 (v) Each macronutrient contribution to diet energy should remain between its minimum and
162 maximum values across the population.

163 **Pathway optimization**

164 Once the graph was created with all possible adequate and acceptable intermediate diets
165 between the initial and target diets, Dijkstra's algorithm was used to identify the optimized
166 pathway from the former to the latter (38). The pathways were optimized to minimize a
167 combined score between total red meat consumption and health risk along the entire pathway.
168 We prioritized the reduction of meat consumption and then, once reduced to its minimum, to
169 the health criterion, using the following relative weighting in our combined optimization
170 criterion:

171 *Optimization criterion* = $(100 - 10^{-8}) \times \text{Meat intake} + 10^{-8} \times \text{Health Risk}$.

172 Meat intake was calculated as the sum of red meat, processed meat, and poultry consumption.

173 The Health Risk (HR) criterion was set to consider the diet-induced long-term risk of chronic
174 diseases based on the latest GBD epidemiological data (7). The HR criterion, first defined in
175 one of our earlier works (35), was enhanced to represent the combined and normalized
176 distance to the theoretical minimum-risk exposure levels (TMREL) for nine food groups
177 (three unhealthy: red meat, processed meat, and sweetened beverages; six healthy: whole
178 grain products, fruits, vegetables, legumes, nuts and seeds, and milk), and five nutrients (one
179 unhealthy: sodium; four healthy: fiber, calcium, EPA+DHA, PUFA). The TMREL were
180 weighted by the relative importance of the proportion of Disability Adjusted Life Years
181 (DALYs) attributable to each of them in France. The HR criterion can range from 0 to 1, from
182 where the diet meets all the TMREL values (minimum risk) to where it is farthest from them
183 (maximum risk). A detailed description of the HR criterion can be found in Supplemental
184 Method 1.

185 **Auxiliary indicators and analyses**

186 The percentage of the Dietary Reference Intake was calculated for all nutrients to assess the
187 changes in nutritional adequacy along the pathways. Secondary analyses were also conducted
188 to identify the limiting nutrients for meat reduction. When the maximum reduction in meat
189 was not reached, an alternative diet was calculated. If the change in the optimized pathway
190 was not a meat reduction, the hypothetical censored alternative diets consisting of a reduction
191 in meat (impossible due to risk of deficiency) were calculated and as well as the nutrient
192 intake as compared to the reference intake for identifying the nutrients of concern. If the meat
193 was reduced, the alternative diet was also calculated by reducing other meat categories (e.g.,
194 processed meat when red meat had been reduced). To assess the changes in diet-related
195 environmental pressures along the pathways, 16 environmental indicators were calculated at
196 each step of the pathway using Agribalyse 3.1 data, as in our previous study (14)
197 (Supplemental Method 4).

198 To identify whether the optimized pathways included modeled diets similar to some observed
199 in the population, a cluster analysis of the individual diets of the INCA3 participants was
200 performed. This analysis was achieved using a data-driven approach to group the observed
201 individual diets into distinct diet profiles based on their 33 food group consumptions
202 (separately for males and females) and a hierarchical ascendant classification (HAC). The
203 number of clusters chosen was based on both the elbow and silhouette methods (39), and the
204 proximity between these diets and the one along the pathways was assessed using the Diet
205 Similarity Index (40,41).

206 **Software and packages**

207 All graph methods were implemented on Python (3.8.3, Python Software Foundation,
208 Hampton, NH, USA) (42). The networkX package version 2.4 was used to implement the
209 graph and to use the Dijkstra algorithm (43). Statistical analyses (HAC) were performed using
210 SAS software (version 9.4, SAS Institute Inc, Cary, NC, USA).

211

212 **Results**

213 **Table 1** presents the initial diets for each population (mean, low or high meat-eaters) and the
214 target diets by sex, expressed in the number of portions (see Supplemental Table 1 for
215 description in grams). The target diets are similar for males and females, with a higher
216 consumption target for legumes and milk and a lower consumption target for other fish for
217 males than females. Supplemental Figure 2 presents the meat intake for the initial and target
218 diets before and after adjustment. The required changes from initial to target diet in the
219 number of portions for each meat category are shown in Supplemental Figure 2: for the mean
220 populations of both sexes, this transition involved, among other dietary changes, a reduction
221 of one portion of red meat and one portion of processed meat per day but no change in
222 poultry.

223 The main characteristics of the graphs and optimized pathways identified for each sex are
224 presented in **Table 2**. In the optimized pathways, the number of intermediate diets (i.e.,
225 nodes) between the initial and target diets ranged between 14 and 23 (Table 1), and the
226 distance (number of nodes) between the initial and target diets was always smaller for females
227 than males.

228

229 The complete pathways are presented in **Figures 1 and 2** for the average male and female
230 populations, respectively, and in Supplemental Figures 3 to 6 for the low and high meat-eaters
231 of each sex. In cases where the initial diet contained at least one portion of red meat (i.e., all
232 but the low meat-eaters), the first step always consisted of a red meat reduction. Likewise,
233 when the target reduction was 3 portions, the first two steps consisted of a red meat reduction,
234 and the last reduction was also delayed. A fruit increase was always present in the first five
235 steps as well as a vegetable increase in the first six steps. In all cases, meat consumption was

236 minimized (i.e., equal to its final target value) from step 13 onwards. When present in the
237 pathway, any decrease in processed meat was preceded or immediately followed by an
238 increase in oily fish. Increases in fruits, vegetables, and fish were required in the females'
239 pathways to allow for the reduction in processed meat and were crucial in the males'
240 pathways for the improvement of the HR criterion.

241 As represented in Supplemental Figures 7-12, many nutrient intakes varied largely along the
242 pathways. When a nutrient was below the reference intake in the initial diet, it increased
243 rapidly (e.g., folate) or more slowly (e.g., iodine and fiber) to finally reach its reference value
244 before or at the end of the target diet pathway (e.g., EPA-DHA). Since the target diets were
245 designed to be nutritionally adequate, the nutrient intake always reached the reference value
246 in the target diet. Some nutrients whose reference intakes were initially exceeded in the initial
247 diets could temporarily fall to a slightly lower level (e.g., Vitamin B6). However, all nutrients
248 remain well above the deficiency threshold, with the exception of bioavailable iron (**Figure**
249 **3**). This exception is visible in the female pathways, where some alternative diets with less
250 processed meat were impossible to construct in the graph (censored diets) because these diets
251 would have contained amounts of bioavailable iron below the deficiency threshold (Figure 3).
252 The similarity between the diet profiles observed in the population (Supplemental Table 2)
253 and the diets modeled along the identified pathways decreased along all pathways
254 (Supplemental Figure 13). The pathways did not appear to converge on any specific profile
255 along the pathways.

256 Regarding the variation of the environmental footprints along the identified pathways, GHGe
257 decreased as meat consumption decreased and stabilized with it for the rest of the pathways
258 (Supplemental Figure 14). In contrast, water use rose with increased consumption of fruits
259 and vegetables, reaching and remaining above its initially observed level (Supplemental
260 Figure 15).

Graph-based analysis of meat reduction pathways

261 Finally, the HR criterion decreased along all pathways, with a sharp decrease in the first part
262 of the pathway (Supplemental Figure 16).

263 **Discussion**

264 By applying graph analysis to study dietary transition, six sequences of dietary changes were
265 identified and characterized that allow for the most rapid reduction in total red meat
266 consumption as part of a pathway toward a healthy diet. The results point out nutritional risks
267 that can arise during such a dietary transition and the dietary levers that can be used to solve
268 them. One of our key findings is that reducing total red meat requires prior or concomitant
269 increases in other foods, especially fruits, vegetables, and fish, while unprocessed red meat
270 can be reduced directly. We also showed that, in females, bioavailable iron adequacy is a
271 significant barrier to total red meat reduction.

272 **Nutritional issues and dietary levers for red meat reduction**

273 Our findings show that a direct and immediate red meat reduction has a low impact on overall
274 nutrient intake. While such an abrupt reduction may lead to an increased risk of inadequacy
275 for some nutrients, such as vitamin B12 and bioavailable iron, the risk of overt deficiency
276 remains very low. Moreover, the risk of inadequacy is then reduced as the pathway
277 progresses, particularly as fish consumption increases. Because the decrease in red meat is
278 directly followed by an increase in other food groups in the identified pathways, these
279 changes should instead be interpreted as substitutions, and in this context, the transient
280 increase in the risk of inadequacy would be canceled out. The target diets still included some
281 marginal consumption of red meat and probably helped the diet optimization process to find a
282 target diet close to the observed one and nutritionally adequate. However, nutritionally
283 adequate diets free of red meat and even all meat are possible to identify. Nevertheless, these
284 diets are more distant from observed diets than the ones used in this study (25,26).

285 In contrast, our findings indicate that the final reduction of total red meat (as processed meat)
286 was delayed. An immediate maximal reduction in total red meat would result in low levels of
287 bioavailable iron and, to a lesser extent, vitamin A, riboflavin, vitamin B6, and vitamin B12,

288 since both types of red meat are important contributors to these nutrient intakes. This
289 reduction in nutrient intake explains why the reduction of processed meat has been delayed on
290 the pathways. The reduction of red meat was prioritized as the portion step was higher for red
291 meat than for processed meat. More specifically, the level of bioavailable iron, which was
292 markedly decreased and approaching the deficiency threshold, proved to be the critical factor
293 limiting the rapid removal of total red meat in females. Bioavailable iron and vitamin A have
294 already been identified as critical nutrients that limit the design of healthy diets with lower or
295 no meat (34,44). Although bioavailable iron levels decreased along the pathway in this study,
296 it remained at relatively adequate levels.

297 Regarding dietary solutions to nutrient issues, the initial reduction in red meat was directly
298 followed by several increases in fruits and vegetables for females or legumes for males, and
299 these substitutions for a more plant-based diet were systematically the first steps of the
300 pathways. Fish also emerged as a critical dietary lever for securing the pathways since it
301 provides essential nutrients at issue when reducing meat, such as bioavailable iron and
302 vitamin B12, and also a valuable source of nutrients that are already inadequate in the initial
303 diets, such as EPA-DHA and iodine.

304 Our study is based on the most recent available data for food consumption and nutrient
305 composition, and it cannot account for future dietary changes. Relatedly, changes in the
306 specific foods consumed within a food group and changes in the availability of food sold
307 would change the nutrient content ascribed to a food group. Changes in fortification could
308 lower some concern for some nutrients, particularly iron, here identified as the most critical.
309 Lastly, iron supplementation, especially in at-risk females, could also be considered a means
310 to support individuals while reducing meat consumption. Our results also suggest that the
311 studied dietary transition should be faster and easier for females, who initially consume less

312 red meat than males but with higher associated nutritional risks, in line with our previous
313 findings using a different modeling approach (26).

314 **Health and environmental impacts**

315 Beyond being safe from the perspective of nutrient adequacy, the pathways were beneficial
316 for long-term health. The two criteria of red meat reduction and improvement of long-term
317 health jointly optimized pathways. They did work together, as the first part of the pathway
318 resulted in a marked decrease in health risk and rapidly tended toward a healthier, more plant-
319 based diet.

320 Other characteristics of the pathway offered useful information on sustainability dimensions.
321 A reduction in GHGe was found, due to the reduction in red meat. An increase in water use
322 was also found, due to the shift to a more plant-based diet with more fruits and vegetables.
323 These results are in line with other studies (14,25), including our previous modeling results
324 (26,35). However, one modelling study has identified diets high in plants and low in meat that
325 have both a lower GHGe and water use (45).

326 **Advantages and limits**

327 The advantages and limits of the general method have been previously discussed in Perraud et
328 al. (27). This approach is the first to identify and analyze an optimized pathway as a series of
329 unitary changes between an initial diet and a specific target diet while applying constraints
330 along the pathway to ensure nutritional adequacy and cultural acceptability. Previous methods
331 either considered pathways as a succession of optimized diets (25) or did not define a target
332 diet (46,47). However, the requirement of a target diet can also be seen as a limitation of the
333 method in that any change in the characteristics of the target diet will result in a change in the
334 generated graphs. Several possibilities exist for identifying a target diet, including that of
335 optimization under constraints used in this work (27,48). Because this graph-based method
336 requires a target diet close enough to the initial diet, a diet like the one proposed by the EAT-

337 Lancet could not be chosen (49). Nevertheless, our approach is useful to analyze the first
338 critical steps of the pathway (i.e., those that enable the direct reduction of meat), and using
339 different healthy target diets may have little impact on the solutions identified for the first
340 steps. In order to better consider the environmental pressures in the analyses, the target diet
341 could be optimized for both long-term health and a combination of environmental pressures.
342 This study was based on a representative French population. However, this population can be
343 taken as an example of a population mostly following a western diet. Moreover, since we
344 studied three subpopulations according to their level of meat intake, the findings are relevant
345 to a wide range of populations.

346 **Conclusion**

347 Using a method based on graph theory, we identified and analyzed the best pathways toward a
348 healthy diet that reduces total red meat as quickly as possible while avoiding nutrient
349 deficiency. Red meat could be decreased in the first steps of the pathways. While reducing red
350 meat tended to lower the adequacy of some nutrients, all pathways operated with no increase
351 in the risk of overt deficiency. Associated increases in other food groups, such as fruit,
352 vegetables, and fish, enabled total red meat to be minimized in the first half of all population
353 pathways. In females, bioavailable iron requires special attention, as it proved to be the most
354 limiting nutrient for total red minimization.

355

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358 primarily responsible for preprocessing the data, conducting trajectory optimization and
359 interpreting the results, with advisory inputs from JW, HF and FM; HF provided some data
360 and tools; EP drafted the manuscript; EP and FM wrote the manuscript with critical comments
361 from JW and HF. All authors approved the final manuscript. The authors report no conflict of
362 interest.

363

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518 **Legends for figures**

519 **Figure 1.** Best pathway identified for males based on their mean dietary intake.

520 The best pathway is identified using optimization criteria combining the total meat intake and
521 the Health Risk Criterion, prioritizing the former over the latter.

522

523 **Figure 2.** Best pathway identified for females based on their mean dietary intake.

524 The best pathway is identified using optimization criteria combining the total meat intake and
525 the Health Risk Criterion, prioritizing the former over the latter.

526

527 **Figure 3.** Changes in bioavailable iron intake (as a percentage of the reference value) along
528 the pathway from initial to target diets by sex and according to meat consumption in the initial
529 diets. Three different initial diets are considered by sex: Low (first quintile), Mean, and High
530 (fifth quintile) meat-eaters. The orange and red lines represent the reference dietary intake and
531 the lower threshold of overt deficiency (ensuring $\leq 5\%$ prevalence of iron-deficiency anemia),
532 respectively. The symbols present the cases of an alternative reduction of one of the total red
533 meat categories (red meat: red triangle, processed meat: pink diamond) when these reductions
534 were not made.

535

536

537 **Table 1.** Portion sizes (g) and number of portions of each food group in the initial and target diets after adjustment by sex and according to meat
 538 consumption in the initial diets (Low (first quintile), Mean, and High (fifth quintile) meat-eaters). Rather than adjusting the target diets, which
 539 could have altered their full nutritional adequacy, we rounded the difference between the initial and target diets and slightly adjusted the initial
 540 diets to differ from the target diets by the integer number of portions. The food group quantity in a diet is the number of portions of the food
 541 group times the portion size, plus the remainder of the division of the food group quantity in the target diet by the portion size.

Food category ¹	Initial diet							Target diet		Remainder (in g)		
	Portion size (g)	Male			Female			Male	Female	Male	Female	
		Low	Mean	High	Low	Mean	High					
		Integer number of portions										
Vegetables	150	0	1	0	1	0	1	2	2	100	87	
Fruits	150	0	0	0	1	0	0	2	2	119	60	
Nuts	25	0	0	0	0	0	0	0	0	11	12	
Refined bread	100	1	1	1	1	1	1	0	0	27	10	
Whole bread	100	0	0	0	0	0	0	0	0	99	62	
Other refined starches	120	0	1	1	0	0	0	1	0	73	98	
Other whole starches	120	0	0	0	0	0	0	0	0	5	9	
Processed products	50	0	1	0	0	0	0	0	0	0	14	
Legumes	50	0	0	0	0	0	0	1	0	36	16	
Poultry	50	0	0	0	0	0	0	0	0	46	41	
Red Meat	50	0	2	2	0	1	2	1	0	4	16	
Processed meat	40	0	1	1	0	1	1	0	0	0	0	
Oily fish	15	0	0	0	0	0	0	1	1	11	5	
Other fish	15	2	2	1	2	1	1	0	2	1	1	
Eggs	8	2	1	1	2	2	2	1	2	3	2	
Milk	125	0	0	0	0	0	0	1	0	65	114	
Fresh dairy products	125	0	0	0	0	0	0	0	0	28	72	

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Sweet milky desserts	125	0	0	0	0	0	0	0	0	0	0	14
Cheese	50	0	0	0	1	0	0	0	0	0	48	12
Animal fats	10	1	1	0	1	1	1	1	0	0	4	0
ALA vegetable fats	10	0	0	0	0	0	0	0	1	0	6	5
Other vegetable fats	10	1	1	0	1	1	1	1	1	0	5	4
Sauces	30	1	1	1	1	1	1	1	1	3	5	10
Sweet products	70	1	1	0	1	1	0	0	1	1	33	30
Drinking water	850	1	1	1	1	1	1	1	1	1	28	291
SSB	250	1	1	1	1	1	1	1	0	0	0	0
Hot drinks	250	1	1	1	2	2	2	2	1	2	129	7
Salt	1,5	1	1	1	1	1	1	1	0	0	0	0
Condiments	2	3	1	2	2	2	2	2	6	3	1	0
Soups	60	1	1	0	1	1	1	1	0	0	0	27
Substitutes	15	0	0	0	0	0	0	0	1	1	14	12
Other foods	6	0	0	0	0	0	0	0	0	0	4	2
Alcoholic drinks	250	1	1	1	0	0	0	0	0	0	0	43
Difference with the target diet		23	23	22	14	18	19					

542 ¹ Nuts: Nuts and seeds, Refined bread: Bread and refined bakery products, Whole bread: Whole meal and semi-refined bread and bakery
543 products, Other whole starches: Other whole and semi-refined starches, Processed products: Processed starch-based products, Eggs: Eggs and
544 egg-based dishes, Animal fats: Animal fats and assimilated fats, ALA vegetable fats: Vegetable fats rich in α -linoleic acid, Other Vegetable fats:
545 Vegetable fats low in α -linoleic acid, Sauces: Sauces and fresh creams, SSB: Sugar-sweetened beverages, including fruit juices, Soups: Soups and
546 bouillons, Substitutes: Substitutes for animal products

547 **Table 2.** Main characteristics of the graphs by sex and according to meat consumption in the
 548 initial diets (Low (first quintile), Mean, and High (fifth quintile) meat-eaters).

Sex	Male			Female			
	Low	Mean	High	Low	Mean	High	
Number of nodes in the graph	360 909	469 903	366 889	7 161	51 820	111 079	
Number of nodes between the initial and target nodes	23	23	22	14	18	19	
Number of neighbors per node	mean	15.0	16.2	15.7	10.4	13.5	14.6
	SD	3.4	2.7	2.9	2.5	2.5	2.5
	min	21	19	19	15	17	18
	max	1	2	2	2	2	3

549

550