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1 *Conservative to disruptive diets for optimizing nutrition, environmental impacts and cost in*
2 *French adults from the NutriNet-Santé cohort*

3
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25 **Abstract**

26 Improving sustainability of diets requires the identification of diets that meet nutritional
27 requirements of populations, promote health, are within planetary boundaries, affordable and
28 acceptable. Here, we explore the extent to which dimensions of sustainability could be
29 optimally aligned and identify more sustainable dietary solutions, from the most conservative
30 to the most disruptive among 12,166 participants of the NutriNet-Santé cohort. We aim to
31 concomitantly lower environmental impacts (including greenhouse gas emissions, cumulative
32 energy demand and land occupation), and increase organic food consumption, and study
33 departure from observed diet (considered as a proxy for acceptability).

34 From the most conservative to the most disruptive scenario, optimized diets were gradually,
35 richer in fruits, vegetables, and soya-based products and markedly poorer in animal-based
36 foods and fatty and sweet foods. The contribution of animal protein to total protein intake
37 gradually decreased by 12% to 70% of the observed value. The greenhouse gas emissions
38 from the food production for the diets gradually decreased across scenarios (% of observed
39 values) by 36% to 86%, land occupation for food production by 32% to 78%, and energy
40 demand by 28% to 72%. Our results offer a benchmark of scenarios of graded diet changes
41 against graded sustainability improvements.

42 **Introduction**

43 In high-income countries, rebalancing diets in favour of plant food is considered a major route
44 to improve the sustainability of food systems ¹⁻⁵. The EAT-Lancet commission concluded that
45 a drastic reduction of red meat consumption, to less than 28 g.d⁻¹, is required to improve the
46 sustainability of diet ⁴. High intakes of animal-based food have been identified as contributing
47 to greenhouse gas emissions, a threat to planetary boundaries ^{5,6} and a risk factor for chronic
48 diseases ^{1,2,5}.

49 There have been attempts to model future sustainable diets with mathematical diet
50 optimization techniques, taking environmental, nutritional, economic and food habit metrics
51 into account ⁷⁻⁹.

52 In almost all previous modelling studies, the environmental impacts of diet have been
53 considered as constraints rather than objectives in the optimization model, *e.g.*, by limiting the
54 final level of greenhouse gas emissions required to maintain global warming below 2°C or
55 gradual reduction of the environmental impacts of diet production ⁷⁻⁹. We are aware of only
56 one such study that tried to minimize three environmental indicators (greenhouse gas
57 emissions (GHGe), water use and land occupation) and monetary cost ¹⁰.

58 Finally, in these modelling studies, the impact of diets on toxicological and ecotoxicological
59 exposure is rarely considered ¹¹. Differences in environmental impacts of diets composed of
60 conventionally grown foods compared to organic ones have been shown, in particular with
61 respect to soil quality and biodiversity ¹²⁻¹⁸ and so, the food production method should be
62 introduced in optimization models as an alternative to intensive farming practices.

63 In general, previous studies have addressed the optimization problem at the level of average
64 diets for the entire population or some of its subgroups ⁷. The inter-individual variability in
65 diet composition, however, would enable greater assessment of the robustness of solutions
66 identified; for example, optimized diets could vary according to the proportion of plant-based
67 foods in the initial diet.

68 Here, we identify and compare the dietary changes needed to achieve a nutritionally adequate
69 and economically acceptable diet with lower diet-related environmental impacts and higher
70 organic food contributions. We used individual-based multi-criteria optimization in a large
71 sample of adult participants. To explore the departures from usual diets that are required, we
72 consider scenarios offering graded levels of suboptimal values for sustainability criteria
73 encompassing nutritional and environmental (using the pReCiPe, a synthetic indicator
74 summarizing three indicators GHGe, land occupation and energy demand) characteristics.
75 Nutritional characteristics of the diets were described using the PANDiet score (a score

76 reflecting the probability to reach nutritional references)¹⁹. To better identify the required
77 changes for dietary habits, we presented the optimized diets according to the level of plant-
78 foods in the baseline diet.

79

80 **Results**

81 *Individual characteristics*

82 We performed the optimization process on a sample composed of 12,308 participants from
83 the NutriNet-Santé cohort. No solution was found by the model for 142 participants. The final
84 sample, composed of 12,166 participants, were likely to be older, with a higher income, living
85 with a partner and without obesity compared to the sample of participants included in the
86 NutriNet-Santé cohort in 2014 (**Supplemental Table 1**). This population included more often
87 female and highly educated people than the general population²⁰. **Table 1** presents the socio-
88 economic and lifestyle characteristics of participants for which optimization succeeded by
89 tertiles of provegetarian score (a score reflecting the preference for plant-based foods without
90 total exclusion of animal food).

91 We found significant differences between tertiles for most of the characteristics tested, except
92 for the proportion of women and income categories. Participants with higher provegetarian
93 score were more likely to be more highly educated, physically active, non-smokers, and
94 moderate or non-drinkers.

95

96 *Intermediate optimization steps and the extent of potential improvements*

97 The characteristics of the observed and optimized diets after the steps 0 (closest diet to the
98 observed diet meeting the nutritional needs), 1 (diet inducing the lowest environmental impact
99 while satisfying nutritional and price constraints) and 2 (diet inducing the highest
100 consumption of organic foods while satisfying nutritional and price constraints, for different
101 scenarios of concomitant reduction in environmental impacts) are shown in **Supplemental**
102 **Figure 1, Supplemental Figure 2 and Supplemental Table 2**.

103 After step 0, the monetary cost of the diet meeting nutritional needs was higher than the
104 monetary costs of the observed diet for 2,711 participants (22.2% of the sample). For these
105 2,711 participants, the maximum monetary cost imposed during the following steps was set to
106 the price obtained in this step 0.

107 After step 1 aiming to estimate the maximum improvement of the environmental impacts of
108 the diet production (E, based on the pReCiPe) without any consideration of organic food

109 intake (O) and diet departure (D), we observed that E could be reduced by as much as 90%,
110 regardless of the baseline provegetarian score.

111 After step 2 aiming to estimate the maximal improvement in O, without any consideration of
112 D, we obtained distinct solutions according to considered scenario of concomitant
113 improvement in E (value of the parameter p%, imposing an E improvement of at least p% of
114 its maximal improvement determined in step 1), but with diets being always composed almost
115 exclusively of organic foods regardless of the p% scenario.

116

117 *Final multi-optimized and acceptable diets*

118 At the end of the optimization process (step 3), we obtained different diet solutions for each of
119 the five considered p% scenarios of combined improvements in E and O, which were
120 constrained to be at least p% of their maximal improvements determined in step 2. The
121 changes in nutrient adequacy (PANDiet), monetary cost, energy density, organic food
122 contribution (O in % of dietary intake), environmental impact (E based on pReCiPe) and
123 animal protein contribution (% of animal in total protein intake) from the observed diet to the
124 optimized diets issued from the five scenarios are presented in **Figure 1** by provegetarian
125 score tertile, and these data are further detailed in **Supplemental Table 3**. The mean
126 population values for the relative variations between optimized and observed diets in the
127 environmental and nutritional indicators are summarized in **Table 2**. From the most
128 conservative (p=25%) to the most disruptive (p=90%) scenario, we observed gradual
129 improvements towards environmentally-friendlier and nutritionally adequate diets, while the
130 monetary cost varied little. Among scenarios of progressive disruption, the environmental
131 impacts (pReCiPe) thus gradually decreased by 33% to 80% while the nutritional adequacy
132 (PANDiet) gradually increased from 16% to 28% of the initial observed values. The adequacy
133 probabilities for the main nutrients (PANDiet subscores) are further detailed in the
134 **Supplemental Table 4**. It is noteworthy that, as expected, most probabilities were close to 1,
135 except for a few whose reference values differed from the constraint being set in **Table 3**. For
136 most indicators, the more conservative (less disruptive) the scenario, the greater the
137 differences between tertiles of provegetarian score.

138 As for the dietary patterns represented in **Figure 2**, the contributions of fruit, vegetables (in
139 particular orange vegetables), starchy foods and soya progressively increased from the most
140 conservative to the most disruptive scenarios, whereas the consumption of meat, dairy
141 products, eggs, mixed dishes, fatty and sweetened or salted foods progressively decreased.
142 The contribution of nuts and legumes increased in the most conservative scenario (25%) but

143 decreased thereafter in the more disruptive scenarios (and notably from p=70%) in favour of
144 further increases in fruit, vegetables and soya. The differences in the structure of diets across
145 tertiles gradually decreased as p increased and were only minor in the most disruptive
146 scenario (p=90%). Finally, changes in food group consumption over scenarios were similar
147 across the different tertiles of provegetarian score, except for fish, whose consumption
148 increased over scenarios only for consumers of fish in the third tertile.
149 Consumption data (g/d) by food groups and scenario for observed, step 2 and step 3 diets per
150 tertile of Provegetarian score are presented in **Supplemental Table 5**.

151

152 *Tensions between environmental impacts and organic consumption*

153 **Figure 3** illustrates the variations in environmental impact (pReCiPe) and organic food
154 contribution (%Org) through the different scenarios. From the observed diet to the most
155 disruptive scenario, as pReCiPe progressively decreased, %Org progressively increased until
156 reaching an inflection point for a pReCiPe of ~0.3, from which %Org stabilized around 95%
157 or even slightly decreased. This inflection point showed a conflict between further reducing
158 pReCiPe (below 0.3) and further increasing %Org (above 95%) at fixed monetary cost once a
159 very low pReCiPe has been achieved.

160

161 **Discussion**

162 This diet optimization study conducted at individual level in a large French sample of adults
163 has identified affordable and nutritionally adequate diets with reduced environmental impacts
164 (pReCiPe) and increased organic food content (%Org), and we graded those diets against
165 thresholds of improvements in these sustainability criteria.

166 From conservative to disruptive scenarios, the changes in food group consumption were
167 progressive. By improving the sustainability (encompassing nutritional, environmental, and
168 economic characteristics) of diets, the progressive substitution of animal products by plant
169 products observed in our work was in line with the results of other optimization studies in
170 high income countries⁹. It would be interesting to compare our solutions with regard to the
171 context and evolution of agricultural sectors in countries like France. For example, our
172 solutions to reduce environmental impacts are characterised by an increase in soya-based
173 products. In the case of imported soya, the transportation phase may lead to counterproductive
174 effects. However, this was not assessed in our study as we considered impacts at the
175 production level only. In addition, their nutritional profile could be advantageous for
176 optimization. For instance, the risks or benefits of high isoflavone consumption from soya

177 have not been assessed. In addition, a number of other legume or nut-based foods were not
178 included (not detailed in the FFQ) in the items considered in the optimization. However,
179 given the ongoing trend to eat more plant protein, the food supply of products rich in plant
180 proteins increases and diversifies so that presumably the place of soya-based foods could be
181 less important in the future than it was at the time when the dietary data were collected in the
182 present study (2014). Along the same line, the solutions obtained revealed a high proportion
183 of organic food. This is in line with the latest French national nutrition and health program, in
184 which it is recommended to increase organic food consumption, if possible. Nevertheless,
185 today the French organic food sector does not meet this societal demand ^{12,21} and this mode of
186 production would need to be expanded to make our prospective scenarios valid. In addition,
187 for the moment, the use of green manure without use for livestock is still very scarce in
188 France. However, the potential development of organic farming and plant-based diets will
189 induce crucial nitrogen needs and this should be considered in the future as the nitrogen from
190 manure or slurry (allowed in organic farming) will be probably insufficient. Finally, ruminant
191 meat consumption was removed from most solutions of disruptive scenarios while dairy
192 product consumption was only reduced compared to observed diets. It would be relevant to
193 assess whether the livestock required to produce this quantity of dairy products is in line with
194 the consumption levels of ruminant meat in each of the scenarios. Some authors have
195 attempted to consider the co-products in their optimization models ²², and indeed reported a
196 lower reduction of the consumption of ruminant meats, but with an extent that strongly
197 depended on the coefficient used to link milk production to meat production. In addition, such
198 a co-product approach makes sense at the population level but not at the individual level.
199 Indeed, it does not seem necessary that each participant's ruminant consumption complies
200 with her/his dairy product consumption as long as the co-products are balanced at the
201 population level. Finally, we observed that fish and seafood consumption decreased on
202 average for the participants of the first two tertiles, notably because of the introduction of
203 constraints. Our objective for adding constraints on fish was to take into account the depletion
204 of fish stocks and the acknowledged toxicological risks related to over-consumption of
205 seafood products. Nevertheless, we can see that with these solutions the nutritional needs for
206 eicosapentenoic acid and docosahexaenoic acid were not covered by the diets. It would be
207 necessary to consider the introduction of other foods that are sources of these nutrients, such
208 as marine oils.

209 The optimized diets generated under our scenarios were in line with observed diets identified
210 as more sustainable or proposed by others scenarios in previous studies ¹⁻⁴. Indeed, they are

211 more plant-based with few fat and sweet foods. Previous results showed that this kind of diet
212 is associated with improved health conditions ^{4,23–26}. However, plant-based diets (100%) may
213 have consequences on nutritional status. On the one hand, the bioavailability of some
214 nutrients (iron, zinc, vitamin A) is jeopardized in plant-based diets due, for instance, to phytic
215 acid. On the other hand, meat and meat products play an important role in bioavailable intakes
216 of protein, iron, zinc and vitamin (A and B12) ²⁷. Consequently, it is important to consider
217 that a shift towards highly plant-based diets may prevent nutritional requirements from being
218 met, although some food synergies may help the absorption ²⁸. In our study, nutritional quality
219 was assessed by the PANDiet which considers bioavailable zinc and iron in its calculation.
220 Although for some nutrients, quality may be impaired, overall, the PANDiet score is
221 progressively improved in scenarios with increasing plant food content. It however reaches a
222 plateau in the most disruptive scenarios, illustrating that nutritional gain becomes low.
223 Moreover, given that the nutritional constraints are fixed, meat, especially from ruminants, is
224 not totally eliminated. Of note, we have not been able to conduct a specific analysis on the
225 individual amino acids as they are not available in our database.

226 We should acknowledge some limitations of the present study. Firstly, we conducted our
227 analyses on diets from volunteers involved in a long-term cohort focusing on nutrition and
228 health. Indeed, the NutriNet-Santé participants are more often women, highly educated and
229 exhibit healthier behaviours compared to the French population ^{20,29}. This may have led to an
230 over-representation of sustainable dietary patterns (rich in vegetables, fruits, whole-grains,
231 legumes and nuts) compared to the general population. Thus, our diet solutions are applicable
232 only to diets similar to those of this sample, and it would be necessary to question our results
233 before their generalization or application even if we have worked on a large number of people
234 with different dietary patterns. Then, environmental indicators were available for organic food
235 only at the production stage. Thus, we used production-related impacts for GHGe, energy and
236 land occupation which may have led to an underestimation of overall impact. This limitation
237 is relative since most of the impacts occur during the production phase ³⁰. Given that data for
238 organic food are scarce, we were able to consider only three environmental indicators. The
239 three indicators included in the pReCiPe can be considered sufficient for an acceptable
240 representativeness of the overall environmental impact ³¹. For some usual foods (*e.g.* tea,
241 etc.), no pReCiPe values were available. We therefore excluded these items in the modelling
242 procedure. In addition, the plant-based meat substitutes that young generation of vegetarians
243 are often fond of ³² may be less environmental friendly ³ than crude plant-based foods and
244 may also depend on the farming system. Moreover, our diet solutions were driven by our

245 methodological approach including definition of the objective functions, constraints, scenarios
246 and process. However, we elected to perform 5 scenarios to propose solutions according to
247 the extent of the changes to be made. We also assumed, as in most diet optimization studies ⁷,
248 that the most acceptable diets are the closest to the observed diets, but this remains simplistic
249 at a time where the eating habits change very quickly. In addition, we worked with ~200
250 generic items representing sub-categories, which was a modest sample compared to the
251 variety of French food offer in terms of food items, but this was in the range of numbers used
252 in other optimization studies. Food-consumption data were self-reported and the use of 5-
253 points ordinal scale may have probably led to overestimation of the actual organic food
254 consumption. However, these data derived from a validated food frequency questionnaire that
255 had shown relative validity and reproducibility ³³. Finally, due to vast gaps in the field, we did
256 not distinguish the food composition according to the model of production (conventional vs.
257 organic), place of purchase or seasonality.

258 In conclusion, for the first time, this study identified at the individual level the existence of
259 sustainable diets that notably comply with a large set of environmental metrics (including
260 GHGEs, energy demand and land occupation) and economical and nutritional criteria, and
261 with high organic food content in a large French adult sample. This exploratory study also
262 offers five scenarios that are graded according to the underlying disruption of the food system,
263 on the one hand, and, on the other hand, the efficiency for meeting the environmental
264 challenges.

265 Our study provides important features concerning the composition of sustainable diets, based
266 on a multi-criteria sustainability approach, under nutritional constraints, and at controlled
267 cost. Our work illustrates the compatibility of various dimensions. This work could contribute
268 to the development of recommendations for sustainable diets. Importantly, the more the
269 impacts are reduced, the more the diets deviate from the initial intakes. All possible levers
270 must be used so as to increase food knowledge of the population regarding sustainable issues.
271 It is, however, important to bear in mind that even small changes on a large scale can lead to
272 significant reductions in impacts.

273 **Materials and Methods**

274 *Study population*

275 The study population was composed of adult volunteers from the prospective NutriNet-Santé
276 cohort, which was launched in May 2009 in France ³⁴. At initiation of the cohort and yearly
277 thereafter, participants completed a baseline set of self-administered questionnaires regarding
278 their dietary intake, socio-economic, anthropometric, health status, and lifestyle

279 characteristics. Participants were also regularly invited to complete complementary
280 questionnaires. This study was conducted in accordance with the Declaration of Helsinki, and
281 all procedures were approved by the Institutional Review Board of the French Institute for
282 Health and Medical Research (IRB Inserm 0000388FWA00005831) and the Commission
283 Nationale de l'Informatique et des Libertés (CNIL 908,450 and 909,216). Electronic informed
284 consent was obtained from all participants. The NutriNet-Santé study was registered in
285 ClinicalTrials.gov (NCT03335644).

286

287 *Assessment of Dietary Data*

288 From June to December 2014, participants were asked to fill in a self-administered semi-
289 quantitative organic food-frequency questionnaire (Org-FFQ) based on a validated FFQ³³.
290 The development and sensitivity analyses of the Org-FFQ have been published elsewhere³⁵.
291 Briefly, the Org-FFQ collected information on consumption frequencies (yearly, monthly,
292 weekly, and daily units) and portion sizes for 264 items over a year. We estimated the total
293 food intake by multiplying the portion size and the consumption frequency for each item. A 5-
294 point ordinal scale (never, rarely, half of the time, often and always) was added to measure the
295 frequency of organic food consumption for 257 food and beverage items produced under the
296 organic label. We obtained the organic share for the 257 food items by attributing the
297 respective percentages: 0, 25, 50, 75 and 1, to the modalities. We evaluated the share of
298 organic food to the diet by dividing the total organic food intake (g/day) by the total food
299 intake (g/day) excluding water.

300 We used the NutriNet-Santé food composition database³⁶ to estimate daily nutrient intake
301 from the diets, regardless of the food production method (organic vs. conventional) due to
302 gaps in the field limiting the coverage of the whole diet. In addition, much of the scientific
303 literature on the topic has underlined that some factors such as weather conditions, crop
304 species, soil type, location, livestock nutrition could prevail over organic vs. conventional
305 practices³⁷. Finally, to assess the nutritional quality of diet, we computed the updated version
306 considering the 2016 ANSES (French National Health Security Agency for food, environment
307 and workplace) guidelines of nutrient-based probability of adequate nutrient intake diet,
308 named PANDiet^{19,38}. It is composed of two subscores: an adequacy composed of nutrients for
309 which intake should be above a reference value and a moderation score for items for which
310 the usual intake should not exceed a reference value.

311 The provegetarian score is a dietary index reflecting the proportion of plant-based food
312 consumed in a diet³⁹. It has been previously developed and adapted in the NutriNet-Santé

313 cohort^{40,41}. We adjusted the consumption (g/d) of 5 animal food groups (eggs, fish, dairy
314 products, meat and added animal fats) and 7 vegetable food groups (fruit, vegetables, nuts,
315 cereals, potatoes, legumes and olive oil) for the total energy intake by using the residual
316 method, separately for men and women. For each plant component, we allocated 1 to 5 points
317 to energy-adjusted sex-specific quintile values. For animal food groups, the quintile values
318 were reversed (from 5 for the first quintile to 1 for the fifth quintile). We obtained the final
319 provegetarian score (range: 12-60 points) by summing the points of vegetable and animal
320 food groups.

321

322 ***Price database and computation of the monetary cost of diet***

323 We assigned a price to each food item considering the mode of food production (organic vs.
324 conventional) as well as and the place of purchase using the 2012 Kantar Worldpanel
325 purchase database and a price database obtained through price collections carried out by
326 members of Bioconsom'acteurs for prices in short supply chains⁴².

327 The main place of food purchase was assessed for 12 food groups gathering 264 items using a
328 secondary questionnaire concomitant with the Org-FFQ. This information was used to assess
329 the individual daily monetary cost of the diet by multiplying the quantities consumed (g/d) by
330 the corresponding item prices (€/g), while accounting for the place of food purchase and the
331 mode of food production.

332

333 ***Environmental impact database and computation of the environmental impacts***

334 The method used to assess the environmental impacts related to raw products as well as the
335 sources of data used have been extensively described in Seconda et al.⁴³. Briefly, we
336 considered three environmental indicators measured per kg of each item: the GHGEs,
337 including carbon dioxide, methane and nitrous oxide emissions, measured as kg of CO₂
338 equivalent by the global warming potential for a 100-year time horizon, the cumulative
339 energy demand in MJ and the land occupation expressed in m² and defined as the area
340 required to produce raw agricultural products without considering the duration of land use
341 Environmental indicators were estimated using standardized procedures for LCA computation
342⁴⁴⁻⁴⁸. The DIALECTE database, comprising 2,000 French farms, half of which are organic,
343 was used to calculate the environmental impacts of agricultural raw product at the farm gate.
344 When DIALECTE⁴⁹ data were too few or lacking, we used other data sources such as
345 Agribalyse⁵⁰ (heated greenhouses products, conventional pork, coffee) and literature results
346 (seafood, imported food such as sugarcane or tea). Environmental impacts were computed for

347 92 agricultural raw products at the farm gate, 62 came from DIALECTE and 30 from other
348 sources.

349 The data were compared to the literature^{30,51} for validation purpose. Impacts of food products
350 were calculated from impacts of raw products using economic factors when the
351 transformation of the raw product yielded several valuable co-products⁵². We computed daily
352 diet-related GHGEs, cumulative energy demand and land occupation per person by
353 multiplying the reported intake of each food item by their respective environmental impacts
354 considering the mode of food production (conventional vs. organic).

355 We used the pReCiPe, a synthetic score^{31,53} to aggregate these three indicators of diet
356 environmental impact into. The ReCiPe system was established to take into account trade-offs
357 and conflicts between environmental indicators and to consider the alignment of midpoint-
358 oriented and endpoint-oriented indicators, using weighing values, as defined by a panel based
359 on European data⁵⁴. Kramer et al.³¹ documented that the three indicators, namely GHGEs,
360 primary energy consumption and land occupation, included in the partial ReCiPe (pReCiPe)
361 allow a satisfactory representativeness (about 90%) of the total environmental impact.

362 However, many other relevant indicators⁵⁵ also exist. We focused on these three indicators
363 due to lack of data concerning LCA for organic food.

364 It is defined as:

$$365 \text{ pReCiPe} = [0.0459 \times \text{GHGEs} + 0.0025 \times \text{CED} + 0.0439 \times \text{LO}]$$

366

367 where GHGEs is greenhouse gas emissions, in kgCO₂ eq/kg, CED is cumulative energy
368 demand, in MJ/kg and LO is land occupation, in m²/kg.

369 We obtained the pReCiPe per day of each individual diet by multiplying the pReCiPe of each
370 food item accounting for the food production method by the daily quantity of food consumed
371 and by summing them up.

372

373 ***Sociodemographic and lifestyle characteristics***

374 Participants filled in validated web-questionnaires collecting data on sociodemographic and
375 lifestyle characteristics^{56,57}. We used the data closest to the Org-FFQ completion date for
376 each participant. Sociodemographic and lifestyle characteristics included sex, age (over 18
377 years), last scholar qualification (<high school diploma, high school diploma, and post-
378 secondary graduate), marital status, household size, monthly income per household unit
379 (<1,200€, between 1,200 and 1,800€, between 1,800 and 2,700€, and >2,700€ per household
380 unit) obtained using the household income per month and the household composition,

381 smoking status (former, occasional, current, or non-smoker), level of physical activity
382 measured by the International Physical Activity questionnaire (IPAQ)⁵⁸, and alcohol
383 consumption status (abstainers, moderate drinkers (<14 g alcohol/day), and heavy drinkers).

384

385 *Optimization process*

386 Optimization functions and constraints

387 We used individual data about food consumption, place of food purchase, nutritional
388 composition, environmental impacts and prices of items to build a model aiming at optimizing
389 diet according to the three following objectives, while ensuring coverage of the nutritional
390 needs and controlling the monetary cost, 1) to minimize the environmental impact of diet
391 production, 2) to maximize the organic food contribution to the diet and 3) to minimize the
392 total departure from the observed diet (initial condition) and the corresponding modelled diet
393 for maximizing its acceptability.

394 Two types of variables composed the optimization model: the quantities consumed and the
395 proportions in the organic form for each item. We removed the items for which environmental
396 impacts were missing (N=25, listed in **Supplemental Method**), so that a maximum of 239
397 items were included. We distinguished three types of items: the initially consumed items, the
398 non-consumed items that can be added to the diet and those that cannot be added to the diet
399 for health or cultural reasons (as meat or sweet food). The first two types of items were
400 included in the optimization model; thus, the number of items in the model depended on each
401 participant.

402 Mathematically, the objective functions for the environmental impact (E), organic intake (O)
403 and diet departure (D) were defined for each participant as follows:

$$404 E = \sum_{i=1}^{239} \left[pReCiPe_{org}(i) * intake(i) * \%_{org}(i) + pReCiPe_{conv}(i) * intake(i) * (1 - \%_{org}(i)) \right]$$

$$405 O = \sum_{i=1}^{235} \left[intake(i) * \%_{org}(i) \right]$$

$$406 D = \sum_{i=1}^{235} \left[\frac{Moy_{obs}(i) - Moy_{opt}(i)}{SD(i)} \right]^2$$

407 with i denoted the item (food or beverage), org and conv denoted organic and conventional,
408 respectively, intake(i) and $\%_{org}(i)$ represented the consumed quantity (g) and proportion of
409 organic for the considered item, and $Moy_{obs}(i)$ and $Moy_{opt}(i)$ represented the mean daily
410 ingested quantities of item i in the observed and optimized diets, respectively.

411 To ensure that optimized diets belong to a conceivable range, we introduced an upper limit for
412 each item, each food category and each food group. The upper limits of the intake are set at

413 the 95th percentile of the distribution of items intakes, food categories or food group by
414 participant categories (men, menopausal women, and non-menopausal women).
415 For each participant, we set as a constraint that the energy intake in the optimized diet was
416 comprised between 92% and 108% of the individual energy requirement (as assessed with
417 estimates of physical activity levels and basal metabolic rate, using Schofield equations).
418 Moreover, to ensure the nutritional adequacy of the optimized diets, we imposed a set of
419 nutritional constraints pertaining to 26 nutrients as presented in **Table 3**. Alcohol intake in
420 the optimized diet had to be below the minimum of the observed intake and the World Health
421 Organization recommendation of 14 g/d. Finally, in order to take into account exposures to
422 harmful substances through fish consumption, we added two additional constraints, according
423 to the French Agency for Food, Environmental and Occupational Health Safety (ANSES)
424 guidelines. We imposed a total fish consumption of less than 28 g/d and the consumption of
425 fatty fish of less than 14 g/d.
426 Finally, we imposed an upper limit of the diet monetary cost. For this purpose, we identified
427 the minimal price required to meet nutritional requirements, by minimizing deviations from
428 the observed diet (function D) under nutritional and food constraints to ensure coverage of the
429 nutritional needs. Thereafter, for the resolution of the optimization, the upper limit of the diet
430 cost was set to the maximum between the observed cost and the cost required to ensure
431 nutritional needs.

432 Hierarchical method to solve the multi-objective problem

433 The optimization was multi-objective including the three objective functions E, O and D. To
434 solve this multi-objective problem, we applied a hierarchical method, as described by
435 Mausser⁵⁹. This method consists in ranking the objective functions in descending order of
436 importance and beginning with linear functions. Each function is then optimized individually,
437 under the constraints of concomitant improvements in the higher-ranked functions of at least a
438 specified fraction (p%) of their previously identified maximum potential improvements.
439 The different steps and deliverables of the hierarchical optimization process as set here are
440 presented in **Figure 4**. After a preliminary step to identify the diet monetary price required to
441 meet nutritional requirements (step 0), we first assessed the maximum potential improvement
442 of environmental impact, by minimizing the E function under the aforementioned constraints
443 (step 1). Then (step 2), the potential improvement in organic food consumption was identified
444 by maximizing the O function, under the usual constraints and an additional constraint
445 corresponding to an improvement in E of at least p% of its maximum improvement assessed
446 in the step 1. Then (step 3), we optimized diet to be as close as possible to the observed diet

447 (minimization of the D function), under the usual constraints and additional constraints
448 corresponding to E and O improvements by at least p% of their previously estimated potential
449 combined improvements assessed in step 2. We conducted 5 scenarios of increasing
450 disruption, where p% was set at 25%, 50%, 70%, 80% and 90%. The p% means that in the
451 final step (step 3), the process achieves p% of the maximum improvement. For instance, in
452 the case of p=25%, the scenario allows to achieve 25% to the possible improvement in
453 pReCiPe, 25% of the improvement in organic food consumption while minimizing the
454 deviations from the observed diet.

455 Optimization Tool

456 The optimization process was performed using the procedure SAS/OR ® optmodel (version
457 9.4; SAS Institute, Inc.), with the Activeset algorithm for non-linear optimizations and the
458 option multistart to avoid solutions being only local optimums. The number of starts and
459 iterations for each step were fixed as a compromise to converge towards a solution within a
460 reasonable calculation time. We repeated the steps for failures once by increasing the number
461 of starts and iterations. we removed from the sample the few participants for whom we still
462 had no solution

463 **Data analysis**

464 Sample Selection

465 We estimated the energy requirement by accounting for the physical activity level and basal
466 metabolic rate computed by Schofield equations ⁶⁰. In this study, we selected participants who
467 completed the Org-FFQ, with available data regarding the place of purchase for the monetary
468 cost of the diet assessment, and with no missing covariates. We also removed from the sample
469 the participants whose energy intake/energy requirement ratio was < 0.80 or > 1.20. Finally,
470 the sample is composed of 12,308 participants.

471 Statistical Analyses

472 We ranked the participants in three categories according to the tertile-values of the
473 provegetarian score based on observed data. We reported findings globally and across tertiles
474 of provegetarian score, as mean difference in % of the observed values or means and standard
475 error (SE). We performed all statistical analyses using SAS (version 9.4; SAS Institute, Inc.).

476

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486

487 **Conflict of interests**

488 The authors declare that they have no competing interests.

489

490 **Authors' contributions**

491 The authors' responsibilities were as follows. JB, DL, BA, MT, SH and EK-G conducted the
492 study; LS, HF, J-F H, FM and EK-G: designed and conducted the research; LS, PP, JB, BL,
493 DL, BA, MT, SH and EK-G: provided essential materials; LS, HF, J-F H, FM, and EK-G:
494 analyzed the data; LS: wrote the paper; EK-G: had primary responsibility for the final content
495 and supervised the research; and all authors: were involved in interpreting the results and
496 editing the manuscript and read and approved the final manuscript.

497

498 **Transparency statement**

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

502

503 **Data availability statement:**

504 Data can be retrieved from the corresponding author upon reasonable request

505

506 **Code availability statement:**

507 Code and programs can be retrieved from the corresponding author upon reasonable request.

508

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518

519 **Number of tables: 3/Number of figures: 4/Supplemental information: 5 SI Tables, 2 SI**
520 **Figure, 1 SI Method**

521

522 **SI Table 1: Comparison between sociodemographic and lifestyle characteristics of**
523 **NutriNet-Santé population, included participants and the final study sample, 2014**

524

525 **SI Table 2: Characteristics of the observed and optimized diets issued from**
526 **intermediary steps (0, 1 and 2) of the optimization process according to different**
527 **scenarios for the total population (N=12,166), NutriNet-Santé 2014**

528

529 **SI Table 3: Characteristics of the observed and optimized diets issued from the 5**
530 **scenarios of increasing improvements in pReCiPe and %Org (final step 3 of the**
531 **optimization process) across tertiles of the provegetarian score (N=12,166), NutriNet-**
532 **Santé 2014**

533

534 **SI Table 4: Probability of adequacy of nutrient intakes for optimized diets issued from**
535 **the 5 scenarios of increasing improvements in pReCiPe and %Org (final step 3 of the**
536 **optimization process), NutriNet-Santé 2014**

537

538 **SI Table 5: Consumption (g/d) by food groups and scenario for observed, step 2 and step**
539 **3 diets across tertiles of the provegetarian score**

540

541 **SI Method 1: Observed consumption (g/d) of items not included in the optimization due**
542 **to missing data for pReCiPe computation**

543

544 **SI Figure 1: Composition of the observed and optimized diets issued from intermediary**
545 **steps 0 and 1 of the optimization process, NutriNet-Santé Study 2014**

546

547 **SI Figure 2: Structure of the observed and optimized diets issued from the five scenarios**
548 **of increasing improvements in pReCiPe (step 2 of the optimization process) across**
549 **tertiles of the provegetarian score, NutriNet-Santé 2014**

550 **Figure 1: Sustainable characteristics of observed and optimized diets**

551 Diet quality (PANDiet), price, energy density, organic food contribution (%Org),
552 environmental impact (pReCiPe) and animal protein contribution are presented for the
553 observed and optimized diets issued from the 5 scenarios of increasing improvements in
554 pReCiPe and %Org across tertiles of the provegetarian score in the observed diets
555 (N=12,166), NutriNet-Santé 2014

556 **Figure 2: Structure of observed and optimized diets**

557 Diet composition as share of the diet (in weight) is presented for the observed and optimized
558 diets issued from the 5 scenarios of increasing improvements in pReCiPe and %Org across
559 tertiles of the provegetarian score (N=12,166), NutriNet-Santé 2014

560

561 **Figure 3: Organic food and environmental impact of observed and optimized diets**

562 Organic food contribution (%Org) according to environmental impact (pReCiPe) is presented
563 for the observed and optimized diets issued from the 5 scenarios of increasing improvements
564 in pReCiPe and %Org (N=12,166), NutriNet-Santé 2014

565

566 **Figure 4: Optimization process**

567

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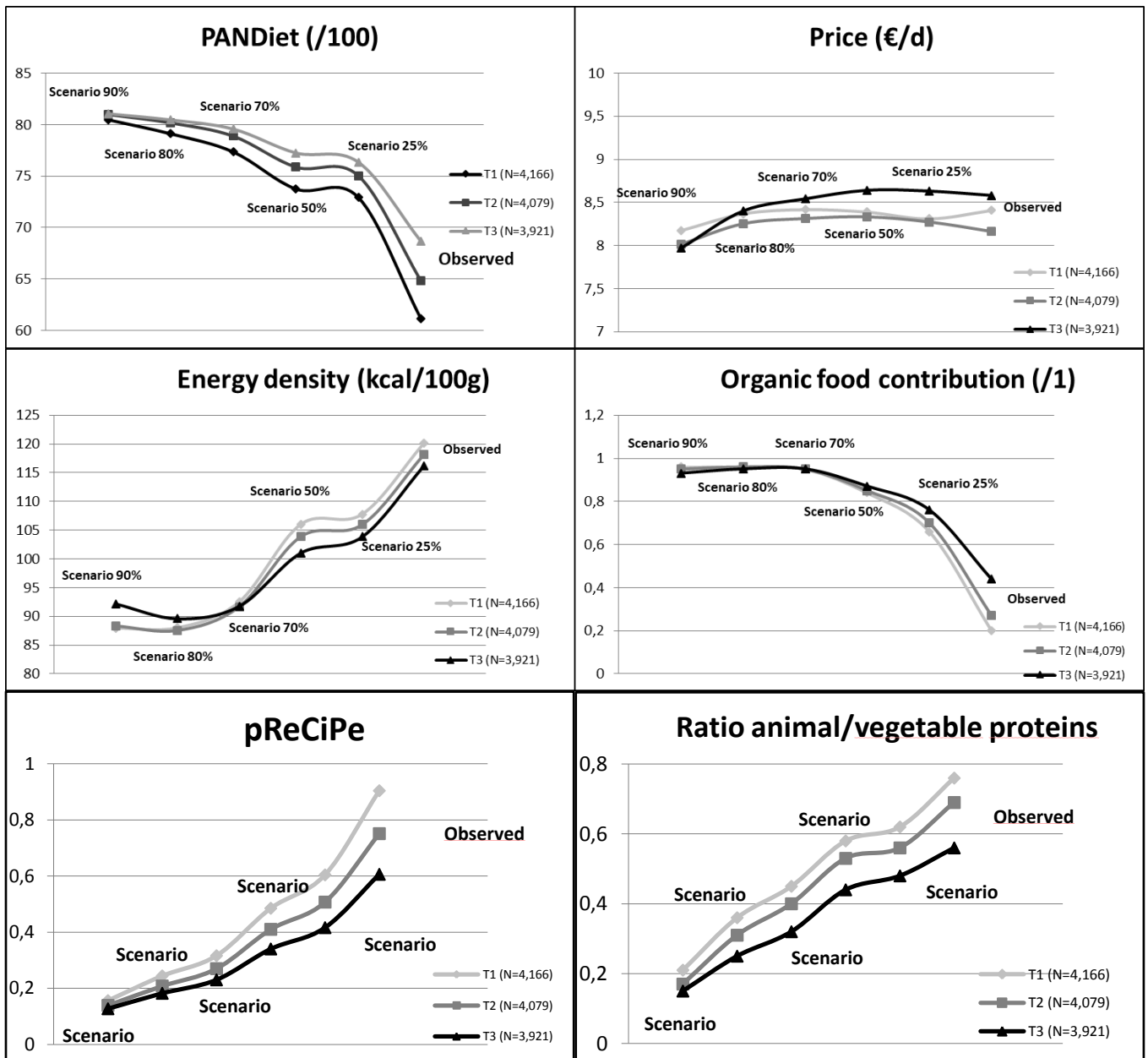
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722 **Figure 1: Sustainable characteristics of observed and optimized diets**
 723 Diet quality (PANDiet), price, energy density, organic food contribution (%Org),
 724 environmental impact (pReCiPe) and animal protein contribution are presented for the
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 727 (N=12,166), NutriNet-Santé 2014



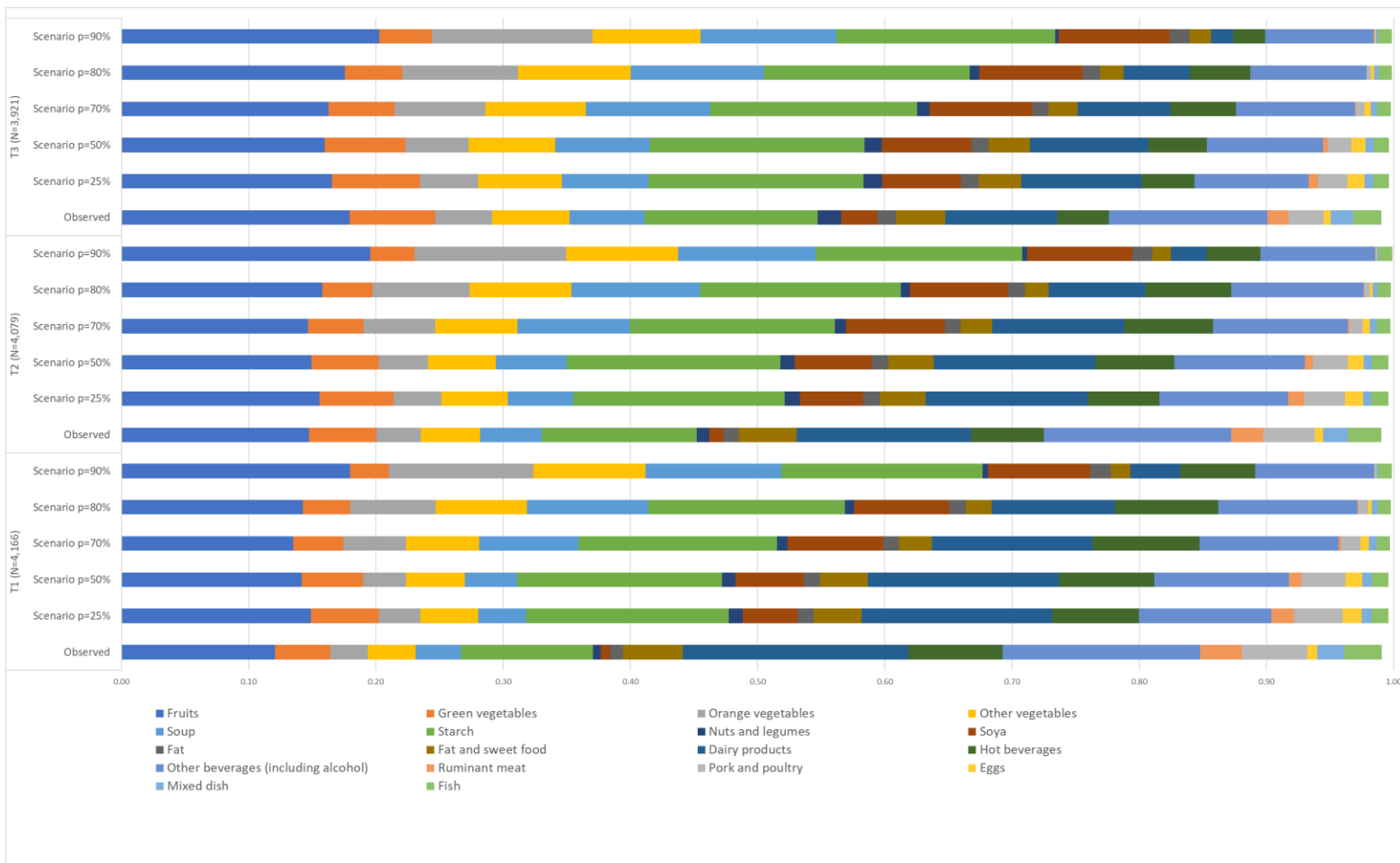
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731 **Figure 2: Structure of observed and optimized diets**

732 Diet composition as share of the diet (in weight) is presented for the observed and optimized
733 diets issued from the 5 scenarios of increasing improvements in pReCiPe and %Org across
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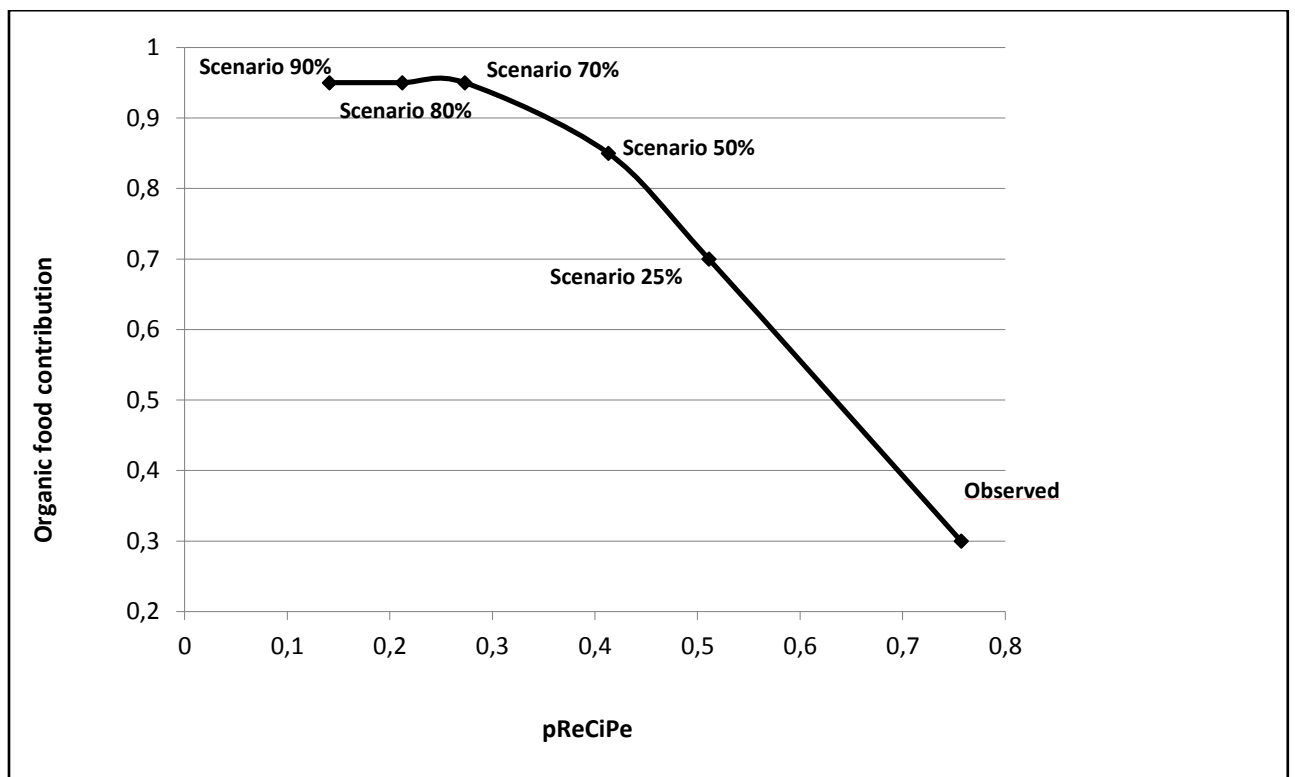
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Figure 3: Organic food and environmental impact of observed and optimized diets

Organic food contribution (%Org) according to environmental impact (pReCiPe) is presented for the observed and optimized diets issued from the 5 scenarios of increasing improvements in pReCiPe and %Org (N=12,166), NutriNet-Santé 2014



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