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Sustainability analysis of French dietary guidelines using multiple criteria

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1 **Abstract**

2 Sustainability is now accounted in some Food-Based Dietary Guidelines (FBDG). In 2017, the French
3 FBDG were updated and incorporated environmental preservation. We conduct a multi-indicator
4 evaluation of the 2001 and 2017 FBDG, based on data from 28,240 participants of the NutriNet-Santé
5 cohort, completing an organic food frequency questionnaire. Indicators related to nutrition,
6 environment (3 indicators and the synthetic pReCiPe score) and economy are used distinguishing
7 organic and conventional farming systems. To estimate compliance with the 2001 and 2017 FBDG,
8 we used two validated adherence scores (PNNS-GS1 and PNNS-GS2, respectively). We estimated
9 numbers of averted deaths by adhering to the FBDG using a Competing Risk Assessment model.
10 Higher adherence to the 2017 guidelines was related to higher plant-based diet, cost and death averted
11 and lower energy intake, lower synthetic environmental score and lower exposure to some pesticides.
12 Overall, larger differences between lowest versus highest PNNS-GS2 were observed than between
13 lowest versus highest PNNS-GS1. Our results suggest that the 2017 guidelines are overall in line with
14 the multiple dimensions of diet sustainability, including health, although at a slight cost increase. If
15 adopted by a large part of the population, these dietary guidelines may contribute to prevent chronic
16 diseases while reducing food-related environmental pressures.

17 In developed countries, western diets are characterized by high intake of sugar, salt, saturated fat and
18 meat, together with extensive consumption of highly processed food, raising major health and
19 environmental concerns ¹. As diet is a major determinant of various non-communicable diseases ²,
20 official food-based dietary guidelines have been developed and disseminated since the 1950's by
21 governments to promote healthy diets ³.

22 Beyond health consequences for individuals, current food systems, from farm to fork, are responsible
23 for about one quarter to one third of Greenhouse Gas emissions (GHGE) and cause major risks in
24 terms of soil, and water pollution and biodiversity loss ¹. This has led to the definition of a sustainable
25 diet as “protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible,
26 economically fair, and affordable, nutritionally adequate, safe, and healthy, while optimizing natural
27 and human resources” ⁴. Recent 2050's projections suggest that unsustainable dietary patterns rich in
28 meat and processed food may lead to an increase in GHGE up to 80% from the current baseline ⁵.
29 Therefore, changing food production, processing, and distribution as well as dietary patterns may lead
30 to substantial reductions in GHGE and may overall improve the sustainability of the diet ⁶.

31 For instance, some plant-based dietary patterns such as the Mediterranean or vegetarian diets which
32 exhibit noticeable beneficial effects on health have been recognized as more respectful of the
33 environment and are considered as a model of sustainable diet ^{1,7,8}. Promoting shifts toward more
34 plant-based diets, as advised by the Food-based Dietary Guidelines (FBDG), may contribute to reduce
35 both GHGE and morbidity/mortality related to dietary factors ^{1,9-11}. A recent report pointed out that the
36 establishment of official dietary guidelines are crucial actions for nutrition policy and education. Thus,
37 they could embrace sustainability by encouraging people to consume plant-based diets ¹².

38 There is a substantial and growing body of evidence supporting the development of integrated dietary
39 approaches to align both long term health and sustainability dimensions ¹³. However, only few
40 countries have developed official food-based dietary guidelines including sustainability as a major
41 policy issue ¹⁴. Historically, this concept is not recent as Joan Dye Gussow for the first time proposed
42 dietary guidelines including sustainability-related dimensions in 1986 ¹⁵.

43 In France, the first food-based dietary guidelines were implemented in 2001 within the framework of
44 the French Nutrition and Health Program (PNNS). The guidelines for the adult population have been

45 extensively modified in 2017 and now emphasize the need for alignment between health and
46 environmental dimensions of the diet ¹⁶. Important modifications have been introduced in 2017 FBDG
47 compared to the 2001 FBDG. Briefly, legumes, red and processed meat have been individualized and
48 adequation cut-offs have been lowered for milk and dairy products, seafood and alcohol intake. Nut
49 intake has also been added and added fat now focused on alpha-linolenic acid rich oils (as canola and
50 walnut oil) and olive oil. Favoring consumption of organic plant foods is now advised as a
51 precautionary principle to limit exposure to pesticides. Of note, weights have been allocated to the
52 different components. To assess the health benefits for individuals to follow these recommendations,
53 we have previously developed and validated two *a priori* dietary indexes, reflecting the level of
54 adherence to the 2001 and 2017 national dietary guidelines, namely two versions of the PNNS-
55 guidelines scores (PNNS-GS1 and PNNS-GS2, respectively) ^{17,18}.

56 We evaluate the associations between various indicators reflecting the dimensions of diet
57 sustainability (nutrition, environment, economic and sanitary aspects) and long-term health impacts
58 (death avoided), and different levels of adherence to the 2017 FBDG. With regard to nutritional
59 aspects, the indicators encompassed the PANDiet score for overarching nutrient adequacy,
60 contribution of organic food to the intake, energy intake and energy density. The following indicators,
61 GHGE, cumulative energy demand, land occupation expressed environmental pressure while pReCiPe
62 expressed overall environmental impact. The cost of the diet as well as exposure to pesticides were
63 also included as economic and sanitary indicators. It should be noted that pressure indicators are
64 different from impact indicators, as they inform users on the pressure human activities place on
65 ecosystems (e.g., the land used to produce a crop) rather than on the potential consequences (impact)
66 due to such pressure ¹⁹. They quantify either resource use or pollution, or both. A second objective is
67 to compare these associations with those found when using the 2001 FBDG. To meet these objectives,
68 we conducted a multi-criteria analysis among a large sample of participants of the French NutriNet-
69 Santé cohort, based on nutritional, environmental, economic and toxicological indicators.

70 **Results**

71 The sample included 75.6% women and mean age was $49.9y \pm 15.9$. Means of PNNS-GS2 were 2.41
72 (SD=3.35) and 0.63 (SD=3.75) for women and men, respectively, while means of PNNS-GS1 were
73 8.27 (SD=1.86) and 8.31 (SD=1.62) for women and men, respectively.

74 **Sample characteristics.** Characteristics of the study population are presented in **Table 1**. Participants
75 with higher PNNS-GS2 (reflecting higher adherence to the 2017 FBDG) had more often higher
76 educational level and monthly household income than individuals with lower PNSS-GS2. They
77 exhibited more often high level of physical activity, a lower body mass index and were more likely to
78 be non-smokers and with a managerial staff or intellectual profession compared to individuals with
79 lower PNSS-GS2.

80 **Food consumptions.** Food group consumptions across quintiles (Q) of PNNS-GS2 are presented in
81 **Supplementary Table 1**. As expected by its construction, higher PNNS-GS2 was associated with
82 higher consumption of fruit and vegetables, legumes and whole grains but also soya-based food, and
83 lower consumption of seafood, meat, poultry, processed meat and dairy products, sweetened foods and
84 fast-food, alcoholic and non-alcoholic beverages and fats. For comparison, food group consumptions
85 across quintiles of PNNS-GS1 are shown in **Supplementary Table 2**.

86 The association between indicators of diet sustainability and adherence to 2001 and 2017 FBDG are
87 presented in **Supplementary Table 3** and relative difference are shown in **Figure 1**.

88 **Nutritional aspects.** The total weight of the diet, the proportion of organic food in the diet and the
89 PANDiet (reflecting the probability of adequacy to nutrient references) were positively associated with
90 the level of adherence, whatever the FBDG score studied. As expected by its construction, the increase
91 of the share of organic food in the diet between Q1 and Q5 was stronger for PNNS-GS2 than for
92 PNNS-GS1 quintiles. Lower energy intake and energy density were related to higher adherence to
93 both FBDG scores.

94 **Environmental aspects.** After adjustment for energy intake, lower diet-related environmental
95 pressure and impacts were associated with higher level of adherence for both scores (except energy
96 demand for the PNNS-GS1), however the decreases observed across quintiles were much greater with

97 PNNS-GS2. For the *pReCiPe* comprising GHGE, energy use and land occupation, a decrease of about
98 25% was observed for PNNS-GS1 and of 50% for PNNS-GS2.

99 **Economical aspects.** Finally, the cost of the diet was positively associated with PNNS-GS2 and
100 PNNS-GS1 but the magnitude of the increase between Q1 and Q5 was smaller for PNNS-GS2.
101 Differences between Q5 and Q1 were 0.91€/d and 1.29€/d for PNNS-GS2 and PNNS-GS1,
102 respectively.

103 Overall, larger differences between Q1 and Q5 for the studied indicators were observed for PNNS-
104 GS2 in comparison with PNNS-GS1 (**Figure 1**).

105 **Pesticides exposure aspects.** Correlations (factor loadings) between exposure to individual pesticides
106 and exposure profiles extracted by non-negative matrix factorization (NMF) are presented in
107 **Supplementary Table 4**. The first NMF-factor was highly positively correlated with exposure to
108 imazalil, profenofos and chlorpyriphos while the second one was positively correlated with exposure
109 to spinosad (mostly used in organic but also in conventional production). The third one was positively
110 correlated with exposure to acetamiprid, carbendazim, chlorpyriphos and dimethoate.

111 Relative difference in NMF-extracted scores between Q5 and Q1 for PNNS-GS1 and PNNS-GS2 are
112 graphically presented in **Figure 2**. Higher PNNS-GS2 was associated with lower scores for the first
113 and third NMF-extracted factors (relative differences Q5 vs. Q1<0). As regards the PNNS-GS1, a
114 positive association was observed with the first NMF-extracted factor (relative differences Q5 vs.
115 Q1>0) and no difference for the NMF-extracted factor 3 was detected. Higher PNNS-GS2 was
116 associated with higher NMF-extracted factor 2. A similar but less strong positive association was
117 observed for the PNNS-GS1.

118 **Health aspects.** Predicted numbers of death averted or delayed (overall and by causes) related to
119 higher PNNS-GS2, as compared to lower PNNS-GS2, and higher PNNS-GS1, are presented in
120 **Figures 3 and 4**. High adherence to 2017 FBDG led to 35,689 predicted averted premature deaths,
121 mostly cardiovascular diseases. When comparing high level (Q5) of PNNS-GS2 to high level of
122 PNNS-GS1, 3,408 deaths were averted or delayed, with some variations depending on the disease. The
123 diseases most affected were heart failure and hypertensive disease, bronchus tract and lung cancer. On

124 the other hand, a high compliance with the 2001 FBDG prevented an additional small number of
125 bronchus and lung cancers compared to high compliance with the 2017 FBDG.

126 **Discussion**

127 This study made it possible to examine the link between compliance with official French dietary
128 recommendations and sustainability through a wide range of indicators covering nutritional,
129 environmental, economic and health dimensions. Indeed, in this large cohort of French adults, we
130 observed that high adherence to the 2017 FBDG leads to a more sustainable diet than not following
131 the guidelines. Environmental pressure indicators related to dietary patterns were drastically lower
132 among participants with high (vs. low) adherence to the 2017 dietary guidelines. In addition, high
133 adherence to the 2017 FBDG leads to much more sustainability than high adherence to the 2001
134 recommendations. Overall, the number of averted or delayed deaths by adhering to 2017 was higher
135 than adhering to the 2001 FBDG. However, taking into consideration current market prices, higher
136 level of adherence to the 2017 FBDG diet was associated with higher diet cost. Interestingly, diet costs
137 of participants with high adherence to 2001 FBDG was higher than those of participants with high
138 adherence to 2017 FBDG.

139 These findings are important in terms of public health as they lend credence to the view that there are
140 co-benefits of aligning dietary recommendations for both health promotion and environment
141 preservation, in the urgent context of climate change. These results provide evidence that 2017 FBDG,
142 designed in line with sustainability considerations, effectively meet this objective.

143 **Nutritional indicators.** It should be noted that the association with the PANDiet, expressing the
144 overall adequacy to nutrient references, was very similar between PNNS-GS1 and PNNS-GS2 despite
145 the limitation of animal-product consumption in the 2017 FBDG. This indicates that the recent
146 modifications in dietary recommendations do not appear to affect the overall nutritional adequacy of
147 the diet also sub-score of components differed (**Supplementary Table 3**). It is also noteworthy that
148 adhering to the 2017 FBDG was negatively associated with energy intake and energy density which
149 are risk factors for obesity²⁰.

150 **Environmental.** Our findings could be interpreted in light of differences in dietary patterns across the
151 different levels of adherence to FBDG. Indeed, the 2017 FBDG promote low consumption of animal

152 products, including the moderation of dairy product consumption and limitation of red meat and
153 processed meat product intake. These lower intakes of animal-based products in Q5 are clearly
154 responsible for the much lower levels of dietary GHGE compared to Q1 ^{1,21}. Despite somewhat lower
155 yields in organic farming ^{22,23}, land occupation was lower for high vs. low adherence to these
156 guidelines. This can be explained by the more plant-based diet among participants following the 2017
157 FBDG. This association was negative, even after adjustment for energy intake. Lower GHGE and land
158 occupation were also related to higher PNNS-GS1, however, the magnitude of the decrease between
159 Q1 and Q5 was smaller for PNNS-GS1. In addition, due to the recommendation of lower pesticides
160 adherence, by including organic food, adherence to 2017 FBDG could also contribute to biodiversity
161 preservation ²⁴. Based on French representative dietary surveys ²⁵, and dietary data on our population
162 ²⁶, it can be postulated that dietary patterns of individuals in Q1 in our study population are close to
163 those of the general French population. In our study, we observed that reaching the highest adherence
164 to the 2017 FBDG (as observed in Q5) would imply a 50% reduction in global environmental impacts
165 (estimated by the pReCiPe) and specifically a 46% reduction in GHGE (when comparing Q5 to Q1)
166 but would require major changes in current French dietary patterns. In order to specifically focus on
167 differences in diet composition for fixed energy intake, the associations were estimated using energy
168 intake adjustment. Indeed, as a strong decrease in daily energy intake was observed across quintiles of
169 adherence, all links would have been driven by the role of energy intake. For instance, without energy
170 adjustment, relative differences between high and low adherence to 2017 FBDG (Q5 vs. Q1 of PNNS-
171 GS2) were -24.0% and -63.1% for dietary cost and GHGE respectively (**Supplementary Table 5**),
172 while they were +12.9% and -46.6% respectively for adjusted parameters.

173 **Economic.** As regards economic aspects, adhering to the 2017 FBDG was related to a higher cost,
174 after adjustment for energy intake. However, this increase was small (less than 1€/d). Healthier
175 products which are more expensive ²⁷ may explain the higher dietary monetary cost of adherence. In
176 addition, organic foods are generally more expensive than conventional foods, due to more extensive
177 practices, lower productivity, higher labor cost or higher farmer's income in organic production ²⁸. The
178 slightly increased cost, in an isocaloric diet, of the new food-based guidelines may be of concern for
179 the most deprived populations for whom food is already an important share of their income. exposure

180 **Exposure to pesticides.** Consumption of organic plant-food as promoted in the 2017 FBDG
181 contributed to a lower exposure to some pesticide residues whereas promoting fruit and vegetable
182 consumption without promoting organic food (2001 FBDG) would lead to a higher exposure. A lower
183 bound scenario was used, which tends to underestimate the exposure. However, this scenario was
184 selected considering that organic foods contain far lower synthetic pesticides residues compared with
185 conventional foods²⁹.

186 **Health.** We also showed, using the EpiDiet model, that high adherence to 2017 FBDG would lead to
187 an important predicted number of averted or delayed deaths (about 35,689 for year 2014). A large part
188 of the averted or delayed deaths were cardiovascular diseases. These results are consistent with the
189 current epidemiological scientific literature about dietary prevention of cardiovascular diseases and
190 cancer^{30,31}, indicating a beneficial role of dietary patterns rich in fruit and vegetables, nuts, whole-
191 grains and fish and a harmful role of red meat, processed meat and sugar-sweetened beverages. These
192 food groups have been specifically emphasized in the 2017 FBDG. Moreover, in line with our present
193 findings, we previously observed in two different French cohorts, that higher PNNS-GS (based on
194 2001 FBDG, and including physical activity) was prospectively inversely associated with
195 cardiovascular diseases and cancer risk³²⁻³⁴. The adherence to the 2017 FBDG, compared to the 2001
196 FBDG, allowed to prevent or delay a substantial number of deaths. It should also be born in mind that
197 number of deaths for some health events was underestimated by the EpiDiet model. This model indeed
198 only accounts for nutritional values of the diet. Indeed, specific other components, such as synthetic
199 pesticide residues or other contaminants such as heavy metals contained in fish are not taken into
200 account. An important component not considering in the model was pesticide exposure now accounted
201 for in the 2017 FBDG. Diet based on organic food has indeed been linked with a reduction in overall
202 cancer risk by our team³⁵ and in specific cancer site risk by others³⁶.

203 **Sustainability.** The potential agreement between healthy and environment-friendly diets has recently
204 been extensively documented^{1,5,11,37-40}. For instance, a modeling study concluded that changes toward
205 more plant-based diets (at least 5 portions/d of fruit and vegetables) would reduce overall mortality by
206 6 to 10% and GHGE from food production by 29 to 70% compared with a reference scenario, in 2050

207 ¹¹. Also Tilman and Clark, through a modeling study have estimated that following a plant-based diet
208 (vegetarian, pescetarian or Mediterranean diets) may reduce all-cause mortality rates from 0% to 18%
209 and GHGE from 30 to 55% ⁵.

210 Recently, a growing number of countries have integrated sustainability or environmental values in
211 their official dietary guidelines ^{41,42}. However, few observational studies, using a multi-criteria
212 approach, have documented the sustainable potential of following FBDGs also focusing on diet
213 sustainability. A recent study was conducted in Spain aiming to compare environmental values of
214 current diets, adherence to FBDG and other diet models, in particular the Mediterranean diet ⁴³. The
215 authors found that shifting current dietary patterns to diets in line with FBDG and Mediterranean diet
216 would lead to 17% and 11% reduction in GHGE, respectively. They also showed that food loss may
217 contribute to 21% of these emissions. Our findings are also consistent with those of a European
218 modelling study documenting co-benefits of meeting dietary recommendations for health and
219 environment ⁴⁴.

220 Some limitations of our work should be highlighted. First, food consumption data were self-reported
221 as no objective measurements to assess food consumption are available in large-scale population
222 studies. However, the methods used in dietary surveys have been validated and organic food
223 consumption assessed by the Org-FFQ has been previously found to be negatively associated with
224 certain pesticide residues in urine ⁴⁵ and positively with some nutritional biomarkers ⁴⁶. Second, the
225 NutriNet-Santé cohort included volunteers, who were probably more concerned by health and diet
226 than general population. While a weighting procedure was applied, a selection bias limiting
227 extrapolation to the general population may remain. Third, there is a lack of data on post-farm
228 environmental pressure for organic agriculture, thus Life Cycle Assessments were limited to farm
229 activities. Therefore, transportation and distribution through the food system were not accounted for in
230 the estimation of the environmental pressure. However, most environmental pressure of food generally
231 occur at the farm level ^{47,48}. Fourth, environmental pressures were assessed for a relatively limited
232 number of indicators. According to Kramer *et al* ⁴⁹, the three indicators included in the pReCiPe can
233 be considered sufficient for an acceptable representativeness of the overall environmental impact.
234 However, there are many more relevant indicators ¹⁹. For instance, in a recent study, Springman *et al*

235 used five of them ⁵⁰. In particular it would be very important to consider for water use which has been
236 previously included in a study conducted in the United Kingdom, France and Germany ⁵¹. In addition,
237 organic food consumption can be used as a proxy of biodiversity preservation ²⁴. Furthermore, as
238 regards exposure to pesticides, some key mineral-based pesticides (for instance copper or sulfur) used
239 in organic agriculture were not available. Finally, the EpiDiet was based on robust data from meta-
240 analysis limiting the parametrization of the model and only accounting for nutritional effect, and
241 morbidity was not accounted for.

242 Some elements should be emphasized. The large sample size covered a wide diversity of dietary
243 patterns. The wide spectrum of accurately collected data and the use of the EpiDiet model allowed to
244 cover a large variety of indicators related to sustainability, and to provide, for the first-time, a
245 thorough evaluation of the sustainability of the FBDG, while accounting for the farming system and
246 other indicators rarely considered. A major strength is also the observational design of our study, as it
247 illustrates that some segments of the population are actually able to closely follow the FBDG. Thus,
248 following the new FBDG may contribute to health improvement and environment preservation, if
249 largely adopted. However, there is still leeway insofar as the very high adherents exhibited only
250 suboptimal but not optimal diet.

251 In conclusion, the present study provided an estimate of the sustainable values of the 2017 French
252 FBDG, using available diet sustainability indicators. Adherence to this new FBDG aligns with
253 virtually all sustainability metrics, apart from a slight increase in cost which should be considered by
254 all stakeholders involved in nutrition, health and sustainability. These results therefore underline the
255 urgent need for the development of public health strategies allowing accessibility to healthy and
256 sustainable diets for all segments of the population. Adopted by a large part of the French population,
257 these 2017 dietary guidelines may highly contribute to preventing diet-related chronic diseases and
258 reduce environmental impacts, in particular by drastically reducing diet-related GHGE.

259 **Methods**

260 This study is based on data from the NutriNet-Santé study.

261 **Population.** The web-based prospective NutriNet-Santé a has been cohort initiated in France in May
262 2009 ⁵². Participants are adults internet users recruited on a voluntary basis from the general French

263 population. This study is conducted in accordance with the Declaration of Helsinki, and all procedures
264 were approved by the Institutional Review Board of the French Institute for Health and Medical
265 Research (IRB Inserm 0000388FWA00005831) and the National Commission on Informatics and
266 Liberty (Commission Nationale de l'Informatique et des Libertés, CNIL 908450 and 909216).
267 Electronic informed consent was obtained from all participants. The NutriNet-Santé study is registered
268 in ClinicalTrials.gov (NCT03335644).

269 **Dietary data.** At inclusion and yearly thereafter, participants completed self-administered
270 questionnaires inquiring about socioeconomic status, anthropometrics, lifestyle, physical activity, and
271 dietary intakes. They were also regularly invited to fill in complementary questionnaires. The present
272 study is based on data collected in the BioNutriNet project, an ancillary project developed within the
273 NutriNet-Santé cohort which has been extensively described elsewhere ²². Briefly, from June to
274 December 2014, a self-administered semi-quantitative organic food frequency questionnaire (Org-
275 FFQ), based on a validated FFQ ⁵³, was administered. The Org-FFQ includes questions on frequency
276 and quantity of food consumed over the last 12 months, completed by a five-point ordinal scale aiming
277 to measure the frequency of organic (under official label) food consumption for 264 items ⁵⁴.
278 Participants were asked to answer the following question for food items that exist in organic 'How
279 often was the product of organic origin?' using the following response modalities: never, rarely, half-
280 of-time, often or always. Organic food consumption was obtained by attributing the respective
281 percentages: 0, 25, 50, 75 and 100 to the modalities. Sensitivity analyses as regards the weighting have
282 been published elsewhere ⁵⁴. The food and beverage items were gathered into 16 food groups as listed
283 in **Supplementary Table 1**. Nutrient intake estimations were derived from a published food
284 composition database ⁵⁵ for generic items independently of the farming system (organic vs.
285 conventional).
286 Under-reporting and over-reporting participants were defined ⁵⁴ as individuals with ratio between
287 energy intake and energy requirement below or above cutoffs previously identified (<0.35 and >1.93
288 were excluded). Energy requirement was estimated using basal metabolic rate (BMR) and physical
289 activity level. BMR was estimated by Schofield equations ⁵⁶ depending on gender, age, weight and
290 height.

291 To assess the nutritional quality of participants' diet, a modified version of the validated PNNS-GS
292 (without physical activity) was computed, here named PNNS-GS1 for clarity purpose. This modified
293 score reflects the adherence to the official French nutritional recommendations set up in 2001 within
294 the framework of the PNNS⁵⁷. This score (theoretical range $-\infty$ to 13.5) includes 12 components: eight
295 refer to food-serving adequacy recommendations (fruit and vegetables; starchy foods; whole grain
296 products; dairy products; meat, eggs and fish; fish and seafood; vegetable fat; water vs. soda) and four
297 refer to moderation in consumption (added fat; salt; sweets; alcohol). Moreover, points are deducted
298 for overconsumption of salt, added sugars, or when energy intake exceeds the estimated energy needs
299 by more than 5%.

300 Recently, the PNNS-GS2 (The theoretical range was $-\infty$ to 14.25) has been developed based on the
301 2017 dietary guidelines and validated against sociodemographic and biological data¹⁸. Guidelines,
302 components, scoring, and weights of both scores are detailed in **Supplementary Table 6**. Penalties
303 were also applied to overconsumption. Cut-offs and scorings were built based on a consensus of
304 experts so as 1 and 0 points were allocated for meeting and not meeting a guideline for healthy foods
305 while 0 and -1 point were allocated for meeting and not meeting a guideline for unhealthy foods. In
306 addition, half-points were allocated linearly to improve discrimination power between cut-offs. An
307 exception concerned milk and dairy products as well as fish for which the relationship to global health
308 has been found non-linear, hence a parabolic-shaped relationship in allocated points.

309 Another holistic nutritional indicator (PANDiet) reflecting the overall probability of nutrient adequacy
310 was computed, as previously published in full details⁵⁸ to focus on nutrients intakes beyond food
311 consumption. Briefly, this score is the mean of an adequacy score (which averages the probabilities of
312 adequacy for 27 nutrients) and a moderation score involving six nutrients and twelve potential penalty
313 values that combine probabilities of exceeding upper limits of intakes.

314 **Environmental pressure indicators.** Assessment of environmental pressure indicators in the
315 BioNutriNet project has been fully described elsewhere⁵⁹. Briefly, three environmental pressure
316 indicators were considered at the farm level (excluding conditioning, transport, processing, storage or
317 recycling stages): the GHGE measured as kg of CO₂ equivalents (CO₂eq), the cumulative energy

318 demand in MJ, and the land occupation expressed in m². Data were collected from the tool
 319 DIALECTE developed by Solagro (Toulouse, France) ⁶⁰. The DIALECTE database aims to depict
 320 French farming systems in order to evaluate the environmental performance of farms base on >60 raw
 321 products. The original database has been completed by other data sources that have been previously
 322 listed ⁵⁹, to obtain the environmental pressure in organic and conventional for 92 raw agricultural
 323 products covering the 264 food items. A set of conversions was used to estimate environmental
 324 pressure to produce food items as consumed by applying economic allocation (accounting for co-
 325 products) and cooking and edibility coefficients.

326 Dietary environmental impacts per day, at the individual level, were computed by multiplying the
 327 daily consumption of each food item by its respective environmental and conversion factor values, and
 328 then summing up all items consumed, while differentiating the farming system (conventional or
 329 organic).

330 To consider trade-offs and conflicts between environmental indicators, the ReCiPe method was
 331 previously developed. This method initially developed in the Netherlands consider the alignment of
 332 midpoint-oriented and endpoint-oriented indicators ⁶¹. In practice, some authors showed that the
 333 greenhouse gas emissions, primary energy consumption and land occupation account for
 334 approximately 90% of the total environmental dimension of the ReCiPe allowing to define the partial
 335 ReCiPe score (pReCiPe) for environmental impact assessment of food product and diet ⁴⁹.

336 The pReCiPe, indicator of environmental impact, was calculated for each individual:

$$337 \quad p\text{ReCiPe} = [0.0459 * \text{GHGE} + 0.0025 * \text{CED} + 0.0439 * \text{LO}]$$

338 Where GHGe is greenhouse gas emissions, in kgCO₂ eq/kg, CED is cumulative energy demand, in
 339 MJ/kg and LO is land occupation, in m²/kg. By construction, the highest the pReCiPe is the highest is
 340 the environmental impact.

341 **Economic data.** In 2014, places of food purchase for all food groups were collected by a specific
 342 web-based questionnaire. Food prices for each of the 264-FFQ items (organic and conventional) for
 343 each place of purchase were estimated by the mean price values obtained from the 2012 Kantar
 344 Worldpanel purchase database from a representative sample of 20,000 French households ⁶². The

345 database was completed by supplementary data on prices collected by the Bioconsom'acteurs
346 association to take into account specific short supply chains.

347 The individual daily diet monetary cost (€/d) was computed by multiplying each intake of foods by the
348 corresponding prices, while accounting for the farming system and the place of purchase, and by then
349 summing up all daily consumed items.

350 **Pesticide exposure.** Exposure to diet-related pesticides, i.e. residues of plant protection product (PPP),
351 was evaluated through the estimation of dietary exposure through plant food items (since they are the
352 most contaminated foods ²⁹). A total of 15 active substances authorized in the EU for PPP at the date
353 of data collection were selected, considering either their frequency of detection above the Maximum
354 Residue Levels, when sufficient data were available, or their Acceptable Daily Intake. Contamination
355 data were obtained from the CVUA Stuttgart (Chemisches und Veterinäruntersuchungsamt) database
356 for 180 plant ingredients constituting of the 264 food items and available in the CVUA database ⁶³.
357 For each active substance, the estimated daily intake (EDI) (in µg/kg body weight/d) was calculated
358 under a lower bound scenario, using the reference method described by Nougadère et al. ⁶⁴. EDI was
359 used to identify pesticide dietary-exposure profiles, as previously described by Traoré et al. ⁶⁵, using
360 NMF ⁶⁶ (**Supplementary Method 1**). This method aims to identify profiles combining the original
361 variables, namely exposure to several pesticides, with a score value for each participant.

362 **Sample selection.** For the present study, we considered the participants of the NutriNet-Santé study
363 having completed the Org-FFQ between June and December 2014 (N=37,685), with no missing
364 covariates (N=37,305), not detected as under- or over-energy reporter (N=35,196), living in mainland
365 France to permit the computation of a weighting procedure described below (N=34,453), and with
366 available data regarding the place of purchase for the computation of the dietary monetary cost,
367 leading to a final sample of 28,340 participants.

368 **Statistical Analyses.** To improve representativeness of the sample compared to the overall French
369 population, the study sample was weighted. For each gender, weighting was calculated using the
370 iterative proportional fitting procedure using 2009 French national census reports ⁶⁷ for age,
371 occupational category, educational level, area of residence and presence of children (<18 years) and
372 marital status. Participants were ranked and categorized into sex-specific weighted quintiles of dietary

373 indexes reflecting the level of adherence to 2001 and 2017 food-based dietary guidelines, using the
374 PNNS-GS1 and PNNS-GS2. Associations between food group consumption, nutritional indicators,
375 environmental impact indicators, dietary costs and pesticide residue exposure, and quintiles of PNNS-
376 GSs were modeled with ANCOVA using observed margins and adjusted for energy intake (unless
377 specified otherwise), providing adjusted means and 95% confidence intervals. The list and details of
378 the sustainability indicators are presented in **Supplementary Table 7**. Multiple testing was
379 accounted for by Tukey adjustment. P-values refer to P-trends estimated using linear contrasts. We
380 used EpiDiet (Evaluate the Potential Impact of a Diet) model to evaluate the health benefits of the
381 2017 FBDG. EpiDiet is a simulation-based nutritional and epidemiologic model implementing the
382 Comparative Risk Assessment framework. Like many other simulation-based risk assessment models
383 ^{68,69}, it quantifies the positive or negative changes in risk related to long term health that would result
384 from changes in the average diet for an individual, groups or population. In this study, we took as
385 baseline and counterfactual situations the extreme quintiles (Q1, Q5) of PNNS-GS2, or the Q5s of
386 PNNS-GS1 and PNNS-GS2, and estimated the health impact of changes in dietary and nutrients
387 intake. Details of the EpiDiet model and its application are presented in **Supplementary Method 2**.
388 The relative risks were obtained from data published for the PRIME model ⁶⁸ and a recent meta-
389 analysis ⁷⁰. Two-sided tests were used and a p-value<0.05 was considered significant. Data
390 management and statistical analyses were performed using SAS (version 9.4; SAS Institute, Inc., Cary,
391 NC, USA). NMF was performed using the NMF R-package ⁷¹.

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

403 EKG, BA, MT, CJ and SH conducted the study.

404 EKG, PP, BL, RV, DL, and JB conducted the research and implemented databases.

405 JW and FM conducted the EPIDiet simulation

406 EKG performed statistical analyses and drafted the manuscript.

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

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

410 **Conflict of Interest**

411 No author declared conflict of interest.

412 **Transparency statement**

413 Dr Kesse-Guyot (the guarantor) affirms that the manuscript is an honest, accurate, and
414 transparent account of the study being reported; that no important aspects of the study have
415 been omitted; and that any discrepancies from the study as planned have been explained.

416 **Data availability statement:** Data can be retrieved from the corresponding author upon
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418 **Code availability statement:** Code and programs can be retrieved from the corresponding
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- 613

614 **Table 1: Participant characteristics across sex-specific quintiles of PNNS-GS2, n=28,340,**
 615 **NutriNet-Santé, 2014¹**

	All	Q1	Q2	Q3	Q4	Q5
Non-weighted N	28,340	4937	5550	5737	5973	6143
Cut-off in women		-0.22<	-0.22-1.86	1.86-3.53	3.53-5.34	>5.34
Cut-off in men		<-2.52	-0.252.52	-0.25-1.72	1.72-3.98	>3.98
Age, y	49.9 ± 15.9	48.1 ± 0.2	49.4 ± 0.2	50.1 ± 0.2	50.9 ± 0.2	51.0 ± 0.2
Education (%)						
< High-school diploma	44.3	47.3	43.3	42.9	43.9	44.3
High school diploma	19.0	20.6	19.4	18.6	18.1	18.4
Postgraduate	36.6	32.2	37.3	38.5	37.9	37.3
Occupation (%)						
Unemployed	4.7	4.8	4.5	4.7	4.7	4.9
Retired	31.7	27.2	31.2	32.4	33.6	34.3
Employee, manual worker	22.7	29.3	24.3	20.4	20.2	19.2
Intermediate profession	16.5	16.2	16.7	18.1	16.3	15.1
Managerial staff and intellectual profession	12.2	9.4	11.4	12.7	14.1	13.4
Never employed	9.5	10.4	9.4	9.0	9.0	9.8
Self-employed, farmer	2.6	2.8	2.3	2.8	2.1	3.2
Monthly income (%)						
Unwilling to answer	7.2	6.5	7.2	7.2	7.3	7.6
< 1,200€	17.8	22.2	17.5	15.7	15.4	18.1
1,200-1,800€	28.4	31.1	30.3	29.3	26.3	25.1
1,800-2,700€	26.7	24.4	26.2	26.8	28.8	27.4
> 2,700€	19.9	15.8	18.8	21.0	22.2	21.8
Physical activity level (%)						
Missing data	12.3	13.1	13.2	12.3	11.8	11.2
Low	19.9	24.7	22.0	20.4	18.8	13.8
Moderate	34.6	32.2	33.0	35.4	34.8	37.4
High	33.2	30.0	31.8	31.9	34.7	37.6
Tobacco status (%)						
Never smoker	51.0	44.4	51.3	52.9	52.6	53.9
Former smoker	37.1	39.2	36.7	35.0	37.9	36.9
Current smoker	11.8	16.4	12.0	12.1	9.5	9.2
Body mass index (kg/m²)	24.16 ± 4.59	25.61 ± 0.06	24.79 ± 0.06	24.19 ± 0.06	23.89 ± 0.06	23.18 ± 0.06

616 Abbreviations: Q= Quintile

617 ¹All values presented are weighted data. Values are means ± SD or percent, as appropriate. P-values are based on
 618 linear contrast test for continuous variables or chi-square test for, all P-values<0.0001
 619 categorical variables

620 **Figure 1: Relative differences for sustainable indicators between high vs. low adherence (Q5 vs.**
621 **Q1) to PNNS-GS1 and PNNS-GS2^{1,2}**

622 Abbreviations: D = relative difference as $(Q5-Q1) * 100/Q1$; Q = Quintile

623 ¹Values are adjusted for energy intake (except daily kcal intake).

624 ²% for diet cost, pReCiPe, Land occupation, GHGE, energy demand, energy density and energy intake are
625 reversed so that a positive value (> reference=0 in red) indicates a positive impact

626

627 **Figure 2: Relative differences for dietary exposure to pesticides between high vs. low adherence**
628 **(Q5 vs. Q1) to PNNS-GS1 and PNNS-GS2**

629 Abbreviations: D = relative difference as $(Q5-Q1) * 100/Q1$; Q = Quintile

630

631 **Figure 3: Estimated number of deaths averted or delayed (year 2014) using the EpiDiet**
632 **comparing high vs. low adherence to 2017 dietary guidelines, n=28,340, NutriNet-Santé, 2014¹**

633 ¹ Values are estimated numbers (95% uncertainty interval based on parameters model uncertainty) for diseases
634 classified according the International Statistical Classification of Diseases and Related Health Problems 10th
635 Revision.

636

637 **Figure 4: Estimated number of deaths averted or delayed (year 2014) using the EpiDiet**
638 **comparing high adherence to 2017 dietary guidelines vs. high adherence to 2001 dietary**
639 **guidelines, n=28,340, NutriNet-Santé, 2014¹**

640 ¹ Values are estimated numbers (95% uncertainty interval based on parameters model uncertainty) for diseases
641 classified according the International Statistical Classification of Diseases and Related Health Problems 10th
642 Revision.