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Plant protein diversity is critical to ensuring the nutritional adequacy of diets when replacing animal with plant protein – observed and modelled diets of French adults (INCA3).^{1,2,3,4}

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³ Supplemental Method 1, Supplemental Tables 1-13 are available via the "Online Supporting Material" link in the online posting of the article and via the same link in the online table of contents at jn.nutrition.org.

⁴ Abbreviations used:

ALA, alpha-linolenic acid; Anses, French Agency for Food, Environmental and Occupational Health and Safety; APF, Animal-protein foods; AS, Adequacy Subscore; BI, Berry-Index; INCA3, Third Individual and National Study on Food Consumption Survey; JD, Jaccard Distance; LA, linoleic acid; MS, Moderation Subscore; PANDiet, Probability of Adequate Nutrient Intake; PF, Protein foods.

1 **Abstract**

2 *Background.* There is a current trend in western countries towards increasing the intake of
3 plant protein. A higher plant protein intake has been associated with nutritional and health
4 benefits, but these may depend on the pattern of plant protein sources.

5 *Objective.* We hypothesized that the diversity of plant foods could be important to nutrient
6 adequacy when increasing plant protein intake in the diet.

7 *Methods.* Using data on 1341 adults (18-64y) from a representative French national dietary
8 survey conducted in 2014-2015 (INCA3), we studied the links between plant protein intake,
9 dietary diversity (using various dimensions) and nutrient adequacy (assessed using the
10 PANDiet scoring system, comprising adequacy (AS) and moderation (MS) sub-scores). We
11 simulated substituting plant-protein foods for animal-protein foods using different models of
12 plant protein diversity.

13 *Results.* We found that overall diet quality was weakly associated with total and protein
14 diversity and more strongly with plant protein diversity. Plant protein intake was inversely
15 associated with animal protein intake, and positively with the PANDiet and MS, but not with
16 the AS. Plant protein intake displayed little diversity, mostly taking the form of grains (61% of
17 plant protein intake), and this diversity was even less marked under a higher plant protein
18 intake. Finally, modelled substitutions showed that reducing animal protein intake increased
19 the MS (by 32%) in a similar manner whichever plant protein was used for substitution,
20 whereas it decreased the AS (by 20%) unless using a much diversified plant protein mix. These
21 simulated improvements in overall adequacy included marked decreases in adequacy
22 regarding certain nutrients that are typically of animal origin.

23 *Conclusion.* We conclude that in French adults the current pattern of plant protein intake is
24 hindering the nutritional benefits of a transition towards more plant protein, indicating that the
25 consumption of plant protein-based foods other than refined grains should be encouraged.

26 *Keywords:* plant protein; animal protein; diet quality; nutrient adequacy; dietary diversity; food
27 substitution.

28 **Introduction**

29 There is a general consensus that feeding the world in 2050 within planet boundaries will
30 require important transformations of the food system, such as reducing food waste and
31 profoundly changing our diets (1,2). The dietary changes anticipated include an increase in the
32 consumption of healthy contributors (fruits, vegetables, nuts, seeds and legumes) at the
33 expense of other foods such as red meats and sugary products (1). Protein consumption is
34 one of the biggest issues because the production of animal protein has important ecological
35 impacts (3,4) and makes the highest contribution to protein intake in western countries (5,6).

36 In western countries, people have started to reduce their meat consumption for reasons that
37 include health, environmental, ethical or economic issues (7–10). Dietary guidelines and public
38 health messages are also consistent with a shift toward more plant protein, setting upper levels
39 for red meat and advocating an increase in plant-based foods such as legumes and nuts
40 (11,12). Positive health outcomes have been associated with consumption of the latter, such
41 as lower risks of cancer (13,14), coronary heart disease (15) and total mortality (16), especially
42 when “healthy” plant-based diets are concerned (15,17). It is now considered that plant protein
43 sources are not alike, since they are coming with different nutrients and other substances, and
44 have differential associations with cardio metabolic risk (18,19).

45 When considering a more plant-based diet, its diversity is generally recommended because
46 mixing protein types has long been viewed as being necessary to obtain an adequate intake
47 of indispensable amino acids (5,20). Classic protein-rich plant such as legumes are presented
48 as a good nutritional lever to increase the share of plant protein in the diet. However, it is also
49 expected that people who are willing to increase their plant protein intake may tend to pursue
50 their prevailing pattern of intake rather than choosing to expand their food repertoire. Yet, the
51 current plant protein pattern varies little in western diets, mainly consisting of contributions from
52 grain products (6). It is still not known how far reliance on current plant protein patterns might
53 ensure the nutrient adequacy of the diet and its long-term health benefits.

54 As a general rule, diversity is often considered as a good indicator or even determinant of
55 dietary quality. Indeed, dietary diversity is often recommended in dietary guidelines as a means
56 of improving nutrient adequacy (21,22). However, recent studies in western countries have
57 revealed that dietary diversity may also be associated with higher food consumption, body
58 weight or BMI (23,24) and a higher intake of the unhealthy foods that are currently available.
59 There is no consensus regarding the measurement of diversity and a wide variety of diversity
60 scores have been developed, some of which include a health component in the diversity score
61 (25). In fact, in terms of diet quality, it may be more relevant to consider diversity within food
62 groups or nutrients that are associated with diet quality, such as total protein or plant proteins.
63 We hypothesize that plant protein diversity may be important to diet quality, and that the lack
64 of variation in the background pattern of protein intake in western countries may limit the
65 favorable effects of a higher plant protein intake on nutritional adequacy of the diet. To study
66 this question, we decided to characterize the relationships between nutrient adequacy, dietary
67 diversity and protein intake, and assess the importance of plant protein diversity to nutrient
68 adequacy using models for substituting animal protein with plant protein.

69

70 **Subjects and methods**

71 ***Study population***

72 The data used in this study were extracted from 24h-dietary recalls of adults involved in the
73 third Individual and National Study on Food Consumption survey (INCA3) performed in
74 mainland France between February 2014 and September 2015, and fully described elsewhere
75 (26,27). Participants aged between 18 and 64 years were included in the study (the nutrient
76 requirements of adults over 65 years old differing from those of younger adults) and
77 participants identified as being under-reporters in INCA3 study (28) were excluded, using the
78 basal metabolic rate as estimated by Henry equation (29) and the cut-off values proposed by
79 Black (30). The final sample thus contained 1341 adults (564 men and 777 women).

80 Dietary intakes were assessed using a series of three non-consecutive 24h-dietary recalls (two
81 on weekdays and one at the weekend) over a 3-week period. The participants were asked by
82 phone to declare all the foods and beverages they had consumed during the day before the
83 call. They were not aware of the days of recall so they could not anticipate and change their
84 food consumption accordingly. Portion sizes were estimated using validated photographs.
85 Dietary records were collected by professional investigators assisted by dietary software. The
86 different nutrient contents of the foods were extracted from the 2016 database from the *French*
87 *Centre d'Information sur la Qualité des Aliments*. Food items were gathered into food sub-
88 groups (Supplemental Table 1), based on the classification used in the INCA3 database (26).

89 ***Measurement of the nutrient adequacy of the diet***

90 The nutrient adequacy of the diet was assessed using the PANDiet 3.0 scoring system, based
91 on the dietary reference intake from the 2016 Anses opinion (31). PANDiet is a 100-point score
92 that measures individual diet quality by assessing the probability of an adequate overall
93 nutrient intake. It is the mean of two sub-scores: the adequacy sub-score (AS) and the
94 moderation sub-score (MS); the higher the score, the better the nutrient adequacy. AS is the
95 average probability of the adequacy of twenty-eight nutrients whose usual intake should be
96 above a reference value, multiplied by 100. MS is the average probability of the adequacy of
97 six nutrients for which an upper bound reference value exists (Supplemental Table 2). The
98 complete construction of the score is described elsewhere (32,33).

99 ***Identification of protein sources***

100 Food items were broken down into their ingredients and each ingredient was assigned to a
101 food family according to their origin, as previously described (34). Proteins from ingredients
102 could thus be identified as relating to animal or plant food. Animal sources of protein were
103 identified from the following animal-based food families: 'Red meat', 'Poultry', 'Fish',
104 'Processed meat', 'Cheeses', 'Milk', 'Yogurt', 'Eggs', 'Other meats' and 'Other dairy products'.
105 Likewise, plant sources of proteins were identified from the following plant-based food families:

106 'Grains' ('Refined grains' and 'Whole grains'), 'Legumes', 'Nuts and seeds', 'Fruits',
107 'Vegetables', 'Potatoes' and 'Other vegetables'.

108 Moreover, a classification of food items and sub-groups was used to identify protein foods and
109 protein food groups, as previously described (32). Food items included in the INCA3 study
110 were classified as protein foods (PF) if they met two criteria: the percentage energy from
111 protein was >10% and the level of intake at the 90th percentile was >5g protein per portion
112 consumed. PF with protein coming entirely from plant sources were defined as plant-protein
113 foods (PPF) and PF with protein coming entirely from animal sources were defined as animal-
114 protein foods (APF).

115 Then, protein food groups were defined as food sub-groups consumed by >10% of the
116 population (at least one consumption over the three days of report) and where, upon all food
117 items composing the sub-group, >25% were protein foods (PF), as previously described (32)
118 (Supplemental Table 1).

119 In what follows, 'plant protein' refers to protein from all plant foods, including those from plants
120 that are not considered as protein-rich plants. In the same way, 'animal protein' refers to protein
121 from all animal foods.

122 ***Measurement of dietary diversity***

123 Dietary diversity was determined in several dimensions, as suggested by de Oliveira Otto *et*
124 *al.*, in order to characterize the different aspects of diversity: count, evenness of the distribution
125 of food intake and dissimilarity of the food items consumed (35). Total diversity, protein
126 diversity and plant protein diversity were all evaluated, and nine diversity scores were chosen
127 to best describe the three dimensions of diversity at its three different levels (Supplemental
128 Method and Supplemental Table 3). Briefly, the count was characterized as the number of
129 different sub-groups consumed. Evenness, which reflected the satisfactory distribution of
130 energy or protein intake among food groups, was measured using the Berry-Index (BI), defined
131 as $1 - \sum_{i=0}^n s_i^2$, where s_i is the share of food group i in the total amount of energy, protein or

132 plant protein intake, and n is the total number of food groups (25,35,36). Dissimilarity, which
133 measured the extent to which food items differed from a nutritional standpoint, was estimated
134 using the Jaccard distance (JD), calculated by estimating the number of attributes in common
135 (here, nutrients) between two food items x and y and unique to each food item, as follows:

136 $JD_{xy} = \frac{B_x + C_y}{A_{xy} + B_x + C_y}$, where A_{xy} is the number of attributes shared by x and y ; B_x is the number of
137 attributes unique to x and C_y is the number of attributes unique to y (35).

138 ***Simulations of substituting plant-protein foods for animal-protein foods***

139 For each individual in the sample, we simulated substitutions of APF (animal-protein foods -
140 protein foods as defined above and only composed of animal protein) with the same amount
141 of energy, without alcohol, from PPF (plant-protein foods as defined above).

142 In a first model, APF were replaced by PPF initially consumed by individuals in order to
143 maintain the same initial food pattern within the individual's food repertoire (in cases where
144 individuals were not consuming PPF on a given day, substitutions were made by considering
145 all the plant foods initially consumed by the individuals).

146 In a second model, APF were replaced by introducing a new mix of PPF. For each plant-based
147 food family, a virtual average PPF was created which had the mean nutritional composition of
148 PPF identified in the plant-based food family. This was done for the following 6 plant-based
149 food families: 'Refined grains', 'Whole grains', 'Legumes', 'Potatoes', 'Vegetables' and 'Nuts'
150 (Supplemental Table 4). Since no PPF were identified in 'Fruits' and 'Other vegetables'
151 families, they were not considered in this process.

152 These average PPF were combined at different proportions which reflected different degrees
153 of plant protein diversity. First, average PPF were combined according to their observed
154 average contribution to plant protein intake in the general population ('prevailing plant protein
155 mix'). We then built five mixes of these average PPF by decreasing successively per 20% the
156 relative proportion of 'Refined grains' (since it is the family that contributes most to plant protein
157 intake – almost 55% – this was the natural lever to increase plant protein diversity) and this

158 resulted in graded levels of plant protein diversity ('diversified plant protein mix'). Substituting
159 PPF for 100kcal of APF involved, for example, replacing 43g of ground beef with 57g of
160 average PPF (27g of 'Refined grains', 2g of 'Whole grains', 2g of 'Legumes', 1g of 'Nuts', 14g
161 of 'Vegetables' and 11g of 'Potatoes') when using the 'prevailing plant protein mix', and with
162 91g of average PPF (8g of 'Whole grains', 10g of 'Legumes', 3g of 'Nuts', 33g of 'Vegetables'
163 and 36g of 'Potatoes') when using the most 'diversified plant protein mix'.

164 **Statistical analyses**

165 The weighting schemes and adaptations of tests and confidence interval calculations proposed
166 in INCA3 were used to account for the complex survey design and ensure the national
167 representativeness of the sample. The food intakes of individuals were weighted according to
168 the day of record (week day or weekend) to take account of variations between days. All protein
169 intakes were initially adjusted for total energy intake according to the residual method (37),
170 except for protein contribution (expressed as %) which were calculated with absolute protein
171 intake. Differences between men and women for quality and diversity scores and protein
172 intakes were evaluated using Student's t test. Correlations between scores were made using
173 Spearman's correlation coefficients, and confidence intervals were estimated using Fisher's Z
174 transformation. Continuous variables are presented as means \pm SDs, and differences across
175 quartiles or across different models of substitutions were assessed by linear models adjusting
176 for sex. Categorical variables are presented as percentages, and differences across quartiles
177 were determined using the χ^2 test. All analyses were performed using SAS version 9.1.
178 Significance was set at $P < 0.05$.

179

180 **Results**

181 There was no difference between sexes regarding the PANDiet score, but the AS was
182 significantly higher in men than in women (+5.8 points) and MS was significantly lower in men
183 than in women (-5.6 points) (Supplemental Table 5). Animal protein contributed to 67% of total

184 protein intake. 'Red meat' was the main contributor to animal protein intake (25% of animal
185 protein intake for men and 22% for women) and 'Grains' was the main contributor to plant
186 protein intake (60% of plant protein intake for men and 62% for women) (Supplemental Table
187 5).

188 ***Associations between nutrient adequacy and total and protein diversity***

189 The INCA3 population was divided into PANDiet quartiles (Supplemental Tables 6 and 7).
190 Total and protein diversity based on count and evenness did not differ significantly across the
191 PANDiet quartiles whereas dissimilarity scores for total and protein diversity were higher in the
192 upper quartiles of PANDiet.

193 Spearman's correlation coefficients between the PANDiet, AS, MS and diversity scores are
194 presented in **Table 1**. Total and protein diversity, based on count and evenness were not (or
195 only weakly) associated with PANDiet, but were positively associated with AS (r between +0.25
196 and +0.39, $P < 0.0001$) and inversely associated with MS (r between -0.36 and -0.18, P
197 < 0.0001). Dissimilarity scores for total and protein diversity were positively associated with
198 PANDiet (respectively +0.24 and +0.21, $P < 0.0001$) and MS (respectively +0.26 and +0.22, P
199 < 0.0001), but poorly inversely associated with AS.

200 ***Associations between nutrient adequacy and plant protein diversity***

201 Plant protein diversity scores were all positively associated with PANDiet (r between +0.07 and
202 +0.16, $P < 0.05$) (Table 1). Plant protein diversity based on evenness was positively associated
203 with AS but not with MS. Plant protein diversity based on count and dissimilarity were positively
204 associated with MS, but not with AS. Across the PANDiet quartiles, plant protein diversity
205 scores were higher among participants with higher PANDiet scores. Participants with a higher
206 PANDiet score consumed more total protein, from both animal and plant sources, with a slightly
207 larger share of the latter (35% in fourth quartile vs 33% in first quartile) (Supplemental Table
208 6).

209 Participants with a higher PANDiet score consumed more proteins from 'Fish', 'Milk', 'Yogurts',
210 'Grains', 'Vegetables', 'Fruits', 'Nuts and seeds' and 'Legumes' families and fewer proteins
211 from 'Cheese', 'Processed meat' and 'Eggs' families than participants with lower PANDiet
212 scores. The contribution of plant-based food families to plant protein intake differed
213 significantly across PANDiet quartiles, with a lower share of refined grains and a higher share
214 of other plant sources, which was in line with a higher BI-PBF score (plant protein diversity
215 defined as evenness) (Supplemental Table 6).

216 ***Association between diversity scores, nutrient adequacy and plant protein*** 217 ***consumption***

218 PANDiet and MS scores were higher under a higher plant protein intake (respectively +6.1
219 points and +12.4 points) but there was no significant difference for AS (**Table 2**). The
220 probabilities of adequacy for AS with respect to protein, fiber, vitamin B-6, folate, magnesium
221 and manganese, etc., were higher under a higher plant protein intake whereas the probabilities
222 of adequacy regarding linoleic acid, vitamin B-12, potassium and zinc were lower. The
223 probability of adequacy within the MS score was higher for total fat, saturated fatty acids,
224 cholesterol and sugars but lower for sodium (Supplemental Table 8).

225 The evenness scores for total diversity (BI-Energy) and plant protein diversity (BI-PBF) were
226 lower under a higher intake of plant protein, whereas plant protein diversity based on count
227 (Ratio-PPF/PF) was higher. There was no association between plant protein and total protein
228 intakes, because plant protein was inversely associated with animal protein intake and with all
229 animal-based food families, except 'Poultry', 'Fish' and 'Yogurt'. The protein intake from all
230 plant-based food families was higher under a higher intake of plant protein except 'Potatoes'
231 (Table 2).

232 The contribution of the 'Grains' family to plant protein intake was significantly higher under a
233 higher intake of plant protein (65% of plant protein intake in the fourth quartile versus 57% in
234 the first quartile). The contributions of 'Nuts and seeds' (+1.4 points) and 'Legumes' (+1.5

235 points) families were also higher while those of 'Fruits' (-2.4 points) and 'Potatoes' (-4.0 points)
236 families were lower in the fourth vs the first quartile of plant protein intake (**Table 2**). Socio-
237 demographic differences were observed across plant protein intake quartiles (Supplemental
238 Table 9).

239 ***Modelled substitutions of animal-protein foods using different level of diversity in plant-***
240 ***protein foods***

241 Modelled substitutions of plant-protein foods (PPF) for animal-protein foods (APF) according
242 to the graded contributions of the different average PPF used for substitution are shown in
243 **Figure 1**. Because mixed foods (comprising both animal and plant protein) were not concerned
244 by the modelled substitution, the complete substitution of APF resulted in plant protein
245 accounting for 78% of total protein intake, rather than 100%. Following results focuses on
246 substitutions of 50% and 100% of APF (corresponding respectively to 51% and 78% of plant
247 protein in total protein intake) with the 'Initial food pattern' and the '100% diversified plant
248 protein mix' models.

249 Energy-adjusted replacements of APF with PPF as they are currently consumed in the general
250 population ('Initial food pattern') led to a reduction in nutrient adequacy, measured by the
251 adequacy sub-score of the PANDiet (-4.9 points for AS at 50% substitution, -12.2 points for
252 AS at 100% substitution). However, when replacements were made with the '100% diversified
253 plant protein mix' model, AS increased at 50% substitution (+0.9 points) and were not
254 significantly different from baseline intake at 100% substitution (Supplemental Tables 10 and
255 11).

256 MS increased when APF were replaced with PPF (up to 19% at 50% substitution and up to
257 32% at 100% substitution), and this was little influenced by the type of PPF used. Finally,
258 PANDiet score increased when APF were replaced with PPF, and the increase was more
259 marked when the mix of PPF used for substitution was more diversified (+5% and +4% at 50%

260 and 100% for the 'Initial food pattern', respectively, and +8% and +13% at 50% and 100% for
261 the '100% diversified plant protein mix', respectively) (Supplemental Tables 10 and 11).

262 The probabilities of adequacy that compose the AS changed significantly when replacing
263 animal-protein foods with plant-protein foods (**Figure 2**). Reductions in the probability of
264 adequacy were seen for DHA and EPA, vitamin B-12, iodine and zinc, regardless of the
265 substitution model. The probability of adequacy for protein, total fat, riboflavin, niacin, calcium
266 and iron also decreased but replacements with more diverse plant-protein foods limited this
267 reduction. When '100% diversified plant protein mix' model was used, probability of adequacy
268 for LA, ALA, fiber, vitamins B-6, C, E, folate, magnesium and potassium increased compared
269 to baseline intake (Supplemental Tables 10 and 11).

270 Compared to the initial intake (83.5 ± 19.2 g/d), total protein intake was lower when replacing
271 APF with PPF (69-71 g/d with a 50% substitution and 55-58 g/d with a 100% substitution of
272 animal protein foods). At 100% of substitution, contributions of plant sources to plant protein
273 intake significantly differ from baseline intake. Respectively for 'Initial food pattern' and '100%
274 diversified plant protein mix' models, 'Refined grains' contributed to 61% and 35% (vs 56% at
275 baseline), 'Whole grains' to 5.9% and 11% (vs 5.1% at baseline), 'Vegetables' to 11% and
276 17% (vs 12% at baseline), 'Potatoes' to 5.6% and 12% (vs 6.8% at baseline), 'Nuts and seeds'
277 to 8.5% and 3.4% (vs 3.2% at baseline), 'Legumes' to 3.7% and 8.2% (vs 2.9% at baseline)
278 (Supplemental Tables 12 and 13).

279

280 **Discussion**

281 We were able to show in this study that higher plant protein intakes favored overall diet quality,
282 mainly by lowering the probabilities of an excessive intake of some nutrients. Surprisingly, plant
283 protein intake was not associated with AS in observed diets. Contrary to total diversity and
284 protein diversity, plant protein diversity was positively associated with overall diet quality.
285 However, plant protein intake and plant protein diversity were inversely related, suggesting

286 that a higher plant protein intake does not involve the utilization of plant foods that would
287 otherwise be little consumed. Finally, and this was the major finding of this study, we were able
288 to reveal that when replacing animal-protein foods with plant-protein foods it was necessary to
289 ensure a much diversified plant protein food pattern in order to maintain or improve the overall
290 adequacy of indispensable nutrients intakes.

291 ***Nutrient adequacy and different dimensions of total and protein diversity***

292 Based on data in the literature (35), we were able to construct a series of scores that could
293 capture several dimensions of diversity and be applied to assessing total, protein and plant
294 protein diversity. Except for dissimilarity scores, we found that total and protein diversity scores
295 were positively associated with AS and inversely with MS, resulting in a weak or no association
296 with the PANDiet. Dissimilarity scores were positively associated with the PANDiet. Scores
297 based on counts and evenness reflect overall diversity and are not directly related to diet
298 quality because they consider the contributions of healthy and unhealthy foods in the same
299 way (35). Dissimilarity scores take account of the intrinsic nutrient composition of food items,
300 and our results showed that eating nutritionally contrasted food items was more positively
301 associated with overall diet quality than eating numerous food items from different subgroups.
302 We found that diversity at the plant protein level was positively associated with the PANDiet
303 score, and people with higher PANDiet scores consumed more plant protein, intake of which
304 was more evenly distributed across plant-based food families. Therefore, diversifying plant
305 protein intake appears to be favorable to nutrient adequacy and seems to occur when more
306 whole grains, legumes, nuts and vegetables are consumed. This is in line with many current
307 or prospective dietary guidelines (1,11,21).

308 ***Inverse association between plant protein intake and diversity***

309 We found no association between plant protein intake and protein diversity and an inverse
310 association with total diversity based on count and evenness. Taken together, these results

311 indicate that a higher intake of plant protein seems to be at the expense of consuming animal
312 protein food groups that make an important contribution to energy intake.

313 It may appear counterintuitive that a higher plant protein intake did not result in higher plant
314 protein food diversity (defined as evenness). Indeed, the intake of different plant-based food
315 groups was less evenly distributed when the plant protein intake was higher and we found that
316 80% of the increase in plant protein intake across different quartiles could be explained by an
317 increase of protein from grains. It is reasonable to expect that when reducing animal protein
318 intake, most people might consume larger quantities of plant protein sources they are more
319 used to eating for cultural and practical reasons, and be less inclined to try new sources of
320 plant protein, although this may also depend on the market availability of new food products
321 (38). However, consumers adhering to plant-based diet are more likely to consume new foods
322 and diversify their plant protein sources compared to regular meat-eaters (39,40).

323 Our findings might have been different in other countries where plant protein practices are not
324 the same. For instance, according to the EPIC study, the contribution of legumes was lower in
325 French women (2-3%, in line with our present findings) than in Greece (7-8%) and Spain (6-
326 16%) (6). If we assume that current or future increases in plant protein intake will be dependent
327 on initial patterns of intake, we could expect that relative increases in legume consumption
328 would be greater in countries where they are consumed more at baseline. However, grain
329 products continue to dominate in the plant protein intake of all western countries (40-69%) (6),
330 so our finding should be largely generalizable. Further studies could interestingly investigate
331 the extent to which transitions to more plant-based diets are dependent on initial consumption
332 patterns.

333 It appears that higher plant protein intakes are associated with a lower animal protein intake
334 but also with a different pattern of intake, which is closer to dietary guideline (11) since we
335 found lower protein intakes from all animal-based food groups except for 'Poultry', 'Fish' and
336 'Yogurt'. Nutrient adequacy is usually higher with diets where more of the animal protein intake
337 is contributed by fish and yogurts and less by processed meat and cheese (34), and cardio

338 metabolic risk is generally not increased when animal products are consumed within a healthy
339 dietary pattern (41). In a recent study, we saw increases in lean poultry, fatty fish and yogurt
340 when modelling optimum stepwise changes to protein intake (42).

341 ***Plant protein diversity is critical to nutrient adequacy when increasing plant protein***
342 ***intake***

343 Higher PANDiet scores with a higher plant protein intake could therefore be ascribed in part to
344 a lower intake of animal protein and a better animal protein pattern. Likewise, when replacing
345 animal-protein foods with plant-protein foods the PANDiet score always rose because of a
346 significant increase in MS scores that were almost not influenced by the type of plant-protein
347 foods used for substitution, and could therefore be ascribed mostly to the reduction in animal-
348 protein foods consumption.

349 In the population studied, a higher plant protein intake was not associated with higher AS
350 scores, unlike the values obtained during a previous study (43). Further, we were able to show
351 that AS did decrease when animal-protein foods were replaced by plant-protein foods. Foods
352 containing animal proteins also supply indispensable nutrients (such as calcium, iron, zinc,
353 vitamins B-12 and D) (44) that favor nutrient adequacy (i.e. the AS score), and a reduction in
354 animal protein intake will lead to a lower intake of these nutrients. Plant-protein foods
355 consumed in larger quantities according to the prevailing pattern would poorly compensate for
356 reduction in animal-protein foods in this context, since plant protein intake is dominated by
357 refined grains. Although grains make an appreciable contribution to indispensable nutrients in
358 western diets overall (45), refined grains are relatively low in vitamins and minerals when
359 compared to certain animal protein foods. By contrast, when using much more diversified
360 plant-protein foods, the replacement of animal-protein foods resulted in the same or higher
361 overall nutrient adequacy.

362 In more detail, these variations in the AS score hid some highly heterogeneous modifications
363 to the probabilities of adequacy by nutrient type. For some nutrients, replacing animal-protein

364 foods with plant-protein foods was beneficial to adequacy because higher amounts of these
365 nutrients are found in plant-protein foods than in animal-protein foods (44). For other nutrients,
366 reducing the intake of animal-protein foods led to lower probabilities of adequacy, but this
367 decrease could be partly compensated for by using a more diversified mix of plant-protein
368 foods. Conversely, the probability of adequacy was always markedly reduced for some
369 nutrients (EPA, DHA, vitamin B-12 and zinc) when animal-protein foods were replaced, as was
370 expected given the importance of animal-protein foods regarding the status of these nutrients
371 (44,46).

372 ***Limitations of the study***

373 This study used observational data that were collected on three non-consecutive days, and
374 this may not have clearly reflected the entire food consumption of individuals. However, our
375 study focused on protein intake, which generally provides an overall structure for the diet, so
376 that protein intakes could be considered reliable with a low level of classification errors.
377 Although the present data are very recent (from the latest national representative survey in
378 2014-2015) they may still not be sufficiently recent to have captured the food transition that is
379 apparently under way at present (47). Further, diversity is a broad concept with multiple
380 complex dimensions and there is no general consensus about how best to appreciate dietary
381 diversity. We chose to assess the different dimensions of diversity using the most recent
382 developments in the field and focused in greater depth on protein and more specifically plant
383 protein diversity, because protein patterns are important characteristics of the diet and protein
384 sources are central to this current food transition. Lastly, the modelled transition from animal
385 to plant-based proteins was performed by replacing animal-protein foods entirely by plant-
386 protein foods, without taking account of any possible concomitant or dependent
387 rearrangements of animal protein intake affecting these changes to meal structure and other
388 practical factors influencing food intake. In this respect, the simulated diets may not be totally
389 realistic, particularly at a high level of substitution. Nevertheless, we believe that these series

390 of modelled transitions offered useful insights into the importance of plant protein diversity to
391 the nutritional adequacy of diets.

392 **Conclusion**

393 In line with recent studies, our data have provided little evidence for any benefits of overall
394 dietary diversity to diet quality, which calls to prioritize diet quality instead of promoting dietary
395 diversity in general. The type of food groups that should be diversified is probably crucial and
396 our data may have identified that plant protein diversity, rather than total protein diversity, is
397 positively associated with nutritional quality. In the context of ongoing or forecasted increases
398 in plant protein intake designed to rebalance the animal/plant protein ratio in western diets, we
399 also found that the potential benefit to nutrient adequacy of increasing plant protein intake is
400 limited by the poor diversity of plant protein intake seen at present, this being dominated by
401 refined grains. A more diverse plant protein intake, with higher contributions from legumes,
402 nuts, seeds and vegetables appears to be critical in the context of increasing plant protein
403 intake.

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Table 1. Spearman's correlation coefficients (r) between PANDiet scores and diversity scores in the French adult population (INCA3, n=1341)¹.

	Count		Evenness		Dissimilarity	
	r (95% CI)	<i>P</i> ²	r (95% CI)	<i>P</i>	r (95% CI)	<i>P</i>
Total diversity	"Div-Tot"		"BI-Energy"		"JD-Tot"	
PANDiet score	-0.06 (-0.12 ; -0.01)	<0.05	-0.00 (-0.05 ; 0.05)	NS	0.24 (0.19 ; 0.29)	<0.0001
Adequacy Sub-score	0.38 (0.34 ; 0.43)	<0.0001	0.25 (0.20 ; 0.30)	<0.0001	-0.06 (-0.12 ; -0.01)	<0.05
Moderation Sub-score	-0.36 (-0.41 ; -0.31)	<0.0001	-0.20 (-0.25 ; -0.15)	<0.0001	0.26 (0.21 ; 0.31)	<0.0001
Protein diversity	"Div-Prot"		"BI-Prot"		"JD-PF"	
PANDiet score	-0.02 (-0.03 ; 0.08)	NS	0.04 (-0.02 ; 0.09)	NS	0.21 (0.16 ; 0.26)	<0.0001
Adequacy Sub-score	0.39 (0.34 ; 0.43)	<0.0001	0.26 (0.21 ; 0.31)	<0.0001	-0.03 (-0.08 ; 0.03)	NS
Moderation Sub-score	-0.29 (-0.34 ; -0.24)	<0.0001	-0.18 (-0.24 ; -0.13)	<0.0001	0.22 (0.16 ; 0.27)	<0.0001
Plant protein diversity	"Ratio-PPF/PF"		"BI-PBF"		"JD-PPF"	
PANDiet score	0.16 (0.11 ; 0.21)	<0.0001	0.14 (0.09 ; 0.19)	<0.0001	0.07 (0.01 ; 0.12)	<0.05
Adequacy Sub-score	-0.07 (-0.12 ; -0.02)	<0.05	0.26 (0.21 ; 0.31)	<0.0001	-0.07 (-0.12 ; -0.01)	<0.05
Moderation Sub-score	0.20 (0.15 ; 0.25)	<0.0001	-0.07 (-0.12 ; -0.01)	<0.05	0.10 (0.05 ; 0.16)	<0.001

¹Data were collected by three 24h recalls

²*P* values for Spearman's correlation coefficients, NS, *P* ≥ 0.05

INCA3, Individual and National Study on Food Consumption Survey 3

Table 2. PANDiet scores and sub-scores, diversity score, total energy and protein intakes, protein intakes from animal-based and plant-based food families according to plant protein intake quartiles in the French adult population (INCA3, n=1341)¹.

	Plant protein intake				<i>P</i> ²
	Q1 (n=335) 0.00 – 24.0 g/d	Q2 (n=335) 24.0 – 27.3 g/d	Q3 (n=336) 27.3 – 30.8 g/d	Q4 (n=335) 30.8 – 54.2 g/d	
PANDiet score (0-100)	55.8 ± 5.56 ³	58.1 ± 5.63*	59.7 ± 5.55*	61.9 ± 5.96*	<0.0001
Adequacy Sub-score (AS) (0-100)	64.1 ± 12.7	60.4 ± 12.5	61.6 ± 11.1*	64.0 ± 10.9	NS
Moderation Sub-score (MS) (0-100)	47.4 ± 15.2	55.7 ± 12.7*	57.7 ± 13.8*	59.8 ± 13.6*	<0.0001
Total div. – Count (“Div-Tot”) (0-75)	26.4 ± 5.05	25.3 ± 4.87*	26.4 ± 4.77*	25.5 ± 5.38*	<0.0001
Total div. – Evenness (“BI-Energy”) (0-1)	0.91 ± 0.06	0.91 ± 0.04	0.91 ± 0.03*	0.88 ± 0.06*	<0.0001
Total div. – Dissimilarity (“JD-Tot”) (0-1)	0.70 ± 0.05	0.70 ± 0.04	0.70 ± 0.04*	0.71 ± 0.05	<0.01
Protein div. – Count (“Div-Prot”) (0-32)	10.2 ± 2.86	9.78 ± 2.53	10.3 ± 2.28	10.0 ± 2.56	NS
Protein div. – Evenness (“BI-Prot”) (0-1)	0.80 ± 0.09	0.81 ± 0.08	0.83 ± 0.06*	0.82 ± 0.08	NS
Protein div. – Dissimilarity (“JD-PF”) (0-1)	0.69 ± 0.04	0.69 ± 0.04	0.69 ± 0.04	0.69 ± 0.05	NS
Plant protein div. – Count (“Ratio-PPF/PF”) (0-1)	0.21 ± 0.09	0.23 ± 0.10*	0.25 ± 0.09*	0.28 ± 0.11*	<0.0001
Plant protein div. – Evenness (“BI-PBF”) (0-1)	0.59 ± 0.12	0.56 ± 0.12*	0.54 ± 0.13*	0.50 ± 0.17*	<0.0001
Plant protein div. – Dissimilarity (“JD-PPF”) (0-1)	0.64 ± 0.15	0.65 ± 0.14	0.62 ± 0.13	0.65 ± 0.12	NS
Total energy, kcal/d	2547 ± 806	2166 ± 788*	2167 ± 729*	2466 ± 736	NS
Total protein ⁴ , g/d	84.1 ± 23.4	82.7 ± 17.9	83.2 ± 16.3	84.1 ± 18.5	NS
Animal protein ⁴ , g/d	63.2 ± 23.7	57.2 ± 17.8*	54.2 ± 16.5*	48.9 ± 18.8*	<0.0001
Protein from animal-based families ⁴ , g/d					
Red meat	17.3 ± 19.8	13.7 ± 16.3*	11.4 ± 11.5*	9.44 ± 14.8*	<0.0001
Cheeses	9.29 ± 8.63	8.92 ± 6.28	8.97 ± 5.95	7.87 ± 6.85*	<0.01
Poultry	7.75 ± 11.0	7.05 ± 10.2	6.88 ± 9.18	8.48 ± 11.5	NS
Processed meat	7.38 ± 9.32	6.54 ± 7.24*	6.14 ± 5.82*	4.77 ± 6.32*	<0.0001
Fish	5.50 ± 8.18	5.92 ± 8.35	6.68 ± 8.24	6.60 ± 11.4	NS
Milk	7.05 ± 8.39	5.93 ± 6.33	5.57 ± 5.46*	4.94 ± 5.70*	<0.0001
Yogurt	3.31 ± 3.73	4.08 ± 4.32	3.49 ± 2.86	3.21 ± 3.26	NS
Eggs	4.25 ± 3.51	3.60 ± 3.38*	3.43 ± 2.99*	2.81 ± 2.81*	<0.0001
Other meats (offal, game)	0.56 ± 3.33	0.82 ± 3.33	1.05 ± 4.07	0.35 ± 2.58	NS
Other dairy products (butter, cream)	0.80 ± 1.04	0.64 ± 0.75	0.61 ± 0.68*	0.46 ± 0.54*	<0.0001
Plant protein ⁴ , g/d	20.8 ± 3.37	25.6 ± 1.01*	28.9 ± 1.05*	35.1 ± 4.31*	<0.0001
Protein from plant-based families ⁴ , g/d					
Grains	11.2 ± 4.30	15.3 ± 3.6*	18.1 ± 3.64*	22.5 ± 6.84*	<0.0001
of which refined grains	9.97 ± 4.73	13.8 ± 4.25 *	16.3 ± 4.48 *	20.1 ± 8.25 *	<0.0001
of which whole grains	1.20 ± 1.82	1.48 ± 1.97	1.82 ± 2.49 *	2.40 ± 4.32 *	<0.0001
Vegetables	2.45 ± 1.71	2.81 ± 2.01*	3.22 ± 1.88*	3.94 ± 2.54*	<0.0001
Potatoes	1.87 ± 2.58	1.56 ± 1.74	1.74 ± 1.77	1.53 ± 2.04	NS
Fruits	1.37 ± 1.18	1.58 ± 1.33*	1.54 ± 1.08*	1.44 ± 1.22*	<0.05
Nuts and seeds	0.66 ± 1.18	1.05 ± 1.66*	1.04 ± 1.48*	1.53 ± 3.16*	<0.0001
Legumes	0.68 ± 2.01	0.75 ± 1.99	0.79 ± 1.53*	1.66 ± 3.77*	<0.0001
Other plant foods (spices, beverages)	2.64 ± 1.74	2.55 ± 1.88	2.46 ± 1.71	2.53 ± 2.64	NS
Plant protein, % total protein	26.6 ± 7.55	30.3 ± 7.18*	34.6 ± 7.21*	41.9 ± 8.83*	<0.0001
Protein from plant-based families, % of plant protein					
Grains	57.1 ± 13.8	60.2 ± 14.5	62.8 ± 13.6*	65.0 ± 16.9*	<0.0001
of which refined grains	52.9 ± 16.2	55.7 ± 17.4	56.9 ± 17.0 *	59.3 ± 21.1	<0.05
of which whole grains	4.26 ± 7.72	4.51 ± 8.4	5.82 ± 9.75	5.73 ± 11.2 *	<0.0001
Vegetables	10.9 ± 7.31	12.3 ± 9.64*	12.3 ± 7.88*	11.2 ± 8.02	<0.05
Potatoes	8.92 ± 8.97	7.09 ± 7.50*	6.24 ± 5.90*	4.9 ± 5.55*	<0.0001
Fruits	6.36 ± 5.99	6.24 ± 5.56	5.51 ± 4.18*	4.01 ± 3.4*	<0.0001
Nuts and seeds	2.73 ± 4.61	2.91 ± 5.81	2.92 ± 4.78	4.13 ± 8.86*	<0.01
Legumes	2.58 ± 6.73	2.36 ± 6.63	2.54 ± 5.21	4.06 ± 8.81*	<0.0001
Other plant foods (spices, beverages)	11.4 ± 7.08	8.98 ± 6.82*	7.80 ± 5.58*	6.72 ± 6.34*	<0.0001

¹ Data were collected by three 24h recalls.

² *P* values are *P*-trends for linear models adjusted for sex. NS, *P* ≥ 0.05

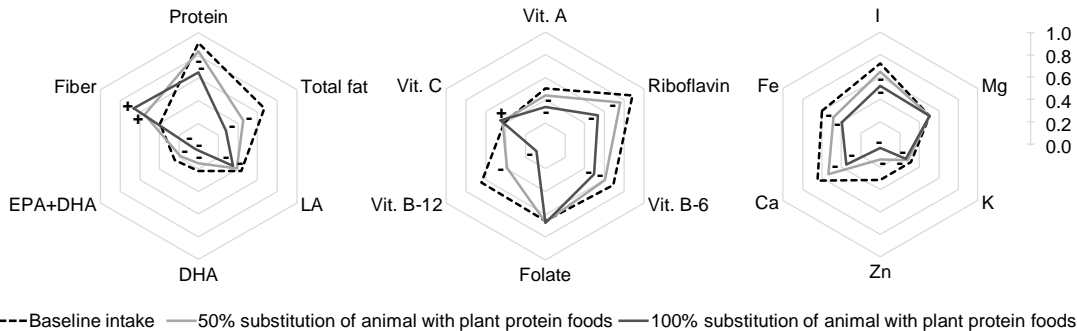
³ Values are means ± SDs weighted for the survey design. * means significantly different from the mean of the first quartile

⁴ Energy-adjusted using the residual method (%plant protein was calculated with plant and animal protein not adjusted)

div, diversity; INCA3, Individual and National Study on Food Consumption Survey 3; Q, quartile

Figure 1. Changes to A. PANDiet score, B. Adequacy Sub-score and C. Moderation Sub-score (C) when replacing animal-protein foods with plant-protein foods, according to different substitution models, in the INCA3 population (n=1341). 'Initial food pattern' corresponded to the model where animal-protein foods were replaced by plant-protein foods as found in the background diet of each individual. Other models corresponded to substitution with an average virtual mix of average plant-protein foods. In the 'Prevailing plant protein mix', food items ('Refined grains', 'Whole grains', 'Legumes', 'Potatoes', 'Vegetables' and 'Nuts and seeds') were combined according to their natural average contribution to plant protein intake in the general population. The mix was then gradually diversified by decreasing the contribution of 'Refined grains', thus increasing the contribution of other food items, leading to five plant protein mixes of graded diversity ('x% diversified plant protein mix'). The percentage refers the decrease of the contribution of 'Refined grains' compared with its contribution to the 'Prevailing plant protein mix'. Data are means for the overall population in different modelled diets. Within-subject variability is not shown for the sake of clarity.

Figure 2. Means of probabilities of adequacy of nutrient intakes according to a model of replacing animal-protein foods with A. Plant-protein foods already consumed by individuals ('Initial food pattern') and B. According to a model involving substitution with a fully diversified mix of average plant-protein foods ('100% diversified plant protein mix'), at different levels of substitution of animal-protein foods (baseline intake, 50% substitution and 100% substitution). + (-) means significantly superior (inferior) to the mean at the baseline intake. Within-subject variability is not shown for the sake of clarity. ALA, alpha-linolenic acid; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; LA, linoleic acid; Vit, vitamin.

A**B**