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**Environmental pressures and pesticide exposure associated with an increase in the share of plant-based foods in the diet**

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

**Number of tables:** 3/**Number of figures:** 3

**Supplemental material:** 5 tables and 2 figures

- 1 Abbreviations:
- 2 DHA: docosahexaenoic acid
- 3 DQI: diet quality index
- 4 EPA: eicosapentaenoic acid
- 5 Food frequency questionnaire: FFQ
- 6 Greenhouse gas emissions: GHGe
- 7 PE: energy from plant food
- 8 PNNS-GS2: Programme National Nutrition Santé – guidelines score
- 9 Sweet and fat foods: SFF
- 10

## 11 **Abstract**

12 *Background:* Diets rich in plant-based foods are encouraged for human health and to preserve  
13 resources and the environment but the nutritional quality and safety of such diets is debated.

14 *Objective:* This study aimed to model nutritionally adequate diets with increasing plant food content  
15 and to characterise the derived diets using a multicriteria approach including, nutrients intake,  
16 environmental pressures and exposure to pesticides

17 *Methods:* Using data of the NutriNet-Santé cohort (N=29,413), we implemented stepwise optimization  
18 models to identified maximum plant-food content under nutritional constraints. Environmental  
19 indicators at the production level were derived from the DIALECTE database, and exposure to  
20 pesticide residues from plant food consumption was estimated using a contamination database.

21 *Results:* Plant-based foods contributed to 64.3% (SD=10.6%) of energy intake in observed diets and  
22 may reach up to 95% in modelled diets without jeopardizing nutritional status. Compared to the  
23 observed situation, an increase in plant-based foods in the diets led to increases in soy-based products  
24 (+480%), dried fruits (+370%), legumes (+317%), whole grains (+251%), oils (+144%) and  
25 vegetables (+93%). Animal products decreased progressively until total eviction, except for beef (-  
26 98%). Dietary quality (estimated using the Diet Quality Index Based on the Probability of Adequate  
27 Nutrient Intake) was improved (up to 17%) as well as GHGe (up to -65%), energy demand (up to -  
28 48%), and land occupation (-56%) for production. Exposures to pesticides from plant-based foods  
29 were increased by 100% conventional production and to a much lesser extent by 100% organic  
30 production.

31 *Conclusions:* This study shows that shifting to nutritionally-adequate plant-based diets requires an in-  
32 depth rearrangement of food groups' consumption but allows a drastic reduction environmental  
33 impact. Increase exposure to pesticide residues and related risks can be mitigated by consuming foods  
34 produced with low pesticide input .**Keywords:** plant-food, diet optimization, pesticides, greenhouse  
35 gas emissions, sustainable diet, healthy diet

36     **Highlights**

- 37     - Plant-based content may make up to 95% (as energy) of diet without jeopardizing the  
38         nutritional status
- 39     - Exposure to pesticide increases with the share of plant foods in the diet if they are not organic

## Introduction

40 Modern western diets, rich in animal products and salt, saturated fat, and sugar, are not sustainable [1].  
41 Responsible for many chronic diseases, , western diets also have harmful consequences on natural  
42 resources and strongly contribute to climate change [2,3]. Since 1950s, population's growth,  
43 modernization and urbanization have led to an intensification of agriculture. In addition, increased  
44 wealth is associated with increased animal-based foods demand [4]. However, production of animal  
45 food for humans is very inefficient in terms of energy, especially in intensive production settings [5],  
46 since a loss of energy occurs throughout the trophic chain.

47 Indeed, the scientific literature robustly documents that food systems, particularly intensive and  
48 industrialized ones, are responsible for major environmental degradation, such as deforestation, water  
49 use and greenhouse gas emissions (GHGe) [6,7]. Additionally, the production of meat, fish, eggs and  
50 dairy products uses ~ 83% of agricultural land globally and contributes 56-58% of the emissions  
51 generated by food production, while providing 37% of the protein supply [8]. Meanwhile some  
52 extensive grazing systems in Europe contribute to High Nature Value farmland [9] and overall,  
53 changes in farming practices may help in mitigate harmful impacts [10].

54 This explains the drastically lower environmental footprint of plant-based diets and even more for  
55 vegetarian or vegan diets [11–15]. Indeed, observational or modelling studies show that the reduction  
56 of animal products in diets is associated with lower environmental pressures, considering mostly  
57 indicators related to climate change or land use [16]. For example, we have recently shown that a  
58 moderate reduction of GHGe was associated with a gradual increase of fruits, vegetables and soy-  
59 based products in the diet and conversely a decrease of animal products [17]. However, existing  
60 optimization studies do not consider potential difference in environmental pressures according to  
61 farming practices.

62 Plant-based diets have been consistently associated with long-term health, i.e. lower risk of chronic  
63 diseases [2,18]. However, plant-based foods include both healthy and unhealthy foods, such as ultra-  
64 processed foods and/or sweetened beverages, desserts, or salty or sweet snacks, so it is important to  
65 clarify which healthy and sustainable plant-based products should be substituted for animal-based  
66 products [19,20]. An issue frequently raised, beyond social norms associated with animal-food  
67 consumption and taste, is related to the nutrients constituting the animal, versus plant-based, protein  
68 package, which may compromise nutritional status for protein, zinc, iron and vitamin B12 [21].

69 However, it has been shown that in Western countries protein undernutrition is rare (except for the  
70 elderly or frail) insofar as if total protein requirements are covered, amino acid intakes are not limiting  
71 [22]. Some authors have also emphasized that the amount and quality of plant-protein is often  
72 underestimated or misunderstood [23]. In addition, we have recently shown in an optimization study  
73 that it is possible to eliminate meat from the diet and that dietary changes can meet the requirements  
74 for iron, zinc, and vitamin A. In that study, other nutrients supplied mainly by meat, such as vitamins  
75 B6 and B12, proteins and essential amino acids, were never limiting [24].

76 Besides, we have shown that a reduction in the consumption of animal products (meat and dairy  
77 products) leads to potentially insufficient intakes of iron and zinc based on official recommendations  
78 [17], but the latter may be overestimated [25].

79 Some authors have qualified the increase in demand for protein-rich foods (related to population  
80 growth and socio-economic development), high biological value of animal proteins, and the low  
81 environmental pressures of plant protein as a “*protein trade-off*” (“human versus ecosystem health”)  
82 [26]. In addition, another issue pertained to the potential elevated chronic exposure to pesticide  
83 residues that are strongly associated with plant-food consumption at the individual level even if food  
84 maximal level of residues are mostly respected [27]. We previously showed that potential exposure to  
85 pesticides residues may be drastically increased for people with highly plant-based diet [28].

86 The primary objective of the present study was to identify optimized diets gradually higher in plant-  
87 based foods (expressed as energy and noted %PE) but fully adequate in all nutrient intakes (including  
88 those conveyed by animal foods, i.e. under nutritional and acceptability constraints), while considering  
89 the beef/milk coproduct link. A second objective was to study the externalities of these diets by  
90 describing the optimized diets in terms of environmental pressures and to evaluate pesticide residue  
91 exposure associated with diet increased in plant-food.

## Methods

### 92 Population

93 This analysis is based on a sample of adults involved in the ongoing web-based prospective NutriNet-  
94 Santé cohort aiming to investigate relationships between nutrition and health [29]. Participants are  
95 recruited on a voluntary basis from the general French population. This study is conducted in  
96 accordance with the Declaration of Helsinki, and all procedures were approved by the Institutional  
97 Review Board of the French Institute for Health and Medical Research (IRB Inserm  
98 0000388FWA00005831) and the National Commission on Informatics and Liberty (Commission  
99 Nationale de l'Informatique et des Libertés, CNIL 908450 and 909216). Electronic informed consent  
100 was obtained from all participants. The NutriNet-Santé study is registered in ClinicalTrials.gov  
101 (NCT03335644).

### 102 Dietary data assessment

103 The dietary data were collected using a self-administered validated semi-quantitative food frequency  
104 questionnaire (FFQ), administered from June to December 2014, extensively described elsewhere  
105 [30]. For each of the 264 food and beverage items, the questionnaire has been augmented by a five-  
106 point ordinal scale to evaluate the mode of production, i.e. organic (under official label) or  
107 conventional [31]. Thus, participants were asked to choose among the following answer modalities:  
108 “never”, “rarely”, “half-of-time”, “often” or “always” in response to the question ‘How often was the  
109 product of organic origin?’. Organic food consumption was estimated by allocating the respective  
110 weights: 0, 25, 50, 75 and 100% to the modalities. Consumption reports are for foods as consumed and  
111 edible part coefficients have been applied. For clarity, food and beverage items were grouped into

112 food groups specifically defined for this optimization modelling (see footnotes to **Fig. 1**). Nutritional  
 113 composition of each item was determined by combining the published NutriNet-Santé food  
 114 composition table (>3000 items) [32] with the 264 FFQ-items as the weighted mean of the nutritional  
 115 content of all corresponding foods. For each food, energy intake from plant or animal source was  
 116 calculated. Energy intake from plant or animal sources was calculated based on validated recipes  
 117 developed by dietitians, taking into account the nature of the ingredients.. Weights were the  
 118 frequencies of consumption in the NutriNet-Santé population. Individual nutrient intakes were  
 119 calculated.

#### 120 **Sociodemographic and lifestyle characteristics**

121 Age, education (<high school diploma, high school diploma, and post-secondary graduate), smoking  
 122 status (former, current, or never-smoker), and physical activity assessed using the International  
 123 Physical Activity questionnaire [33] were collected using pre-validated questionnaires updated each  
 124 year. [34,35]. For this study, we used the data closest to the FFQ completion date.

#### 125 **Dietary indicators**

126 The nutritional quality of the optimized diets was assessed using three dietary indexes.

127 The nutrient-based PANDiet (Diet Quality Index Based on the Probability of Adequate Nutrient  
 128 Intake) contains two subscales reflecting *adequacy* and *moderation* [36]. For each nutrient, the  
 129 ‘probability of adequacy’, i.e. intake above minimum values (*adequacy* score) or below maximum  
 130 values (*moderation* score) is calculated on the basis of nutrient reference values. The final score is the  
 131 average of the two sub-scores. The adequacy sub-score is the average of the probabilities of adequacy  
 132 for 28 nutrients and the moderation sub-score includes 6 nutrients and 12 penalty values referring to  
 133 the probabilities of exceeding upper limits of intakes. The PANDiet ranges from 0 to 100 points, with  
 134 a higher score reflecting better adherence to French nutritional recommendations and adequate nutrient  
 135 intake. The calculation to estimate the adequacy of the usual intake for a given nutrient is as follows:

$$136 \quad \text{Prob} \left( \frac{y-r}{SDr} \right)$$

137 Where Prob: is the *probnorm* function of SAS®, y: daily mean intake, r: the reference value, SDr: the  
 138 interindividual variability.

139 The second score was based on food group consumption and has been recently developed to assess the  
 140 quality of plant and animal foods [37]. Each component (healthy/unhealthy plant-based/animal food  
 141 consumption) ranged between 0 and 5 points for a total maximum score of 85. Components and  
 142 scoring are presented on **Supplemental Fig 1**.

143 Third, the sPNNS-GS2 is a validated score, ranging from  $-\infty$  to 14.25, reflecting adherence to the 2017  
 144 French food-based dietary guidelines proposed by the High Council of Public Health [38,39]. It is  
 145 composed of 12 weighted components for moderation or adequation and penalty for energy intake was  
 146 applied. Components and scoring are presented in **Supplemental Fig. 2**.

## 147 **Environmental pressure indicators**

148 Food-related environmental indicators were computed using upstream life cycle analysis (LCA) from  
 149 the DIALECTE database developed by Solagro [40]. This database has the particularity of covering  
 150 conventional and organic farms. GHGe (kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>eq)), cumulative energy demand  
 151 (MJ), and land occupation (m<sup>2</sup>) were computed at the farm perimeter excluding downstream steps such  
 152 as conditioning, transport, processing, storage or recycling stages. Details, data and computation have  
 153 been broadly described elsewhere [41].

## 154 **Data of 92 raw agricultural products, economic allocation (accounting for coproducts), as well as** 155 **cooking and edibility coefficients were used to estimate environmental pressures related to the** 156 **production of the 264 food items. Pesticide residue exposure**

157 A food contamination database was developed from the data provided by the CVUA in Stuttgart. It  
 158 consists of 6 billion data points on pesticide residue levels collected in Europe during the period 2012-  
 159 2015 for foods of plant origin, both organic and conventional (the database does not cover foods of  
 160 animal origin, which are known to be much less contaminated by pesticide residues than foods of plant  
 161 origin). The data collection and computation have been extensively described elsewhere [30]. The  
 162 plant-based food of the FFQ were decomposed into 442 ingredients for which the mean of  
 163 contamination for a list of compounds was computed. Pesticide residues included active substances,  
 164 such as organophosphates, pyrethroids, others and active substances allowed in organic farming such  
 165 as natural pyrethrins and spinosad. A synthetic indicator was calculated as the sum of exposure inverse  
 166 weighted on the Acceptable Daily Intake (ADI).

## 167 **Coproduct factors for ruminant products**

168 As previously published [17], we considered a coproduct factor between milk and beef. Indeed,  
 169 increase in plant protein is associated with a decrease in beef consumption. However, in particular to  
 170 meet calcium requirement, milk consumption is not suppressed implying that cattle breeding persists.  
 171 In 2010 in France, 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight)  
 172 [42] were produced, of which 41% was from dairy herd, i.e., 0.62 million tons of beef [43].  
 173 Considering a meat to carcass weight ratio of 68% [44], and further yields of 90% during distribution  
 174 (due to 10% distribution losses) and 68% during consumption (due to 32% losses by cooking, bones  
 175 and wastes) [44] and that 1L of milk corresponded to 10g of meat when applying the equation:

$$\begin{aligned}
 & 25 \text{ million tons of Milk (L)} \\
 & = 1.52 \text{ million tons of beef} \times 41\% \times 68\%_{\text{carcass yield}} \times 90\%_{\text{distribution yield}} \times \\
 & \quad 68\%_{\text{preparation yield}}
 \end{aligned}$$

## 179 **Weighting of nutritional reference**

180 The nutritional reference values are established separately for men and women since they have  
 181 significantly different physiological requirements [45]. In addition, a subsequent distinction is made  
 182 between women with high vs low iron requirements. It is estimated that about 20% of menstruating  
 183 women have high iron requirements [45]. In this study, to improve clarity, we defined an average



184 individual constituted of 50% men and 50% women, reflecting the French distribution. In addition, for  
185 women, we considered 50% postmenopausal women and 50% non-menopausal women with low and  
186 high iron requirement respectively. The assignment of high iron requirements to all menstruating  
187 women allows to mimic the strictest situation. Reference values for each nutrient were defined as the  
188 weighted mean and are presented in **Table 1**.

189 For mean, 5<sup>th</sup> and 95<sup>th</sup> percentiles (see below) values of observed food item intakes, we calculated  
190 weighted averages after calculation of individual weights so that the proportions defined above were  
191 respected.

### 192 **Modelling the increase of the contribution of plant food to energy intake**

193 Using non-linear optimization modelling, we identified optimized consumptions of 264 different food  
194 items, as well as their respective proportions in organic. We obtained optimized diets with minimal  
195 diet departure from the initial (observed) diets, while maintaining a set of constraints including  
196 nutritional (adequate nutrient intakes), acceptability, and coproduction constraints. An additional  
197 constraint was imposed, which was the gradual increase of the percentage of energy obtained from  
198 plant-based foods until the maximal value identified in a preliminary step. Optimized nutritionally  
199 adequate diets were developed from initial conditions based on observed food consumptions and  
200 nutritional composition of food items [46,47].

201 The list of fixed constraints was as follows:

- 202 - Nutritional constraints on daily energy intake and a set of nutrients were defined according to  
203 the upper and/or lower reference values. Lower bounds were defined as recommended dietary  
204 allowance (population reference intake), adequate intake, or lower bound of reference range  
205 for the intake in the French population of ANSES [45] based on the 2021 EFSA opinion [48].  
206 For adequate intake based on observed mean intake, the lower limit was set at the weighted 5<sup>th</sup>  
207 percentile value. Upper bounds were defined as the maximum tolerable intakes for vitamins  
208 and minerals when available, or the upper limit of the reference intake range otherwise.
- 209 - For zinc and iron, bioavailability was considered using the published formula [49,50]. Further  
210 details are presented in **Supplemental Material**.
- 211 - Acceptability constraints were defined at the food group level, with upper bounds set at the  
212 weighted 95<sup>th</sup> percentiles values.
- 213 - To comply with some contaminant constraints, such as heavy metals, we added a constraints  
214 as regarding total fish consumption ( $\leq 2$  portions / week) [39].
- 215 - Coproduction constraint limited the consumption of milk to a proportion of that of beef, using  
216 the factor between milk and beef defined as reported above.

217 The modelling process was conducted in two steps:

218 In the first model, we searched to identify the maximal contribution of plant-based foods to diet  
219 energy (%PE) satisfying the all the fixed constraints, and the objective function was hence defined as  
220 the equation:

221 
$$\text{Max \%PE} = \sum_i^{264} \left[ \frac{\text{Kcal-Plant}_i \times \text{Opt}_i}{\text{Kcal}_i \times \text{Opt}_i} \right]$$

222 where  $i$  is the food item,  $\text{Kcal-Plant}_i$  and  $\text{Kcal}_i$  denote plant and total energy value in the food item ( $i$ ),  
223 respectively and  $\text{Opt}_i$  denote the daily consumption of the food item ( $i$ ) in the optimized model.

224  
225 Next, in the main stepwise models, for identifying a culturally acceptable dietary trajectory towards  
226 that maximal plant-derived energetic content, plant-energy was included as a gradual additional  
227 constraint (in addition to the fixed constraints) following this equation:

228 
$$\%PE \geq \lambda\% \Leftrightarrow \sum_i^{264} \left[ \frac{\text{Kcal-Plant}_i \times \text{Opt}_i}{\text{Kcal}_i \times \text{Opt}_i} \right] \times 100 \geq \lambda\%$$

229 where  $i$  is the food item,  $\text{Kcal-Plant}_i$  and  $\text{Kcal}_i$  denotes plant and total energy value for the food  
230 item ( $i$ ), respectively and  $\text{Opt}_i$  denotes the daily consumption of the food item ( $i$ ) in the optimized  
231 model.  $\lambda$  ranges from the observed value (65%) to the maximum identified in the preliminary step by  
232 5% increment.

233 The objective function was to minimize at each step the total departure (TD) from the previous  
234 modelled diet, as the equation:

235 
$$\text{Min TD} = \sum_i^{264} \left[ \frac{\text{Opt}_{i[[n]]} - \text{Opt}_{i[[n-1]]}}{\text{SD}_i} \right]^2$$

236 Where  $\text{Opt}_{i[[n]]}$  and  $\text{Opt}_{i[[n-1]]}$  denote the daily consumption of food item ( $i$ ) in the  $n$  and  $n-1$  optimized  
237 models, respectively and  $\text{SD}_i$  was the standard deviation of the daily consumption of food item ( $i$ ) over  
238 the whole population in the initial (observed) condition.

239  
240 Diet optimization was performed using the procedure SAS/OR ® *optmodel* (version 9.4; SAS  
241 Institute, Inc.) using a non-linear optimization algorithm with multi-start option to warrant that  
242 identified solutions were not only local optima [47].

243 For each model, we conducted an analysis of the standardized dual values to identify the most  
244 so-called active constraints of the model, i.e. constraints limiting the objective gain, i.e.  
245 minimizing diet departure while complying with all the constraints, compared to the inactive  
246 variables that do not drive the model.

247 This allowed the identification of limiting nutrients This analysis was performed using an  
248 approach described in a previous work [51], by calculating the standardized dual values  
249 corresponding to the potential gain in objective in the case of a 100% relaxation of the  
250 limiting bound of the constraint [52].”

### 251 **Statistical analysis**

252 For the baseline situation of the present study, we considered participants of the NutriNet-Santé study  
253 who had completed the Org-FFQ between June and December 2014 (N=37,685), with no missing

254 covariates (N=37,305), not detected as under- or over-energy reporter (N=35,196), living in mainland  
255 France (N=34,453), and with available data regarding the place of purchase for the computation of the  
256 dietary monetary cost as published elsewhere [53], leading to a final sample of 29,413 participants  
257 (**Supplemental Fig. 3**). The sociodemographic and lifestyle characteristics of the three initial  
258 populations (men, premenopausal and menopausal women) and of the average individual were  
259 estimated as mean (SD) or percentage.

260 The optimized diets identified were described for the average individual by the following indicators:

- 261 1) dietary consumption by food groups,
- 262 2) relevant nutrients intakes, as regards plant to animal food rebalancing,
- 263 3) environmental pressures (GHGe, cumulative energy demand and land occupation),
- 264 4) exposure to pesticide residues for two scenarios (100% conventional and 100% organic). To  
265 do that, we applied the method as recommended by WHO [54]. For each active substance, the  
266 estimated daily intake (EDI) (in  $\mu\text{g}/\text{kg}$  body weight/d) was calculated under a lower-bound scenario,  
267 using the reference method described by Nougadère et al. [55], combining food consumption,  
268 contamination, farming practices and body weight after applying edible coefficients for cooking and  
269 peeling. A synthetic indicator of exposure was calculated as the average exposure to each molecule.

270 Secondary analyses were conducted. First, all the procedures were repeated across 3 subgroups (based  
271 on tertile value of the distribution of protein from plant-foods to total) with different values of %PE at  
272 baseline: 50%, 65% and 80%. Second, all the procedures were repeated by modelling the increase in  
273 the ratio of plant protein instead of the ratio of energy from plants.

274 All statistical analyses were performed using SAS® (version 9.4; SAS Institute, Inc., Cary, NC, USA)  
275 and figures were drawn using R version 3.6. The non-linear optimization problem was performed  
276 using the NLP solver of the OPTMODEL procedure of SAS software version 9.4 (SAS Institute Inc.,  
277 Cary, NC, USA).

## Results

278 The characteristics of the reference population are presented in **Supplemental Table 1**. This  
279 population initially included 29,413 participants (75 % women), with a mean age of 54.5y. The  
280 characteristics of the average individual are also presented. In the observed diet, the proportion of  
281 energy intake from plant-based foods was on average 65%.

282 The first model, aiming at identifying the maximum part of plant-based foods (expressed as a  
283 percentage of diet energy) in the diet under nutritional (nutrient requirements by taking iron and zinc  
284 bioavailability into account), acceptability and coproduction constraints, revealed that it is possible to  
285 reach up to 95% of energy intake from plant-based foods.

286 The %PE was then constrained to gradually increased by 5% increments from the basal scenario  
287 (keeping the observed value of 65% of energy from plant-based foods but meeting nutritional and  
288 other constraints) to the final scenario (reaching the maximal value of 95% of energy from plant-based  
289 foods always allowing the satisfaction of constraints).

290 Modeled diet compositions across these scenarios are presented in **Fig. 1**. Progressive increase by  
 291 increments of 5% in %PE was associated with a progressive decrease or a total removal of meat  
 292 (ruminant, pork and poultry), dairy products, eggs, fat and dressing, fruit juices, prepared dishes/fast  
 293 food, sweet and fat foods (SFF). On contrary, across scenarios, there was a progressive increase in  
 294 dried fruit, legumes, soy-based products, vegetables, vegetable oil and whole-grain products. We  
 295 observed a bell-shaped relationship for cereal, fruit, and beverages (fruit nectar, syrup, soda (with or  
 296 without sugar, plant-based beverages (except soy-based), milk consumed with tea/coffee). Potatoes  
 297 showed a bell- shaped distribution but a drastic increase in the 95%PE scenario. Of note, some food  
 298 groups were increased as early as the basal scenario (65%PE) so as to correct the nutritional  
 299 inadequacies of the observed diets (that did not comply with some nutritional constraints): beef,  
 300 poultry, eggs, cereals, fast-food, fruit, legumes, whole grain products, oil, prepared dishes/fast food  
 301 and SFF. Fish was stable across all scenario.

302 Nutrient contents of the diets and dietary indexes are shown in **Table 2**. The basal scenario (65%PE)  
 303 under nutritional constraints led to an increase in energy intake (both from animal and plant-based  
 304 foods and similar results for proteins). As a result of nutritional constraints, DHA (docosahexaenoic  
 305 acid) + EPA (eicosapentaenoic acid), bioavailable iron, fibre and all micronutrient content of the  
 306 diet were improved (from plus 1% for vitamin B9 to 21% for bioavailable iron). Then, the gradual  
 307 increase in %PE (from 65 up to 95%) was associated with decreases in total and animal protein (-28%  
 308 and -80% respectively) and an increase in plant protein (+72%). DHA and EPA intakes were stable  
 309 across scenarios as well as bioavailable zinc and sodium.

310 As expected, the basal scenario (65%PE) that corrected the nutritional inadequacies of the observed  
 311 diet led to a healthier diet as reflected by an overall increase in PANDiet (+8%) and specifically of its  
 312 adequation subscore. Similarly, the cDQI was improved (+32%) as well as each of its plant and animal  
 313 subscores. Through scenarios of gradual %PE, the PANDiet gradually increased, until it reaches a  
 314 plateau. Specifically, its adequation subscore was stable while its moderation subscore improved  
 315 (+49%). As regards the cDQI, a small decrease was observed due to a decrease in aDQI. As regards  
 316 the sPNNs-GS2, the basal scenario led to a strong increase in sPNNs-GS2 (+129%). Across scenario,  
 317 gradual increase %PE led to increase in these both scores (+8 and +22% respectively) with maximal  
 318 values attained at around 80-85%.

319 The active constraints (i.e. limiting the model) in the basal scenario were, in descending order,  
 320 EPA+DHA, energy intake, alpha-linolenic acid, saturated fatty acids, fiber, sodium, alpha-linoleic  
 321 acid, and vitamin C. The active constraints in the 95% scenario were, in descending order, energy  
 322 intake, bioavailable zinc, EPA+DHA, calcium, sodium, iodine, sugar without lactose, vitamin C and  
 323 vitamin B12. Of note, vitamin B12 was limiting only in the last scenario (data not tabulated).

324 Environmental indicators for observed and optimized diets and each modelled scenario are showed in  
 325 **Table 3**. Due to an increase in energy intake in the optimized diets, imposed by the energy  
 326 requirements constraint (**Table 1**), the basal model scenario was associated with higher values

327 compared to observed ones for GHGe, energy demand and land occupation, whatever the farming  
328 method. In the following scenarios, the gradual increase in energy from plant-based foods led to  
329 marked gradual decreases in all indicators, comparable whatever the farming method, around -70% for  
330 GHGe, -50% for energy demand and -60% for land occupation between the final and initial.

331 Exposure to pesticide residues from plant-based foods are presented as 100% organic or 100%  
332 conventional for each scenario in **Fig. 2**. When modelling pesticide residues exposures, the increase in  
333 plant-based foods led to higher exposures to most of pesticides in the 100% conventional scenario,  
334 with some fluctuations depending on the structure of the modelled diet, conversely, 100% organic  
335 allowed to markedly limit exposure to synthetic pesticides. However, spinosad, which is approved in  
336 organic farming, increased. The exposure across scenarios are tabulated in **Supplemental Table 2** and  
337 **Supplemental Table 3** as % of the ADI. In relative value, compared to the observed situation, the  
338 synthetic indicator of exposure to pesticides increased in both farming systems (+46% in conventional  
339 and +124% in organic), but values in organic were dramatically lower than in conventional (-84%  
340 between the organic and conventional scenarios at 95%PE).

341 A number of sensitivity analyses were conducted. The first method explore the influence of the  
342 observed level of energy intake from plant-based foods on the scenarios. Gradual optimized diets  
343 derived in subsamples with 50 %PE, 65%PE, and 80%PE led to similar shapes of dietary trajectories.  
344 There were however some differences since the optimized consumptions of dried fruits and nuts,  
345 legumes, soy-based products, vegetables, and whole grain products increased in line with the baseline  
346 values of the %PE. Food group consumptions in the observed and optimized diets of the final scenario  
347 (95%PE) are presented in **Figure 3**. The higher the %PE in the observed situation, the higher the  
348 optimized consumption of dried fruits and nuts, legumes, soy-based products, vegetables, and whole  
349 grain products.

350 The second sensitivity analyses modelled a gradual increase in plant proteins rather than in plant  
351 energy. The maximum contribution of plant proteins achievable for complying with the set of  
352 constraints was 80%. Consumptions in scenarios of gradual increase in plant proteins are shown in  
353 **Supplemental Fig. 4**. Findings were similar to those of the increase in %PE models but beef and milk  
354 decreased more rapidly while legumes increased more rapidly. In addition, sweet and fat product were  
355 higher in optimized diets. Compared to those of the increase in %PE models, findings were similar in  
356 terms of trends but maximum PANDiet was lower (76.47 vs. 81.97) (**Supplemental Tables 4**). Also,  
357 decrease in GHGe was stronger in conventional (1.01 vs. 1.46 kgCO<sub>2</sub>eq/d) and in organic 0.93 vs.  
358 1.44 kgCO<sub>2</sub>eq/d) (**Supplemental Table 5**).

## Discussion

359 In this study evaluating a gradually increase in proportion of plant-based foods in the diet, we showed  
360 that it is possible to increase the caloric proportion of plant foods up to 95% (corresponding to 82% of  
361 protein from plant foods), without jeopardizing nutritional requirements in the French context of non-  
362 fortified foods. This increase in the proportion of plant-based foods is associated with a significant

363 reduction in environmental pressures and, in particular of GHGe (about -65%, in conventional and in  
364 organic scenario) as well as land occupation (-about -55%, in conventional and in organic scenario).  
365 Although it has been shown in previous studies that a higher consumption of plant food is related to a  
366 higher exposure to pesticides, this is the first study to put it in the context of dietary changes for  
367 environmental sustainability. Nonetheless, compared to a 100% conventional diet, a 100% organic diet  
368 resulted in significantly lower exposure to pesticides residues (on average -85%).

369 The most limiting nutrients that were stuck at their bounds (requirements or upper limits) in nearly all  
370 the optimized diets across scenarios were DHA+EPA, calcium, sodium, and bioavailable zinc.  
371 Following previous work documenting a likely overestimated nutritional reference for zinc [25], we  
372 selected a compromise between nutritional reference and deficiency threshold to set the constraint at  
373 the observed value to not over-shape the model. In spite of this release, the zinc constraint remained  
374 the most limiting in the basal scenario (65%PE). Sugars except lactose and sodium were also active  
375 constraints at the upper bound. As previously documented [56,57], accounting for the bioavailability  
376 of iron and zinc using validated equations showed that such nutrients are key elements to consider in  
377 plant-based diets.

378 It should be noted that adequate nutrient intake can be achieved up to a scenario with 95% PE (or  $\approx$   
379 80% protein from plant foods). This shows that a predominantly plant-based diet can provide adequate  
380 nutrient intake.

381 In that scenario, some nutrients from animal-based foods were critical, particularly zinc, EPA and  
382 DHA, calcium, iodine, and vitamin B12 and nutritional constraints were no longer achievable above  
383 the 95%PE scenario (mostly vitamin B12 and EPA+DHA constraints). Thus, our findings suggest the  
384 existence of levers for increase plant-foods in the diet without compromising nutritional quality.

385 Constraints to ensure nutrient requirements in the modelled diets resulted in an increase in the  
386 adequacy subscore (+19%) of PANDiet, from the first scenario, but this subscore then remained stable  
387 in the scenarios of gradual increases in plant foods. In contrast, the moderation subscore of PANDiet  
388 gradually improved.

389 Similarly, the cDQI improved significantly in the first scenario and then increased very slightly, and  
390 finally decreased. The plant component (pDQI) reached a plateau, while the animal component (aDQI)  
391 decreases with the gradual removal of animal-based foods. Overall, the quality of the diet is  
392 significantly improved with increasing plant foods in the diet and appears to peak around 80-85% of  
393 energy from plant foods. The association between the diet contribution of plant-based foods and diet  
394 quality [58], estimated through holistic approaches such as dietary indexes, has been documented in  
395 the scientific literature [58]. However, data are relatively scarce, mostly focused on vegetarians and  
396 vegans diets in comparisons with meat-eaters through dietary indexes based on food group intakes  
397 rather than on nutrients intakes and requirements [59].

398 Two recent studies have focused on the identification of the healthier plant to total protein ratio to be  
399 achieved while meeting nutritional references [60,61]. One of these studies focused only on nutritional

400 aspects without reporting environmental pressures and reported an optimal ratio between 45% and  
401 60% [61]. The second study documented that plant-based protein ratios could range from 15% to 80%  
402 without undermining the quality of diet [60]. However, as in our study, the optimized diets were  
403 different from the observed diets, and environmental pressures were diminished as the proportion of  
404 plant proteins increased. It is also worth noting that even though the modeling and population were  
405 different, the 80% plant protein ratio identified in the second study was very close to the value found  
406 (the model with 95% energy intake led to a 80% plant-based protein ratio) in our study. Based on  
407 observed data, we previously showed that a provegetarian score is positively associated with the  
408 PANDiet score reflecting the probability of adequacy to nutritional references [62]. Of note, we used  
409 the cDQI distinguishing the quality of foods from animal and plant origin [37], which allows a better  
410 understanding of the combination of plant and animal foods that provide nutrients.

411 In terms of food consumption, the gradual increase in protein and energy from plant foods resulted to  
412 quite similar diets for both models. However, the models, as combinatory processes based on different  
413 objectives, led to some disparities, especially for foods with different protein contents. For example,  
414 for dairy products, the model aiming to reduce animal protein will favour milk that is less rich in  
415 protein than fresh dairy products. Besides, a salient point concerns the increase in exposure to  
416 pesticide residues associated with a diet rich in plant-based food. Indeed, fruit and vegetables are the  
417 food groups exhibiting the highest levels of pesticide residues, along with legumes and whole-grain  
418 cereals [27] while animal foods are generally much less contaminated. Organic farming prohibits the  
419 use of synthetic pesticides and thus organically grown plant-based foods contain fewer and less often  
420 pesticide residues than their conventional counterparts thus allowing to reduce exposure to pesticides  
421 residues [63,64]. However, contaminations by remnant molecules are possible as the conversion  
422 towards organic farming is recent and some molecules are persistent [65].

423 Of note exposure to individual compounds were mostly under ADI but it is now stated that exposure  
424 to low doses of mixture of pesticides residues may be harmful [66].

425 As pesticide use also depends on crop types, the scenarios of gradual increase in plant-based foods led  
426 to increases or decreases in the total exposure. However, the overall food exposure indicator increased  
427 in both farming practices, but was six times more in conventional than in organic farming. All specific  
428 exposures were lower in organic than in conventional farming, except for the molecules which are  
429 authorized in organic farming, namely spinosad and pyrethrins. These findings are in line with those  
430 documented recently as regards the level of diet-related pesticides exposure according to different  
431 diets [28].

432 Knowledge of the increased risk of disease associated with chronic exposure to pesticides, particularly  
433 in the occupational population, is growing [67–69], but ad hoc studies should be conducted in the  
434 general population to better assess the potential risks associated with pesticide mixtures.

435 Consistent with the literature on observational data [13,14,70] or modelled data using optimization  
436 algorithms [11–13], the increase in the contribution of plant-based foods to diet was associated herein

437 with lower environmental pressures. We hence obtained a 65% GHGe reduction for the final scenario  
438 with 95% of energy from plant-based foods compared to the observed situation, which also  
439 corresponds to the difference observed between omnivores and vegetarians [71]. This quantified  
440 reduction corresponds to the lower value of a vegetarian diet reported in the review by  
441 Aleksandrowicz et al. [13] although the LCA were estimated at the farm level only in our study. We  
442 also obtained land use and energy demand decreases, which were of very similar extents whatever the  
443 mode of production. In the organic compared to the conventional production farming system, land  
444 occupation was higher and energy demand was lower, but the differences according farming practices  
445 were attenuated across scenario.

446 However, diets that are much higher in plant-based foods than in animal foods can raise agronomic  
447 issues such as the alternative use of permanent grasslands in case of reduction in livestock farming. In  
448 particular, because some areas, especially mountainous ones, are ideal for livestock farming. It should  
449 also be noted that carbon sequestration is not sufficient to offset beef emissions, in particular because  
450 the carbon sinks are eventually saturated [72]. In that context, some strategies, although insufficient at  
451 present, have been proposed to mitigate gas emissions by ruminants including animal and feed  
452 management, diet formulation and rumen manipulation [73]. Most of the soybeans used for animal  
453 feed in France and Europe are imported from Latin America, which contributes significantly to  
454 deforestation in these countries [74]. Despite public policy efforts [75], this type of soy production is  
455 unsustainable (because it is transported from a far distance) and cannot be part of a sustainable food  
456 system. The high consumption of soy products identified in the present study would therefore require a  
457 reallocation of soybean production locally and appropriate and sustainable management practices to  
458 allow for sustainable soy production for human consumption [76].

459 Overall, our results are coherent with the literature comparing GHG emissions from observed diets  
460 more or less rich in animal products, with lower emissions for diets richer in plant-based foods  
461 [13,14], although such observed diets do not necessarily meet the nutritional requirements.

462 The final scenario (95%PE) had similarities to the 2030 scenario modelled in the Netherlands, except  
463 that it included more fruits and vegetables, less dairy products, and significantly more soy-based  
464 products [77]. Similar to our findings, fish was still needed to ensure EPA+DHA intakes. While the  
465 LCAs used herein are based on the farm perimeter, GHGe were comparable in this study and ours. We  
466 recently conducted a diet optimization model study showing that it is possible to reduce GHGs by 50%  
467 in the NutriNet-Santé population without eliminating all animal-based foods [17]. The present study  
468 demonstrated that, under nutritional constraints, it is possible to further reduce GHGs by up to -65%  
469 by eliminating almost all animal products while meeting nutritional requirements.

470 The acceptability of these diets is questionable, especially since very high fiber intake may cause  
471 intestinal discomfort for certain populations [78]. However, the aim of this work is purely cognitive,  
472 that is, we study the consequences of the degree of vegetation without making recommendations on  
473 the degree to be achieved.



474 Our study has limitations which should be highlighted. First, composition data in terms of amino acids  
475 were not available to better characterize the adequacy of indispensable amino acid beyond that of  
476 protein (nitrogen). However, some literature argues that in countries without protein insufficiency,  
477 these could not be a limiting issue [79]. Second, life cycle assessments were restricted to the  
478 production stage because they were not available in the organic system for the entire system. Although  
479 the production stage is the main source of pressure, it would be interesting to be able to consider the  
480 pressures up to the plate especially for GHGe and energy demand. In addition, it is well documented  
481 that LCA misestimates some ecosystem services in particular for agroecological practices [80]. The  
482 environmental analysis encompassed three major indicators [81] which, although important, are not  
483 sufficient to conduct a comprehensive analysis in particular as regards blue water and biodiversity  
484 loss. Consumption data were collected in 2014 and therefore do not accurately reflect current eating  
485 habits. The same applies to environmental and pesticide residue data. Data will need to be updated to  
486 allow to examine how models may evolve. Finally, participants were volunteers, and therefore  
487 probably more concerned by nutritional issues. Thus, the observed diet (starting point of the  
488 optimization) was already richer in plant-based foods than that of the general population but in the  
489 secondary analysis showed that similar findings were observed even in a group with low plant-based  
490 food in the observed situation.

491 Nonetheless, the strengths of our study are multiple. We used a multicriteria approach when modeling  
492 diets (by considering nutritional requirements, cultural acceptability and coproduction links) and when  
493 evaluating diet impacts (on both health, environment and safety indicators), by moreover  
494 distinguishing between the organic and standard/conventional farming systems. We have considered  
495 the coproduction links between beef and milk, but it would have been interesting to consider the link  
496 between oil and oilcake for rapeseed, for example, but data are lacking to estimate these factors.  
497 Finally, the list of foods was highly detailed, allowing to select those with the most nutritional interest,  
498 and a wide set of nutritional reference values were used, including bioavailability for zinc and iron,  
499 which may be an issue in plant-based diets.

### **Conclusion**

500 This study documented in an original way the possibility to increase the plant part of the diet up to an  
501 extreme level while providing nutritionally adequate diets. This leads to a drastic reduction of some  
502 environmental indicators, in particular land occupation and GHGe, and is therefore an important lever  
503 in the framework of the climate strategy. However, the increase in plant-based foods consumptions  
504 leads to a substantial increase in exposure to pesticide residues, in particular for farming practice using  
505 synthetic pesticides, which should be thoroughly characterized in terms of risk. The increase in the  
506 proportion of plant-based foods in the diet, which is beneficial for both human health and the planet,  
507 must therefore be accompanied by appropriate policies allowing a wide access to plant products with a  
508 low content of pesticide residues (e.g. organic products).

509

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#### **Data availability**

704 Script and data would be available upon reasonable request to the corresponding author  
705 [emmanuelle.kesse-guyot@inrae.fr](mailto:emmanuelle.kesse-guyot@inrae.fr). Researchers from public institutions can submit a collaboration  
706 request including information on the institution and a brief description of the project to  
707 [collaboration@etude-nutrinet-sante.fr](mailto:collaboration@etude-nutrinet-sante.fr). All requests will be reviewed by the steering committee of the  
708 NutriNet-Santé study. A financial contribution may be requested. If the collaboration is accepted, a  
709 data access agreement will be necessary and appropriate authorizations from the competent  
710 administrative authorities may be needed. In accordance with existing regulations, no personal data  
711 will be accessible.

#### **The authors' contributions**

712 EKG, BL, PR, SH, DL, PP and JB, conducted the research and implemented databases.  
713 EKG conducted the diet optimization and BA, HF, AD, FM and JB provided intellectual guidance.  
714 EKG performed statistical analyses and drafted the manuscript.  
715 All authors critically helped in the interpretation of results, revised the manuscript and provided  
716 relevant intellectual input. They all read and approved the final manuscript.  
717 EKG had primary responsibility for the final content, she is the guarantor.

#### **Conflict of Interest**

718 No author declared conflict of interest.

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726 to submit the paper.

727 **Table 1: Nutritional constraints used in the optimization models**

Unit		Men		Women		Average individual <sup>1</sup>	
		Lower reference	Upper reference	Lower reference	Upper reference	Lower reference	Upper reference
Energy intake	Kcal/d	ER - 8%	ER + 8%	ER - 8%	ER + 8%	ER - 8%	ER + 8%
Protein	kg of BW/d	0.83	2.3	0.83	2.3	0.83	2.3
Vitamin A	µg/d	750	3000	650	3000	700	3000
Vitamin B1	µg /1000 kcal/d	0.3	-	0.3	-	0.3	-
Vitamin B2	mg /1000 kcal/d	0.55	-	0.55	-	0.55	-
Vitamin B3	µg /1000 kcal/d	5.44	900	5.44	900	5.44	900
Vitamin B5	mg/d	P5	-	P5	-	Weighted P5	-
Vitamin B6	mg/d	1.7	25	1.6	25	1.65	25
Vitamin B9	µg/d	330	-	330	-	330	-
Vitamin B12	µg/d	4	-	4	-	4	-
Vitamin C	mg/d	110	-	110	-	110	-
Vitamin E	g/d	P5	-	P5	-	Weighted P5	-
Vitamin K	µg/d	P5	-	P5	-	Weighted P5	-
Calcium	mg/d	950	2500	950	2500	950	2500
Copper	mg/d	P5	5	P5	5	Weighted P5	
Bioavailable Iron	mg/d	1.76	-	2.56 / 1.76 <sup>2</sup>	-	1.92	-
Iodine	µg/f	150	600	150	600	150	600
Magnesium	mg/d	P5	-	P5	-	Weighted P5	-
Manganese	mg/d	P5	-	P5	-	Weighted P5	-
Phosphorus	mg/d	550	-	550	-	550	-
Potassium	mg/d	3500	-	3500	-	3500	-
Selenium	µg/d	70	300	70	300	70	300
Sodium	mg/d	1500	2300	1500 mg	2300	1500	2300
Bioavailable zinc	mg/d	(0.642 + 0.038 kg of body weight)		(0.642 + 0.038 kg of body weight)		3.3 <sup>3</sup>	
Saturated fatty acids	% EI/d	-	12	-	12	-	12
Linoleic acid	% EI/d	4	-	4	-	4	-
Alpha-linolenic acid	% EI/d	1	-	1	-	1	-
linoleic acid / alpha-linolenic acid	-	-	5	-	5	-	5

eicosapentaenoic acid + docosahexaenoic acid	g/d	0.5	-	0.5	-	0.5	-
Sugar without lactose	g/d	-	100	-	100	-	100
fibre	g/d	30	-	30	-	30	-

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728 Abbreviations: ER, energy requirement;

729 <sup>1</sup> The average individual was the weighted mean as follows: 50% men, 25% women M<sup>-</sup>, 25% M<sup>+</sup>

730 <sup>2</sup> High and low iron requirements

731

732 **Table 2: Nutritional and health indicators across scenarios of increase in % of energy from**  
 733 **plant-based foods<sup>1</sup>**

	Obs	65% basal	$\Delta 65\%$ vs. obs	70%	75%	80%	85%	90%	95%	$\Delta 95\%$ vs. obs	$\Delta 95\%$ vs. 65%
<b>Nutrients</b>											
EI (Kcal/d)	2001	2370	18%	2372	2461	2380	2370	2370	2375	19%	0%
EI from plant-based food (Kcal/d)	1415	1658	17%	1661	1846	1904	2016	2134	2256	59%	36%
EI from animal-based food (Kcal/d)	586	713	22%	711	615	475	355	236	119	-80%	-83%
EI from plant food (%)	71	70	-2%	70	75	80	85	90	95	34%	36%
Protein intake (g/d)	91	107	18%	107	103	95	87	81	77	-15%	-28%
% EI from protein	18	18	0%	18	17	16	15	14	13	-28%	-28%
Plant protein (g/d)	29	37	27%	37	41	44	48	53	63	118%	72%
Animal protein (g/d)	62	70	13%	70	62	51	39	28	14	-78%	-80%
% Protein from plant-based food	31	34	11%	35	40	47	55	65	82	164%	138%
Vitamin B12 (µg/d)	6.5	7.09	9%	7.08	6.7	6.5	6.36	6.37	4	-38%	-44%
DHA+EPA (g/d)	0.44	0.50	14%	0.50	0.50	0.50	0.50	0.50	0.50	14%	0%
Selenium	81.34	87.53	8%	87.52	85.7	81.15	73.1	70.43	74.18	-9%	-15%
Potassium	3808	3560	-7%	3561	3616	3652	3660	3838	4769	25%	34%
Vitamin B9	419.42	424.37	1%	424.54	438.64	467.6	500.5	574.62	719.88	72%	70%
Bioavailable zinc (mg/d)	3.3	3.41	3%	3.4	3.3	3.3	3.3	3.3	3.3	0%	-3%
Bioavailable iron (mg/d)	1.7	2.06	21%	2.06	2.02	2.06	2.09	2.2	2.29	35%	11%
Calcium (mg/d)	1115	948	-15%	948	948	947	947	947	950	-15%	0%
Fibers (g/d)	23.35	30	28%	30	32.32	34.87	36.68	40.15	47.84	105%	59%
Sodium (mg/d)	2502	2294	-8%	2294	2294	2294	2294	2294	2300	-8%	0%
<b>Indexes</b>											
PANDiet	64.98	70.28	8%	70.32	72.11	77.92	81.24	81.12	81.97	26%	17%
PANDiet adequation subscore	78.86	93.51	19%	93.51	93.45	93.54	93.53	93.69	93.85	19%	0%
PANDiet moderation subscore	51.1	47.06	-8%	47.12	50.77	62.3	68.95	68.56	70.08	37%	9%
cDQI	48.43	63.88	32%	63.89	64.56	65.83	56.55	55.75	58.7	21%	-8%
pDQI	32.86	42.6	30%	42.59	42.45	43.75	43.33	42.4	44.58	36%	5%
aDQI	15.57	21.28	37%	21.29	22.11	22.07	13.22	13.35	14.12	-9%	-34%
PNNS-GS2	2.73	6.25	129%	6.25	6.73	7.25	6.75	6.75	6.75	147%	8%

734 Abbreviations: aDQI, animal diet quality index; cDQI, diet quality index; DHA, docosahexaenoic  
 735 acid; EPA, eicosapentaenoic acid; PANDiet, Diet Quality Index Based on the Probability of Adequate  
 736 Nutrient Intake; sPNNS-GS2: simplified Programme National Nutrition Santé guidelines score; Obs,  
 737 observed diet; pDQI, plant diet quality index; PUFA, polyunsaturated fatty acids;  
 738 <sup>1</sup>Values are estimates for incremental 5% increases in the % of energy intake from plant-based foods.  
 739 The basal scenario (65%) correspond to the modelled diet when the proportion of energy intake from  
 740 plant-based foods is set at the observed value of proportion of energy intake from plant-based foods  
 741 under nutritional, fish consumption limitation and coproducts constraints. Next scenarios increase  
 742 plant-based foods energy from 65% up to 95%.

743 **Table 3: Environmental indicators for observed diet and trajectories of increase in proportion of**  
 744 **energy intake from plant-based foods<sup>1</sup>**

	Obs	65%	$\Delta_{65\% \text{ vs. obs}}$	70%	75%	80%	85%	90%	95%	$\Delta_{95\% \text{ vs. obs}}$	$\Delta_{95\% \text{ vs. 65\%}}$
100% conventional production											
GHGe (kgCO <sub>2</sub> eq/d)	4.06	4.57	13%	4.56	4.08	3.58	3.03	2.17	1.46	-64%	-68%
Energy demand (MJ/d)	18.14	19.43	7%	19.41	18.06	15.97	13.69	11.92	9.37	-48%	-52%
Land occupation (m <sup>2</sup> /d)	9.79	11.56	18%	11.55	10.57	9.54	8.33	6.11	4.48	-54%	-61%
100% organic production											
GHGe (kgCO <sub>2</sub> eq/d)	4.09	4.68	14%	4.67	4.13	3.61	3.03	2.14	1.44	-65%	-69%
Energy demand (MJ/d)	16.63	18.74	13%	18.71	17.4	15.52	13.51	11.58	9.54	-43%	-49%
Land occupation (m <sup>2</sup> /d)	13.35	15.74	18%	15.72	14.29	12.67	10.88	7.98	5.81	-56%	-63%

745 Abbreviations: GHGe, greenhouse gas emissions; Obs, observed diet

746 <sup>1</sup>Values are estimates for incremental 5% increases in the % of energy intake from plant-based foods.

747 The basal scenario (65%) correspond to the modelled diet when the proportion of energy intake from

748 plant-based foods is set at the observed value of proportion of energy intake from plant-based foods

749 under nutritional, fish consumption limitation and coproducts constraints. Next scenarios increase

750 plant-based foods energy from 65% up to 95%.

**Figure 1: Composition (g/d) of the observed and optimized scenarios modelling modelled diets with gradual increase in the proportion of energy intake from plant-based foods<sup>1,2</sup>**

Abbreviations: Obs, observed diet. <sup>1</sup>Food group consumption (g/d) in the observed diets and in the modelled diets being nutritionally, culturally and environmentally optimized so as to ensure gradual increase in the proportion of energy intake from plant-based foods. The basal scenario (65%) correspond to the modelled diet when the proportion of energy intake from plant-based foods is set at the observed value of proportion of energy intake from plant-based foods under nutritional, fish consumption limitation and coproducts constraints. Next scenarios increase plant-based foods energy from 65% up to 95%.

<sup>2</sup>Vegetables include all vegetables and soups, fruit include fresh fruit, fruit in syrup and compote, dried fruit and seeds, fish include seafood, dairy product include yogurts, fresh cheese and cheese, potatoes include other tubers, cereals include breakfast cereal low in sugar, bread semolina, rice and pasta, sweet and fat foods include croissants, pastries, chocolate, biscuits, milky dessert, ice cream, honey and marmalade, cakes, chips, salted oilseeds, salted biscuits, beverages include fruit nectar, syrup, soda (with or without sugar), plant-based beverages (except soy-based), milk consumed with tea/coffee, fast-food include sandwich, prepared foods such as pizza, hamburger, ravioli, panini, salted pancake, etc., soy-based food include tofu, soy meat substitute and vegetable patties, soy yogurt, soy milk, and fats include fresh cream and butter.

**Figure 2: Estimated daily exposure to pesticide residues ( $\mu\text{g}/\text{kg bw}/\text{day}$ ), in observed and modelled diets with gradual increase in proportion of energy intake from plant-based foods, according to 100%-conventional and 100%-organic modelling<sup>1,2,3</sup>**

Abbreviations: ADI: acceptable daily intake; Obs, observed diet.

<sup>1</sup>The basal scenario (65%) correspond to the modelled diet when the proportion of energy intake from plant-based foods is set at the observed value of proportion of energy intake from plant-based foods under nutritional, fish consumption limitation and coproducts constraints. Next scenarios increase plant-based foods energy from 65% up to 95%.

<sup>2</sup>The overall estimation is calculated as the sum of individual exposure weighted by 1/DJA (without anthraquinone which has no ADI)

<sup>3</sup>Natural pyrethrins and Spinosad are authorized in certified organic production.

**Figure 3: Variations in the composition (g/d) of the observed diet and 95% energy from plant food modelled diets according to observed level of plant food consumption<sup>1,2</sup>**

Abbreviations: Obs, observed diet. SFF, sweet and fat foods

“Obs Low” corresponds to observed consumption in the group with at least 50% of energy from plant food at baseline.

“Obs Mid” corresponds to observed consumption in the group with at least 65% of energy from plant food at baseline.

“Obs High” corresponds to observed consumption in the group with at least 80% of energy from plant food at baseline.

“95% Low” corresponds to the final scenario in the group with at least 50% of energy from plant food at baseline.

“95% Mid” corresponds to the final scenario in the group with at least 65% of energy from plant food at baseline.

“95% High” corresponds to the final scenario in the group with at least 80% of energy from plant food at baseline.

<sup>1</sup>Food group consumption (g/d) in the observed diets and in the 95%PE model according initial %PE.

<sup>2</sup>Vegetables include all vegetables and soups, fruit include fresh fruit, fruit in syrup and compote, dried fruit and seeds, fish include seafood, dairy product include yogurts, fresh cheese and cheese, potatoes include other tubers, cereals include breakfast cereal low in sugar, bread semolina, rice and pasta, sweet and fat foods include croissants, pastries, chocolate, biscuits, milky dessert, ice cream, honey and marmalade, cakes, chips, salted oilseeds, salted biscuits, beverages include fruit nectar, syrup, soda (with or without sugar), plant-based beverages (except soy-based), milk consumed with tea/coffee, fast-food include sandwich, prepared foods such as pizza, hamburger, ravioli, panini, salted pancake, etc., soy-based foods include tofu, soy meat substitute and soy yogurt, soy milk, and fats include fresh cream and butter.