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1 Nutritionally adequate and environmentally respectful diets are possible for different diet groups:  
2 an optimized study from the NutriNet-Santé cohort

Emmanuelle Kesse-Guyot<sup>1</sup>, Benjamin Allès<sup>1</sup>, Joséphine Brunin<sup>1,2</sup>, Hélène Fouillet<sup>3</sup>, Alison Dussiot<sup>3</sup>, François Mariotti<sup>3</sup>, Brigitte Langevin<sup>4</sup>, Florine Berthy<sup>1</sup>, Mathilde Touvier<sup>1</sup>, Chantal Julia<sup>1,5</sup>, Serge Hercberg<sup>1,5</sup>, Denis Lairon<sup>6</sup>, Carine Barbier<sup>7</sup>, Christian Couturier<sup>4</sup>, Philippe Pointereau<sup>4</sup>, Julia Baudry<sup>1</sup>

<sup>1</sup> Sorbonne Paris Nord University, Inserm, INRAE, Cnam, Nutritional Epidemiology Research Team (EREN), Epidemiology and Statistics Research Center – University of Paris Cité (CRESS), 93017 Bobigny, France

<sup>2</sup> ADEME, Agence de l'Environnement et de la Maîtrise de l'Energie), 49004 Angers, France

<sup>3</sup> Paris-Saclay University, UMR PNCA, AgroParisTech, INRAE, 75005, Paris, France

<sup>4</sup> Solagro, 75, Voie TOEC, CS 27608, F-31076 Toulouse Cedex 3, France

<sup>5</sup> Département de Santé Publique, Hôpital Avicenne, 93017 Bobigny, France

<sup>6</sup> Aix Marseille Université, Inserm, INRAE, C2VN, 13005 Marseille, France

<sup>7</sup> CNRS, UMR CIRED, 73 rue Jean François Breton, 34398 Montpellier, France.

**Correspondence:**

Email: [emmanuelle.kesse-guyot@inrae.fr](mailto:emmanuelle.kesse-guyot@inrae.fr)

Equipe de Recherche en Epidémiologie Nutritionnelle (EREN)

SMBH Université Sorbonne Paris Nord, 74 rue Marcel Cachin, 93017 Bobigny, France

**Running title:** Rebalancing plant and animal food

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NutriNet-Santé cohort is registered at: <https://clinicaltrials.gov/ct2/show/NCT03335644>

**Data availability:** Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval. Researchers from public institutions can submit a collaboration request including information on the institution and a brief description of the project to [collaboration@etude-nutrinet-sante.fr](mailto:collaboration@etude-nutrinet-sante.fr). All requests will be reviewed by the steering

committee of the NutriNet-Santé study. If the collaboration is accepted, a data access agreement will be necessary and appropriate authorizations from the competent administrative authorities may be needed.

In accordance with existing regulations, no personal data will be accessible.

**Abbreviations:**

- 3 AS, adequation sub-score
- 4 cDQI, Diet Quality Index
- CED, cumulative energy demand
- GHGe, greenhouse gas emissions
- LO, land occupation
- 5 M1, model 1
- 6 MF, Final Model
- 7 MS, moderation sub-score
- 8 Obs, observed situation
- 9 PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake
- 10 pReCiPe, partial ReCiPe
- 11 sPNNS-GS2: simplified Programme National Nutrition Santé guidelines score; observed diet;
- 12 PF, plant-based food
- 13 SFA, saturated fatty acids

## 14 **Abstract**

15 **Background:** While research has shown that vegetarian diets have a low environmental impact, few  
16 studies have examined the environmental impacts and nutritional adequacy of these diets together,  
17 although vegetarian diets can lead to nutritional issues.

18 **Objectives:** Our objective is to optimize and compare six types of diets with varying degrees of plant  
19 foods (lacto-, ovo-lacto- and pescovegetarian and diets with low-, medium- and high meat content)  
20 under nutritional constraints.

21 **Methods:** Consumption data in 30,000 participants are derived from the French NutriNet-Santé cohort  
22 using a food-frequency questionnaire. Diets are optimized by a non-linear algorithm minimizing the  
23 diet deviation while meeting multiple constraints at both the individual and population levels: non-  
24 increase of the cost and environmental impacts (as pReCipe accounting for greenhouse gas emissions,  
25 cumulative energy demand and land occupation, distinguishing production methods: organic and  
26 conventional), under epidemiological, nutritional (based on nutrient reference values), and  
27 acceptability (according to the diet type) constraints.

28 **Results:** Optimized diets were successfully identified for each diet type, except that it was impossible  
29 to meet the EPA+DHA requirements in lacto- and ovo-lacto-vegetarians. In all cases, meat consumption  
30 was redistributed or reduced and the consumption of legumes (including soy-based products),  
31 wholegrains, and vegetables were increased, while some food groups, such as potatoes, fruit juices and  
32 alcoholic beverages, were entirely removed from the diets. The lower environmental impacts (as well  
33 as individual indicators) observed for vegetarians can be attained even when nutritional references  
34 were reached except for long-chain omega 3 fatty acids.

35 **Conclusions:** A low-meat diet could be considered as a target for the general population in the context  
36 of sustainable transitions, although all diets tested can be overall nutritionally adequate, except for 3-n  
37 fatty acids, when planned appropriately.

38 **Keywords:** plant-based diets, diet optimization, vegetarians, meat consumers, nutritional references,  
39 sustainable diet, healthy diets

40

## 41 **Introduction**

42 Currently, westernized diets (i.e. characterized by high levels of sugar, saturated fat and salt) are  
43 associated with nutrition-related chronic diseases while, the healthiness of diets rich in plant-based  
44 foods is now well documented (1,2). Thus, worldwide, a total of 11 million deaths and 255 life years  
45 are attributable to dietary factors (2).

46 Moreover, current dietary patterns have significant detrimental effects on the environment as the  
47 production of current Western diets is a major contributor to greenhouse gas emissions (GHGe) and  
48 cause permanent damage to natural resources, many of which have already reached planetary limits  
49 (3). In that context, three pillars have been defined to limit the environmental impacts of food systems:  
50 improving agricultural practices, reducing waste and losses, changing dietary patterns and promote  
51 consumption of local and seasonal products (4,5). As regards dietary patterns, numerous observational  
52 and modelling studies have documented that diets richer in plant products have reduced environmental  
53 pressures compared to diets containing meat, with ruminant meat being a major determinant of  
54 emissions (6–13), regardless of the functional unit considered (10). A recent literature review (9) noted  
55 that compared to Western diets, an ovo-lacto-vegetarian diet resulted in a 35% reduction in GHGe, a  
56 42% reduction in land use and a 28% reduction in water use. Vegan diets, compared to current western  
57 diets, performed even better, -49% and -49.5% for GHGe and land use respectively, but were  
58 associated with a higher water use (+17%).

59 There is thus an overall improvement towards better environmental indicators when increasing plant-  
60 based food consumption, from omnivorous to vegetarian and finally, vegan diets, with the exception  
61 of water use in vegan diets. For example, we documented, in an observational study, that the pReCiPe  
62 (a synthetic indicator integrating GHGe, energy demand and land use) was 61% lower in vegetarians  
63 compared to meat eaters (14).

64 However, these results are often derived from observational studies (comparison of different  
65 populations according to their types of diets) or from simulation studies, in particular from studies  
66 using substitution scenarios. Such observed or modelled diets may not be adequate from a nutrient  
67 point of view. For instance, a recent study comparing 11 typical diets representing habitual dietary  
68 habits showed that typical diets were not necessarily nutritionally adequate or environmentally-

69 friendly (15). Furthermore, the different sustainability dimensions are rarely considered together, in  
70 particular because the economic dimensions is often lacking (9), although potential conflicts may arise  
71 between dimensions. While the lower environmental pressures associated with plant-based diets are  
72 well documented, meatless diets or diets devoid of any animal products may not provide adequate  
73 intake of some key nutrients provided by animal sources (16–18). To address the question of nutrient  
74 security, diet optimization is particularly suitable as it allows to impose meeting the nutritional  
75 references. However, studies have generally insufficient numbers of individuals following rarely  
76 adopted alternative diets (11). Although interesting from an environmental point of view, the vegan  
77 diet, characterized by a total exclusion of animal products, exhibits (in case of no dietary supplement)  
78 low or no intakes for nutrients mainly provided by animal products, such as EPA, DHA and vitamin  
79 B12, but also potentially calcium, iodine and bioavailable iron and zinc (19–21). For instance, a  
80 scenario study conducted in the Netherlands (22) showed that entirely replacing meat and dairy by  
81 plant-based foods drastically lowered environmental pressures (more than 40 %) but led to inadequate  
82 intakes of zinc, thiamin, vitamins A and B12, and calcium. Also, a 30 % reduction in animal foods led  
83 to improvement of saturated fatty acids, sodium, fiber and vitamin D intakes, and environmental  
84 pressures were lowered by 14 % leading the authors to suggest that replacing a part of animal foods  
85 was interesting concomitantly for environment and health.

86 Thus, the objectives of the present study are to identify for a spectrum of diets observed in a French  
87 cohort study, ranging from meat-rich diets to vegetarian diets, nutritionally adequate diets (by imposing  
88 the respect of nutritional constraints) and to compare optimized diet to the observed situation. Second,  
89 we analyze their environmental pressures and costs. We run sequential models to describe the trade-offs  
90 between nutritional, environmental and economic dimensions. Vegan diets is not considered in this  
91 study because some animal-specific nutrient requirements cannot be met through diet alone.

## 92 **Methods**

### 93 *Population*

94 This study is conducted on a sample of adults from the web-based prospective nutritional NutriNet-  
95 Santé cohort (23). The participants are volunteers recruited from the general French population. This  
96 study is conducted in accordance with the Declaration of Helsinki, and all procedures were approved

97 by the Institutional Review Board of the French Institute for Health and Medical Research (IRB  
98 Inserm 0000388FWA00005831) and the National Commission on Informatics and Liberty  
99 (Commission Nationale de l'Informatique et des Libertés, CNIL 908450 and 909216). Electronic  
100 informed consent was obtained from all participants. The NutriNet-Santé study is registered in  
101 ClinicalTrials.gov (NCT03335644).

### 102 ***Sociodemographic and lifestyle data***

103 Sociodemographic characteristics, including age, education (<high school diploma, high school  
104 diploma, and post-secondary graduate), lifestyles, i.e. smoking status (former, current, or never-  
105 smoker) and physical activity assessed using the International Physical Activity questionnaire (24) as  
106 well as anthropometrics (25), are collected using pre-validated questionnaires each year (26,27). We  
107 reported data closest to the FFQ (2014).

### 108 ***Dietary data collection and diet definition***

109 The dietary data were collected in 2014 via a self-administered semi-quantitative food frequency  
110 questionnaire (FFQ), aiming to distinguish organic (under official label) and conventional food  
111 consumption (28). This tool is based on a previously validated 264 items food frequency questionnaire  
112 (29) improved by a five-point scale to evaluate the mode of production of food (30). For each food  
113 item, participants reported the frequency of food consumed as organic by ticking the following  
114 modalities: “never”, “rarely”, “half-of-time”, “often” or “always” in response to the question ‘How  
115 often was the product of organic origin?’. Weight was allocated to each modality, i.e. 0, 25, 50, 75 and  
116 100%, respectively. Nutrient intakes were calculated using a published food composition table (31).  
117 Six groups of individuals with varying proportions of animal products are formed, corresponding to  
118 six diet types. Meat includes red meat, poultry, offal and processed meat.  
119 Pescovegetarians are defined as participants consuming less than 1g/d of meat but consuming fish.  
120 Ovolactovegetarians are those consuming less than 1g/d of meat and seafood but consuming eggs, and  
121 lactovegetarians those consuming less than 1g/d of egg, meat and seafood but consuming dairies. Low,  
122 medium and high consumers of meat are defined as those having a total meat intake <50g/d, 50g/d to  
123 100g/d and >100g/d, respectively.

124 To depict the overall quality of observed and modeled diets, the cDQI (comprehensive Diet Quality  
125 Index), the PANDiet (Diet Quality Index Based on the Probability of Adequate Nutrient Intake) and  
126 the sPNNS-GS2 (simplified Programme National Nutrition Santé-Guidelines Score 2) dietary indexes  
127 are computed.

128 The cDQI (range 0-85) is based on food group consumption and has been recently developed to assess  
129 the quality of the diet (32). It is composed of a vegetal sub-score (up to 55 points) and an animal sub-  
130 score (up to 30 points). For each sub-score, the components provide 0 to 5 points based on increasing  
131 thresholds for beneficial components and decreasing thresholds for non-beneficial components.

132 Intermediate points are allocated for intermediate consumptions (32).

133 The PANDiet score is based on the probability of adequacy for 27 nutrients and fibers, based on  
134 nutrient intake or bioavailability, and the probability of moderation for 6 nutrients. In addition penalty  
135 values are given for 12 nutrients in the case of exceeding upper limits of intakes (33). The PANDiet  
136 score ranges from 0 to 100 points (a higher score reflects better adherence to the French nutrient-based  
137 recommendations and adequate nutrient intake (34)).

138 The healthiness of diet is estimated using the sPNNS-GS2 (35), a validated index aiming to estimate  
139 the adherence to the official French food-based dietary guidelines (36). The sPNNS-GS2 (theoretical  
140 range:  $-\infty$  to 14.25), consists of 6 adequacy components and 7 moderation components, based on  
141 epidemiological evidence. The components are weighted according to the level of evidence for the  
142 associations with health and a penalty on energy intake is also given. The sPNNS-GS2 includes  
143 components related to fruit and vegetables, legumes, whole grain, nuts, fish, red meat, processed meat,  
144 sweet products, sweet beverages, added lipids, alcohol, dairy products, and salt. Scoring and  
145 computation have been extensively described elsewhere (35).

#### 146 ***Environmental pressure data***

147 Environmental indicators related to food-production are computed using life cycle analysis (LCA)  
148 using the DIALECTE database developed by Solagro (37), distinguishing organic and conventional  
149 farming. We considered GHGe (kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>eq)), cumulative energy demand (MJ),  
150 and land occupation (m<sup>2</sup>). Downstream steps, including conditioning, transport, processing, storage or



151 recycling stages, are not included in the perimeter of the LCA. Extensive details have been described  
 152 elsewhere (38). Nuts are excluded from the analysis as environmental indicators are not available.  
 153 As regards environmental impacts, the pReCiPe (partial ReCiPe), a synthetic estimate of overall  
 154 environmental impact based on GHGe, cumulative energy demand and land occupation per kg of diet,  
 155 is computed. The pReCiPe, standardized by the consumption quantities, enables to consider potential  
 156 trade-offs between indicators (39), and is calculated as follows (1):

$$157 \quad (1) \quad pReCiPe = \frac{\sum_{i=1}^n 0.0459 \times Qte_i \times GHGe_i + 0.0025 \times Qte_i \times CED_i + 0.0469 \times Qte_i \times LO_i}{\sum_{i=1}^n Qte_i}$$

158  
 159 Where  $i$  is the number of foods consumed and  $Qte_i$  is the quantity of  $i$  which is consumed.  
 160  $GHGe_i$ , in kg of  $CO_2eq/d$ ,  $CED_i$ , in MJ/d and  $LO_i$ , in  $m^2/d$  are the GHGe, CED and LO to produce 1  
 161 kg of the food  $i$ . A greater pReCiPe reflects a higher environmental impact.

## 162 ***Economic data***

163 A price database for each food item, accounting for the place of purchase collected concomitantly with  
 164 food consumption and the type of farming method (organic or conventional), is computed based on the  
 165 Kantar Wordpanel purchase database® (40) including 20,000 representative households and an *ad-hoc*  
 166 collection in short food-supply chains (28).

## 167 ***Coproduct factor linking milk to beef***

168 We consider a coproduct factor linking milk to beef as milk production is not possible without meat  
 169 production. This is of particular interest in the present work since some types of vegetarian diets  
 170 include dairy product intake. To do so, we use the following information:

171 - 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight) were produced in  
 172 2010 in France (41),

173 - 41% of beef was from dairy herd corresponding to 0.62 million tons of beef (42).

174 Postulating a meat to carcass weight ratio of 68%, 10% distribution losses, 32% losses at the consumer  
 175 level (cooking, bones and wastes) (43), we apply the following equation (2):

176 (2) 25 million tons of milk (L) = 1.52 million tons of beef  $\times$  41%  $\times$  68%<sub>carcass yield</sub>  $\times$   
 177 90%<sub>distribution yield</sub>  $\times$  68%<sub>preparation yield</sub>

178 Leading to 1L of milk corresponding to 10g of beef.

179 In this study, the coproduction constraint linking beef and milk consumption is considered at the  
 180 whole population level, i.e. accounting for all types of diets and their repartition.

### 181 ***Weighting of nutritional reference values***

182 Due to significantly different physiological needs, the French nutritional reference values are  
 183 established separately for males and females (34). Furthermore, a distinction is made between females  
 184 with high and low iron requirements. We therefore derive new nutritional reference values, based on  
 185 an average individual, consisting of 50% males and 50% females. In addition, for females, we further  
 186 consider that 50% of females have low requirements and 50% have high iron requirements. The  
 187 reference values for each nutrient for this average individual are therefore defined as the weighted  
 188 average requirements of males, females with high and low iron (**Supplementary Table 1**).

### 189 ***Optimization model***

190 Optimized diets are derived from each of the 6 observed diet types, using food item attributes,  
 191 including nutritional composition, environmental indicators (GHGe, CED and LO to compute  
 192 pReCiPe) and individual cost (as organic and conventional).

193 The optimized diets are identified using the procedure SAS/OR ® *optmodel* (version 9.4; SAS  
 194 Institute, Inc.). A non-linear optimization algorithm with multistart is used to select a solution that is  
 195 not only a local minimum, by modelling the 6 diet types concomitantly (to apply a beef-milk co-  
 196 production constraint at the population level).

197 The objective function that we use aimed at minimizing the total deviation (TD) from the 6 observed  
 198 diets, as follows (3):

$$199 \quad (3) \text{ Min TD} = \sum_j^6 \sum_i^{257} \left[ \frac{Opt_{i,j} - Obs_{i,j}}{SD_{i,j}} \right]^2$$

200 Where  $Opt_{i,j}$  and  $Obs_{i,j}$  respectively denote the optimized and observed daily consumptions of the  
 201 food item (i) for the diet group (j), with  $SD_{i,j}$  being its standard deviation in the observed situation.

202 A first model is computed under nutritional, epidemiological and coproducts constraints only  
203 (described below) – M1. As environmental pressures increase, a second model is performed imposing  
204 an additional environmental constraint which leads to increase in cost (from 3 to 6.4%). Thus, the final  
205 model includes both constraints, enforcing the cost of the diet and the pReCiPe below the observed  
206 values – MF.

207 The set of constraints was as follows:

#### 208 *-Nutritional references*

209 The nutritional constraints, which include daily energy intake and a set of nutrients, are based on the  
210 upper and/or lower ANSES 2016 reference values (34). Lower bounds are defined as either  
211 recommended dietary allowance (population reference intake), adequate intake, or lower bound of  
212 reference range for the intake in the French population (34).

213 For adequate intake, based on observed mean intake, the lower limit is set at the 5<sup>th</sup> weighted  
214 percentile value of the overall population. Upper bounds are defined as the maximum tolerable intakes  
215 for vitamins and minerals or the upper limit of the reference intake range. For zinc and iron,  
216 bioavailability is considered using published formula (**Supplementary Material**) (44,45). The  
217 reference values are shown in **Supplementary Table 1**.

218 Since no optimized diets could be found for lactovegetarian and ovolactovegetarian diets, we lower  
219 the constraint on EPA+DHA to half of the value (i.e. 0.25g/d).

#### 220 *-Epidemiological thresholds*

221 To comply with official French dietary guidelines (36) the model imposes:

- 222 - Consumption of red meat  $\leq 500$ g/week
- 223 - Consumption of processed meat  $\leq 150$ g/week
- 224 - Consumption of fish = 2 portions/week, including one portion of fatty fish
- 225 - Consumption of fruit and vegetables  $\geq 5$  portions /day.

#### 226 *-Coproducts constraint*

227 The optimization procedure is based on a double indexing considering the consumption of each food  $i$   
228 and the indexed sub-populations  $j$  so that beef consumption of the three meat-consumers populations  
229 stayed in line with the dairy products consumption of the six diet groups. We keep the observed

230 occurrence of the diets, which were 1.09%, 1.03%, 1.59%, 16.08%, 31.01% and 49.2% for lacto,  
231 ovolacto, pescovegetarians and low, medium, and high consumers of meat, respectively.

### 232 *-Acceptability constraint*

233 Acceptability constraints are defined at the consumed food group level, with upper bounds set at the  
234 weighted 95<sup>th</sup> percentiles values for each food group in each diet.

### 235 *-Additional constraints for environmental pressures and cost*

236 In the final model (MF), an environmental constraint imposes an optimized pReCiPe  $\leq$  its observed  
237 value and a diet-related monetary cost  $\leq$  its observed value.

238 For mean of observed food group consumption, nutrients intake as well as 5<sup>th</sup> and 95<sup>th</sup> percentiles (see  
239 below) values according to diet are also weighted so as to respect the male/female distribution/ratio  
240 defined above.

### 241 *Statistical analysis*

242 The baseline situation is based on data of the participants of the NutriNet-Santé study who had  
243 completed the FFQ between June and December 2014 (N=37,685), with no missing covariates  
244 (N=37,305), who are not under-energy reporters (N=35,196), living in mainland France (N=34,453)  
245 and with information as regards the place of purchase for the computation of the dietary monetary cost  
246 (N= 29,413). Finally, 87 vegans are removed from the sample for a total 29,326 individuals  
247 (**Supplementary Figure 1**). The sociodemographic, lifestyle characteristics of the six initial groups  
248 are estimated as mean (SD) or percentage. The observed and optimized diets, for each group, are  
249 described as food group consumption, nutrients intakes, dietary indexes, environmental pressures  
250 (GHGe, CED LO and pReCiPe), and monetary cost of the diet.

251 All statistical analyses are performed using SAS® (version 9.4; SAS Institute, Inc., Cary, NC, USA)  
252 and figures were performed developed using R version 3.6.

## 253 **Results**

### 254 *Characteristics of the baseline study sample (weighted data)*

255 The average age was 54.5 (SD=14.1) years old. High consumers of meat (>100g/day) were the most  
256 numerous (49%). The proportion of vegetarians of any type was 3.7%. The characteristics of the diet  
257 types are presented in **Table 1**. Low meat consumers had the lowest daily energy intake, while high

258 meat consumers had the highest. The highest sPNNS-GS2 was observed in pescovegetarians and the  
259 lowest in high meat-eaters. The organic ratio was highest in lactovegetarians (62%) and lowest in high  
260 meat-eaters (23%) (**Table 2**). Many of the observed nutrient intakes were not in line with the nutrient  
261 references, whichever the diet considered (**Supplementary Table 2**). Note that in the observed  
262 situation, high and medium meat diets were too rich in saturated fatty acids and sodium. Conversely,  
263 total energy intake was rather low in all diet groups. Most diets did not provide enough EPA+DHA  
264 and bioavailable iron, and the intake of fiber was too low in all meat-eater groups.

265 Environmental impact of vegetarians was  $\frac{1}{4}$  of that of high meat-eaters (**Table 2**). Low meat-eaters  
266 had an intermediate environmental impact. The highest diet cost was observed for the lactovegetarian  
267 diet, followed by the ovolactovegetarian and high meat diets.

#### 268 *Optimization of diets according to nutritional, epidemiological and coproducts constraints*

269 The first model (M1) (**Figure 1**) (namely, without the environmental and price constraints and with  
270 the nutritional, dietary guideline and coproduct constraints) led to a restructuring of diets. In particular,  
271 milk and alcohol were excluded and intake of fruit juice was strongly reduced in all diets. Beef  
272 consumption increased for low and medium meat diets whereas pork consumption decreased and  
273 poultry and egg consumption increased for all meat diets. Dairy product consumption decreased for all  
274 diets except the lactovegetarian diet, where it increased.

275 For all diets, there was a large increase in the consumption of dried fruits, legumes, soy-based food,  
276 wholegrain products, vegetable oil, prepared dishes and beverages, while vegetable consumption  
277 increased only moderately. Overall, the consumption of other fat and dressing decreased in favor of  
278 vegetable oil consumption. Moreover, fruit and potatoes consumption decreased in all diets. In model  
279 M1, compared to the observed situation, the pReCiPe was increased from 17% (ovolactovegetarian  
280 diet) to 63% (medium meat diet).

281 Of note, no organic foods were selected (as the nutritional values used were the same for both farming  
282 system) (**Table2**).

283 *Optimization of diets according to nutritional, epidemiological, coproducts constraints, pReCiPe and*  
284 *cost*

285 In model MF, the addition of constraints on pReCiPe and diet cost ( $\leq$  observed values), led to some  
286 redistributions within only a few food groups (**Figure 1, Supplementary Supplemental Tables 3 and**  
287 **4**) as strong changes were observed when imposing nutritional adequacy (M1). In particular, with  
288 regard to meat, compared to the model M1, a reduction of beef consumption was observed for the  
289 benefit of pork. Consumption of vegetables slightly increased while consumption of vegetable oil  
290 decreased, except for the high meat diet. In addition, consumption of potatoes was further reduced.  
291 Changes in individual environmental indicators are also presented (**Supplementary Figure 2**).

292 Regarding nutrient intakes (**Table 3 and Supplementary Table 5**), by construction, the nutritional  
293 references were reached, except EPA+DHA in non-fish eaters who were at their lower target value  
294 (i.e. 0.25g). The percentage of proteins of plant origin fluctuated from 31% (high meat diet) to 76%  
295 (lactovegetarian diet) (**Table 3**). The overall nutritional quality of the diet, as assessed by the different  
296 scores (**Table 2 and Figure 2**), varied from 53.14 (lactovegetarian diet) to 62.99 (pescovegetarian  
297 diet) for the cDQI, 74.68 (high meat diet) to 82.84 (pescovegetarian diet) for the PANDiet and, 6.08  
298 (high meat diet) to 11.25 (lactovegetarian diet) for the sPNNS-GS2 in model MF. The nutritional and  
299 health constraints induced changes in nutritional profiles. In particular, saturated fatty acids decreased  
300 in high meat consumers and increased in ovo and lactovegetarians, while a strong increase of animal-  
301 based proteins in lactovegetarians and an increase of plant-based proteins in all diet groups, especially  
302 in small and medium meat diets, was observed. Strong increases of fiber, vitamin B12, and  
303 bioavailable iron and zinc were observed as well as a reduction of sodium in high meat consumers.  
304 High meat consumers benefited the most from the nutritional constraints with a 962% increase in  
305 sPNNS-GS2 while low meat consumers showed a 63% increase (**Table 2 and Supplementary Table**  
306 **5**).

307 Regarding the cDQI, which considers the quality of animal and vegetable products, the lacto- and  
308 ovolactovegetarian diets had the lowest scores and the pescovegetarian group had the highest score.

309 A reduction of diet monetary cost was observed in the final optimized model, ranging from -6% in  
310 medium meat diet to -26% in pescovegetarian diet. The lowest cost was observed for low meat  
311 consumers and the highest for lactovegetarians (**Table 2 and Supplementary Table 5**).

312 In model MF, that included the pReCiPe and cost constraints, organic foods were selected, but their  
313 proportion in the diet was much lower than in the observed situation, ranging from 5.9% in high meat  
314 diet to 8.80% in pescovegetarian diet.

315 Some limiting nutrients (elevated dual value) differed according to the diet (**Supplementary Table 6**),  
316 but bioavailable zinc and EPA+DHA were limiting in all diets.

## 317 **Discussion**

318 Using a multicriteria approach, we were able to identify optimized diets that comply with the French  
319 nutritional references, in line with the dietary recommendations, while maintaining constant diet  
320 monetary cost and environmental impact, for all the six diets studied.

### 321 *Nutrient adequacy and diet quality*

322 The scientific literature documenting potentially inadequate intakes of certain nutrients, in particular  
323 iron, zinc, vitamin A, and B6, among individuals following vegetarian diets and in particular in vegans  
324 is plentiful (16–18). In the present work, we were able to identify vegetarian diets with adequate  
325 nutrient intakes, similar to the diets of meat-eaters. One important exception was the intake of  
326 EPA+DHA in vegetarian diets excluding fish, for which we had to halve the target, since the principal  
327 vector (seafood) is not part of these diets. However, it should be born in mind, that due to missing  
328 values for some environmental indicators, nuts, which provide omega-3 ALA, were not considered in  
329 the optimization procedure.

330 In addition, the obtained diets appeared to be healthy, since they were in line with the PNNS  
331 guidelines in terms of food consumption. Adherence to the PNNS-GS has been indeed associated with  
332 long-term health benefits (46–48). This suggests that adequacy to most nutritional references is  
333 conceivable with meat-free diets but implies a high degree of restructuring within and between food  
334 groups, as illustrated by drastic modifications when compared to observed diets. However, such  
335 drastic modifications were also noted for the high-meat diet in order to reach the nutritional references.

336 It should be also noted that plant-based foods contain anti-nutritional factors that may result in lower  
337 bioavailability or digestibility of certain nutrients (49). We accounted for the bioavailability of iron  
338 and zinc using validated equations but similar considerations could be made for some other nutrients  
339 such as proteins. However, even when considering a lower digestibility of plant-based proteins, total  
340 protein intake remains higher when compared to recommended allowance (33).

341 In the present study, we also found that both observed and optimized low meat diets were both the  
342 healthiest and the cheapest as compared to diets of medium or high meat-eaters. Their PANDiet and  
343 PNNS-GS2 score levels were higher than those observed among medium and high consumers of meat  
344 in the observational settings. This is in line with previous studies documenting higher quality of plant-  
345 based diets compared to diets rich in meat (9,50,51).

#### 346 *Optimized food consumption*

347 In the optimized diets, the rearrangement of the diets was characterized by an increase in legumes and  
348 soy-based products, and a decrease in dairy products. This is consistent with the literature  
349 documenting that legumes are an effective lever for transition towards sustainable diets (6,52). In  
350 addition, meat consumption was drastically reduced in high meat diet. Some food groups such as milk,  
351 fruit juice and alcoholic beverages were completely or almost completely removed from the diets,  
352 suggesting that these food groups were not the best vectors of micronutrients such as calcium or fibers.  
353 Our findings suggest that these diets should be carefully addressed to avoid micronutrient deficiencies.  
354 Among meat-eaters, poultry consumption increased while beef and pork decreased. In any case, for  
355 modelled diets for meat-eaters, total optimized beef and pork consumption reached levels below 75g  
356 per day, from 15g for low consumers to  $\approx 70$  for high consumers, in order to meet nutritional and  
357 epidemiological constraints. Thus, our results suggest that optimized diets of low meat consumers may  
358 comply with different sustainability dimensions, including nutritional/health, acceptability (as  
359 vegetarian diets would not be necessarily well accepted in the general French population),  
360 environmental and economic sustainability. This is of particular interest since low-meat diet might be  
361 accepted by a greatest number of people since vegetarian diets remain relatively **uncommon** in  
362 European countries (53). In Interestingly, the consumption of beef and pork in this group was close to



363 the threshold recommended by the Eat-Lancet diet (52). Similarly, the consumption of wholegrain  
364 products, dairy products, vegetable oils, potatoes, poultry, vegetables and fish were within the target  
365 values of the Eat-Lancet diet. However, the consumption of pulses (including soy-based products as  
366 defined in the Eat-Lancet diet) were very high in our study but we considered soy-based beverages  
367 which contain a lot of water. Soy-based foods may be optimized diet of this group of low consumers  
368 of meat was also in line with the Mediterranean diet, whose sustainability has been consistently  
369 recognized (10,54,55). However, some adverse health effects of soy foods have been suspected (56).  
370 Thus, the models may need to be revised if the level of evidence increases.

### 371 ***Resources and environment***

372 In the observed diets, a great variability was observed according to the diets with regard to the food  
373 production related environmental pressures and impact (which accounted for differential role of modes  
374 of production (organic or conventional)). The pReCiPe, reflecting environmental impact, was -73%  
375 lower for the lactovegetarian diet compared to the high meat diet. Of note, low meat consumers  
376 exhibited an intermediate level for the pReCiPe.

377 In previous observational studies, vegans and vegetarians exhibited far lower GHGe related to diet  
378 than consumers of meat (57–59). For instance, in a small study carried out in Italy, vegetarian and  
379 vegan diets had 34% and 40% lower GHGe, respectively, than omnivorous diets (57). Also, in a work  
380 by Scarborough et al., conducted in the EPIC-Oxford cohort study (58), medium meat-eaters, low  
381 meat-eaters, fish-eaters, vegetarians and vegans showed GHGe reduced by 22%, 35%, 46%, 47%, and  
382 60%, compared to high meat-eaters.

383 Such findings based on observed situations, are consistent with the scientific literature, based on  
384 different scenarios, documenting that diets including small amounts or no animal products exert lower  
385 environmental pressures (7–9,13,60,61) than those of meat eaters, in particular with regard to GHGe,  
386 due to the large impact of animal food production (62). It is noteworthy that these estimates vary  
387 greatly, between -45% (61) and -70% (13), depending on the type of study (scenarios of substitutions  
388 or observational data), the choice of the substitutions made within the scenarios, and the baseline diet  
389 (particularly the level of meat consumption) within the observational studies. However, variations in  
390 environmental pressures and impacts associated with diet types may not be fully aligned with nutrient

391 adequacy, as vegetarian diets with their lower impacts may be associated with some intake  
392 inadequacies. Optimization models have been widely used to identify sustainable or environmentally  
393 friendly diets (61), but such analysis has not been conducted by diet type. We identified only one  
394 modeling study using this type of modeling for various diet types. However, the study was not  
395 conducted in adults (63). This approach is very useful, however, because it allows us to highlight  
396 nutritional issues and identify dietary levers under nutritional constraints.

### 397 *Multicriteria analysis*

398 In our study, applying nutritional constraints led to an overall increase in environmental impact  
399 compared to the observed situation. This seems, although not strictly comparable, consistent with  
400 some studies documenting potential lack of alignment between dietary guidelines and environmental  
401 objectives (64). However, some studies have shown the opposite in specific countries such as Spain  
402 (65) and France (46). Concerning, monetary cost, findings are inconsistent. Some authors showed that  
403 diets following European dietary guidelines are more expensive than current diets (46,65,66) while  
404 one study argued that the Mediterranean diet can be inexpensive (67), and finally another study has  
405 found that the Western diet is expensive (68). We have shown here the ability to combine the  
406 sustainability dimensions to design healthy diets with costs and environmental impact below or equal  
407 to the observed situation.

408 Considering low meat consumers' diet, which corresponds to "flexitarian" diets (69), as of particular  
409 interest since, plant and animal farming have complementary and indispensable roles in healthy and  
410 sustainable food systems (5,70). Such a low meat diet has also been described as more sustainable than  
411 diet with elevated consumption of meat from a health perspective (71). Diets derived from the first  
412 model did not include organic foods because no constraints were set on this parameter and nutritional  
413 composition did not consider potential differences related to farming methods. In the final model,  
414 under cost and environmental impact constraints, some organic foods were introduced because they  
415 had lower environmental pressures as previously published (38). [However, because conventional  
416 foods are overall cheaper than organic foods, the cost-constrained model favors conventional foods  
417 first. Thus, the proportions of organic food in the final diets were much lower than in the observed  
418 situation. This shows that among nutritionally adequate alternatives, those that modulate](#)

419 environmental and price pressures favor conventional foods, when toxicity aspects (e.g., exposure to  
420 synthetic pesticides) are not considered in the model.

421 In addition, the proportion of organic food was the highest for the low meat diet compared to the other  
422 studied diets, while the diet monetary cost was the lowest. Compared to the observed situation, at  
423 similar dietary monetary cost, organic foods were less represented as energy intake was far higher in  
424 modelled diets than the observed level due to the constraint. This is worth underlining since, compared  
425 to conventional farming, organic farming exhibits several benefits and notably contribute to an  
426 agroecological management of resources and environment preservation (72). It would be important to  
427 consider such factors in future diet modelling studies as well as indicators such as biodiversity, or  
428 water pollution (72–74) or toxicity. Frequencies and quantities of pesticide residues are indeed far  
429 more important in conventionally produced plant-based foods (75). We previously documented that  
430 plant-rich diets including only conventionally grown produce can lead to a strong increase in to  
431 pesticide residue exposure (76).

#### 432 *Limitations and strengths*

433 Our study has limitations which should be emphasized. First, LCA were restricted to the  
434 production stage since post farm data were not available for the whole organic system. While the  
435 production is the main cause of environmental pressures (3), it would be also important to consider the  
436 pressures up to the plate. In addition, it is well documented that LCA misestimates some ecosystem  
437 services in particular for agroecological practices (77). In particular, nuts were excluded from the  
438 present analysis because environmental indicators were not available for these products even though  
439 they may be important vector of certain nutrients, especially for vegetarian diets. Second, our  
440 environmental analysis encompassed three major indicators (39) which, although important, did not  
441 allow to conduct a comprehensive analysis, in particular we did not have data on biodiversity loss.  
442 Finally, participants were volunteers, and therefore more concerned by nutritional and health issues.  
443 Thus, the observed diet (starting point of the optimization) was healthier, especially richer in plant  
444 foods, than that of the general population (28,78).  
445 Nonetheless, the strengths of our study are multiple. We used a multicriteria approach including  
446 various parameters, including nutrition, consideration of coproduct factors, health, environment and

447 sanitary indicators and we distinguished the organic farming system from the standard conventional  
448 farming system. Finally, the list of foods was highly detailed, allowing to select food items of  
449 particular nutritional interest. We also used a wide set of nutritional reference values,, including  
450 bioavailability for zinc and iron, which may be a nutritional issue in plant-based diets (79).  
451 A wide range of proposals have been described to implement sustainable diets (52). Among these,  
452 actions should include the mobilization of consumers and more generally a transformation of the food  
453 systems by involving all the stakeholders. Policies should encompass measures aiming to guiding  
454 choices (by promoting sustainable dietary guidelines), but also policy measures aiming to restrict  
455 unhealthy choices (by providing economic support to sustainable system) and tax incentives and  
456 discouraging measures.

#### 457 **Conclusion**

458 In this optimization study, it appears that vegetarian (including pescovegetarian) diets, which are more  
459 respectful of the environment and natural resources, can meet nutritional references, even for nutrients  
460 provided mostly by animal-based food sources (except for long-chain omega 3 fatty acids among non-  
461 fish eaters), but this requires appropriate food choices. Given the potential lack of acceptability of  
462 meatless diets by a large part of the population, a diet characterized by low meat consumption (29g/d  
463 including beef, pork and poultry, which corresponds to  $\approx 1$  serving/week) and a high amounts of  
464 vegetables, fruits, wholegrain products and legumes may be an acceptable trade-off for the general  
465 population, as it is close to the dietary guidelines, has a low monetary cost and has half of the  
466 environmental that the diet of high-meat eaters.

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477 **The authors' contributions are as follows:**

478 EKG, BA, BL, SH, DL, PP and JB, led the BioNutriNet project on which the data used.

479 EKG conducted the diet optimization and BA, HF, CB, CC and JB provided conceptual assistance in  
480 the context of SISAE project.

481 EKG wrote the statistical script, conducted analyses and drafted the manuscript.

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

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

485 **Conflict of Interest**

486 No author declared conflict of interest.

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766 **Table 1: Description of the weighted sample, by diet group, NutriNet-Santé Study (n=29,326,**  
 767 **2014)<sup>1</sup>:**

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
<b>% of the sample</b>	1.09	1.03	1.59	16.08	31.01	49.2
<b>% Females</b>	50	50	50	50	50	50
<b>Age (y)</b>	43 (14)	46 (14)	53 (13)	55 (15)	55 (14)	55 (14)
<b>Body mass index (kg/m<sup>2</sup>)</b>	21.99 (3.84)	22.93 (6.40)	22.29 (3.26)	23.04 (3.79)	24.15 (4.03)	25.32 (4.68)
<b>Education (%)</b>						
< High-school diploma	11.6	13.8	15.2	23.8	21.9	19.7
High school diploma	18.6	12.2	16.5	14.2	12.9	13.5
Postgraduate	69.8	74.1	68.3	62.0	65.2	66.9
<b>Occupation (%)</b>						
Unemployed	11.3	7.3	5.2	3.4	3.5	4.6
Retired	14.0	15.9	28.7	40.9	43.9	39.5
Employee, manual worker	18.6	17.4	16.5	13.5	11.0	10.6
Intermediate professions	12.3	13.1	14.6	13.9	12.7	13.4
Managerial staff, intellectual profession	25.8	28.7	24.6	21.1	22.7	24.4
Never employed	13.0	15.1	7.9	5.3	4.5	5.6
Self-employed, farmer	5.0	2.5	2.6	1.9	1.8	1.8
<b>Physical activity level (%)</b>						
Missing data	9.7	10.4	10.5	9.6	8.6	6.9
Low	15.7	18.1	20.2	17.1	10.9	12.1
Moderate	36.4	36.2	34.2	33.3	41.7	38.6
High	38.2	35.3	35.1	40.0	38.8	42.3
<b>Tobacco status (%)</b>						
Never smoker	55.0	46.4	44.1	44.6	46.5	48.3
Former smoker	36.8	39.6	44.9	44.0	44.4	42.6
Current smoker	8.2	14.1	11.1	11.4	9.2	9.1



<b>Energy intake (kcal/d)</b>	2073 (647)	1993 (582)	1964 (686)	1741 (573)	1845 (526)	2298 (650)
<b>cDQI</b>	47.06 (6.13)	50.03 (6.68)	54.98 (7.42)	51.71 (8.25)	48.28 (8.68)	45.40 (8.36)
<b>PANDiet</b>	72.54 (6.19)	68.92 (7.57)	70.65 (7.68)	68.53 (8.11)	66.99 (7.54)	62.09 (7.08)
<b>sPNNS-GS2</b>	5.64 (1.97)	5.58 (2.07)	5.72 (2.28)	5.05 (2.49)	3.70 (2.66)	0.57 (3.25)

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768 Abbreviations: cDQI, Diet Quality Index, sPNNS-GS2, simplified Programme National Nutrition

769 Santé-guidelines score

770 <sup>1</sup>All data are weighted as explained in the method section.

771 <sup>2</sup>Values are mean (SD) or % as appropriate. P-values across groups based on Chi<sup>2</sup> or ANOVA tests

772 were <0.001 (not tabulated).

773 **Table 2: Environmental and cost analysis for observed and modelled diets by diet group<sup>1</sup>**

	pReCiPe <sup>2</sup>			Cost €/d			Organic (%)		
	Obs	M1	MF	Obs	M1	MF	Obs	M1	MF
<b>Lactovegetarian</b>	0.10 (0.04)	0.12	0.10	9.04 (4.98)	7.88	8.13	62 (29)	0	8.11
<b>Ovolactovegetarian</b>	0.12 (0.04)	0.14	0.12	8.09 (3.81)	6.79	7.00	59 (29)	0	6.77
<b>Pescovegetarian</b>	0.11 (0.04)	0.13	0.11	8.94 (4.77)	6.21	6.58	56 (31)	0	8.80
<b>Low-meat</b>	0.17 (0.07)	0.23	0.17	6.70 (2.89)	5.93	6.27	42 (31)	0	8.43
<b>Medium-meat</b>	0.24 (0.09)	0.39	0.24	6.95 (2.50)	6.21	6.53	30 (26)	0	6.14
<b>High-meat</b>	0.38 (0.18)	0.45	0.38	8.77 (2.91)	6.74	6.98	23 (23)	0	5.90

774 Abbreviations: M1, model 1; MF, Final Model; Obs, observed situation; pReCiPe, partial ReCiPe

775 <sup>1</sup>Values are means (SD) or optimized values

776 <sup>2</sup>The pReCiPe (partial ReCiPe) is a synthetic estimate of overall environmental impact based on  
777 greenhouse gas emissions (GHGe), cumulative energy demand (CED) and land occupation (LO) per  
778 kg of diet calculated as follows (1):

$$779 \quad (1) \quad pReCiPe = \frac{\sum_{i=1}^n 0.0459 \times Qte_i \times GHGe_i + 0.0025 \times Qte_i \times CED_i + 0.0469 \times Qte_i \times LO_i}{\sum_{i=1}^n Qte_i}$$

780 Where i is the number of foods consumed and Qte<sub>i</sub> is the quantity of i which is consumed.

781 GHGe<sub>i</sub>, in kg of CO<sub>2</sub>eq/d, CED<sub>i</sub>, in MJ/d and LO<sub>i</sub>, in m<sup>2</sup>/d are the GHGe, CED and LO to produce 1  
782 kg of the food i. A greater pReCiPe reflects a higher environmental impact.

783

784 **Table 3: Nutritional analysis and quality indexes for each modelled diet <sup>1</sup>**

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
<b>Nutrients</b>						
Energy Intake (Kcal/d)	2317	2312	2158	2127	2151	2300
SFA (g/d)	23.63	29.51	25.62	28.12	28.69	30.67
Animal protein (g/d)	24.97	33.72	28.94	43.96	61.09	83.55
Plant protein (g/d)	79.14	68.09	63.90	51.31	43.19	38.12
% Protein from PF	76.02	66.88	68.82	53.86	41.42	31.33
DHA+EPA (g/d)	0.25	0.25	0.50	0.50	0.50	0.50
Selenium (µg/d)	99.82	99.28	91.51	85.61	81.71	89.46
Potassium (g/d)	4772	4430	4266	3854	3839	3976
Calcium (mg/d)	1410	1415	1334	1473	1420	1426
Vitamin A (µg/d)	1260	1348	1190	1123	1302	1868
Vitamin B6 (mg/d)	2.95	2.93	2.68	2.29	2.38	2.54
Vitamin B9 (µg/d)	788.17	701.50	648.48	510.47	506.24	503.65
Vitamin B12 (µg/d)	4.49	4.85	5.22	6.45	7.74	12.76
Bioavailable zinc (mg/d)	3.58	3.66	3.53	3.71	3.95	4.34
Bioavailable iron (mg/d)	2.01	1.95	1.91	1.95	2.15	2.54
Fiber (g/d)	50.92	44.73	45.70	35.20	32.88	30.00
Sodium (mg/d)	2300	2300	2300	2300	2300	2300
<b>Dietary Indexes</b>						
cDQI	53.14	56.04	62.99	60.13	61.35	61.06
PANDiet	82.47	71.02	82.84	82.18	79.18	74.68
AS	91.87	92.46	95.20	95.21	95.03	95.37
MS	73.06	49.58	70.47	69.16	63.32	54.00

PNNS-GS2	11.25	8.75	10.75	8.25	7.75	6.08
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785 Abbreviations: AS, adequation sub-score; cDQI, diet quality index; PANDiet, Diet Quality Index

786 Based on the Probability of Adequate Nutrient Intake; MS, moderation sub-score; sPNNS-GS2:

787 simplified Programme National Nutrition Santé guidelines score; PF, plant-based food; SFA, saturated

788 fatty acids.

789 <sup>1</sup>Values are optimized values of the final model under nutritional, cost and pReCiPe Constraints

790

791 **Figure 1: Food group consumption for each observed and optimized diets, by diet group<sup>1,2</sup>**

792 Abbreviations: M1, first model; MF, final model; Obs, observed diet; SFF, sweet and fat foods.

793 <sup>1</sup>Food group consumption (g/d) in the observed diets (red) and in the modelled diets are nutritionally,  
794 culturally and environmentally optimized so as to ensure gradual increase in the proportion of energy  
795 intake from plant-based foods. M1 (green) is the first model under nutritional, epidemiological and  
796 coproduction constraints. MF (blue) is the final model including constraints on pReCiPe and cost  
797 (below the observed values).

798 <sup>2</sup>Dairy products include yogurts, fresh cheese and cheese and milk consumed with tea/coffee; fish  
799 includes seafood, cereals include breakfast cereals with no added sugar, bread semolina, rice and  
800 pasta; fruits include fresh fruit, fruit in syrup and compote, dried fruit and seeds; potatoes include  
801 potatoes and other tubers; soy-based foods include tofu, soy meat substitute and vegetable patties, soy  
802 yogurt, soy milk; vegetables include all vegetables and soups; oil includes all vegetable oils; other fats  
803 include fresh cream and butter; prepared dishes include sandwich, dishes such as pizza, hamburger,  
804 ravioli, panini, salted pancake; sweet and fat foods (SFF) include croissants, pastries, chocolate,  
805 biscuits, milky desserts, ice cream, honey and marmalade, cakes, chips, salted oilseeds, salted biscuits;  
806 and beverages include fruit nectar, syrup, soda (with or without sugar), plant-based beverages (except  
807 soy-based drinks).

808

809 **Figure 2: Dietary scores for observed and optimized diets, by diet group**

810 Abbreviations: cDQI, diet quality index; M1, first model; MF, final model; Obs, observed diet;

811 PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; sPNNS-GS2,

812 simplified Programme National Nutrition Santé-Guidelines Score 2

813