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Environmental impacts and consumption of UPF: identification of the most important food chain steps, results among French adults

Emmanuelle Kesse-Guyot¹, Benjamin Allès¹, Joséphine Brunin^{1,2}, Hélène Fouillet³, Alison Dussiot⁴, Florine Berthy¹, Elie Perraud³, Serge Hercberg^{1,4}, Chantal Julia^{1,4}, François Mariotti³, Mélanie Deschasaux-Tanguy¹, Bernard Srour¹, Denis Lairon⁵, Philippe Pointereau⁶, Julia Baudry^{1,7}, Mathilde Touvier^{1,7}

¹ Sorbonne Paris Nord University, Inserm, INRAE, Cnam, Nutritional Epidemiology Research Team (EREN), Epidemiology and Statistics Research Center –Paris Cité University (CRESS), 93017 Bobigny, France

² ADEME, (Agence de l'Environnement et de la Maîtrise de l'Energie), 49004 Angers, France

³ Paris-Saclay University, UMR PNCA, AgroParisTech, INRAE, 75005 Paris, France

⁴ Département de Santé Publique, Hôpital Avicenne, 93017 Bobigny, France

⁵ Aix Marseille Université, Inserm, INRAE, C2VN, 13005 Marseille, France

⁶ Solagro, 75, Voie TOEC, CS 27608, F-31076 Toulouse Cedex 3, France

⁷ Authors equally contributed

Correspondence : Email: emmanuelle.kesse-guyot@inrae.fr

Equipe de Recherche en Epidémiologie Nutritionnelle (EREN)

SMBH Université Sorbonne Paris Nord, 74 rue Marcel Cachin, 93017 Bobigny, France

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Abstract

1 **Background** Scientific literature about environmental pressures associated with dietary patterns has
2 been considerably growing over the last decade. However, few studies have analyzed the
3 environmental impacts associated with the consumption of ultra-processed food (UPF) and which
4 steps of the food chain that contribute the most to environmental pressures. The objective of this study
5 was to investigate, in a representative sample of the adult French population, the environmental
6 pressures of diets according to UPF consumption.

7 **Methods** The study was conducted in 2,121 adults of the French nationally representative survey
8 INCA 3. Food intakes were analyzed to define the %UPF (in weight) in the diet according to NOVA
9 classification. Using detailed environmental data of foods from Agribalyse, we assessed the
10 contribution of UPF to 14 environmental pressure indicators and the contribution of the different food
11 chain stages to the impact: production, processing, storage, packaging, transport and retailing at the
12 food level. The data was described according to quintiles of % of UPF in the diet and analyzed using
13 crude and energy-adjusted models.

14 **Results** Overall, UPF represented 19% of the diet and contributions total GHGe, water use, land use,
15 and energy demand were 24%, 23%, 23% and 26%, respectively Compared to low consumers of UPF
16 (Q1, median UPF= 7%), high consumers (Q5, median UPF= 35%) had a higher energy intake (+22%).
17 Higher energy intake explained the higher pressures observed in Q5 for certain indicators. After
18 energy adjustment, GHGe and land use were not associated with %UPF in the diet however, an
19 inverse association was observed between %UPF and water use and energy demand. The processing
20 and packaging stages were significant contributor to energy demand.

21 **Conclusions** Diets rich in UPF, compared to low, were overall associated with higher contribution of
22 post-farm stages, in particular processing regarding energy demand.

23 **Keywords:** Environmental footprint, ultra-processed food, diet, food chain

Highlights

- Regardless of the % UPF in the diet, GHGe, land use and water use pressures mostly occurred at the stage of agricultural production, in contrast, packaging and processing stages were also important contributors to energy demand
- Overall, without energy-adjustment, higher UPF consumption was associated with higher environmental impact, in particular GHGe and land use
- A large part of the higher pressures observed among participants with higher UPF consumption was explained by their higher dietary energy intake since the associations did not remain or were even reversed after energy adjustment
- Low UPF consumers had overall higher water footprint (due to their higher fruit and vegetable consumption and relatively higher animal-based foods consumption compared to high UPF consumers)
- Contribution of the UPF category to total impact/pressure varied across indicators, with a high contribution of the UPF category to energy demand, due to the processing stages.

Non-technical summary

The present study conducted in a French nutritional surveillance study has documented that some food-related environmental pressures (from production to consumption), namely GHG emissions, land use and water use, occur mainly at the agricultural production stage and in iso-caloric model, GHG emissions and water use were not associated with %UPF in the diet while the diet of high consumers of UPF used less water. However, the contribution of ultra-processed foods varies across the environmental indicators, with in particular a higher contribution of %UPF in the diet than other foods to energy demand, due to processing steps. In the 5th quintile of %UPF, UPF consumption represent 35% of the diet (as weight) and the processing step contribute to 42% of the energy demand.

Introduction

24 In the recent decades, food systems and food supplies have become largely globalized with changes
25 occurring at all steps of the food chain, from production to consumption (1). Urbanization and
26 modernization have profoundly changed eating habits (2). Diets first in Western industrialized
27 countries and now in many lower and middle-income countries are characterized by high consumption
28 of animal products but also salt, fat and sugar, and recognized as major risk factors for many chronic
29 diseases (3). Besides, the consumption of “ultra-processed foods” (UPF), has grown around the world
30 and now reaches more than half of daily energy intake in the UK and US (4) and is 31% in France (5).
31 These are foods that underwent extensive chemical or physical transformations and/or containing
32 cosmetic food additives or other industrial ingredients (e.g. hydrogenated oils, fructose syrup, etc.).
33 Although not systematically, they often contain on average higher amounts of saturated fat, salt, and
34 sugar and lower amounts of fibers, micronutrients and potentially healthy active compounds (6). In the
35 last decade, a growing body of studies suggesting a role of UPF consumption on health has emerged.
36 This literature is broadly growing, leading to the first reviews and meta-analyses summarizing findings
37 from prospective studies and consistently showing associations between UPF consumption and
38 increased risk of many non-communicable diseases (4,7–13). Most of the studies are based on the
39 NOVA classification, which, besides the above described “ultra-processed food” category,
40 distinguishes “unprocessed or minimally processed foods” (fresh, dried, grounded, chilled, frozen,
41 pasteurized or fermented staple foods such as fruits, vegetables, pulses, rice, pasta, eggs, meat, fish or
42 milk), “processed culinary ingredients” (salt, vegetable oils, butter, sugar and other substances
43 extracted from foods and used in kitchens to transform unprocessed or minimally processed foods into
44 culinary preparations) and “processed foods” (canned vegetables with added salt, sugar-coated dry
45 fruits, meat products only preserved by salting, cheeses and freshly made unpackaged breads, and
46 other products manufactured with the addition of salt, sugar or other substances of the “processed
47 culinary ingredients” group) (6).

48 Beyond health issues, the current global food system greatly contributes to the degradation of the
49 environment by undermining natural resources, including water and forests, and jeopardizing climate
50 stability by increase of greenhouse gas emissions (GHGe) (14,15). However, even if the raw material
51 production stage is the most impacting for the environment, post-production steps (e.g. processing,
52 packaging, and transport) in the food industry are also resource-intensive (16,17) and are important
53 contributors of GHGe and energy demand. A recent time-series study conducted in Brazil showed that
54 the share of unprocessed foods in the diet decreased over a 30-year period, while the share of
55 processed and UPF increased, especially UPF based on animal products, doubling their contribution to
56 total diet-related environmental impacts over the same period (18). Another recent study, conducted in
57 the Netherlands, reported that, compared to minimally processed food consumption, UPF consumption
58 contributed more to GHGe but less to water use (19).

59 The shortcomings of studies investigating environmental pressures associated with UPF have been
60 described in the literature and include, among other things, the failure to take into account some
61 ingredients and imprecise data on the processing and packaging stages (20). In addition, scientific
62 literature documenting environmental pressures related to UPF food or intakes is very scarce (21)
63 (19,21,22) and focused on data from life cycle assessment (LCA) covering the entire chain, without
64 individualizing its different stages (production, processing, storage, packaging, transport and
65 retailing).

66 However, some authors reported that consumption of discretionary foods (foods high in saturated fats,
67 sugars, salt and/or alcohol that can be eaten occasionally in small amounts, but are not a necessary part
68 of the diet) may contribute to an important part of diet-related environmental pressures (including
69 water use, energy use and GHGe). Energy density of such eating habits could be a strong determinant
70 of environmental pressures (23,24). In addition, the food processing sector is an important contributor
71 to total food loss and waste (along the entire food supply chain) generated by retailers and consumers
72 (25).

73 While the role of UPF on human health, based on the NOVA classification, is becoming well
74 documented, it is now important to estimate, using a systematic methodological approach, the impact
75 of UPF on planetary health, as part of a holistic approach to health.

76 In this context, the aim of the present study was to estimate environmental pressures associated with
77 the four NOVA categories of the food consumed and for different stages of the whole food chain, in a
78 French representative study that included a large set of environmental indicators.

Results

79 The characteristics of the total study population and according to quintiles of %UPF (expressed as g/d)
80 are presented in **Table 1**. The studied population included 2,121 participants (58% women), with a
81 mean age of 47 years (SD=16). In this population, %UPF was 18.16 (SD=11.66) and 20.59
82 (SD=12.06) in women and men, respectively. The contributions of food groups to UPF consumption
83 were presented in **Supplementary Figure 1**.

84 Participants with higher %UPF were more often male, younger, less educated, with lower income and
85 were more often unemployed or students. In addition, %UPF was inversely related to proportion of
86 NOVA1 in the diet (Q5 vs. Q1=-38%).

87 Dietary consumption greatly differed according to the %UPF in the diet (**Table 2 and Supplemental**
88 **Table 1**). In energy-adjusted models (**Table 2**), participants with high %UPF (Q5), compared to low
89 (Q1), had higher consumption of sweetened beverages, fruit juices, legumes, soup, and prepared
90 dishes, and lower consumption of non-sweetened beverages, whole grain and refined cereals, fruits,
91 vegetables, animal and vegetable fat, eggs, fish, and red meat. No linear relationship was observed for
92 alcoholic beverages, sweet and fat foods, condiments, potatoes, dairy products, processed meat, and
93 poultry. Food-group environmental pressures across quintiles were presented in **Supplementary**
94 **Figure 2**.

95 Energy intake increased across quintiles (Q5 vs. Q1=+22%) (**Table 3**). Higher %UPF was associated
96 with higher intake of carbohydrates and sugar, and lower intake of protein, fibers and most
97 micronutrients (total and non-heme iron, copper, magnesium, potassium, selenium, vitamins C and
98 B12, and zinc). Of note, for saturated fatty acids and lipids no linear trends were observed.
99 Overall, quality of the diet was lower in Q5 compared to Q1, with a decrease in sPNNS-GS2 (from
100 0.01 to -1.47), reflecting the adherence to the food-based dietary guidelines, and PANDiet (59.64 to
101 59.89%), reflecting the overall adequacy to nutrient-based references, across quintiles (**Table 3**).
102 Overall, diet-related environmental pressures greatly differed depending on whether energy
103 adjustment was applied or not (**Table 4**).
104 In the unadjusted model, most environmental indicators were higher among participants with higher
105 %UPF, including GHGe (Q5 vs. Q1: +15%), land use (+17%), fossils resource use (8%), marine and
106 terrestrial eutrophication (+13% and 15%), particulate matter (+13%), ionizing radiation (+16%) and
107 the overall endpoint ecological footprint (EF) score (+11%). On the contrary, water use was inversely
108 associated with %UPF with a lower mean value found in Q5 compared to Q1 (-7%).
109 When adjustment for energy intake was applied, some associations were no longer significant,
110 including GHGe while the negative association with regard to water use was slightly strengthened (Q5
111 vs. Q1 %UPF=-17%). In addition, associations regarding resource use, freshwater and marine
112 eutrophication, and ozone formation were reversed as well as the association concerning the global EF
113 score (-6%).
114 GHGe, land use, energy demand and water use, according to quintiles of %UPF are presented by food
115 supply chain stages in **Figure 1** and **Supplemental Table 2** (energy-adjusted models). Overall,
116 whatever the quintile, agricultural production of raw material was the main driver for GHGe, land use
117 and water use, while packaging and processing stages were also important contributors to the energy
118 demand pressure. The substantial differences between %UPF quintiles (Q5 vs. Q1) were higher
119 impacts of the processing stage on water use (+53%), GHGe (+42%) and energy demand (+37%). The
120 role of consumption step was relatively small. Interestingly, environmental pressures of packaging
121 were higher in Q1 than in Q5 and packaging was not an important contributor to UPF climate impacts
122 in our study
123 Concerning results by NOVA class (**Figure 2** and **Supplemental Table 3**), NOVA1 (unprocessed)
124 food consumption greatly contributed to each environmental indicator. However, the contribution
125 of UPF consumption to environmental pressures greatly differed according to indicators. In the
126 whole sample, UPF represented 19% of the consumption and contributions of UPF in the diet to
127 total GHGe, water use, land use, and energy demand were 24%, 23%, 23% and 26%, respectively.
128 In sensitivity analyses, results regarding % UPF as calorie are presented in **Supplemental Table 4**.
129 Overall, the results were similar but trend across quartiles was less evident. Notably, the association
130 between GHGe and level in UPF in the diet remained in the energy-adjusted model (+11%).

The substitution model from NOVA1 (unprocessed) to UPF consumption (modeled as a continuous variable) (Figure 3) produced similar trends to the models adjusted for energy intake (Figure 1). Specifically, when replacing %NOVA 1 with %UPF, a slight decrease in water use was observed at the production stage up to 50% of %UPF in the diet. A strong increase in energy demand at the processing stage was also observed. Substituting %NOVA1 by %UPF also led to increased energy demand for all the food stages, except the production stage but the confidence interval was large when %UPF in the diet was high. With regard to GHGe and land use, substituting NOVA1 with UPF in the diet increased GHGe and land use up to 30% of UPF but then decreased them thereafter (production stage).**Discussion**

131 In the present study conducted in a representative survey of the French population, we observed that
132 participants with a higher percentage of UPF had a higher energy intake, which explained their higher
133 pressure for most of the studied indicators. Most environmental pressures occurred at the stage of
134 agricultural production, apart from energy demand for which the processing and packaging stages was
135 also an important contributor. NOVA1 (unprocessed or minimally processed) food consumption
136 highly contributed to land use and GHGe in all quintiles. NOVA4 (UPF) food consumption greatly
137 contributed to energy demand with.

138
139 To our knowledge, only one study previously investigated the environmental pressure of individual
140 whole diet considering different degree of food processing evaluated through the NOVA classification
141 (21). Comparison of our results with those of this study is not straightforward, since it has been
142 conducted in a Brazilian population, which may have exhibited some dissimilarities as regards dietary
143 habits and environmental pressures associated to food production and processing. As found herein,
144 this study reported difference in energy intake and GHGe according to level of UPF in the diet. Also,
145 in our study, the positive relationship between GHGe and %UPF did not remain significant after
146 adjustment for energy. In the study by Garzillo *et al* (21), the singular role of energy intake was not
147 available as the authors also adjusted for sociodemographic factors, which may be considered
148 questionable inasmuch as this is not supposed to confuse the relation when focusing on the link
149 between dietary patterns and environmental pressures. Moreover, when %UPF was expressed in kcal,
150 as performed in the study of Garzillo *et al.*, the associations between GHGe and quintiles of %UPF
151 remained statistically significant even in the energy-adjusted model. Besides, our findings related to
152 water footprint were not similar to those observed in the Brazilian study, since they documented a
153 higher food-related water use in participants with higher levels of UPF in their diet, which did not
154 remain after energy intake adjustment. In contrast, in our study, a higher water footprint from the
155 whole diet of participants was observed among low %UPF participants, the association was even
156 strengthened after adjustment for energy intake. This latter result was attributable primarily to the fact
157 that participants who consumed lower amounts of UPF and, thus, in proportion, more NOVA1
158 (unprocessed or minimally processed) food, tended to have higher consumption of fruit and

159 vegetables, non-alcoholic beverages and red meat. This is also clearly observed in our substitution
160 model modelled with %UPF in the diet as a continuous variable. Thus, our finding is consistent with
161 the literature documenting a higher water footprint in plant-rich diets (26) and a lower use of blue
162 water in UPF-rich diets (19). Similarly, at constant energy intake, the fact that the association between
163 %UPF in the diet and GHGe and land use disappeared, is related to the somewhat higher red meat,
164 dairy products, fruit, vegetables, and fish consumption (all classified as NOVA1, unprocessed or
165 minimally processed) among low consumers of UPF compared to high consumers, as previously
166 reported (5). This is quite unexpected as it has been documented that production for UPF is often very
167 intensive and requires large amounts of fertilizers and pesticides (27). Of note, meat, in particular
168 ruminant meat, is the strongest contributor to GHGe (17,28). These findings were consistent with the
169 strong increase in environmental pressure with %UPF when adjustment for NOVA1 was performed.
170 The present work is the first to explore the pressures associated with the production stage and all post-
171 farm stages including processing, packaging, transport and supply, according to the degree of
172 processing in the diet. Our results showed an important role of post-farm stages in energy demand
173 whatever the %UPF in the diet. The agricultural production stage is the main contributor to diet-
174 related GHGe, land and water use while with regard to energy demand, this is less evident since post-
175 farm stages play also an important role in the total pressure.

176 Our findings indicate that environmental impacts of UPF consumption could be linked to at least two
177 main factors. First, the higher energy intake of high consumers of UPF is a major determinant of their
178 diet-related impacts (29,30). Second, the higher number of post-farming stages for UPF production
179 can lead to an increase in energy demand and various environmental pressures. Indeed, UPF are, by
180 definition, related to more industrial processing, more packaging (for instance, they represent 2/3 and
181 more than 70% of packaged foods in France and in the US, respectively), and longer transport which
182 may substantially contribute to environmental impact of food (27). Consistently with the scientific
183 literature (16,17,27), even if the production stage is the most impacting stage for the environmental
184 resources depletion, it appeared that the food processing consumes a large amount of fossil resources.
185 However, in our study, environmental footprint of packaging step was higher among low consumers of
186 UPF than among high consumers.

187 On the contrary, it has been suggested that UPF (on a 100kcal basis) are less GHG emitting and
188 environmentally harmful (water and land use) than some minimally/unprocessed foods, in particular if
189 they contain small amount of animal ingredients (14,17,19,31). This last aspect is consistent with 1)
190 our results when dietary energy intake was accounted for, as most the pressures decreased across the
191 quintiles, and 2) with a recent British study analyzing foods properties that documented that processed
192 foods have lower nutritional quality, but also lower GHGe and were less expensive than minimally
193 processed foods, regardless of their total fat, salt and/or sugar content (31). In addition, our findings
194 from the substitution model (NOVA1, unprocessed or minimally processed) by UPF are entirely

195 consistent with the recent findings from a Dutch study (19), in which authors documented that UPF,
196 although unhealthier compared to unprocessed foods, are less associated with water use.

197 Regarding eutrophication, our results can be interpreted in light of the few studies that have explored
198 the association with the consumption of prepared foods. In an European study, the consumption of
199 ready meals was one of the weakest food contributors to eutrophication (32), which is consistent with
200 our results showing that diets rich in UPF have less impacts on marine eutrophication and freshwater
201 eutrophication.

202 Moreover, while some studies have documented that UPF production contributes to a large proportion
203 of diet-related fertilizer use, we did not identified any association between UPF consumption and
204 acidification or terrestrial eutrophication (22).

205 Studies that have explored the environmental pressures of UPF in details are very limited and none of
206 them considered the details of the post-agricultural stages, even though this element is essential to
207 accurately assess environmental impacts of such foods.

208 In addition, it has been documented that production of UPF is also associated with the use of fertilizers
209 and pesticides, deforestation and biodiversity loss as well as packaging (2,20,33,34). With respect to
210 our findings as regards water use, the benefit is less convincing since, as previously emphasized (26),
211 healthy diets rich in fruits, vegetables and nuts are water consuming. Thus, some discrepancies exist in
212 alignment of foods as regards environmental sustainability and health impacts. For instance, it is now
213 well known that sugar, salt and food staples can have lower environmental impacts per calorie than
214 fruits, vegetables, and animal-based foods (35,36). The main lever to achieve food sustainability
215 remains the reduction of red meat and processed meat intake, as this would benefit for both human
216 health and the environment (14).

217 In addition to potential human health benefits (4,7–13), the reduction of high UPF consumption,
218 associated with a greater overall consumption energy intake, could be a driver in the transition towards
219 a more sustainable food system, by contributing to the reduction of GHGe, energy demand, land use,
220 soil and water degradation, and pollution and, thus, an important factor to consider in the fight against
221 the global syndemic of obesity, undernutrition, and climate change (37).

222

223 In terms of application, a widespread series of proposals have been proposed to implement changes
224 towards more healthy and sustainable diets (38). First of all, mobilization of the consumers is essential
225 and more generally radical changes of the food systems are needed. The changes should involve all
226 stakeholders through the implementation of measures to guide food choices (by promoting the
227 limitation of UPF consumption, as done in the French dietary guidelines), but also through policy
228 measures aiming to restrict unhealthy choices (for instance tax or disincentives), in particular because
229 healthy foods are often expensive. Our study exhibits some limitations and strengths. First, the study
230 was based on diets of French adults in a relatively small – though representative – sample, limiting the
231 diversity of dietary patterns such as vegetarian diets. For example, participants in INCA 3 had an

232 average age of 47 years, whereas consumers of UPF have been shown to be young (39). In addition,
233 this study was conducted among French adults in 2014 and thus has a particular temporal and
234 geographical context (in terms of LCAs and dietary patterns). Therefore, our results cannot be
235 generalized to other populations. The environmental impacts of ultra-processed foods should be
236 examined in other settings and contexts in future studies. Second, limitations were somewhat inherent
237 to the matching between Agribalyse 3.01 and INCA 3, as food databases were independently
238 developed, and environmental indicators were not available for certain foods (for instance, culinary
239 aids) or not detailed (for instance, type of mushrooms). However, the lack of direct matching
240 concerned only 3% of the food items. Third, even though the Agribalyse database is very rich and
241 accurate, some elements have been prioritized. For example, regarding packaging, only B2C
242 (business-to-consumer) packaging was considered and not B2B (business-to-business). Regarding
243 processing, the focus was driven by stages related to mass and yield changes and some other lacking
244 have been underlined (40). As regards transport, average values along the value chain were considered
245 but transport from the supply point to the household was not considered. Finally, the data were based
246 on LCA according to the standardized guidelines and methodologies but did not consider the type of
247 farming system (organic or conventional), limiting the consideration of the variety of practices along
248 the food chain. In addition, some indicators such as biodiversity loss were not available. Finally,
249 specific data on waste were not available avoiding to focus on potentially avoidable environmental
250 impact.

251 As to the strengths of our study, dietary data was collected in a nationally representative sample of the
252 adult population of France in 2015-2016. Furthermore, the consumption and pressures data were
253 collected using standardized methodologies. In addition, environmental data were validated by several
254 expert entities (40). Finally, the detail of pressures by stage of the value chain allowed us to consider
255 for the first time the contribution of UPF while taking into account the different stages.

Conclusion

256 This study is the first to explore the contribution of UPF consumption to different environmental
257 pressures, while detailing the different stages of the food chain. As high consumers of ultra-processed
258 foods generally have higher energy intake, overall their diets were associated with a higher footprint.
259 In addition, the consumption of UPF had a substantial role on some indicators, particularly on energy
260 demand through the processing stage. Such investigations could be considered in the development of
261 sustainable dietary guidelines in light of the previously documented links between UPF and human
262 health.

Methods

Population

263 This study was based on the French nationally representative survey INCA 3 conducted in 2014-2015
264 by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) and
265 including 2,121 adult participants who provided dietary consumption data using a validated method
266

267 (41). The design of the study, recruitment and survey plan (defining individual weight), as well as the
268 methods have been detailed elsewhere (41).

269 Participants were selected according to a three-stage random sampling plan (geographical units,
270 dwellings then individuals) drawn at random by the National Institute of Statistics and Economic
271 Studies (INSEE), based on the annual population census in 2011. One individual per dwelling was
272 then drawn at random from among the eligible individuals at the time of contact with the household.
273 Individual weight was calculated according to INSEE method to improve representativeness according
274 to region, size of the urban area, occupation and socio-professional category of the household
275 reference person, size of the household, level of education, sex and age (42). The INCA 3 study
276 protocol was authorised by the National Commission on Informatics and Liberty, after a favourable
277 opinion from the Advisory Committee on Information Processing in Health Research (CCTIRS). The
278 study also received a favourable opinion from the Conseil National de l'Information Statistique (CNIS)
279 on 15 June 2011 (n°121/D030) and was awarded the label of “general interest” and statistical quality
280 by the INSEE Label Committee (n°47/Label/D120). The data collected in the INCA 3 study are
281 available on the website [https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-](https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudes-alimentaires-de-letude-inca-3/)
282 [habitudes-alimentaires-de-letude-inca-3/](https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudes-alimentaires-de-letude-inca-3/).

283 The data collected in the INCA 3 cross-sectional study included food and drink consumption and
284 socio-demographic and lifestyle characteristics.

285 *Dietary data*

286 Detailed consumption data were collected over 3 non-consecutive days (2 weekdays and 1 weekend
287 day) distributed over approximately three weeks, using the 24-hour recall method conducted by
288 telephone by trained interviewers using a standardized validated software (GloboDiet)(43). The
289 quantification of portion sizes was carried out using a picture booklet of food portions and household
290 measurements.

291 Dietary intakes were calculated using the 2016 food composition database published by the French
292 Information Centre on Food Quality (44).

293 Mixed foods were decomposed using the standardized recipes validated by dietitians.

294 All food items were classified according to the NOVA classification (6,45) as previously extensively
295 described (46). At the individual level, the percentages (in weight) of the diet in NOVA1 (unprocessed
296 or minimally processed foods), NOVA2 (culinary ingredients), NOVA3 (processed foods), and
297 NOVA4 (UPF, ultra-processed food) were computed as described in the **Supplemental Material 1**.

298 The overall quality of the diet was assessed using two dietary scores, namely the sPNNS-GS2 (47) and
299 the PANDiet (48), which have extensively been described. Further details are presented in

300 **Supplemental Material 2.**

301 *Environmental indicators*

302 Diet-related environmental pressures were estimated using data from the French database Agribalyse®
303 3.0.1 developed by the French Agency for the Environment and Energy Management (ADEME).

304 Agribalyse® 3.0.1 contains environmental indicators for 2,497 foods consumed in France for which
305 nutritional contents is also available (49) using the same taxonomy. A total of 14 midpoint indicators
306 were available: GHGe, ozone depletion, particulate matters, ionizing radiation (effect on human
307 health), ecotoxicity, photochemical ozone formation (effect on human health), acidification, terrestrial
308 eutrophication, freshwater eutrophication, marine eutrophication, land use, water use, resource use,
309 minerals and metals and resource use, fossils and one endpoint ecological footprint (EF) calculated
310 according to the product environmental footprint (PEF) methodology (50).

311 Environmental indicator estimations were based on the method of LCA whose scope is "from field to
312 plate". The perimeter of the indicators covers each step of the value chain: agricultural production,
313 transport, processing, packaging, distribution and retailing, preparation at the consumer's level and
314 disposal of packaging. These different stages have been split into two phases 1) production and 2)
315 post-farm. The methodology has been extensively explained in *ad hoc* published reports (40,51)
316 summarized in **Supplemental Material 3**.

317 *Statistical analysis*

318 Participants were ranked and divided into weighted quintiles of %UPF. Socio-demographic and
319 dietary characteristics were described across weighted quintiles of %UPF using ANOVA, or
320 ANCOVA models when adjustment for energy intake was performed. Micronutrient and fiber intakes
321 were adjusted for energy intake using the residual method (52) and macronutrients were reported as %
322 of total energy intake.

323 The contribution of main food groups to environmental pressure of the diet are also described across
324 quintiles of %UPF.

325 In the main analysis, diet-related environmental footprints, according to quintiles of %UPF in the diet,
326 were first estimated overall, using crude and energy-adjusted ANOVA and ANCOVA models. The
327 assumptions of the models have been verified using standard tests. For the 4 indicators that are well
328 documented in the literature and therefore the most robust (GHGe, water use, land use, and energy
329 demand), we also examined the contribution of the different food system stages to the environmental
330 pressures. Finally, the respective contribution of the different NOVA food category to the different
331 environmental pressures was assessed in the whole sample.

332 Several sensitivity analyses were conducted. Firstly UPF vs. %NOVA1 (unprocessed or minimally
333 processed) substitution was modeled (52) for each indicator and farm and post-farm steps. The
334 principle of the substitution model is based on the inclusion into the model of the following
335 independent variables: total energy intake, and consumption of the different NOVA groups (as % of
336 in the diet (including %UPF), except %NOVA1. The β coefficient of %UPF ($\beta_{\%UPF}$) refers to the
337 substitution of NOVA1 by UPF, with all other variables held constant (%NOVA2, %NOVA3, and
338 energy intake). We used a spline regression to obtain a continuous representation.

339 For instance, for GHGe and a substitution of NOVA1 by UPF, we focus on the $\beta_{\%UPF}$ coefficient of
340 the model which can be written as follows:

341
$$\text{GHGe} = \beta_{\% \text{UPF}} \times \% \text{UPF} + \beta_{\% \text{NOVA2}} \times \% \text{NOVA2} + \beta_{\% \text{NOVA3}} \times \% \text{NOVA3} + \beta_{\text{EI}} \times \text{EI} + \varepsilon ,$$

342

343 Secondly, the main analysis described above was reperformed using the %UPF as % of total energy
344 intake instead of total weight. For this purpose, due to distribution of individual weightings, quartiles
345 were considered.

346 All tests were two-sided and a P-value <0.05 was considered significant. Statistical analyses were
347 performed using SAS Software (version 9.4, SAS Institute Inc, Cary, NC, USA) and figures were
348 performed developed using R version 3.6.

Data described in the manuscript, code book, and analytic code will be made available upon request
pending application and approval to collaboration@etude-nutrinet-sante.fr.

349 **The authors' contributions**

350 EKG conducted the research, implemented the databases, conducted the analyses and wrote the
351 manuscript.

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

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

Conflict of Interest

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Correspondence: emmanuelle.kesse-guyot@inrae.fr

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Table 1: Characteristics of study participants according to quintiles of %UPF, (INCA 3 study, n=2,121)¹

	Total sample %	%UPF	Q1	Q2	Q3	Q4	Q5	P for trend ²
%UPF cut-off³	-		0-<9.95	9.95-<14.68	14.68-<20.25	20.25-<28.44	>28.44	
%NOVA1	69.83 (10.42)		82.67 (6.29)	76.4 (6.54)	70.17 (7.30)	65.86 (6.33)	51.46 (10.42)	<.0001
%NOVA2	1.50 (0.01)		1.50 (1.06)	1.52 (1.00)	1.49 (1.15)	1.52 (1.22)	1.47 (1.09)	<.0001
%NOVA3	9.43 (0.43)		9.37 (5.40)	9.66 (6.06)	10.97 (7.00)	8.61 (5.80)	8.39 (5.84)	0.84
%UPF	19.29 (10.86)		6.56 (2.29)	12.43 (1.3)	17.4 (1.51)	24.02 (2.47)	38.78 (10.38)	<.0001
N	2,121	-	471	420	429	393	408	
Weighted N	2,121	-	421.36	425.13	425.86	422.35	426.30	
Sex								<.0001
Men	41.82	20.59 (12.06)	38.96	45.53	51.02	53.14	53.71	
Women	58.18	18.16 (11.66)	61.04	54.47	48.98	46.86	46.29	
Age (y)	46.9 (16.3)	-	54.5 (13.6)	51.2 (15.0)	50.0 (15.1)	49.2 (17)	47.29 (18.1)	<.0001
Education								0.09
Primary+College	37.86	19.90 (12.88)	48.72	50.07	46.77	47.09	47.14	
High school	20.79	20.77 (13.03)	16.8	14.94	14.1	21.4	24.6	
Undergraduate level	21.12	18.83 (10.51)	16.33	16.18	17.46	16.57	18.12	
Postgraduate level	20.18	16.56 (9.41)	18.16	18.41	21.67	14.94	10.14	
No information	0.05	13.27 (.)	0	0.41	0	0	0	
Living area								0.23
Rural	26.97	19.60 (12.18)	26.64	24.44	22.87	28.53	26.07	
2,000-19,999 inhab.	19.42	19.57 (13.08)	18.18	18.78	17.9	17.75	16.88	
20,000-99,999 inhab.	13.81	18.83 (10.53)	12.11	10.03	11.7	13.42	13.68	
≥100,000 inhab.	28.95	19.01 (11.70)	28.68	31.38	31.66	31.76	34.69	
Paris area	10.84	18.30 (11.02)	14.38	15.38	15.86	8.54	8.68	
BMI (kg.m²)	25.86 (4.82)	-	25.96 (4.67)	25.64 (4.59)	25.8 (4.57)	25.75 (5.02)	25.65 (5.25)	0.05

526 Abbreviations: BMI, body mass index; inhab: inhabitants, NOVA1, unprocessed or minimally processed food,

527 NOVA2, culinary ingredients; NOVA3, processed food; UPF, ultra-processed food

528 ¹Values are n, means (SD) or % as appropriate, all data are weighted

529 ²P-value for linear trend is estimated using linear contrast

530 ³Values are ranges of %UPF (in weight)

Table 2: Consumption of food groups (g/d) according to %UPF (in %) quintiles, (INCA 3 study, N=2,121)¹

	<i>Total sample</i>	Q1	Q2	Q3	Q4	Q5	<i>ΔQ5 vs. Q1²</i>	<i>P for trend³</i>
Alcoholic beverages	122.0 (92.7)	106.6 (11.1)	131.4 (11.0)	122.3 (11.0)	109.9 (11.0)	141.2 (11.0)	32	0.18
Sweetened beverages	105.4 (94.7)	29.7 (10.9)	41.3 (10.8)	44.7 (10.8)	117.8 (10.9)	315.8 (10.8)	963	<.0001
Non-sweetened beverages	1,394.2 (320.0)	1,797.4 (30.8)	1,583.4 (30.4)	1,385.4 (30.6)	1,229.0 (30.6)	898.8 (30.6)	-50	<.0001
Sweet and fat foods	109.5 (50.5)	97.2 (3.5)	112.0 (3.4)	103.7 (3.5)	119.8 (3.5)	116.3 (3.5)	20	0.10
Condiments	26.5 (4.7)	24.4 (1.5)	25.3 (1.5)	27.6 (1.5)	30.2 (1.5)	25.2 (1.5)	4	0.16
Whole grains	6.5 (1.3)	7.4 (1.0)	7.6 (1.0)	7.4 (1.0)	5.6 (1.0)	4.2 (1.0)	-43	0.01
Refined cereals	181.3 (62.8)	206.8 (5.0)	183.3 (4.9)	196.3 (4.9)	159.1 (4.9)	156.8 (4.9)	-24	<.0001
Fruits	144.1 (33.0)	186.3 (6.6)	161.3 (6.5)	147.7 (6.5)	116.9 (6.6)	100.5 (6.6)	-46	<.0001
Fruit juice	62.6 (16.1)	47.8 (4.8)	57.7 (4.8)	66.2 (4.8)	65.4 (4.8)	78.3 (4.8)	64	<.0001
Vegetables	141.6 (32.4)	186.2 (5.4)	157.9 (5.3)	139.1 (5.4)	121.9 (5.4)	94.9 (5.4)	-49	<.0001
Legumes	7.4 (5.0)	6.2 (1.2)	7.0 (1.2)	5.1 (1.2)	10.7 (1.2)	8.5 (1.2)	39	0.03
Soup	98.5 (46.7)	26.8 (8.3)	60.1 (8.2)	117.8 (8.3)	154.0 (8.3)	146.3 (8.3)	447	<.0001
Potatoes	45.9 (19.1)	47.6 (3.5)	41.5 (3.4)	47.5 (3.4)	42.3 (3.4)	50.7 (3.4)	7	0.52
Nuts	3.2 (1.3)	4.1 (0.4)	3.2 (0.4)	3.2 (0.4)	2.9 (0.4)	2.5 (0.4)	-38	0.01
Animal fat	9.4 (3.3)	10.7 (0.7)	9.0 (0.6)	9.7 (0.6)	9.6 (0.6)	7.8 (0.6)	-27	0.01
Vegetable fat	8.2 (1.5)	10.1 (0.5)	8.4 (0.5)	6.8 (0.5)	7.5 (0.5)	8.4 (0.5)	-17	<.0001
Prepared dishes	114.2 (26.8)	109.3 (5.4)	110.7 (5.3)	104.5 (5.4)	122.0 (5.4)	125.9 (5.4)	15	0.01
Dairy products	185.2 (30.9)	183.8 (8.4)	187.3 (8.3)	186.6 (8.3)	205.8 (8.3)	161.8 (8.3)	-12	0.34
Eggs	13.9 (1.7)	17.6 (1.3)	14.8 (1.3)	10.9 (1.3)	13.8 (1.3)	11.8 (1.3)	-33	<.0001
Fish	28.3 (3.9)	35.5 (2.0)	29.8 (1.9)	25.1 (1.9)	24.4 (1.9)	25.6 (1.9)	-28	<.0001
Red meat	51.0 (16.0)	55.5 (2.7)	52.9 (2.6)	49.7 (2.7)	49.6 (2.7)	46.4 (2.7)	-17	0.01
Processed meat	30.3 (14.4)	27.8 (1.8)	29.2 (1.7)	32.4 (1.7)	31.2 (1.8)	31.4 (1.8)	13	0.10
Poultry	26.9 (3.7)	28.3 (1.8)	26.4 (1.8)	29.2 (1.8)	22.6 (1.8)	27.7 (1.8)	-2	0.37

531 Abbreviations: Q, quintile; UPF, ultra-processed food

532 Non-sweetened beverages include coffee, tea; sweetened beverages encompass soda, fruit juice etc.;

533 sweet and fat foods include biscuits, breakfast cereals and snacking products; refined cereals

534 encompass bread, pasta, rice (but not breakfast cereals); soup include dehydrated commercial soup;

535 prepared dishes include fish fritters, cordon bleu, industrial cereal cakes, pâté, nuggets etc.

536 ¹Values are means (standard errors of the means) adjusted for total energy intake

537 ²Relative difference

538 ³P-value for linear trend is estimated using linear contrast

Table 3: Nutrient intakes and dietary scores according to %UPF quintiles, (INCA 3 study, n=2,121)¹

	Q1	Q2	Q3	Q4	Q5	P for trend ⁴
Alcohol-free energy intake (kcal/d) ²	1,782.70 (34.81)	1,949.69 (34.66)	2,133.58 (34.63)	2,110.19 (34.77)	2,178.44 (34.61)	<.0001
Lipids ³ (%EI/d)	34.47 (0.30)	33.49 (0.30)	33.11 (0.30)	33.90 (0.30)	33.42 (0.30)	0.14
Proteins ³ (%EI/d)	17.91 (0.18)	17.09 (0.18)	16.75 (0.18)	16.43 (0.18)	15.85 (0.18)	<.0001
Carbohydrates ³ (%EI/d)	47.62 (0.33)	49.42 (0.33)	50.14 (0.33)	49.66 (0.33)	50.72 (0.33)	<.0001
Sugar ³ (%EI/d)	16.12 (0.27)	16.99 (0.27)	17.10 (0.27)	18.47 (0.27)	20.03 (0.27)	<.0001
Animal protein ³ (%EI/d)	25.94 (0.40)	24.23 (0.40)	23.60 (0.40)	23.44 (0.40)	22.75 (0.40)	<.0001
Plant protein ³ (%EI/d)	12.90 (0.15)	13.27 (0.15)	13.44 (0.15)	13.38 (0.15)	13.00 (0.15)	0.51
SFA (g/d)	31.47 (0.38)	31.44 (0.38)	31.62 (0.38)	32.68 (0.38)	30.83 (0.38)	0.96
Atherogenic SFA ⁵ (g/d)	20.25 (0.25)	20.26 (0.25)	20.00 (0.25)	20.78 (0.25)	19.74 (0.25)	0.54
EPA+DHA (g/d)	0.31 (0.02)	0.34 (0.02)	0.25 (0.02)	0.25 (0.02)	0.28 (0.02)	0.03
Linoleic FA (g/d)	7.11 (0.13)	6.81 (0.13)	6.57 (0.13)	6.89 (0.13)	6.91 (0.13)	0.45
Alpha-linolenic FA (g/d)	1.03 (0.03)	1.01 (0.02)	0.96 (0.02)	0.92 (0.02)	0.93 (0.02)	<.0001
PUFA (g/d)	10.08 (0.17)	9.54 (0.17)	9.20 (0.17)	9.41 (0.17)	9.75 (0.17)	0.15
Beta-carotene (µg/d)	2737 (129)	2563 (127)	2890 (128)	2715 (121)	2445 (128)	0.29
Calcium (mg/d)	921.50 (15.06)	909.39 (14.86)	913.67 (14.92)	948.43 (14.94)	845.54 (14.93)	0.02
Cholesterol (mg/d)	340.33 (6.56)	329.32 (6.47)	315.25 (6.50)	323.13 (6.51)	293.95 (6.51)	<.0001
Copper (mg/d)	1.85 (0.04)	1.76 (0.04)	1.81 (0.04)	1.53 (0.04)	1.44 (0.04)	<.0001
Iron (mg/d)	10.47 (0.13)	10.78 (0.13)	10.58 (0.13)	10.10 (0.13)	10.02 (0.13)	<.0001
Non-heme iron (mg/d)	9.26 (0.11)	9.55 (0.11)	9.29 (0.11)	8.85 (0.11)	8.82 (0.11)	<.0001
Zinc (mg/d)	9.70 (0.15)	9.76 (0.15)	9.47 (0.15)	9.41 (0.15)	8.64 (0.15)	<.0001
Fiber (g/d)	20.42 (0.25)	20.04 (0.24)	20.12 (0.24)	19.58 (0.24)	18.23 (0.24)	<.0001
Iodine (µg/d)	147.58 (2.72)	153.14 (2.68)	148.20 (2.70)	156.15 (2.70)	143.66 (2.70)	0.58
Magnesium (mg/d)	354.69 (4.26)	355.80 (4.21)	336.18 (4.22)	331.81 (4.23)	316.67 (4.23)	<.0001
Manganese (mg/d)	3.48 (0.05)	3.22 (0.05)	3.18 (0.05)	2.76 (0.05)	2.66 (0.05)	<.0001
Phosphorus (mg/d)	1,221 (11)	1,206 (11)	1,185 (11)	1,179 (11)	1,136 (11)	<.0001
Phytates (µg/d)	618.87 (9.67)	612.97 (9.54)	594.88 (9.58)	579.84 (9.59)	569.60 (9.59)	<.0001
Polyols (mg/d)	1.23 (0.06)	1.26 (0.06)	1.19 (0.06)	0.97 (0.06)	0.94 (0.06)	<.0001
Potassium (mg/d)	3,226 (35)	3,188 (34)	3,054 (34)	3,028 (34)	2,873 (34)	<.0001
Retinol (µg/d)	474.30 (33.43)	491.88 (32.98)	500.93 (33.11)	435.60 (33.16)	377.45 (33.15)	0.02
Selenium (µg/d)	130.67 (2.04)	123.18 (2.01)	125.71 (2.02)	122.92 (2.02)	113.86 (2.02)	<.0001
Sodium (mg/d)	2,978 (43)	3,033 (43)	3,263 (43)	3,273 (43)	3,059 (43)	<.0001
Vitamin B1 (mg/d)	1.20 (0.02)	1.20 (0.02)	1.21 (0.02)	1.23 (0.02)	1.18 (0.02)	0.87
Vitamin B2 (mg/d)	1.80 (0.03)	1.80 (0.03)	1.74 (0.03)	1.83 (0.03)	1.75 (0.03)	0.52
Vitamin B3 (mg/d)	20.45 (0.35)	20.56 (0.35)	19.70 (0.35)	19.46 (0.35)	20.14 (0.35)	0.13
Vitamin B5 (mg/d)	5.58 (0.07)	5.68 (0.07)	5.52 (0.07)	5.60 (0.07)	5.46 (0.07)	0.16
Vitamin B6 (mg/d)	1.71 (0.02)	1.71 (0.02)	1.70 (0.02)	1.67 (0.02)	1.70 (0.02)	0.41
Vitamin B9 (µg/d)	308.39 (4.24)	306.96 (4.18)	300.22 (4.20)	293.86 (4.21)	279.98 (4.20)	<.0001
Vitamin B12 (µg/d)	5.58 (0.20)	5.64 (0.20)	5.32 (0.20)	4.79 (0.20)	4.62 (0.20)	<.0001
Vitamin C (mg/d)	95.89 (2.65)	89.08 (2.61)	93.03 (2.62)	85.96 (2.63)	81.68 (2.62)	<.0001
Vitamin E (mg/d)	10.37 (0.18)	9.71 (0.17)	9.14 (0.17)	9.31 (0.17)	9.59 (0.17)	<.0001
PANDiet (/100)	59.64 (0.28)	59.59 (0.28)	59.08 (0.28)	57.99 (0.28)	56.89 (0.28)	<.0001
sPNNS-GS2 (/14.25)	0.01 (0.14)	-0.26 (0.14)	-0.62 (0.14)	-1.13 (0.14)	-1.47 (0.14)	<.0001

539 Abbreviations: EI, alcohol-free energy intake; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; FA,
540 fatty acids; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; PUFA,
541 polyunsaturated fatty acids; Q, quintile; SFA, saturated fatty acids; sPNNS-GS2, simplified Programme National
542 Nutrition Santé-Guidelines Score 2; UPF, ultra-processed food

543 ¹Values are means (standard errors of the means) adjusted for energy intake using the residual method or
544 standard adjustment for contribution of macronutrient to alcohol-free energy intake, PANDiet, and sPNNS-GS2.

545 ²Values are crude means (SD)

546 ³Values are expressed as % of total energy intake

547 ⁴P-value for linear trend is estimated using linear contrast

548 ⁵Atherogenic fatty acids include lauric and myristic and palmitic acids

Table 4: Daily diet-related environmental indicators according to %UPF quintiles, (INCA 3 study, n=2,121) ^{1,2}

Crude	Q1	Q2	Q3	Q4	Q5	P-trend³
Climate change (GHGe) (kg CO ₂ eq)	5.42 (5.15-.5.69)	5.81 (5.54-6.08)	5.96 (5.69-6.23)	6.19 (5.92-6.45)	6.24 (5.98-6.51)	0.003
Water use (m ³ world eq)	6.90 (6.62-7.18)	6.55 (6.27-6.83)	6.64 (6.36-6.92)	6.15 (5.87-6.43)	6.44 (6.16-6.72)	0.01
Land use (pt)	255.41 (240.34-270.48)	272.07 (257.07-287.08)	281.54 (266.55-296.53)	290.87 (275.82- 305.92)	299.58 (284.59-314.56)	0.01
Energy demand (MJ)	58.81 (56.94-60.67)	60.82 (58.96-62.68)	63.34 (61.49-65.20)	61.68 (59.82-63.55)	63.23 (61.37-65.08)	0.01
Acidification (mol H ⁺ eq)	0.066 (0.002)	0.069 (0.002)	0.071 (0.002)	0.073 (0.002)	0.075 (0.002)	0.01
Resource use, minerals and metals (kg Sb eq)	9.73 (9.38-10.07)	10.04 (9.70-10.38)	10.00 (9.66-10.34)	9.58 (9.24-9.92)	9.63 (9.29-9.97)	0.25
Eutrophication, freshwater (kg P eq)	1.02 (0.97-1.07)	1.03 (0.98-1.08)	1.01 (0.96-1.06)	0.98 (0.93-1.03)	1.02 (0.97-1.06)	0.25
Eutrophication, marine (kg N eq)	20.96 (19.99-21.93)	22.57 (21.61-23.54)	23.53 (22.57-24.50)	22.88 (21.91-23.85)	23.61 (22.65-24.58)	0.06
Eutrophication, terrestrial (mol N eq)	0.26 (0.25-0.28)	0.28 (0.26-0.29)	0.28 (0.27-0.30)	0.30 (0.28-0.31)	0.30 (0.29-0.31)	0.01
Photochemical ozone formation (kg NMVOC eq)	16.19 (15.40-16.97)	16.69 (15.91-17.47)	16.52 (15.74-17.30)	16.87 (16.09-17.66)	17.00 (16.23-17.78)	0.37
Ozone depletion (kg CFC-11eq)	0.53 (0.45-0.62)	0.56 (0.48-0.64)	0.51 (0.43-0.59)	0.66 (0.58-0.74)	0.51 (0.43-0.59)	0.80
Particulate matter (disease incidence)	0.48 (0.46-0.50)	0.51 (0.48-0.53)	0.52 (0.49-0.54)	0.53 (0.51-0.55)	0.54 (0.52-0.56)	0.01
Ionising radiation (kBq U235 eq)	1.27 (1.22-1.31)	1.34 (1.30-1.38)	1.44 (1.40-1.49)	1.42 (1.37-1.46)	1.47 (1.43-1.52)	<.0001
EF score ⁴	0.66 (0.63-0.69)	0.69 (0.67-.72)	0.71 (0.68-0.74)	0.71 (0.69-0.74)	0.73 (0.70-0.75)	0.02
Adjusted for dietary energy intake	Q1	Q2	Q3	Q4	Q5	P-trend³
Climate change (GHGe) (kg CO ₂ eq)	5.93 (5.71-6.15)	5.84 (5.62-6.05)	5.59 (5.37-5.80)	5.93 (5.71-6.14)	5.82 (5.60-6.03)	0.19
Water use (m ³ world eq)	7.34 (7.09-7.59)	6.58 (6.34-6.82)	6.32 (6.07-6.56)	5.92 (5.68-6.17)	6.07 (5.82-6.31)	<.0001
Land use (pt)	280.28 (267.28-293.28)	273.46 (260.63-286.28)	263.24 (250.36-276.12)	278.17 (265.27-291.07)	278.65 (265.76-291.54)	0.31
Energy demand (MJ)	63.38 (62.17-64.58)	61.07 (59.89-62.26)	59.98 (58.79-61.17)	59.35 (58.16-60.54)	59.38 (58.19-60.57)	<.0001
Acidification (mol H ⁺ eq)	0.072 (0.001)	0.070 (0.001)	0.067 (0.001)	0.070 (0.001)	0.070 (0.001)	0.11
Resource use, minerals and metals (kg Sb eq)	10.49 (10.25-10.74)	10.08 (9.84-10.33)	9.44 (9.19-9.68)	9.19 (8.94-9.43)	8.99 (8.74-9.23)	<.0001
Eutrophication, freshwater (kg P eq)	1.09 (1.05-1.13)	1.04 (0.99-1.08)	0.96 (0.92-1.00)	0.94 (0.90-0.99)	0.96 (0.91-1.00)	<.0001
Eutrophication, marine (kg N eq)	22.94 (22.19-3.69)	22.68 (21.94-3.42)	22.07 (21.33-2.82)	21.87 (21.12-22.61)	21.95 (21.20-22.69)	0.001
Eutrophication, terrestrial (mol N eq)	0.29 (0.27-0.30)	0.28 (0.27-0.29)	0.27 (0.26-0.28)	0.28 (0.27-0.29)	0.28 (0.27-0.29)	0.20
Photochemical ozone formation (kg NMVOC eq)	17.38 (16.69-8.07)	16.75 (16.07-7.44)	15.64 (14.96-16.33)	16.26 (15.57-6.95)	16.00 (15.31-6.69)	0.01
Ozone depletion (kg CFC-11eq)	0.58 (0.49-0.66)	0.56 (0.48-0.64)	0.48 (0.40-0.56)	0.64 (0.55-0.72)	0.47 (0.39-0.55)	0.39
Particulate matter (disease incidence)	0.52 (0.51-0.54)	0.51 (0.49-0.53)	0.49 (0.47-0.50)	0.51 (0.49-0.53)	0.50 (0.49-0.52)	0.06
Ionising radiation (kBq U235 eq)	1.38 (1.35-1.41)	1.35 (1.32-1.37)	1.36 (1.34-1.39)	1.36 (1.33-1.39)	1.38 (1.35-1.41)	0.53
EF score ⁴	0.72 (0.70-0.74)	0.69 (0.68-0.71)	0.67 (0.65-0.69)	0.68 (0.66-0.70)	0.68 (0.66-0.70)	0.002

549 Abbreviation: EF, ecological footprint; GHGe, greenhouse gas emissions; Q, quintile; UPF, ultra-processed food

550 ¹Units are as follows: kg CO₂ eq, carbon dioxide equivalent; m³ world eq, water use in cubic meters of water; land use is estimated as loss of soil organic matter content in
551 kilograms of carbon deficit (kg C deficit) dimensionless and expressed as Points (Pt); MJ, megajoule; mol H⁺ eq, equivalent of moles hydron; kg Sb eq, equivalent of
552 kilograms of antimony; kg P eq, equivalent of kilograms of phosphorus, kg N eq, equivalent of kilograms of nitrogen; mol N eq, equivalent of moles of nitrogen; kg NMVOC
553 (Non-methane volatile organic compounds) eq, equivalent of kilograms of non-methane volatile organic compounds; kg CFC-11eq, equivalent of kilograms of
554 trichlorofluoromethane (Freon-11); Emission of particulate matter in change in mortality due to particulate matter emissions; kg U235 eq, equivalent of kilobecquerels of
555 Uranium 235

556 ²Values are means (95%CI) (crude or energy-adjusted)

557 ³P-value for linear trend is estimated using contrast

558 ⁴For the EF (environmental footprint) score, the higher it is, the more impactful it is

Figure 1: Farm and post-farm stages contribution to daily diet-related environmental indicators according to %UPF quintiles (INCA 3 study, n=2,121), adjusted for energy intake^{1,2}

559

560 Panel A corresponds to the pressures, in absolute values, of each stage. Panel B corresponds to the pressures, in
561 relative value (%), of each stage

562 Abbreviation: Q, quintile; UPF, ultra-processed food

563 ¹Climate change (Greenhouse gas emissions), energy demand, land use and water use are expressed in kg
564 CO₂eq, m³ world eq, pt, MJ, respectively

565 ²Energy-adjusted values

566

Figure 2: Contribution of NOVA class consumption to daily diet-related environmental indicators (INCA 3 study, n=2,121), adjusted for energy intake

567 Consumption, climate change (Greenhouse gas emissions), energy demand, land use and water use are expressed
568 in g/d, kg CO₂eq, m³ world eq, pt, MJ, respectively. Panel B corresponds to same data but in relative value (%).

569 Abbreviation: NOVA1, unprocessed or minimally processed food, NOVA2, culinary ingredients; NOVA3,
570 processed food; Q, quintile; UPF, ultra-processed food.

571

Figure 3: Daily diet-related environmental indicators for each step of the food chain for the substitution model of %UPF (INCA 3 study, n=2,121)^{1,2}

572 ¹Climate change (Greenhouse gas emissions), energy demand, land use and water use are initially expressed in
573 kg CO₂eq/d, m³ world eq/d, pt/d, MJ/d, respectively

574 ² The model explores the variations in environmental pressures at each step of the food chain system associated
575 with the substitution of NOVA1 (unprocessed or minimally processed) foods (as % of in the diet) by NOVA4
576 (UPF) foods (as % of in the diet). For example, the model for GHGe can be written as:

577 is:

$$578 \text{GHGe} = \beta_{\% \text{UPF}} \times \% \text{UPF} + \beta_{\% \text{NOVA2}} \times \% \text{NOVA2} + \beta_{\% \text{NOVA3}} \times \% \text{NOVA3} + \beta_{\text{EI}} \times \text{EI} + \varepsilon,$$

579 where *EI* is total energy intake.

580