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Halving food-related greenhouse gas emissions can be achieved by redistributing meat consumption: progressive optimization Results of the NutriNet-Santé cohort

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1 **Abstract 300 words**

2 **Background:** Diet-related greenhouse gas emissions (GHGe) mainly comes from animal-sourced
3 foods. As progressive changes are more acceptable for a sustainable food transition, we aimed to
4 identify nutritionally adequate and culturally acceptable optimized diets ensuring a gradual reduction
5 in GHGe, using observed diet from a large sample of French adults, while considering the mode of
6 food production (organic vs conventional farming) and the co-production link between milk and beef.

7 **Material and method:** Based on the consumption of 257 organic and conventional foods among
8 29,413 participants (75% women, age: 53.5±14.0y) of the NutriNet-Santé study, we modelled optimal
9 diets according to GHGe reduction scenarios in 5% steps, from 0 to 50% with nutritional,
10 acceptability, and coproduct constraints, for men, premenopausal and menopausal women separately.

11 **Results:** Gradual GHGe decrease under these constraints led to optimal diets with an overall decrease
12 in animal foods, with marked reductions in dairy products (up to -83%), together with a stable but
13 largely redistributed meat consumption in favor of poultry (up to +182%) and pork (up to +46%) and
14 at the expense of ruminant meat (down to -92%). Amounts of legumes increases dramatically (up to
15 +238%). The greater the reduction in diet-related GHGe, the lower the cumulative energy demand
16 (about -25%) and land use (about -43%). The proportion of organic food increased from ~30% in the
17 observed diets to ~70% in the optimized diets.

18 **Conclusion:** Our results suggest that meeting both nutrient reference value and environmental
19 objectives of up to 50% GHGe reduction requires the reduction of animal foods together with
20 important substitutions between animal food groups, which result in drastic reductions in beef and
21 dairy products. Further research is required to explore alignment with long-term health value and
22 conflict with acceptability, in particular for even greater GHGe reductions.

23 1. Introduction

24 The current environmental crisis, beyond the irreversible damage to natural resources, is characterized
25 by climate change and global warming (defined as the increase of both air and sea surface temperature
26 over a long period of time (>30 years)). Thus, anthropogenic global warming in 2017 was +1°C
27 compared to pre-industrial levels (1850-1900), *i.e.* about 0.2°C per decade (1).

28 Food systems are responsible for about 30% of global greenhouse gas emissions (GHGe) (2) and are
29 major users of fresh water, therefore largely contributing to climate change (3). Unless action is taken
30 in the next decades, various prospective scenarios have estimated that, by 2050, unsustainable diets
31 will lead to an additional 80% rise in GHGe compared to the current situation (4). To mitigate climate
32 change below 1.5°C, some scenarios have documented that halving agricultural carbon footprint by
33 2050 would be necessary (5) and this would require strong dietary changes on a global scale (6).

34 The scientific literature about GHGe related to dietary patterns, based on optimization-based
35 modelling and observational data, is growing and is consistently reporting that plant-based diets
36 exhibit lower GHGe compared to those rich in animal products (7–10). Plant-based dietary patterns
37 can also help to prevent chronic diseases (3,11–14), underlying co-benefits of plant-based diets for
38 climate mitigation and human health promotion. Clark et al. (14) have documented, based on
39 metadata, that beneficial foods for health, apart from fish, generally exhibit lower environmental
40 pressures, encompassing GHGe, acidification, eutrophication, land and water use. Conversely, some
41 foods which could be detrimental for health, such as red meat and processed meat (associated with
42 increased risk for various health outcomes, including mortality and morbidity due to coronary heart
43 diseases, stroke, diabetes and colorectal cancer), are also the highest contributors to diet-related GHGe
44 and large variations in GHGe exist across food groups (14).

45 However, the question of how to achieve changes in dietary behavior including a reduction in meat
46 consumption and more generally animal-based food has not been resolved (15). Indeed, food choices
47 are diverse and based on multiple influencing factors which may constitute barriers (15,16). Thus, the
48 strategies accompanying the transitions towards greater sustainability and in particular lower GHGe
49 should be multiple and adapted to different types of consumers (17). We may hypothesize that among
50 traditional high meat consumers, a first step of the transition can be based on intra-food group
51 substitutions, especially due to cultural traits that hinder large reduction in meat consumption (18,19).
52 For instance, in France, a previous study modelled a gradual reduction in GHGe and showed that a
53 30% reduction was possible without drastically deviating from the current diets while respecting
54 nutritional constraints and diet cost (20). Among the gaps in existing studies we can mention the
55 following. First, most modelling studies used GHGe as constraints or objective function (10) but few
56 have considered other environmental indicators in their analysis - as descriptors, constraints or
57 objective - despite the fact that some conflicts are known to occur among the different environmental
58 dimensions, which are related to the general organization of the food system, such as energy demand
59 and land occupation (21). Besides, few studies have distinguished conventional and eco-friendly

60 production systems, as the data are generally based on life cycle assessment (LCA) for generic foods.
61 Although organic farming has not been systematically related to lower GHGe, energy demand is lower
62 while land use is higher compared to conventional agriculture (22,23). In a previous work based on
63 observational data distinguishing between organic and conventional diets, we observed that diets with
64 high GHGe were higher in animal-based food, more caloric and nutritionally less healthy (24). Thus,
65 the role of various food systems on environmental pressure has not been yet considered enough (25).
66 Finally, food systems also include some important structural determinants of food production, such as
67 the fact that co-productions rules are often operating, as for milk and beef meat productions, but is
68 rarely considered (26–28).

69 We can hypothesize that transitions to sustainable diets will require to activate all the levers and
70 substitution is one of them. Thus, the objective of this study was to test whether the possibility to
71 reduce GHGe of production by 50% as defined in the Paris agreement (29) in a set of culturally
72 acceptable diets. We modelled dietary pattern characteristics with gradual decreasing GHGe under
73 nutritional, coproduction and acceptability constraints and to relate these dietary patterns to other
74 environmental indicators while considering two different food production systems, organic and
75 conventional.

76 **2. Methods**

77 **2.1 Population**

78 The population included adults participating in the ongoing web-based prospective NutriNet-Santé
79 cohort initiated in France in May 2009 (and on-going) whose aim is to investigate relationships
80 between nutrition and health (30). Participants are recruited on a voluntary basis from the general
81 French population. This study is conducted in accordance with the Declaration of Helsinki, and all
82 procedures were approved by the Institutional Review Board of the French Institute for Health and
83 Medical Research (IRB Inserm 0000388FWA00005831) and the National Commission on Informatics
84 and Liberty (Commission Nationale de l'Informatique et des Libertés, CNIL 908450 and 909216).
85 Electronic informed consent was obtained from all participants. The NutriNet-Santé study is registered
86 in ClinicalTrials.gov (NCT03335644). At baseline and every year thereafter, participants provide data
87 about their sociodemographic and economic status, anthropometrics, lifestyles and dietary intakes
88 through self-administered questionnaires. They are also regularly invited to fill in complementary
89 questionnaires.

90 **2.2 Sociodemographic and lifestyle characteristics**

91 Participants completed regularly validated questionnaires about sociodemographic and lifestyle
92 features (31,32), thus data from the sociodemographic questionnaires that were the closest to the
93 dietary questionnaire were used. Sociodemographic and lifestyle characteristics encompassed gender,
94 age, education (<high school diploma, high school diploma, and post-secondary graduate), smoking

95 status (former, current, or never-smoker), and physical activity assessed using the International
96 Physical Activity questionnaire (33).

97 2.3 Dietary data assessment

98 The present study is based on dietary data collected through a self-administered validated semi-
99 quantitative food frequency questionnaire (FFQ), administered from June to December 2014. This
100 questionnaire has been enriched by a five-point ordinal scale for each of the 264 food and beverage
101 items to evaluate the share of organic food consumption (under official labels) (34). Organic
102 production is one of the official signs of quality and origin in France. This method is governed by a
103 European regulation since 1991, with the overall objectives of ensuring respect of the environment,
104 biodiversity and animal welfare (35) recently updated (EU regulations 2018/848 and 2020/464 coming
105 into force in January 2022. More specifically, for each item, participants were asked ‘How often was
106 the product of organic origin?’ with the following answer modalities: “never”, “rarely”, “half-of-
107 time”, “often” or “always”. This questionnaire developed within the frame of the BioNutriNet project
108 has been extensively described elsewhere (22). Organic food consumption was estimated by allocating
109 the respective weights: 0, 25, 50, 75 and 100 to the modalities. For clarity purpose, food and beverage
110 items were grouped into 16 food groups as presented in **Appendix A**. Nutrient intake were calculated
111 using a published food composition database (36).

112 2.4 Environmental pressure indicators

113 Environmental indicators were assessed using the DIALECTE tool, established by Solagro
 114 (Toulouse, France) (37), whose aim is to evaluate environmental impacts of French farming
 115 systems using attributional life cycle analysis (LCA) without considering land use change. The
 116 perimeter of LCA was restricted to the agricultural production phase (conditioning, transport,
 117 processing, storage or recycling stages were not considered). Upstream processes were
 118 therefore included in the assessment, such as input production or energy supply. Three
 119 environmental indicators were considered at the farm level: the GHGe measured as kg of CO₂
 120 equivalents (CO₂eq), the cumulative energy demand (CED) in MJ, and the land occupation
 121 expressed in m² for >60 raw products (24). The original database has been completed by other
 122 data sources that have been previously listed (24), to obtain environmental pressures in organic
 123 and conventional of 92 raw agricultural products covering the 264 food items. Data have been
 124 published elsewhere (24). Environmental pressures of the FFQ food items as consumed were
 125 retrieved from the 92 raw agricultural products by using a set of conversion coefficients
 126 (economic allocation (accounting for co-products) and cooking and edibility coefficients).

127 Coproduct factors for ruminant products

128 We considered a meat to carcass weight ratio of 68% (38), and further yields of 90% during
 129 distribution (due to 10% distribution losses) and 68% during consumption (due to 32% losses by
 130 cooking, bones and wastes) (38).

131 In 2010 in France, 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight)
 132 (5) were produced, of which 41% was from dairy herd, i.e., 0.62 million tons of beef (39). Thus, 1L of
 133 milk corresponded to 10g of beef when applying the equation (1):

$$134 \quad (1) \quad 25 \text{ million tons of Milk (L)} = 1.52 \text{ million tons of beef} \times 41\% \times 68\%_{\text{carcass yield}} \times$$

$$135 \quad \quad \quad 90\%_{\text{distribution yield}} \times 68\%_{\text{preparation yield}}$$

136 Furthermore, we considered that 8L of milk are required to make 1kg of cheese and 1L of milk to
 137 make 1kg of fresh dairy products, using the average figures from French processing chains.

138 2.6 Diets modelling and optimization

139 As nutrient requirements vary according to population subgroups, participants were grouped as men,
 140 premenopausal women and menopausal women and diets were modeled for each subgroup to account
 141 for differences in iron intake requirements. Postmenopausal women were considered to have a low
 142 iron requirement and premenopausal women have a high iron requirement (the highest reference
 143 value, i.e. the reference covering 97.5% of the women requirements; of note most women (80%) have
 144 much lower requirements). Data related to observed food consumption as well as attributes of food
 145 items, *i.e.* nutritional composition, environmental pressures and production mode (conventional or

146 organic), were used to define optimized diets being nutritionally adequate, acceptable, and more
147 sustainable.

148 Nutritional adequacy was ensured by a set of nutritional constraints by considering, in particular,
149 nutrient bioavailability for iron and zinc, as described in **Appendix B**.

150 The list of constraints was as follows:

- 151 - Nutritional constraints on total energy and 31 nutrients, with upper and/or lower bounds based
152 on nutrient reference intakes. Lower bounds were taken as recommended dietary allowance
153 (population reference intake) or adequate intake, or lower bound of reference intake range for
154 the French population (40) as mostly derived from the EFSA opinion (41). For some nutrients,
155 when the adequate intake was based on the observed average intake, the lower bound was set
156 as the value of the 5th percentile. Reference intakes also included upper levels, as tolerable
157 upper intakes for vitamins and minerals, when identified, and upper bound of reference intake
158 range.
- 159 - Acceptability constraints on some food groups, with upper bounds set as the population-
160 specific 95th percentiles for 37 *ad-hoc* food groups. Additional moderation constraints on
161 some food groups (dairy products ≤ 2 portions/d, fish ≤ 2 portions/week with 1 of fatty fish, and
162 red meat < 500 g/week), to comply with national public health moderation recommendations
163 for animal products, as prescribed in French food-based dietary guidelines (42).
- 164 - Co-production constraint limiting the consumption of milk to a proportion of that of beef,
165 using the factor between milk and beef defined above in Eq. (1).
- 166 - Environmental constraint for a given (from 0 to -50 % by 5% decrement) reduction in GHGe
167 compared to the observed situation. For each food, during diet optimization, the model
168 selected the production option (conventional or organic) exhibiting lower GHGe.

169
170 The objective corresponded to the maximization of acceptability, i.e. minimizing the total departure
171 (D) from the observed diet (initial condition), as follows:

$$172 \quad \text{Min } D = \sum_i^{257} \left[\frac{\text{Obs}_i - \text{Opt}_i}{SD_i} \right]^2$$

173 where Obs_i and Opt_i denote the daily consumption of food item (i) in the observed and optimized
174 diets, respectively and SD_i is the standard deviation of the observed daily consumption of food item
175 (i).

176 The climatic improvement approach was examined using scenarios of 5% gradual decreases in GHGe,
177 by using a GHGe constraint in each scenario from 0% (basal model: $\text{GHGe} \leq \text{Observed situation}$) to -
178 50%.

179 The optimization process was performed using the procedure SAS/OR ® *optmodel* (version 9.4; SAS
180 Institute, Inc.) using the *nlp* non-linear optimization algorithm (since the objective and some

181 nutritional constraints were non-linear) and *multistart* option (to ensure that solutions were not only
182 local optimums).

183 During diet optimization, we estimated the standardized dual values (i.e., the dual values associated
184 with each constraint that has been standardized by its limiting bound), which represent the potential
185 gain in objective for a 100% relaxation of each constraint's limiting bound. This allowed to identify
186 the active (*vs.* inactive) constraints and compare their relative influences on the results. To conduct
187 this sensitivity analysis even further, some alternative models were also tested, with either introducing
188 some flexibility in some constraints (like the bioavailable zinc and iron nutritional constraints) or the
189 suppression of some other (like the co-production constraint).

190 Consumptions of food groups, animal- and plant-based products, nutrient intakes, percentage of
191 organic production mode per food group, monetary costs, environmental pressures (GHGe, cumulative
192 energy demand and land occupation) and the pReCiPe, as previously described (22), were calculated
193 for each optimized diet.

194 The pReCiPe (partial ReCiPe), a synthetic estimate of environmental impact based on GHGe,
195 cumulative energy demand and land occupation, which enables to consider potential trade-offs
196 between indicators (43), was calculated as follows:

$$197 \quad pReCiPe = 0.0459 \times GHGe + 0.0025 \times CED + 0.0439 \times LO$$

198
199 with GHGe, in kg of CO₂eq/d, CED, in MJ/d and LO, in m²/d. The higher the pReCiPe, the higher the
200 environmental impact.

201 2.7 Statistical analysis

202 For the present study, we considered participants of the NutriNet-Santé study who had completed the
203 Org-FFQ between June and December 2014 (N=37,685), with no missing covariates (N=37,305), not
204 detected as under- or over-energy reporter (N=35,196), living in mainland France (N=34,453), and
205 with available data regarding the place of purchase for the computation of the dietary monetary cost,
206 leading to a final sample of 29,413 participants. The sociodemographic, lifestyle and dietary
207 characteristics were presented by subgroup (men, premenopausal and menopausal women).

208 Dietary consumptions per subgroup were presented as observed mean (SD) or optimized values for
209 scenarios for the main 16 food groups and further specifically detailed among both animal and plant-
210 based foods.

211 All statistical analyses were performed using SAS (version 9.4; SAS Institute, Inc., Cary, NC, USA).

212 3. Results

213 3.1 Sample characteristics.

214 The sociodemographic characteristics of the sample are presented in **Table 1**. The sample included in
215 the present analysis was constituted of 7,416 men, 9,710 premenopausal women and 12,287

216 menopausal women. The mean age was 53.5y (SD=14.0). Most of the sample was postgraduate (64%)
217 and few individuals were current smokers (11%) or exhibited a low physical activity level (19%).
218 For each population (men, premenopausal and menopausal women), the food group consumptions for
219 the observed diet and the optimized diet under each model and by each scenario of GHGe reduction
220 are presented in **Appendix C**.

221 3.2 Overall dietary changes

222 The overall food group composition of optimized diets meeting the set of nutritional, acceptability,
223 moderation and coproduct constraints without (basal scenario, 0% reduction in GHGe) or with gradual
224 GHGe reduction (following scenarios, up to 50% of the observed pressures), are presented in **Figure**
225 **1**. In the basal scenario (0% reduction in GHGe, where the optimized diet was the closest diet to the
226 observed diet that meet the nutritional, acceptability, moderation and coproduct constraints), nutrient
227 constraints resulted in decreases in butter (up to -80% vs observed diet), dairy products (up to -64%),
228 extra-foods (up to -75%), non-alcoholic beverages (up to -54%) and fish (up to -45%) and in contrast
229 increases in soya-based food (up to +390%), eggs (up to +140%) and mixed dishes (up to +156%),
230 with also some sex-specific effects (whole starchy foods 45% decrease in men but 70% increase in
231 women, starchy foods and vegetable oils 54% and 145% respectively increase in men). In the
232 following scenarios, as detailed in the **Appendix D**, fulfilment of the environmental constraints of
233 gradual up to 50% decrease in GHGe was ensured by gradual further increases in soya-based food in
234 women (up to +68% vs basal scenario) and eggs in all groups (up to +24%) and by gradual further
235 decreases in extra-foods in all groups (up to -68%), whole grains & starchy foods, mixed dishes and
236 dairy products in men (-95%, -32% and -32% respectively), in meat and vegetables oils in women (up
237 to -27% and -29%, respectively).

238 3.3 Animal-based foods consumption

239 **Figure 2** presents the detailed intakes of animal-based foods in observed diets and in the optimized
240 diets for the basal (0% reduction in GHGe) and following (up to 50% gradual decrease in GHGe)
241 scenarios. Compared to the observed diets, in the basal scenario meeting the nutritional requirements,
242 all optimized diets (whatever the population) were characterized by a reduction in total animal
243 products (up to -44%), with suppression of milk and reductions in dairy products and cheese (up to -
244 66% and -30%, respectively) and fish (up to -45%, to be reduced to its maximal recommendation), and
245 in contrast increases in eggs and poultry (up to +140% and +182%, respectively). Moreover, in the
246 basal scenario compared to the observed situation, so as to ensure the nutrient requirements and
247 animal-based food dietary guidelines, ruminant meat increased (up to +30% in postmenopausal
248 women) while pork meat decreased (up to -89% in men). These trends for ruminant and pork meats
249 were then reversed during the following scenarios of up to 50% reduction in GHGe, which were
250 systematically characterized by concomitant and gradual decrease in ruminant meat (up to -91%
251 compared to the basal model with no GHGe decrease) and increase in pork (up to +964%). The GHGe
252 50% reduction was also ensured, to a lesser extent, by some sex-specific effects in line with those

253 already observed in the basal scenario, namely a further dairy products reduction in men and a further
254 egg increase in women.

255 Finally, compared to the observed diets, ensuring both nutritional needs, acceptability, moderation and
256 coproduction constraints and 50% GHGe reduction was achieved by strong reductions in the
257 consumptions of fish and ruminant meat (up to -23 g/d and -52 g/d) together with strong reductions in
258 the consumptions of milk and dairy products (up to -65 g/d and -115 g/d), while the consumptions of
259 poultry, eggs and pork increased (up to +46 g/d, +18 g/d and +18 g/d). Overall, if the total meat
260 consumption remained relatively similar between the observed and optimized diets, it was strongly
261 redistributed between meat types, as the contribution of poultry to total meat consumption greatly
262 increased from 18%-24% in observed diets to 43%-50% in optimized diets, while the contribution of
263 pork more moderately increased from 39%-42% to 46%-54% and the contribution of ruminant meat
264 greatly decreased from 34%-41% to 3%-5%.

265 3.4 Plant-based foods consumption

266 **Figure 3** presents the detailed intakes of plant-based foods in the observed and optimized diets for the
267 basal (0% reduction in GHGe) and following (up to 50% gradual decrease in GHGe) scenarios.

268 Compared to the observed diets, in the basal scenario meeting the nutritional requirements, all
269 optimized diets were characterized by strong increases in legumes (up to +238%, i.e., +45g/d) and
270 decreases in soups, soya-based food and fruits in all groups (up to -97%, -81% and -34%, i.e., -73 g/d
271 and -3.6 g/d and -91 g/d respectively). Whole grains and starchy foods decreased in men (-63%, i.e. -
272 59 g/d) but increase in women (up to +52%, i.e. 34 g/d). These effects were similar or even slightly
273 further strengthened in the following scenarios of up to 50% GHGe reduction. Indeed, whole grains
274 and starchy foods decreased in premenopausal women, increased in menopausal women and were
275 almost totally suppressed in men. The 50% GHGe reduction was also achieved by a reduction in
276 potatoes (up to -69%, i.e., -21 g/d).

277 3.5 Environmental and cost characteristics

278 The evolution of environmental and monetary cost indicators across the different scenarios is
279 presented in **Table 2**. Compared to the observed situation, the basal scenario meeting the nutrient
280 reference values (without GHGe reduction) yielded an increase in almost all these indicators (energy
281 demand and land occupation, pReCiPe and monetary cost of the diet). In the following scenarios of
282 gradual GHGe reduction, all these indicators then gradually decreased and reached lower values than
283 those observed for the environmental indicators, but not for the diet monetary cost. Indeed, compared
284 to the observed situation, in the last scenario of 50% GHGe reduction, the energy demand was lowered
285 by up to -29%, land occupation by -48% and pReCiPe by -47%, while the monetary cost of the diet
286 increased between +9% and +20%.

287 The share of organic food, starting from 26-32% in the observed diets, increased greatly and rapidly
288 from the basal scenario and then stabilized around 65-70% in all optimized diets. As detailed in the

289 **Appendix E**, while animal foods were consumed mostly as non-organic, plant-based food were
290 consumed as organic in optimized diet.

291 3.6 Nutrient characteristics

292 The nutrient intakes according to the observed and optimized diets are presented in **Table 3** Notably,
293 in all optimized diets, the intakes of fibers and bioavailable zinc, which were insufficient in the
294 observed diets, were leveled up to their reference value and were then kept unchanged. We found
295 similar results for the intakes of bioavailable iron and vitamin B12, except that while they also
296 increased in all the optimized compared to observed diets, they nevertheless decreased among
297 optimized diets along with GHGe reductions. The intake of phytates was also gradually decreased as
298 GHGe was reduced, allowing meeting reference values for bioavailable iron and zinc. Calcium intake
299 increased in all optimized diets, except in menopausal women.

300 3.7 Active constraints and sensitivity analysis

301 Analysis of the standardized dual values showed that the most limiting constraints were, in descending
302 order, bioavailable zinc, EPA+DHA (eicosapentaenoic acid + docosahexaenoic acid), energy intake,
303 sodium and saturated fatty acids in men and bioavailable zinc, EPA+DHA and sodium in women. The
304 redistribution between ruminant meat and pork across modeling scenarios was driven by the
305 compromise between satisfying the nutritional constraints for bioavailable zinc and iron and sodium
306 requirements and the environmental constraint of GHGe reduction, as tested by alternative models
307 where we allowed some flexibility in the requirements for each of these nutrients one by one (data not
308 shown).

309 The sensitivity analysis also showed that the nutritional constraints for bioavailable zinc and iron were
310 determinant for the distribution between meat and whole grains products having a phytate content that
311 limit the zinc and iron bioavailabilities. Indeed, as shown in **Appendix F**, we verified that allowing
312 some flexibility for bioavailable zinc led to meat reduction together with whole grains and starch
313 foods increase (in men: 110 g/d *vs.* 2 g/d of whole grains and starch foods with *vs.* without flexibility,
314 respectively, under the 50% reduction in GHGe scenario).

315 Moreover, as shown in **Appendix G**, the constraint on livestock co-products had little influence on the
316 modeling results that were fairly similar with or without considering this constraint.

317 4. Discussion

318 In the present diet optimization study, the minimal changes in current French diets necessary to first
319 meet nutrient reference values and then reduce GHGe by up to 50% were characterized by an overall
320 decrease in the consumption of foods of animal origin with notably suppression of milk and strong
321 reductions in dairy products and cheese, together with a stable but largely redistributed meat
322 consumption in favor of poultry and pork and against ruminant meat, as well as marked increases in
323 the consumptions of legumes. It should be noted that strong dietary changes were induced as soon as
324 the first, basal stage consisting in modelling diets meeting nutrient reference values (under

325 acceptability and moderation constraints), without any reduction in GHGe (which were however
326 constrained to avoid any increase). From this first stage, the consumption of animal products decreases
327 and the model opted for organic plant products, which are more efficient than non-organic ones to
328 limit GHGe. During the second stage, GHGe reductions by up to 50% mainly resulted from a
329 redistribution between meat types against ruminant meat, within total consumptions of meat and
330 animal products remaining relatively stable. Noteworthy, the model selects the most efficient farming
331 practice for each food (organic or not) thus the entire optimized consumption of each food item is
332 either organic or conventional which does not reflect the reality of consumer behavior.
333 Notably, in addition to food behaviors, a major challenge to improve the sustainability of food systems
334 is the reduction of losses and waste (44). The lack of quantitative data about waste for each food did
335 not allow us to consider this dimension in our models. This is all the more complex, as waste occurs at
336 each link of the food system chain and depends on both the production and processing methods
337

338 This study, by considering environmental pressures associated with food production while accounting
339 for farming practices, as well as numerous detailed food items, allowed intra-group substitutions by
340 favoring less emitter foods. This brings new insights since nowadays most French consumers are
341 unlikely to be ready to follow drastic plant-based diets such as vegetarian or vegan diets, that would
342 represent a radical change in eating habits for the highest consumers of animal products, and would
343 require steps over time. In the meantime, small, low-impact dietary changes for a large proportion of
344 the population are probably more acceptable than substantial changes as strong changes may need
345 more time (45). Overall, our results are coherent with literature findings comparing emissions from
346 observed diets more or less rich in animal products, which have documented lower emissions for diets
347 richer in plant foods (7,46–48). However, such observed diets do not necessarily meet the nutritional
348 requirements.

349
350 Optimization modelling enables to identify environmental-friendly diets in line with nutrient
351 requirements, (e.g. by avoiding counter-productive effects such as increase in consumption of sweet
352 and fat products) (15). Scientific literature using diet optimization for exploring potential GHGe
353 reduction under nutrient constraints is plentiful (7–10,48). Overall, from these studies, it appears that a
354 drastic and specific reduction of ruminant meat as well as dairy products consumption is the main
355 lever for GHGe reduction from diet, which is in line with our results. We indeed found that dairy
356 products and ruminant meat have to be drastically decreased, without being totally suppressed, which
357 is somewhat different from the results of a recent diet optimization study that identified the need to
358 completely eliminate ruminant meat while maintaining dairy products (excluding butter and cheese) to
359 comply with the 2030 and 2050 GHGe reduction targets (being much stronger than those modelled
360 here) in the Netherlands (49). However this study, as well as most of the others, did not take into
361 account nutrient bioavailability in nutrient constraints and did not include coproduction constraints,

362 whereas these important parameters may shape the modelling results and the order of magnitude of
363 potential decreases and increases according to food groups (9). Herein, as previously done (26–28), we
364 have considered and controlled the bioavailability of iron and zinc using validated equations for their
365 absorption. We have shown that considering the bioavailability of iron and zinc was crucial for the
366 concomitant variations in meat and whole grains products, whereas considering beef-milk
367 coproduction had little influence in our context.

368
369 A wide heterogeneity exists in terms of methodological aspects across modelling studies (50). First,
370 the number of food items can vary greatly and we worked with a relatively large number of food items
371 (~250) (9), with the notable feature of allowing the choice (or a mix) between two modes of
372 production (organic or conventional) for each food item. Second, contrary to what has been most often
373 done, we have considered constraints on food groups but not on food items so as to allow intra-group
374 substitutions. These acceptability constraints based on the 95th percentile of each population, including
375 participants with healthier diets than the general population, allowed stronger increases in some food
376 groups. Finally, we have adopted a quadratic rather than a linear formulation for the objective function
377 of diet departure to minimize, so as to favor more numerous but smaller changes rather than fewer but
378 larger changes during optimization (51). All these methodological choices have provided levers for
379 optimized diets, since we had a wide inventory of food items and since intra-group substitutions were
380 favored by different means as modeled here.

381
382 In our particular context, under all the considered nutritional and acceptability constraints and by
383 accounting for the influence of anti-nutritional factors like phytate on zinc and iron bioavailabilities,
384 total meat was maintained relatively stable, because of a decrease in whole grains and starchy foods
385 (and thus a decrease in phytate), although it was qualitatively remodeled in disfavor of ruminant meat
386 so as to reduce GHGe. In line with our results, a diet optimization study among old Dutch adults with
387 50% reduction in GHGs found unchanged total meat consumption with an increased contribution of
388 poultry and pork and a decreased contribution of beef (52).

389
390 Several options regarding plant foods merit further discussion. In the optimized diets, non-alcoholic
391 beverages (including coffee and tea) were strongly reduced (up to -54%), as they are poor in nutrients
392 and represent important environmental pressures at the post-production stage. However, as culturally
393 deeply entrenched in our usual diets, such drops could be an important limitation and all the more so
394 since positive health effects have been reported (53). It should be noted that whole grains and starchy
395 foods, whose beneficial role on health is well-documented (54), were lowered in optimized diets
396 (almost in men), and this may be ascribed to their phytates content limiting the iron and zinc
397 bioavailability. Such a prominent role in optimized solutions raises the issue related to nutritional
398 constraints relying on nutritional references which are based on calculated physiological requirements

399 as for zinc, for instance, reliable biomarkers are lacking (55). Thus, while we have defined the nutrient
400 constraints according to the French nutritional references and the literature equations for
401 bioavailability, the methods of definition may be highly conservative and slightly lower intakes may
402 not result in clear adverse effect on health, such as over-deficiency. Of note, the nutritional reference
403 for fiber (i.e. >30g/d) favors the increase in foods with high content such as legumes, while reducing
404 the ruminant meat for reducing GHGe required a reduction in phytate intake to allow sufficient
405 absorption of iron and zinc, which in turn has favored the reduction of starchy foods. This was clearly
406 illustrated by an alternative model allowing flexibility on zinc, with which whole grains foods did
407 increase. Moreover, in the optimized diets, fish consumption was limited by an upper value. Fish and
408 seafood are the major supplier of EPA and DHA that should be consumed at the highest level of their
409 reference value. This reflects the fact that EPA+DHA is a limiting constraint for more sustainable diets
410 and suggest that other and presumably better sustainable diets might be identified when introducing
411 other new sources of these fatty acids.

412
413 Finally, the proportion of organic foods drastically increased (in weight) from ~30% in the observed
414 diets to ~70% in all the optimized diets, which explained the monetary cost increase of optimized diets
415 (56). At the individual diet level, we previously reported that regular organic food consumers exhibit
416 diets with a lower impact regarding GHGe, land use and energy demand but dietary patterns (i.e.
417 plant-based patterns) prevailed on the mode of production in this association (22). However, at the
418 food item level, organic farming may play a substantial role in reducing GHGe, depending on the food
419 considered (23,57,58). Our results illustrate that when optimizing diets by selecting specific products
420 like in the present study, rather than by only substituting some conventional by organic products at
421 constant diet, as some consumers can do, organic foods can greatly help to the reduction of GHGe, as
422 previously shown in our observational studies (59). The consumption of organic foods increases from
423 the first step (i.e. 0% reduction in GHGe corresponding to modeling diet with $\text{GHGe} \leq \text{observed}$
424 value) which means that the foods preferentially selected to respect the nutritional constraints are more
425 efficient as organic to maintain GHGe. However, due to modeling, one food is selected 100% as
426 organic or 100% as conventional what does not reflect the reality of behaviors. This is interesting as an
427 increased consumption of organic foods can have beneficial consequences on two levels. First, on the
428 environmental level as organic production systems also exhibit improved energy efficiency (60), better
429 biophysics and biological quality of soils (57,61) and are valuable for plant and animal biodiversity
430 (57,60,61). Second, on the sanitary level, as high plant-based diets based on organic agriculture may
431 lead to much lower exposure to pesticide residues (22,62,63), motivating the promotion of plant
432 products produced without synthetic pesticides in the new French food-based dietary guidelines (64).

433
434 As regards the obtained solutions, optimized diets exhibited high consumption of fruits and vegetables
435 (>500g/d), low consumption of red meat (<500g/week), processed meat (<150g/week), sweet

436 products, low intake in salt and moderated consumption of dairy products, in line with the French
437 food-based guidelines (42). Importantly, consumption of legumes among menopausal women was
438 somewhat low and the consumption of whole grains and starchy foods was very low in men. As
439 scientific literature has documented a notable beneficial role of plant-food diets, beyond fiber intake
440 which are controlled in the present study, for health and environment (3), further steps of the
441 transition, probably further away from the observed diets would require to introduce a higher plant
442 versus animal food ratio. For instance, in the same cohort we previously described low emitting
443 dietary patterns (GHGe for production lower than about 2.2 kg CO₂ eq) that were richer in plant-based
444 food than the present solution but nutritional adequacy was not assessed (24). Higher shares of healthy
445 plant protein such as whole grains and lower consumption of animal protein as red meat are
446 considered as part of a healthy diet as documented by epidemiological data (65,66) and may be
447 warranted for a full sustainable transition together with GHGe. Finally, the nutritional values of highly
448 plant-based diets should be tested in the future by deleting or relaxing acceptability constraints,
449 considering alignment with healthy eating patterns as defined from epidemiological data or by using
450 hierarchical optimization as we did in a recent study (67). Finally, it has been previously documented
451 that healthier diets are often more expensive (68). In line with this, the optimized diets were more
452 expensive than the observed diet, constituting a potential barrier for some consumers. Without
453 appropriate policies, this may jeopardize food security due to inaccessibility and potential low
454 availability for vulnerable populations.

455 Some limitations of our work should be highlighted. First, the NutriNet-Santé cohort included
456 volunteers who were probably more concerned by health and diet issues than the general population,
457 limiting extrapolation to the general population as these participants exhibit diet rich in plant-based
458 food. For instance, lowering energy intake is a well-known lever for reducing GHGe (69,70) but in
459 this population including “small eaters”, energy intake increased in the basal model to reach the
460 requirement. Second, post-farm environmental pressures for organic agriculture are lacking, thus life
461 cycle assessments were limited to farm activities which have most impacts in the food system.
462 Therefore, our scenarios may be insufficient to meet the global climatic objective, since some steps
463 following food production were not considered. Concerning environmental indicators, LCA were used
464 while it is recognized that some ecosystem services related to agroecological practices are misestimate
465 by this method (25). Third, beyond GHGe, we considered two other environmental pressures for
466 descriptive purpose, those three allowing an acceptable representativeness of the overall
467 environmental impact (43), but other dimensions such as water use or biodiversity should be studied.
468 However, in further works, it would be very important to consider water use in particular in the
469 context of vegetable and fruit and the production of corn, mainly for feeding monogastric livestock
470 breeding. We observed a decrease in land occupation with the gradual reduction in GHGe.
471 Reallocation of released land may induce important fluctuations in GHGe which are the results of
472 carbon balance of managed forests, agricultural soil organic carbon stocks soil and reallocation

473 (grassland, deforestation, afforestation, artificialization etc.)(71). But, an important factor that was not
474 considered is land use reallocation since this analysis used attributional LCAs. Thus, the change in the
475 type of meat consumed would have also an effect on the demand for arable land and therefore on
476 carbon stocks and on GHGs (72). Notably, in addition to food behaviors, a major challenge to improve
477 the sustainability of food systems is the food losses and waste reduction (44). The lack of quantitative
478 data about waste for each food did not allow us to consider this important dimension in our models.
479 This is all the more complex, as waste occurs at each link of the food system chain and depends on
480 both the type production and level of processing. The reallocation of permanent grasslands is also an
481 issue We have also assumed, as in most diet optimization studies (9), that the most acceptable diets are
482 those the closest to the observed diets. While this classical assumption makes it possible to define a
483 simple and very restrictive metric of cultural acceptability, it is known to account only very
484 imperfectly for true acceptability as stronger dietary changes may occur, at least in certain segments of
485 the population. Besides, this study integrates many strengths such as the level of detail for food
486 consumption, the detailed and reliable consideration of the updated nutritional recommendations
487 (including bioavailability of the micronutrients of concern in our context, iron and zinc, which is
488 seldom done), the consideration of different food production methods and the corresponding
489 environmental indicators.

490

491 In conclusion, this study in adults provides detailed results on the possible dietary changes that can be
492 implemented to mitigate GHGe up to 50% with minimal departure from the observed diet. We were
493 here able to identify more sustainable diets, being nutritionally adequate and culturally acceptable, and
494 from which meat was not excluded. Because the present optimized nutrition model preferentially
495 allowed intra-category substitutions, the plant/animal food ratio was not noticeably altered. Although
496 adequate according to a large set of lower and upper nutrient reference values, the modelled diets may
497 be sub-optimal for long-term health, which may benefit from further decrease in red meat and higher
498 increases in whole grains. Furthermore, reducing the consumption of foods of animal origin,
499 particularly beef and lamb, as well as milk and dairies, is necessary not only for environmental or
500 health reasons but also for animal welfare considerations. Lastly, future research will be needed to
501 document even greater reductions as this 50% is unlikely to be sufficient and further research focusing
502 on specific subgroups, e.g. according to age or socioeconomic status would be of interest to fine-tune
503 the optimized diet.

504

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512 **5. The authors' contributions are as follows:**

513 EKG, BA, MT, and SH conducted the study.

514 EKG, JB, BL, SH, DL and PP conducted the research and implemented databases.

515 EKG, HF, AD, and FM conducted the diet optimization.

516 EKG performed statistical analyses and drafted the manuscript.

517 All authors critically helped in the interpretation of results, revised the manuscript and provided relevant
518 intellectual input. They all read and approved the final manuscript.

519 EKG had primary responsibility for the final content, she is the guarantor.

520 **6. Conflict of Interest**

521 No author declared conflict of interest.

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736 **Figure 1: Overall composition (g/d) of the observed and optimized diets according to the**
737 **modelling scenario and population group (color figure)**

738 Main food groups intakes (g/d) in the observed diets and in the diets being nutritionally, culturally and
739 environmentally optimized so as to ensure gradual reduction in greenhouse gas emissions (GHGe)
740 from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal women, C: menopausal
741 women.

742 **Figure 2: Composition in animal-based foods in the observed and optimized diets**
743 **according to the modelling scenario and population group (color figure)**

744 Detailed animal foods intakes (g/d) in the observed diets and in the diets being nutritionally, culturally
745 and environmentally optimized so as to ensure gradual reduction in greenhouse gas emissions (GHGe)
746 from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal women, C: menopausal
747 women.

748
749 **Figure 3: Composition in plant-based foods in the observed and optimized diets according**
750 **to the modelling scenario and population group (color figure)**

751 Detailed plant-based foods intakes (g/d) in the observed diets and in the diets being nutritionally,
752 culturally and environmentally optimized so as to ensure gradual reduction in greenhouse gas
753 emissions (GHGe) from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal
754 women, C: menopausal women.