



HAL
open science

Dietary protein consumption profiles show contrasting impacts on environmental and health indicators

Elie Perraud, Juhui Wang, Marion Salomé, François Mariotti, Emmanuelle Kesse-Guyot

► To cite this version:

Elie Perraud, Juhui Wang, Marion Salomé, François Mariotti, Emmanuelle Kesse-Guyot. Dietary protein consumption profiles show contrasting impacts on environmental and health indicators. *Science of the Total Environment*, 2023, 856 (1), pp.159052. 10.1016/j.scitotenv.2022.159052 . hal-03823126

HAL Id: hal-03823126

<https://hal.science/hal-03823126v1>

Submitted on 20 Oct 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

Author File

1 Title: Dietary protein consumption profiles show contrasting impacts
2 on environmental and health indicators.

3 Authors: Elie Perraud¹, Juhui Wang¹, Marion Salomé¹, François Mariotti^{1##}, Emmanuelle Kesse-Guyot^{2#},

4 Affiliations:

5 ¹ Université Paris-Saclay, AgroParisTech, INRAE, UMR PNCA, 75005, Paris, France

6 ² Sorbonne Paris Nord University, Institut National de la Santé et de la Recherche Médicale
7 (INSERM), Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement
8 (INRAE), Conservatoire National des Arts et Métiers (CNAM), Nutritional Epidemiology Research
9 Team (EREN), Epidemiology and Statistics Research Center–University of Paris (CRESS), Bobigny,
10 France

11 # these authors contributed equally to this work.

12 * to whom correspondence should be addressed, at francois.mariotti@agroparistech.fr

13

14 **Financial support:**

15 This research received no external funding.

16 **Conflict of Interest**

17 None.

18 **Number of tables:** 1

19 **Number of figures:** 3

20 **Supplemental material:** 25

21

22

Author File

23 Abstract

24 Patterns of protein intake are strong characteristics of diets, and protein sources have been linked to
25 the environmental and nutrition/health impacts of diets. However, few studies have worked on protein
26 profiles, and most of them have focused on specific diets like vegetarian or vegan diets. Furthermore,
27 the description of the environmental impact of diets has often been limited to greenhouse gas
28 emissions (GHGe) and land use. This paper analyzes the alignment of environmental pressures and
29 nutritional impacts in a diversity of representative protein profiles of a western population.

30 Using data from a representative survey in France (INCA3, n = 1,125), we identified protein profiles
31 using hierarchical ascendant classification on protein intake (g) from main protein sources (refined
32 grains, whole grains, dairy, eggs, ruminant meat, poultry, pork, processed meat, fish, fruits &
33 vegetables, pulses). We assessed their diet quality using 6 dietary scores, including assessment of
34 long-term risk for health, and associated 14 environmental pressure indicators using the Agribalyse
35 database completed by the SHARP database for GHGe.

36 Five protein profiles were identified according to the high contributions of ruminant meat, pork,
37 poultry, fish, or, conversely, as low contribution from meat. The profile including the lowest protein
38 from meat had the lowest impact on almost all environmental indicators and had the lowest long-term
39 risk. Conversely, the profile with high protein from ruminant-based foods had the highest pressures on
40 most environmental indicators, including GHGe.

41 We found that the protein profile with low contribution from meat has great potential for human health
42 and environment preservation. Shifting a large part of the population toward this profile could be an
43 easy first step toward building a more sustainable diet.

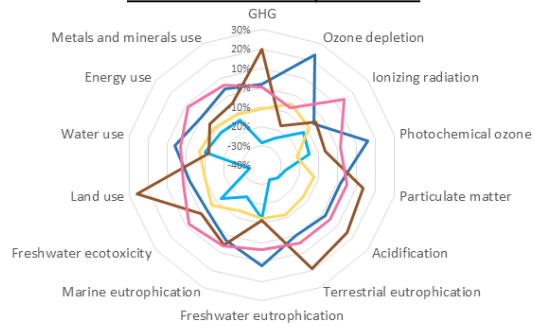
44

Author File

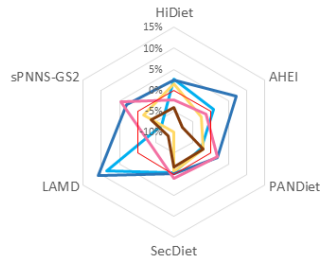
Protein profiles



Environmental pressure



Diet quality



Author File

- 46 List of abbreviation and acronyms
- 47 ADEME: *Agence de la transition écologique*
- 48 AHEI-2010: Alternative Healthy Eating Index
- 49 CIQUAL: *French Centre d'Information sur la Qualité des Aliments*
- 50 CTUe: Comparative Toxic Unit for ecosystems
- 51 DHA: docosahexaenoic acid
- 52 EPA: eicosapentaenoic acid
- 53 GHGe: greenhouse gas emission
- 54 INCA3: Third individual and national study on food consumption survey
- 55 LAMD: Literature-Based Adherence Score to the Mediterranean Diet
- 56 LCA: life cycle analyses
- 57 LCI: life cycle inventory
- 58 NMF: Non-negative Matrix Factorization
- 59 PM: particulate matter PUFA: polyunsaturated fatty acids
- 60 sPNNS-GS2: simplified *Programme National Nutrition Santé* Guideline Score 2
- 61

Author File

62

63 1 Introduction

64 Chronic diseases strongly influenced by diets are leading causes of morbidity and mortality around the
65 world (GBD 2013 Mortality and Causes of Death Collaborators, 2015). The food systems underlying
66 these diets are responsible for a third of global greenhouse gas emissions (GHGe) (Crippa et al., 2021)
67 and influence several other environmental indicators (Willett et al., 2019). More and more studies are
68 showing the significant environmental pressures of meat and dairy food production compared to plant
69 food production (González et al., 2011; Nijdam et al., 2012). For example, beef produces 7.1 g protein
70 /kg CO₂ eq compared to beans producing 246 g protein/kg CO₂ eq (González et al., 2011). The same
71 relationship was seen for land use with beef protein needing between 15 m². y⁻¹. kg⁻¹ in industrial
72 systems to 420 m². y⁻¹. kg⁻¹ for extensive pastoral systems in contrast to pulses needing between 3 to 8
73 m².y.kg⁻¹ for the production of 1kg of protein (Nijdam et al., 2012). The amount of water used for
74 protein production shows similar extremes of variation, with beef using 728 L/100 grams of protein,
75 and peas and other pulses using around 200 L/100 grams of protein (Ritchie and Roser, 2020).

76 Protein profiles largely define diets (De Gavelle et al., 2018; Marini et al., 2021), since protein food
77 sources contribute other nutrients that tend to cluster together as a “protein package”, e.g. SFA and
78 absorbed iron with red meat and fiber and PUFA with plant protein sources (Mariotti, 2019). They are
79 also associated with other types of foods as part of dietary patterns (De Gavelle et al., 2018;
80 de Gavelle et al., 2019; Mariotti, 2019). Protein profiles in diets are thus key to both environmental
81 and health issues (Clarys et al., 2014; González-García et al., 2018; Seconda et al., 2018).

82 Several diets have been modeled to improve the population’s health while concomitantly considering
83 the environmental issues. These diets display drastic differences in protein profile compared to current
84 westernized diets (Kramer et al., 2017; Seconda et al., 2021; Willett et al., 2019; Wilson et al., 2019).
85 For example, the EAT-Lancet diet includes higher consumption of fruit, vegetable, and whole grains,
86 and is very low in red and processed meat (Willett et al., 2019). This shift in plant and animal sources
87 tend to reverse the plant-animal protein ratio compared to the one observed in modern diets. In the
88 EPIC Oxford study, when compared to a high meat diet, a low meat diet (<50 g/day), was associated

Author File

89 with a lower carbon footprint by 920 kg CO₂eq every year (Scarborough et al., 2014). Similarly, the
90 association between the consumption of food group sources of protein and long-term health has been
91 widely studied (Micha et al., 2017a; Turner and Lloyd, 2017). For example, red and processed meats
92 have been associated with several non-communicable diseases like colorectal carcinoma, type 2
93 diabetes, and cardiovascular disease (Boada et al., 2016; Micha et al., 2010). In contrast, plant protein
94 intakes have been associated with long-term health benefits (Mariotti, 2019; Naghshi et al., 2020).
95 Thus, compliance with dietary guidelines (Herforth et al., 2019), including those from France (Chaltiel
96 et al., 2019), implies a shift of the dietary protein patterns to diets that include lowering meat
97 consumption in some subgroups of the population in Western countries (Brunin et al., 2021; Dagevos,
98 2021). Many healthy dietary patterns promoted via states official national guidelines include specific
99 recommendations regarding protein sources (Canada, 2020; Chang and Koegel, 2017; ODPHP, 2021).
100 However, contemporary data specifying the link between diet and its impact on both the health and
101 environment is primarily based on single food groups rather than dietary profiles, and does not focus
102 specifically on protein patterns.

103 It is important to note that studies that intended to depict the sustainability of diet profiles rather than
104 of isolated food groups have focused mostly on restrictive diets consumed by a minority, such as
105 vegetarian or vegan diets, which were compared with the whole omnivore population (Chai et al.,
106 2019; Fresán and Sabaté, 2019; Rabès et al., 2020; Rosi et al., 2017). Still, no literature to date has
107 studied the intermediate proteins profiles that represent most of the profiles seen in the population.

108 Furthermore, while several criteria are used to estimate the nutritional or health value of diets, very
109 few environmental indicators are reported. Indeed, most studies limit their indicators to GHGe and
110 land occupation (Aleksandrowicz et al., 2016; Jones et al., 2016). Although these two indicators are
111 important, often a markers of the whole environmental footprint (Kramer et al., 2017), they remain
112 limited in depicting the environmental impact along several dimensions.

113 In order to inform the future diet transition, it is essential to advance accurate knowledge on the
114 relationship between dietary profiles as naturally occurring in the diversity of people diets, and
115 environmental pressures, and nutritional/health quality. In the present study, we aimed to analyze the

Author File

116 potential alignment between environmental pressures and nutritional/health impacts of the main
117 protein profiles identified in a French representative population.

118 2 Methods

119

120 2.1 Studied population and dietary data

121 This study used data from the third individual and national study on food consumption survey
122 (INCA3) performed in France between 2014 and 2015 (Dubuisson et al., 2019; French Agency for
123 Food, Environmental and Occupational Health Safety (ANSES), 2017). 347 participants identified as
124 under-reporters were excluded using the basal metabolic rate as estimated by the Henry equation
125 (Henry, 2005), using the cut-off values recommended by Black (Black, 2000). Since nutrient
126 requirements for older adults differ from younger ones, the 649 older adults (above 54 years old for
127 women and 64 years old for men) were excluded. The final sample was composed of 1125 adults,
128 including 564 men and 561 women.

129 Data were collected by three non-consecutive 24h-dietary recalls (two during the week and one at the
130 weekend) over a 3-week period. The nutrient content values of the food were extracted from the 2016
131 database of the *French Centre d'Information sur la Qualité des Aliments* (CIQUAL) (ANSES, 2016).

132

133 2.2 Diet quality assessment

134 Six scores were used to compare the different impacts of the diet on health and nutritional status.

135 Three of them evaluated the adherence to a specific diet or dietary recommendations were calculated.

136 The Literature-Based Adherence Score to the Mediterranean Diet (LAMAD) assesses adherence to the
137 Mediterranean diet. The LAMAD score includes three negative components (meat, dairy products, and
138 alcohol) and six positive components (fruits, vegetables, legumes, grains, fish, and olive oil). The
139 consumption of each food group is classified into three categories using cutoff points (Supplemental

Author File

140 Table 1)(Sofi et al., 2014). The Alternative Healthy Eating Index (AHEI-2010) is a modified Healthy
141 Eating Index, assessing the adherence to *Dietary Guidelines for Americans*, improving target food
142 choices and macronutrient sources associated with reduced chronic disease risk (Chiuve et al., 2012).
143 Since information on *trans* fatty acids was not available, only ten parameters were considered, namely
144 vegetables, fruit, whole grains, sugar-sweetened beverages and fruit juice, nuts and legumes,
145 red/processed meat, long-chain (n-3) fatty acids (EPA + DHA), polyunsaturated fatty acids (PUFA),
146 sodium, and alcohol. All AHEI-2010 components were scored from 0 (worst) to 10 (best), resulting in
147 a total AHEI-2010 score ranging from 0 (non-adherence) to 100 (perfect adherence). The scoring
148 criteria are described in Supplemental Table 2. The sPNNS-GS2 (simplified *Programme National*
149 *Nutrition Santé* Guideline Score 2) assesses the adherence to the French Food-based Dietary
150 Guidelines (Chaltiel et al., 2019). Components, scoring and weighting are shown in Supplemental
151 Table 3.

152 The PANDiet evaluates the probability of adequate nutrient intake. This score is a 100-point
153 probabilistic score evaluating adequate overall nutrient intake. It combines an adequacy sub-score and
154 a moderation sub-score. The adequacy sub-score is calculated as the average probability of adequacy
155 of nutrients for which the usual intake should be above a reference value, multiplied by 100. For a
156 given nutrient, the probability of adequacy was determined from either the Estimated Average
157 Requirement or the Adequate Intake, and its variability. The moderation sub-score was calculated as
158 the average of probabilities of inadequacy of six nutrients for which an upper bound reference value
159 exists, together with penalty values. For the six nutrients, the probability of adequacy was calculated,
160 using the upper bound of the acceptable macronutrient distribution range (De Gavelle et al., 2018).

161 The SecDiet evaluates nutrient deficiency risk. This score is based on the intake of twelve critical
162 nutrients for nutritional risk of overt deficiency (Salomé et al., 2021). For each nutrient, we calculated
163 the probability of having sufficient-enough intake to avoid overt nutrient deficiency. We used the
164 probability distribution of the standard normal distribution for nutrient requirements while taking into
165 account the mean intake, the day-to-day intake variability, the inter-individual variability and the
166 nutrient deficiency threshold.

Author File

167 The HiDiet was used to assess the diet impact on long-term mortality and morbidity (Perraud et al.,
168 2022). The HiDiet score is based on the principle of the Comparative Risk Assessment but applied to
169 the risk of one individual and so is an individual version of the EpiDiet (Evaluate the Potential Impact
170 of a Diet) (Dussiot et al., 2022; Kesse-Guyot et al., 2020). The conceptual basis and methodological
171 foundation of the two models are the same which are laid out in the Comparative Risk Assessment
172 framework. It allows for the evaluation of the potential impacts of dietary changes on the long-term
173 morbidity and mortality caused by some diet-related diseases.

174 In this study, we set up the HiDiet model with values reported in a series of validated international
175 meta-analyses published by a European team (Bechthold et al., 2019; Schwingshackl et al., 2019,
176 2018, 2017a, 2017b). As in our previous study (Dussiot et al., 2022), we selected 12 diet-related
177 factors (including consumption of fruit, vegetables, nuts or seeds, whole grains, unprocessed red
178 meats, processed meats, sugar-sweetened beverages, fish, dairy products, eggs, refined grains, and
179 legumes) and 4 diet-related diseases (including coronary heart disease, stroke, type 2 diabetes, and
180 colorectal cancer).

181 The reference population considered was the French adult population (18 and 64 years old) in 2014,
182 stratified into sub-populations by 5-year age-bands and sex. The population demographics and
183 national disease-specific deaths were provided by the National Institute of Statistics and Economic
184 Studies (INSEE, 2017), and by the Epidemiological Centre on Medical Causes of Death (CépiDc,
185 2018), respectively. For each individual, two dietary scenarios were built. Here, the two scenarios that
186 are compared are the baseline one, where the individual daily intakes (of each food and beverage
187 group) is the average daily intake in the general population but keeping the individual characteristics
188 (age, sex), and the counterfactual scenario is the present situation of the individual, i.e. its actual
189 consumption. Using these two scenarios, it is possible to assess the positive or negative impact of a
190 dietary change from the first one to the other.

191

192

Author File

193 2.3 Protein profile

194 Protein foods were defined as foods having more than 10% of their energy as protein and providing at
195 least 5g/d of protein in high consumers (i.e. at the 90th percentile of the INCA3) (De Gavelle et al.,
196 2018). Protein foods were then classified into twelve groups of protein sources (refined grains, whole
197 grains, dairy, eggs, ruminant meat, poultry, pork, processed meat, fish, fruits – vegetables, pulses, and
198 others) exhibiting differences in nutritional properties and according to classical dietary classification.
199 Each individual daily intake of protein from a protein group was then calculated by summing the
200 protein intake from the consumption of each food of that group.

201

202 2.4 Agribalyse database and environmental database

203 The Agribalyse database was used to assess environmental indicators of the diet. This database was
204 developed by the *Agence de la transition écologique* (ADEME) using life cycle analyses (LCA) to
205 assess the environmental pressure of foods eaten in France between 2005 and 2009 with a scope "from
206 field to plate" (ADEME, 2020a). Agribalyse is a database reporting 14 environmental indicators
207 (Supplemental Method 1): greenhouse gas emissions in carbon dioxide equivalent (kg CO₂ eq);
208 exposure ionizing radiation in equivalent of kilobecquerels of Uranium 235 (kg U₂₃₅ eq);
209 photochemical ozone (O₃) formation in equivalent of kilograms of non-methane volatile organic
210 compounds (kg NMVOC eq); ozone depletion in equivalent of kilograms of trichlorofluoromethane
211 (Freon-11); emission of particulate matter in change in mortality due to particulate matter emissions;
212 acidification in equivalent of moles hydron (mol H⁺ eq); terrestrial eutrophication in equivalent of
213 moles of nitrogen (mol N eq); freshwater eutrophication in equivalent of kilograms of phosphorus (kg
214 P eq); marine eutrophication in equivalent of kilograms of nitrogen (kg N eq); freshwater ecotoxicity
215 in Comparative Toxic Unit for ecosystems (CTUe) an indicator based on a model called USEtox;
216 water use in cubic meters of water; land use in loss of soil organic matter content in kilograms of
217 carbon deficit (kg C deficit); fossils resource use in MJ; and metals and minerals resource use in
218 equivalent of kilograms of antimony (kg Sb eq). Agribalyse assessed the environmental pressures of

Author File

219 both single and multi-ingredients foods. Further description of the Agribalyse method is presented in
220 Supplemental Method 1.

221 Here the Agribalyse database was used to assess the food eaten as listed in INCA3 (n= 1761)
222 (Supplemental Figure 1). Two different methods were used to complete the database resulting in 46
223 missing data: one specifically for GHGe and a second one for the other environmental impacts in
224 Agribalyse (the method is described in detail in Supplemental Figure 2 and Supplemental Figure 3).

225 Data from the SHARP database were used to complete missing values for the GHGe indicator
226 (Mertens et al., 2019). This database also includes data on land use but because the unit is different,
227 we were unable to impute the data. Supplemental method 2 explains the process of merging the
228 Agribalyse and SHARP database to the foods eaten in the population.

229 2.5 Statistical analysis

230 We performed a cluster analysis, using a data driven approach to group the INCA3 individual
231 participants into separate protein profile. First, we used a Non-negative Matrix Factorization (NMF)
232 on 11 main protein groups. The protein group composed of the varied other types of protein foods was
233 not included to keep factors interpretability. NMF is a method for identifying independent factors
234 adapted for non-negative data with excess zeros (Lee and Seung, 1999) and has already been used by
235 our team to identify dietary profiles in another survey (De Gavelle et al., 2018). Specifically, the Ls-
236 nmf method (Wang et al., 2006) was used, and decomposition in six factors was conserved since it had
237 the best R² value. Then we used hierarchical ascendant classification on the factors to identify protein
238 profiles in the population. The number of clusters chosen was based on both the elbow and silhouette
239 methods (Kaufman and Rousseeuw, 2005). The consumption of the 12 proteins groups between all
240 profiles was compared using an ANOVA. The environmental indicators and diet quality scores of the
241 protein profiles were compared using an ANCOVA adjusted for energy intake. Two by two
242 comparison were made using Tuckey adjustment. Statistical analyses were performed using SAS
243 software (version 9.4, SAS Institute Inc, Cary, NC, USA) and R version 4.0.3.

244

Author File

245 3 Results

246 3.1 Food group consumption and environmental and nutritional indicators

247 3.1.1 Consumption

248 The hierarchical ascendant classification identified five distinct profiles (figure 1). The characteristics
249 of the population and the different profiles are described in Table 1. Profile 1 (Low meat profile)
250 represents consumers with a low protein intake from meat (9 g/day vs. 20.8 g/day in the total
251 population), who also have a relatively higher intake of protein from dairy products (13.9 g/day vs. 9.8
252 g/day in the total population). Supplemental Table 5 shows that the higher dairy protein intake mostly
253 comes from the higher consumption of milk (88 g/day vs. 80 g/day in the total population) and cheese
254 (54 g/day vs. 42 g/day in the total population).

255 Profile 2 (Poultry profile) represents people with high intakes of protein from poultry (10.8 g/day vs.
256 5.3 g/day in the total population), while profile 3 (Fish profile) represents individuals with the highest
257 fish protein intake (9.6 g/day vs. 4.4 g/day in the total population). Profile 4 (Ruminant meat profile)
258 represents individuals whose protein intake is largely contributed by ruminant meat proteins (12.4
259 g/day vs. 6.1 g/day in the total population), and profile 5 (Pork profile) represents people with high
260 intakes of protein from pork (9.6 g/day vs. 2.7 g/day in the total population).

261 The consumption of 33 food groups in grams per day is also presented in Supplemental Table 5.

262 3.1.2 Environmental indicators

263 Figure 2 presents the environmental indicators for each protein profile (see Supplemental Table 6).
264 The profile with high intake of protein from ruminant has the highest environmental pressure for 5 of
265 the 14 indicators. Notably, this profile also has the highest GHGe (7.7 kg CO₂ eq/day vs. 6.4 kg CO₂
266 eq/day in the total population). Compared to the total population, the land use, the emission of
267 particulate matter, the acidification, and the terrestrial eutrophication are also at their highest for this
268 profile, being 26%, 14%, 16%, and 19% higher, respectively.

Author File

269 The profile with high intake of protein from fish and the one with the highest pork protein intake have
270 the next most elevated GHGe (6.6 kg CO₂ eq/day and 6.4 kg CO₂ eq/day). For the other indicators,
271 these two profiles are different. The profile with high intake of protein from pork contributes the most
272 to freshwater ecotoxicity (164 CTUe/day vs. 151 CTUe/day in the total population), marine
273 eutrophication (26 kg N eq/day vs. 25 kg N eq/day in the total population), ionizing radiation (1.7 kg
274 U235eq/day vs. 1.5 kg U235eq/day in the total population), energy use (67 MJ/day vs. 62 MJ/day in
275 the total population), and metals and minerals use (10.3 kg Sb eq/day vs. 9.7 kg Sb eq/day in the total
276 population). For profile with high intake of protein from fish, it contributes the most to ozone
277 depletion (0.73 Freon-11/day vs. 0.59 Freon-11/day in the total population), photochemical ozone (20
278 kg NMVOC/day vs. 17 kg NMVOC/day in the total population), freshwater eutrophication (1.15kg P
279 eq/day vs. 1.03 kg P eq/day in the total population) and water use (7.1m³/day of water vs. 6.7 1m³/day
280 of water in the total population).

281 The profiles with the lowest environmental impacts are the poultry profile and the low meat profile.
282 These profiles emit the smallest amount of GHGe with 5.6 kg CO₂ eq/day for the high consumers of
283 poultry protein and 4.6 for the low meat consumers. This last profile has the lowest impact for most
284 environmental indicators (11 from the 14 indicators) and is the second-best profile for the three others.

285 Supplemental Figures 3 to 16 show the variability of the environmental indicators for each food group,
286 and Supplemental Table 7 describes each food group's contribution to every environmental indicator
287 for each profile.

288 3.1.3 Nutritional quality

289 Figure 3 shows the nutritional and health scores of the different profiles. The profile with high fish
290 consumers has the highest scores for the AHEI, the LAMD, and the second-best score for the
291 PNNSGS2, the SecDiet, the PANDiet, and the HiDiet. The profile with the lowest meat protein
292 consumption has the highest HiDiet score, and the one with the highest ruminant meat protein intake
293 has the lowest HiDiet score (respectively +3% and -4% compared to the total population). The profile
294 with the lowest meat protein consumption also has the lowest PANDiet (-3%) and a neutral SecDiet
295 (0%) score. The value of the health scores are presented in Supplemental Table 8.

Author File

296 4 Discussion

297 In this study, we have identified five distinct profiles based on protein consumption, which show the
298 variety of protein consumption patterns. These patterns are easy to interpret, and display contrasting
299 characteristics on both environmental and nutritional/health dimensions.

300

301 4.1 Environmental differences between profiles

302 The high ruminant meat protein consumption profile was one of the worst regarding health scores and
303 environmental indicators. This is in line with the modeled diets and dietary guidelines featuring low
304 red meat intake (Kesse-Guyot et al., 2020; Willett et al., 2019). Although ruminant meat is well known
305 for its high environmental pressures from GHGe and land use (Clark et al., 2018; Poore and Nemecek,
306 2018), our study has shown that actual protein intake from meat is also associated with other
307 environmental pressures. The particulate matter (PM) production is significantly higher in the diet of
308 people with high intake of protein from ruminant meat. This is in part ascribed to ruminant meat with
309 a high production of PM coming from manure (Garcia et al., 2013). It could be argued that this is not
310 an important issue given the small percentage of particulate matter coming from agriculture compared
311 to other sources like transport (Cambra-López et al., 2010). However, this percentage is growing, with
312 PM emissions from agriculture being estimated at about 25% of total emissions in the Netherlands
313 (Cambra-López et al., 2010). The Global Burden of Disease estimated that air pollution is responsible
314 for about 1.2% of premature deaths and 0.5% of lost life years (Cohen et al., 2005). It is considered as
315 the ninth larger risk factor contributing to deaths in the United States (The US Burden of Disease
316 Collaborators, 2018). Acidification causing soil degradation (Goulding, 2016) and acid rain are other
317 environmental impact of animal production. The dominant sources of acidification in agriculture come
318 from ammonia emissions released used for feed production and manure production. With a higher feed
319 conversion ratio and an important manure production, ruminants thus have a higher acidification
320 power per meat produced (Röös et al., 2013).

Author File

321 The low meat profile had the smallest environmental pressure. This is in line with the literature as
322 most publications pointed out that meat, especially from ruminant and to a lesser extent from
323 monogastric, has by far the most significant environmental impact, specifically for GHGe (Poore and
324 Nemecek, 2018). Indeed, low GHGe in this profile should be ascribed to the very low consumption of
325 ruminant meat. This is similar with other studies showing plant-based diets having lower GHGe
326 compare to omnivorous diet (Rabès et al., 2020). Note that dairy intake was relatively high for this
327 profile – in fact the highest of the 5 profiles – which may be considered a practical conflict between
328 the production of ruminant meat and the production of milk. This is because of the co-production
329 factor; in France, if the bovine dairy protein intake is above 0.43 times the bovine meat protein intake,
330 there is an excess meat production (Barré et al., 2018). In the case of the low meat consumer profile,
331 the bovine dairy protein consumption exceeded this number. However, this issue only occurred in the
332 hypothetical situation where the entire population follows this diet, with no meat exportation or dairy
333 importation. Moreover, changes in the dairy systems, like a change in the life span of dairy cows,
334 could potentially strongly modify this factor.

335 It is also important to note that a high share of red meat consumed comes from dairy cows in France
336 (Assmann, 2020). Thus, the allocation of the environmental pressure using biophysics systems in the
337 life cycle inventory (LCI) is considered. The literature showed different types of allocations
338 underlying different choices. These choices came from 4 criteria: compliance with recommendations,
339 stability in time and space, and practical aspects (Wilfart et al., 2021). Agribalyse allocation for dairy
340 and ruminant meat is based on the metabolic energy required to produce each co-product
341 (Supplemental Method 1). On a food basis, the indicators already studied, like GHGe, have a similar
342 order of magnitude of allocations as other studies (Clune et al., 2017), indicating the choices made in
343 Agribalyse (ADEME, 2020b) are similar to that of most published studies.

344 This low-meat protein profile also has drawbacks on a nutritional aspect, with the lowest PANDiet
345 values of all profiles. This is mainly explained by the low intake of nutrient-dense food sources, in
346 particular red meat, which is not offset by higher intakes of fruits and vegetables. It should be noted
347 that even if it is the most plant-based profile, the consumption of pulses, whole grains and other

Author File

348 recommended plant food groups is far from what is recommended in optimization studies (Dussiot et
349 al., 2022; Willett et al., 2019). Moreover, the nutrient security in this low-meat profile was not lower
350 than that of the general population, confirming that even if there are some slightly lower intakes of
351 some nutrients, there is no overall increase in the risk of overt deficiency. As far as long-term health is
352 concerned, this profile has the lowest estimated risk of long-term morbidity or mortality from coronary
353 heart disease, stroke, type 2 diabetes, and colorectal cancer, as assessed using the HiDiet score. Given
354 that the small increase in nutrient inadequacy does not increase the risk of overt deficiency, this profile
355 shows strong co-benefits for environmental and human health.

356 Compared to the other profiles high in animal flesh (meat or fish), the profile with high intakes of
357 protein from poultry has a lower impact on most of the environmental indicators. In fact, GHGe are
358 specifically one of the advantages of this profile. Similar results from previous studies show that
359 poultry produces the lowest GHGe among all types of meat (González et al., 2011; Nijdam et al.,
360 2012).

361 Surprisingly, this profile exhibited poor dietary scores with values under the population average for all
362 scores except the HiDiet. This latter score was the only one in line with the epidemiological data
363 showing that poultry consumption was not associated with a higher risk of mortality or morbidity (Du
364 et al., 2020; Makiuchi et al., 2020; Micha et al., 2017a, 2017b). The low scores for the other nutritional
365 and health scores may be explained by the low fish consumption and the fact that other food categories
366 with a positive weight in these health and nutritional scores are low in the poultry profile.

367 The profile with a high fish consumption has high values for all health and nutritional scores. This was
368 expected as fish consumption is positively weighted in all of the scores considered in this study. Fish
369 is a very good contributor to bioavailable nutrients and has well-known health benefits against chronic
370 disease (Bogard et al., 2019). The high intake of indispensable nutrients associated with the higher
371 level of protein for fish but also an overall dietary profile of higher quality explains the high PANDiet
372 and SecDiet score. In contrast, this high fish intake has some important drawbacks on the
373 environmental indicators. As described before, water use and photochemical ozone formation are two
374 important issues of fish consumption (Ruiz-Salmón et al., 2021). It is important to note that there is

Author File

375 significant variability between fish species, and it may be possible to improve the health and
376 environmental impact by consuming different fish species (ADEME, 2020a). However, these results
377 need to be verified with other LCA as environmental pressures from fish are not precise, being mostly
378 measured indirectly.

379 4.2 Limits and strengths

380 First, it should be noted that INCA3 survey was conducted between 2014 and 2015, so diets may have
381 changed since then, and the sample of 1125 individuals that we used is small. However, it is the latest
382 French representative survey to date. The environmental database Agribalyse has also some
383 limitations. For example, the quantification of soil carbon storage and removal is not considered in the
384 calculation of the GHGe. Biodiversity and the impact of phytosanitary products are also not yet
385 calculated. Land use is often a proxy for lost biodiversity. However, in the Agribalyse database, land
386 use is expressed in the loss of Soil Carbon and cannot be used similarly to when expressed in hectares
387 or m². Another drawback is that there is no information about farming practices (such as organic
388 production) for foods production that are consumed in the survey, and the environmental indicators are
389 only for mean of consumed foods differing in farming practices. However, this database includes a
390 large variety of environmental indicators covering the entire food chain from production to the plate
391 and virtually all the foods consumed by the French population since it was created for this purpose.
392 Though, it should be noted that several of these indicators are strongly linked to fuel use.

393 Finally, the major strength of this study is the variety of indicators and food described in a
394 representative survey. Using this information, it was possible to precisely describe 14 environmental
395 indicators and 6 nutritional and health dietary scores for five protein profiles in a representative sample
396 of the French population

397 5 Conclusion

398 In the present study, we showed that the profiles of protein intake of the population are varied and
399 have contrasting associations with health and environmental impacts. Using the Agribalyse study, we
400 could assess 14 environmental pressures, which we brought together with 6 health indicators. The

Author File

401 protein profile marked by ruminant meat had the worst scores on both health and environmental
402 aspects, especially regarding GHGe, land use, and particulate matter emissions, and long-term health.
403 Conversely, the most environment-friendly protein profile is very low in meat, and this profile also
404 had the lowest risk for long-term morbidity and mortality. Apart from the protein profile low in meat,
405 the profile with high intakes of protein from poultry has a lower impact on most of the environmental
406 indicators, including GHGe. The fish protein profile had overall the best diet quality indicators but
407 mixed values for environmental indicators, with high water use and photochemical ozone formation.
408 As we studied real profiles identified in the general population, the differences in health and
409 environmental impacts between profiles may be useful to consider realistic targets for acceptable
410 changes in the diet. These changes may be more practical than those identified by modeling studies.
411 Our results thus support the importance of protein profiles for health and environmental impacts

Author File

Acknowledgments and statement of authors' contributions to manuscript

EP, FM, and EK-G: designed the research; EP: conducted the research; EP, FM, and EK-G analyzed the data; MS, and J-FH provided methodological support; EP drafted the first version of the manuscript, EP, FM, and EK-G wrote the manuscript and all authors provided critical comments on the manuscript. EP, FM, and EK-G had primary responsibility for the final content, and all authors read and approved the final manuscript.

Author File

6 References

- 412 ADEME, 2020a. Agribalyse v3.0 [WWW Document]. URL <https://agribalyse.ademe.fr/app> (accessed
413 7.22.21).
- 414 ADEME, 2020b. Agribalyse 3.0 The french agricultural and food LCI database. Methodology for food
415 products [WWW Document]. URL [https://3613321239-files.gitbook.io/~files/v0/b/gitbook-
416 legacy-files/o/assets%2F-M7H-JTDnDsswmNDPy-z%2F-Mg5HjHpDb_OmwzPVGwH%2F-
417 Mg5JXgw-WwSpTJqxwz%2FMethodology%20AGB%203.0-%2020200528_MAIN-
418 CLEAN-vf2.pdf?alt=media&token=aeae9b55-77b9-49bb-a800-ab559137d7ca](https://3613321239-files.gitbook.io/~files/v0/b/gitbook-legacy-files/o/assets%2F-M7H-JTDnDsswmNDPy-z%2F-Mg5HjHpDb_OmwzPVGwH%2F-Mg5JXgw-WwSpTJqxwz%2FMethodology%20AGB%203.0-%2020200528_MAIN-CLEAN-vf2.pdf?alt=media&token=aeae9b55-77b9-49bb-a800-ab559137d7ca) (accessed
419 5.31.22).
- 420 Aleksandrowicz, L., Green, R., Joy, E.J.M., Smith, P., Haines, A., 2016. The Impacts of Dietary
421 Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic
422 Review. *PLOS ONE* 11, e0165797. <https://doi.org/10.1371/journal.pone.0165797>
- 423 ANSES, 2016. Table de composition nutritionnelle des aliments CIQUAL.
- 424 Assmann, L., 2020. bovins 2020 Productions lait et viande (PUBLICATION DE L'INSTITUT DE
425 L'ÉLEVAGE ET DE LA CNE No. 0020 501 010). Institut de l'Élevage, Paris.
- 426 Barré, T., Perignon, M., Gazan, R., Vieux, F., Micard, V., Amiot, M.-J., Darmon, N., 2018. Integrating
427 nutrient bioavailability and co-production links when identifying sustainable diets: How low
428 should we reduce meat consumption? *PLOS ONE* 13, e0191767.
429 <https://doi.org/10.1371/journal.pone.0191767>
- 430 Bechthold, A., Boeing, H., Schwedhelm, C., Hoffmann, G., Knüppel, S., Iqbal, K., De Henauw, S.,
431 Michels, N., Devleeschauwer, B., Schlesinger, S., Schwingshackl, L., 2019. Food groups and
432 risk of coronary heart disease, stroke and heart failure: A systematic review and dose-response
433 meta-analysis of prospective studies. *Crit. Rev. Food Sci. Nutr.* 59, 1071–1090.
434 <https://doi.org/10.1080/10408398.2017.1392288>
- 435 Black, A.E., 2000. Critical evaluation of energy intake using the Goldberg cut-off for energy
436 intake:basal metabolic rate. A practical guide to its calculation, use and limitations. *Int. J.*
437 *Obes.* 24, 1119–1130. <https://doi.org/10.1038/sj.ijo.0801376>
- 438 Boada, L.D., Henríquez-Hernández, L.A., Luzardo, O.P., 2016. The impact of red and processed meat
439 consumption on cancer and other health outcomes: Epidemiological evidences. *Food Chem.*
440 *Toxicol.* 92, 236–244. <https://doi.org/10.1016/j.fct.2016.04.008>
- 441 Bogard, J.R., Farmery, A.K., Little, D.C., Fulton, E.A., Cook, M., 2019. Will fish be part of future
442 healthy and sustainable diets? *Lancet Planet. Health* 3, e159–e160.
443 [https://doi.org/10.1016/S2542-5196\(19\)30018-X](https://doi.org/10.1016/S2542-5196(19)30018-X)
- 444 Brunin, J., Pointereau, P., Allès, B., Touvier, M., Hercberg, S., Lairon, D., Baudry, J., Kesse-Guyot,
445 E., 2021. Are recent dietary changes observed in the NutriNet-Santé participants healthier and
446 more sustainable? *Eur. J. Nutr.* 1–15. <https://doi.org/10.1007/s00394-021-02631-y>
- 447 Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., Torres, A.G., 2010. Airborne particulate
448 matter from livestock production systems: A review of an air pollution problem. *Environ.*
449 *Pollut.* 158, 1–17. <https://doi.org/10.1016/j.envpol.2009.07.011>
- 450 Canada, H., 2020. Eat protein foods [WWW Document]. *Can. Food Guide*. URL [https://food-
451 guide.canada.ca/en/healthy-eating-recommendations/make-it-a-habit-to-eat-vegetables-fruit-
452 whole-grains-and-protein-foods/eat-protein-foods/](https://food-guide.canada.ca/en/healthy-eating-recommendations/make-it-a-habit-to-eat-vegetables-fruit-whole-grains-and-protein-foods/eat-protein-foods/) (accessed 4.20.22).
- 453 CépiDc, 2018. Classification internationale des maladies (CIM) | CépiDc [WWW Document]. URL
454 [https://www.cepidc.inserm.fr/causes-medicales-de-deces/classification-internationale-des-
455 maladies-cim](https://www.cepidc.inserm.fr/causes-medicales-de-deces/classification-internationale-des-maladies-cim) (accessed 1.24.22).
- 456 Chai, B.C., van der Voort, J.R., Grofelnik, K., Eliasdottir, H.G., Klöss, I., Perez-Cueto, F.J.A., 2019.
457 Which Diet Has the Least Environmental Impact on Our Planet? A Systematic Review of
458 Vegan, Vegetarian and Omnivorous Diets. *Sustainability* 11, 4110.
459 <https://doi.org/10.3390/su11154110>
- 460 Chaltiel, D., Adjibade, M., Deschamps, V., Touvier, M., Hercberg, S., Julia, C., Kesse-Guyot, E.,
461 2019. Programme National Nutrition Santé – guidelines score 2 (PNNS-GS2): development
462 and validation of a diet quality score reflecting the 2017 French dietary guidelines. *Br. J. Nutr.*
463 122, 331–342. <https://doi.org/10.1017/S0007114519001181>

Author File

- 464 Chang, S., Koegel, K., 2017. Back to Basics: All About MyPlate Food Groups. *J. Acad. Nutr. Diet.*
465 117, 1351–1353. <https://doi.org/10.1016/j.jand.2017.06.376>
- 466 Chiuve, S.E., Fung, T.T., Rimm, E.B., Hu, F.B., McCullough, M.L., Wang, M., Stampfer, M.J.,
467 Willett, W.C., 2012. Alternative Dietary Indices Both Strongly Predict Risk of Chronic
468 Disease. *J. Nutr.* 142, 1009–1018. <https://doi.org/10.3945/jn.111.157222>
- 469 Clark, M., Hill, J., Tilman, D., 2018. The Diet, Health, and Environment Trilemma. *Annu. Rev.*
470 *Environ. Resour.* 43, 109–134. <https://doi.org/10.1146/annurev-environ-102017-025957>
- 471 Clarys, P., Deliens, T., Huybrechts, I., Deriemaeker, P., Vanaelst, B., De Keyzer, W., Hebbelinck, M.,
472 Mullie, P., 2014. Comparison of Nutritional Quality of the Vegan, Vegetarian, Semi-
473 Vegetarian, Pesco-Vegetarian and Omnivorous Diet. *Nutrients* 6, 1318–1332.
474 <https://doi.org/10.3390/nu6031318>
- 475 Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for
476 different fresh food categories. *J. Clean. Prod., Towards eco-efficient agriculture and food*
477 *systems: selected papers addressing the global challenges for food systems, including those*
478 *presented at the Conference “LCA for Feeding the planet and energy for life” (6-8 October*
479 *2015, Stresa & Milan Expo, Italy)* 140, 766–783. <https://doi.org/10.1016/j.jclepro.2016.04.082>
- 480 Cohen, A.J., Ross Anderson, H., Ostro, B., Pandey, K.D., Krzyzanowski, M., Künzli, N., Gutschmidt,
481 K., Pope, A., Romieu, I., Samet, J.M., Smith, K., 2005. The Global Burden of Disease Due to
482 Outdoor Air Pollution. *J. Toxicol. Environ. Health A* 68, 1301–1307.
483 <https://doi.org/10.1080/15287390590936166>
- 484 Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food
485 systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* 2, 198–
486 209. <https://doi.org/10.1038/s43016-021-00225-9>
- 487 Dagevos, H., 2021. Finding flexitarians: Current studies on meat eaters and meat reducers. *Trends*
488 *Food Sci. Technol.* 114, 530–539. <https://doi.org/10.1016/j.tifs.2021.06.021>
- 489 De Gavelle, E., Huneau, J.-F., Mariotti, F., 2018. Patterns of Protein Food Intake Are Associated with
490 Nutrient Adequacy in the General French Adult Population. *Nutrients* 10, 226.
491 <https://doi.org/10.3390/nu10020226>
- 492 de Gavelle, E., Huneau, J.-F., Fouillet, H., Mariotti, F., 2019. The Initial Dietary Pattern Should Be
493 Considered when Changing Protein Food Portion Sizes to Increase Nutrient Adequacy in
494 French Adults. *J. Nutr.* 149, 488–496. <https://doi.org/10.1093/jn/nxy275>
- 495 Du, H., Guo, Y., Bennett, D.A., Bragg, F., Bian, Z., Chadni, M., Yu, C., Chen, Y., Tan, Y., Millwood,
496 I.Y., Gan, W., Yang, L., Yao, P., Luo, G., Li, J., Qin, Y., Lv, J., Lin, X., Key, T., Chen, J.,
497 Clarke, R., Li, L., Chen, Z., 2020. Red meat, poultry and fish consumption and risk of
498 diabetes: a 9 year prospective cohort study of the China Kadoorie Biobank. *Diabetologia* 63,
499 767–779. <https://doi.org/10.1007/s00125-020-05091-x>
- 500 Dubuisson, C., Dufour, A., Carrillo, S., Drouillet-Pinard, P., Havard, S., Volatier, J.-L., 2019. The
501 Third French Individual and National Food Consumption (INCA3) Survey 2014–2015:
502 method, design and participation rate in the framework of a European harmonization process.
503 *Public Health Nutr.* 22, 584–600. <https://doi.org/10.1017/S1368980018002896>
- 504 Dussiot, A., Fouillet, H., Wang, J., Salomé, M., Huneau, J.-F., Kesse-Guyot, E., Mariotti, F., 2022.
505 Modeled healthy eating patterns are largely constrained by currently estimated requirements
506 for bioavailable iron and zinc—a diet optimization study in French adults. *Am. J. Clin. Nutr.*
507 115, 958–969. <https://doi.org/10.1093/ajcn/nqab373>
- 508 French Agency for Food, Environmental and Occupational Health Safety (ANSES), 2017. Opinion of
509 the French Agency for Food, Environmental and Occupational Health & Safety on “the Third
510 Individual and National Survey on Food Consumption (INCA3 survey)” [WWW Document].
511 URL <https://www.anses.fr/en/system/files/NUT2014SA0234EN.pdf> (accessed 7.8.21).
- 512 Fresán, U., Sabaté, J., 2019. Vegetarian Diets: Planetary Health and Its Alignment with Human
513 Health. *Adv. Nutr.* 10, S380–S388. <https://doi.org/10.1093/advances/nmz019>
- 514 Garcia, J., Bennett, D.H., Tancredi, D., Schenker, M.B., Mitchell, D., Mitloehner, F.M., 2013. A
515 Survey of Particulate Matter on California Dairy Farms. *J. Environ. Qual.* 42, 40–47.
516 <https://doi.org/10.2134/jeq2012.0169>
- 517 GBD 2013 Mortality and Causes of Death Collaborators, 2015. Global, regional, and national age–sex
518 specific all-cause and cause-specific mortality for 240 causes of death, 1990–2013: a

Author File

- 519 systematic analysis for the Global Burden of Disease Study 2013. *The Lancet* 385, 117–171.
520 [https://doi.org/10.1016/S0140-6736\(14\)61682-2](https://doi.org/10.1016/S0140-6736(14)61682-2)
- 521 González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011. Protein efficiency per unit energy and per
522 unit greenhouse gas emissions: Potential contribution of diet choices to climate change
523 mitigation. *Food Policy* 36, 562–570. <https://doi.org/10.1016/j.foodpol.2011.07.003>
- 524 González-García, S., Esteve-Llorens, X., Moreira, M.T., Feijoo, G., 2018. Carbon footprint and
525 nutritional quality of different human dietary choices. *Sci. Total Environ.* 644, 77–94.
526 <https://doi.org/10.1016/j.scitotenv.2018.06.339>
- 527 Goulding, K.W.T., 2016. Soil acidification and the importance of liming agricultural soils with
528 particular reference to the United Kingdom. *Soil Use Manag.* 32, 390–399.
529 <https://doi.org/10.1111/sum.12270>
- 530 Henry, C., 2005. Basal metabolic rate studies in humans: measurement and development of new
531 equations. *Public Health Nutr.* 8, 1133–1152. <https://doi.org/10.1079/PHN2005801>
- 532 Herforth, A., Arimond, M., Álvarez-Sánchez, C., Coates, J., Christianson, K., Muehlhoff, E., 2019. A
533 Global Review of Food-Based Dietary Guidelines. *Adv. Nutr.* 10, 590–605.
534 <https://doi.org/10.1093/advances/nmy130>
- 535 INSEE, 2017. Évolution et structure de la population en 2014 | Insee [WWW Document]. URL
536 <https://www.insee.fr/fr/statistiques/2862200> (accessed 1.24.22).
- 537 Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., Shapiro, L.F., 2016. A Systematic Review of
538 the Measurement of Sustainable Diets. *Adv. Nutr.* 7, 641–664.
539 <https://doi.org/10.3945/an.115.011015>
- 540 Kaufman, L., Rousseeuw, P.J., 2005. Finding Groups in Data. An introduction to cluster analysis.
- 541 Kesse-Guyot, E., Chaltiel, D., Wang, J., Pointereau, P., Langevin, B., Allès, B., Rebouillat, P., Lairon,
542 D., Vidal, R., Mariotti, F., Egnell, M., Touvier, M., Julia, C., Baudry, J., Hercberg, S., 2020.
543 Sustainability analysis of French dietary guidelines using multiple criteria. *Nat. Sustain.* 3,
544 377–385. <https://doi.org/10.1038/s41893-020-0495-8>
- 545 Kramer, G.F., Tyszler, M., Veer, P. van't, Blonk, H., 2017. Decreasing the overall environmental
546 impact of the Dutch diet: how to find healthy and sustainable diets with limited changes.
547 *Public Health Nutr.* 20, 1699–1709. <https://doi.org/10.1017/S1368980017000349>
- 548 Lee, D.D., Seung, H.S., 1999. Learning the parts of objects by non-negative matrix factorization.
549 *Nature* 401, 788–791. <https://doi.org/10.1038/44565>
- 550 Makiuchi, T., Sobue, T., Kitamura, T., Ishihara, J., Sawada, N., Iwasaki, M., Yamaji, T., Shimazu, T.,
551 Tsugane, S., 2020. Relationship between Meat/Fish Consumption and Biliary Tract Cancer:
552 The Japan Public Health Center–Based Prospective Study. *Cancer Epidemiol. Prev. Biomark.*
553 29, 95–102. <https://doi.org/10.1158/1055-9965.EPI-19-0514>
- 554 Marini, M., Angouria-Tsorochidou, E., Caro, D., Thomsen, M., 2021. Daily intake of heavy metals
555 and minerals in food – A case study of four Danish dietary profiles. *J. Clean. Prod.* 280,
556 124279. <https://doi.org/10.1016/j.jclepro.2020.124279>
- 557 Mariotti, F., 2019. Animal and Plant Protein Sources and Cardiometabolic Health. *Adv. Nutr.* 10,
558 S351–S366. <https://doi.org/10.1093/advances/nmy110>
- 559 Mertens, E., Kaptijn, G., Kuijsten, A., van Zanten, H., Geleijnse, J.M., van 't Veer, P., 2019. SHARP-
560 Indicators Database towards a public database for environmental sustainability. *Data Brief* 27.
561 <https://doi.org/10.1016/j.dib.2019.104617>
- 562 Micha, R., Peñalvo, J.L., Cudhea, F., Imamura, F., Rehm, C.D., Mozaffarian, D., 2017a. Association
563 Between Dietary Factors and Mortality From Heart Disease, Stroke, and Type 2 Diabetes in
564 the United States. *JAMA* 317, 912–924. <https://doi.org/10.1001/jama.2017.0947>
- 565 Micha, R., Shulkin, M.L., Peñalvo, J.L., Khatibzadeh, S., Singh, G.M., Rao, M., Fahimi, S., Powles,
566 J., Mozaffarian, D., 2017b. Etiologic effects and optimal intakes of foods and nutrients for risk
567 of cardiovascular diseases and diabetes: Systematic reviews and meta-analyses from the
568 Nutrition and Chronic Diseases Expert Group (NutriCoDE). *PLOS ONE* 12, e0175149.
569 <https://doi.org/10.1371/journal.pone.0175149>
- 570 Micha, R., Wallace, S.K., Mozaffarian, D., 2010. Red and Processed Meat Consumption and Risk of
571 Incident Coronary Heart Disease, Stroke, and Diabetes Mellitus. *Circulation* 121, 2271–2283.
572 <https://doi.org/10.1161/CIRCULATIONAHA.109.924977>

Author File

- 573 Naghshi, S., Sadeghi, O., Willett, W.C., Esmailzadeh, A., 2020. Dietary intake of total, animal, and
574 plant proteins and risk of all cause, cardiovascular, and cancer mortality: systematic review
575 and dose-response meta-analysis of prospective cohort studies. *BMJ* 370, m2412.
576 <https://doi.org/10.1136/bmj.m2412>
- 577 Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: Review of land use and carbon
578 footprints from life cycle assessments of animal food products and their substitutes. *Food*
579 *Policy* 37, 760–770. <https://doi.org/10.1016/j.foodpol.2012.08.002>
- 580 ODPHP, 2021. 2015-2020 Dietary Guidelines | health.gov [WWW Document]. URL
581 [https://health.gov/our-work/nutrition-physical-activity/dietary-guidelines/previous-dietary-](https://health.gov/our-work/nutrition-physical-activity/dietary-guidelines/previous-dietary-guidelines/2015)
582 [guidelines/2015](https://health.gov/our-work/nutrition-physical-activity/dietary-guidelines/previous-dietary-guidelines/2015) (accessed 4.20.22).
- 583 Perraud, E., Wang, J., Salomé, M., Huneau, J.-F., Lapidus, N., Mariotti, F., 2022. Plant and Animal
584 Protein Intakes Largely Explain the Nutritional Quality and Health Value of Diets Higher in
585 Plants: A Path Analysis in French Adults. *Front. Nutr.* 9.
- 586 Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and
587 consumers. *Science* 360, 987–992. <https://doi.org/10.1126/science.aaq0216>
- 588 Rabès, A., Seconda, L., Langevin, B., Allès, B., Touvier, M., Hercberg, S., Lairon, D., Baudry, J.,
589 Pointereau, P., Kesse-Guyot, E., 2020. Greenhouse gas emissions, energy demand and land
590 use associated with omnivorous, pesco-vegetarian, vegetarian, and vegan diets accounting for
591 farming practices. *Sustain. Prod. Consum.* 22, 138–146.
592 <https://doi.org/10.1016/j.spc.2020.02.010>
- 593 Ritchie, H., Roser, M., 2020. Environmental Impacts of Food Production. Our World Data.
- 594 Rööös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P.-A., 2013. Can carbon footprint serve as an
595 indicator of the environmental impact of meat production? *Ecol. Indic.* 24, 573–581.
596 <https://doi.org/10.1016/j.ecolind.2012.08.004>
- 597 Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., Di Cagno, R., Ruini, L., Ciati,
598 R., Angelino, D., Maddock, J., Gobbetti, M., Brighenti, F., Del Rio, D., Scazzina, F., 2017.
599 Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. *Sci. Rep.* 7, 6105.
600 <https://doi.org/10.1038/s41598-017-06466-8>
- 601 Ruiz-Salmón, I., Laso, J., Margallo, M., Villanueva-Rey, P., Rodríguez, E., Quinteiro, P., Dias, A.C.,
602 Almeida, C., Nunes, M.L., Marques, A., Cortés, A., Moreira, M.T., Feijoo, G., Loubet, P.,
603 Sonnemann, G., Morse, A.P., Cooney, R., Clifford, E., Regueiro, L., Méndez, D., Anglada, C.,
604 Noirot, C., Rowan, N., Vázquez-Rowe, I., Aldaco, R., 2021. Life cycle assessment of fish and
605 seafood processed products – A review of methodologies and new challenges. *Sci. Total*
606 *Environ.* 761, 144094. <https://doi.org/10.1016/j.scitotenv.2020.144094>
- 607 Salomé, M., Kesse-Guyot, E., Fouillet, H., Touvier, M., Hercberg, S., Huneau, J.-F., Mariotti, F.,
608 2021. Development and evaluation of a new dietary index assessing nutrient security by
609 aggregating probabilistic estimates of the risk of nutrient deficiency in two French adult
610 populations. *Br. J. Nutr.* 126, 1225–1236. <https://doi.org/10.1017/S0007114520005115>
- 611 Scarborough, P., Appleby, P.N., Mizdrak, A., Briggs, A.D.M., Travis, R.C., Bradbury, K.E., Key, T.J.,
612 2014. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in
613 the UK. *Clim. Change* 125, 179–192. <https://doi.org/10.1007/s10584-014-1169-1>
- 614 Schwingshackl, L., Boeing, H., Stelmach-Mardas, M., Gottschald, M., Dietrich, S., Hoffmann, G.,
615 Chaimani, A., 2017a. Dietary Supplements and Risk of Cause-Specific Death, Cardiovascular
616 Disease, and Cancer: A Systematic Review and Meta-Analysis of Primary Prevention Trials.
617 *Adv. Nutr.* 8, 27–39. <https://doi.org/10.3945/an.116.013516>
- 618 Schwingshackl, L., Hoffmann, G., Lampousi, A.-M., Knüppel, S., Iqbal, K., Schwedhelm, C.,
619 Bechthold, A., Schlesinger, S., Boeing, H., 2017b. Food groups and risk of type 2 diabetes
620 mellitus: a systematic review and meta-analysis of prospective studies. *Eur. J. Epidemiol.* 32,
621 363–375. <https://doi.org/10.1007/s10654-017-0246-y>
- 622 Schwingshackl, L., Knüppel, S., Michels, N., Schwedhelm, C., Hoffmann, G., Iqbal, K., De Henauw,
623 S., Boeing, H., Devleeschauwer, B., 2019. Intake of 12 food groups and disability-adjusted
624 life years from coronary heart disease, stroke, type 2 diabetes, and colorectal cancer in 16
625 European countries. *Eur. J. Epidemiol.* 34, 765–775. [https://doi.org/10.1007/s10654-019-](https://doi.org/10.1007/s10654-019-00523-4)
626 [00523-4](https://doi.org/10.1007/s10654-019-00523-4)

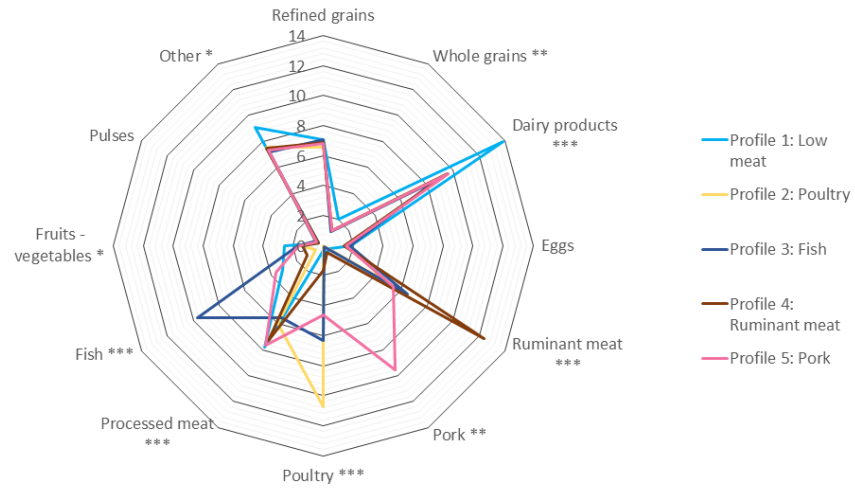
Author File

- 627 Schwingshackl, L., Schwedhelm, C., Hoffmann, G., Knüppel, S., Laure Preterre, A., Iqbal, K.,
628 Bechthold, A., De Henauw, S., Michels, N., Devleeschauwer, B., Boeing, H., Schlesinger, S.,
629 2018. Food groups and risk of colorectal cancer. *Int. J. Cancer* 142, 1748–1758.
630 <https://doi.org/10.1002/ijc.31198>
- 631 Seconda, L., Baudry, J., Allès, B., Boizot-Szantai, C., Soler, L.-G., Galan, P., Hercberg, S., Langevin,
632 B., Lairon, D., Pointereau, P., Kesse-Guyot, E., 2018. Comparing nutritional, economic, and
633 environmental performances of diets according to their levels of greenhouse gas emissions.
634 *Clim. Change* 148, 155–172. <https://doi.org/10.1007/s10584-018-2195-1>
- 635 Seconda, L., Fouillet, H., Huneau, J.-F., Pointereau, P., Baudry, J., Langevin, B., Lairon, D., Allès, B.,
636 Touvier, M., Hercberg, S., Mariotti, F., Kesse-Guyot, E., 2021. Conservative to disruptive
637 diets for optimizing nutrition, environmental impacts and cost in French adults from the
638 NutriNet-Santé cohort. *Nat. Food* 2, 174–182. <https://doi.org/10.1038/s43016-021-00227-7>
- 639 Sofi, F., Macchi, C., Abbate, R., Gensini, G.F., Casini, A., 2014. Mediterranean diet and health status:
640 an updated meta-analysis and a proposal for a literature-based adherence score. *Public Health*
641 *Nutr.* 17, 2769–2782. <https://doi.org/10.1017/S1368980013003169>
- 642 The US Burden of Disease Collaborators, 2018. The State of US Health, 1990-2016: Burden of
643 Diseases, Injuries, and Risk Factors Among US States. *JAMA* 319, 1444–1472.
644 <https://doi.org/10.1001/jama.2018.0158>
- 645 Turner, N.D., Lloyd, S.K., 2017. Association between red meat consumption and colon cancer: A
646 systematic review of experimental results. *Exp. Biol. Med.* 242, 813–839.
647 <https://doi.org/10.1177/1535370217693117>
- 648 Wang, G., Kossenkov, A.V., Ochs, M.F., 2006. LS-NMF: a modified non-negative matrix
649 factorization algorithm utilizing uncertainty estimates. *BMC Bioinformatics* 7.
650 <https://doi.org/10.1186/1471-2105-7-175>
- 651 Wilfart, A., Gac, A., Salaün, Y., Aubin, J., Espagnol, S., 2021. Allocation in the LCA of meat
652 products: is agreement possible? *Clean. Environ. Syst.* 2, 100028.
653 <https://doi.org/10.1016/j.cesys.2021.100028>
- 654 Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman,
655 D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C.,
656 Zurayk, R., Rivera, J.A., Vries, W.D., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M.,
657 Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M.,
658 Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L.,
659 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from
660 sustainable food systems. *The Lancet* 393, 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- 662 Wilson, N., Cleghorn, C.L., Cobiac, L.J., Mizdrak, A., Nghiem, N., 2019. Achieving Healthy and
663 Sustainable Diets: A Review of the Results of Recent Mathematical Optimization Studies.
664 *Adv. Nutr.* 10, S389–S403. <https://doi.org/10.1093/advances/nmz037>
- 665

666

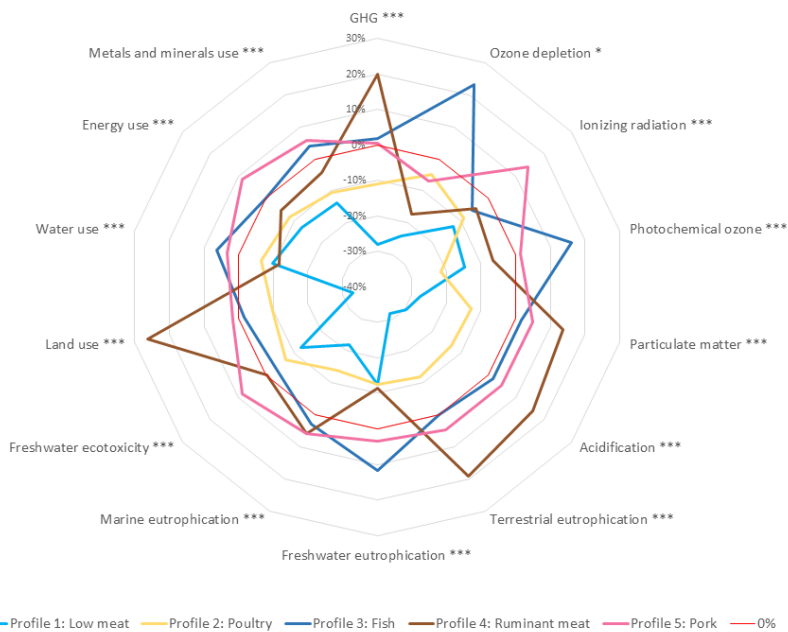
Author File

LEGEND FOR FIGURES



667 **Figure 1** Consumption (g/day) of protein groups in individuals in the 5 protein profile as identified in
668 the dietary survey (INCA3). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

669

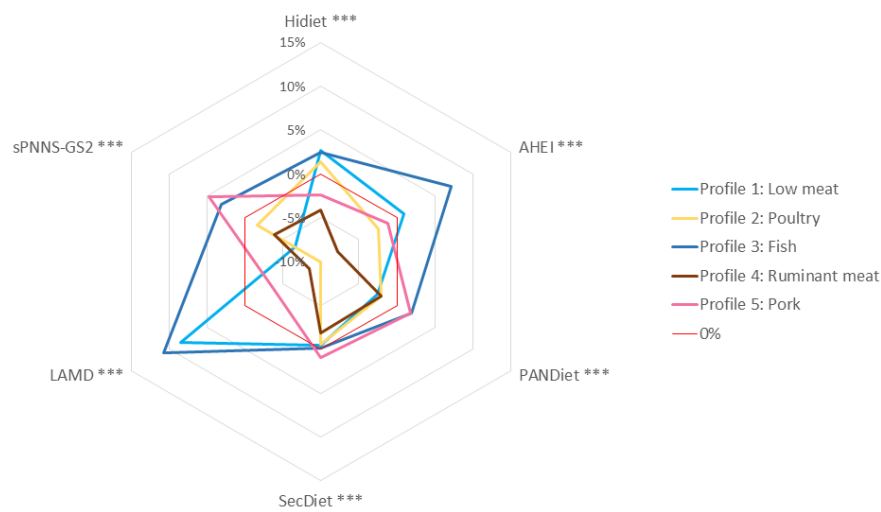


670

671 **Figure 2.** Environmental indicators associated with the diet consumed by individuals in the 5 protein
 672 profiles as identified in the dietary survey (INCA3). Data are in percentage of difference to the mean
 673 value of the total population. GHGe is the emission of greenhouse gases measured in kg CO₂ eq. The
 674 ozone depletion is in kg CFC-11eq. The photochemical ozone formation is in kg of Non-Methane
 675 Volatile Organic Compounds eq. Particulate matter is in kg of PM_{2.5} emitted. The acidification is in
 676 mol H⁺ eq. The terrestrial eutrophication is in mol N eq, the freshwater eutrophication is in kg P eq,
 677 and the marine eutrophication is in kg N eq. The freshwater ecotoxicity is based on the USEtox model.
 678 Land use is in kg C deficit, water use in m³, fossils resource use in MJ, and Metals and minerals use in
 679 kg SB eq. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

680

Author File



681

682 **Figure 3.** Nutritional and health indicators by profile. All data are in percentage of difference to the
683 mean value of the population. The HiDiet was used to assess the diet impact on long-term mortality
684 and morbidity (variation between -1 and 1). The Alternative Healthy Eating Index (AHEI-2010) is a
685 modified Healthy Eating Index, assessing the adherence to *Dietary Guidelines for Americans*,
686 improving target food choices and macronutrient sources associated with reduced chronic disease risk
687 (maxpoint = 100). The PANDiet evaluates the probability of adequate nutrient intake (maxpoint =
688 100). The SecDiet evaluates the nutrient risk of overt deficiency (maxpoint = 1). The Literature-Based
689 Adherence Score to the Mediterranean Diet (LAMD) assesses adherence to the Mediterranean diet
690 (maxpoint = 16). sPNNS-GS2 the adherence to the French Food-based Dietary Guidelines (maxpoint
691 = 10.5). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$