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

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1   Nutritionally adequate and environmentally respectful diets are possible for different diet groups:

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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. 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-, ovolacto- 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 ovolactovegetarians. 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 ovolactovegetarian 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_2 equivalents (CO_2eq)), cumulative energy demand (MJ),

150   and land occupation (m^2). 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 $$(1) \quad pReCiPe = \frac{\sum_{i=1}^{n} 0.0459 \times Qte_i \times GHGe_i + 0.0025 \times Qte_i \times CED_i \times + 0.0469 \times Qte_i \times LO_i}{\sum_{i=1}^{n} Qte_i}$$

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%$_{carcass\ yield}$ $\times$

177   90%$_{distribution\ yield}$ $\times$ 68%$_{preparation\ yield}$

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

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 5th 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 ≤500g/week

223   -   Consumption of processed meat ≤150g/week

224   -   Consumption of fish = 2 portions/week, including one portion of fatty fish

225   -   Consumption of fruit and vegetables ≥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 95th 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 5th and 95th 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 ¼ 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 (≤ 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 ≈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 ≈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.

474   of the NutriNet-Santé cohort. Nicolas Dechamp (data-manager/statisticians); Merveille Kouam (health

475   event validator); Maria Gomes (participant support)

476   Alexandre De Sa (dietitian), Rebecca Lutchia (dietitian)

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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765

766 **Table 1: Description of the weighted sample, by diet group, NutriNet-Santé Study (n=29,326,**

767 **2014)[1]:**

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
% of the sample	1.09	1.03	1.59	16.08	31.01	49.2
% Females	50	50	50	50	50	50
Age (y)	43 (14)	46 (14)	53 (13)	55 (15)	55 (14)	55 (14)
Body mass index (kg/m²)	21.99 (3.84)	22.93 (6.40)	22.29 (3.26)	23.04 (3.79)	24.15 (4.03)	25.32 (4.68)
Education (%)						
< 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
Occupation (%)						
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
Physical activity level (%)						
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
Tobacco status (%)						
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

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

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

Santé-guidelines score

[1]All data are weighted as explained in the method section.

[2]Values are mean (SD) or % as appropriate. P-values across groups based on Chi² or ANOVA tests

were <0.001 (not tabulated).

Table 2: Environmental and cost analysis for observed and modelled diets by diet group[1]

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

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

[1]Values are means (SD) or optimized values

[2]The pReCiPe (partial ReCiPe) is a synthetic estimate of overall environmental impact based on

greenhouse gas emissions (GHGe), cumulative energy demand (CED) and land occupation (LO) per

kg of diet calculated as follows (1):

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

Where i is the number of foods consumed and Qte_i is the quantity of i which is consumed.

$GHGe_i$, in kg of CO2eq/d, CED_i, in MJ/d and LO_i, in m2/d are the GHGe, CED and LO to produce 1

kg of the food i. A greater pReCiPe reflects a higher environmental impact.

784 **Table 3: Nutritional analysis and quality indexes for each modelled diet [1]**

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
Nutrients						
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
Dietary Indexes						
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

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 [1]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[1,2]**

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

793 [1]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 [2]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