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Hélène Fouillet, Jean-François Huneau, Elie Perraud, Alison Dussiot, Juhui Wang, et al.. Plant to animal protein ratio in the diet of the elderly: potential for increase and impacts on nutrient adequacy and long-term health-a diet optimization study. The American Journal of Clinical Nutrition, 2025, 122 (2), pp.556-570. ⟨10.1016/j.ajcnut.2025.06.011⟩. ⟨hal-05166884v2⟩

HAL Id: hal-05166884
https://hal.inrae.fr/hal-05166884v2

Submitted on 18 Aug 2025

Plant to animal protein ratio in the diet of the elderly: potential for increase and impacts on nutrient adequacy and long-term health – a diet optimization study

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Sources of support for the work: This research did not receive any specific grants from funding agencies in the public, commercial or not-for-profit sectors.

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Running title: Plant protein share in the elderly.

Abbreviations used: IAA, Indispensable amino acids; DALYs, Disability-adjusted life-years; *DD*, Diet departure; GBD, Global Burden of Diseases; *HR*, Health risk; %PP, Percentage of plant protein in the diet; TMREL, Theoretical minimum risk exposure level; SP, standard protein requirement (population reference intake of 0.83 g/kg/d); HP, high protein requirement (population reference intake of 1 g/kg/d).

4 Figures, 2 Tables

11 Supplementary Data (6 Supplemental Figures, 6 Supplemental Tables)

Abstract

Background: The percentage of plant protein in the diet (%PP) is increasing in high-income countries, but concerns exist regarding the elderly, who may require more protein and indispensable amino acids (IAA) than younger adults, although this remains debated.

Objective: We aimed to assess how much %PP can be safely increased in older adults depending on estimated protein requirement, and identify nutritional issues and dietary levers as %PP increases.

Methods: Observed diets were extracted from dietary intakes of ≥65y French adults (INCA3, n=433). Using diet optimization, we modeled diets with graded %PP values ensuring full nutrient adequacy—applying constraints on energy and 34 nutrient intakes (accounting for bioavailability) and considering standard or higher protein requirements (reference intakes of 0.83 or 1 g/kg/d, respectively)—while minimizing chronic disease risk from specific food group over- or under-consumption (based on Global Burden of Disease data), with only as much departure from dietary habits as necessary.

Results: All modeled diets differed markedly from current unhealthy diet. Whatever the protein requirement considered, the same ~25%-70% %PP range was compatible with minimal chronic disease risk and full nutrient adequacy. As %PP increased, iodine, calcium, EPA+DHA, bioavailable iron, vitamins A, B12, and riboflavin became critical; protein was only a concern at high requirement; IAA were never problematic under protein adequacy. Sensitivity analysis revealed that raising consumption limits for legumes, nuts, vegetables, and fruit could broaden the adequate %PP range by supplying more limiting nutrients.

Conclusions: Diets must be sufficiently rich in protein to ensure protein adequacy at higher requirements, with no risk of IAA inadequacy when protein intake is sufficient. For sustainability, %PP can potentially increase from the current ~1/3 to ~2/3 in an aging population while improving health and nutrient adequacy, provided sufficient seafood and dairy products remain. Further increases would require nutrient fortification/supplementation and/or new foods.

Keywords:

Elderly; Protein requirement; Nutrient adequacy; Heath risk; Diet optimization.

Introduction

The world’s population is rapidly aging; in European countries such as France, people aged 65 y and older represented 20% of the population in 2020 and are likely to account for 30% of the population in 2050 (1). Dietary changes in this age group designed to reduce the global diet-related disease burden and environmental footprint may have substantial implications for public health, healthcare expenditure and planetary health.

From a public health perspective, diet quality encompasses both nutrient adequacy—i.e., meeting nutrient reference intakes from the combination of consumed foods, which is a prerequisite for normal physiological functions and health—and the prevention of chronic diseases, which also depends on the types and amounts of foods included in the diet. As evidenced by the Global Burden of Disease (GBD) study (2), the long-term risks of cardiovascular diseases, diabetes, and cancer increase with the overconsumption of some unhealthy animal-based foods (i.e., red and processed meats) and/or the underconsumption of some healthy plant-based foods (i.e., whole grains, vegetables, fruits, pulses, and nuts and seeds). A shift towards more plant-based diets should not only improve certain aspects of nutrient adequacy—by enabling more adequate intakes of folate, fiber, and unsaturated fatty acids, while reducing saturated fat intake (3)—but also benefit long-term human health, as such a change in dietary patterns would lower the incidence of cardiovascular diseases, diabetes and cancer (4-6). Furthermore, it would also benefit planetary health by reducing diet-related greenhouse gas emissions and land and energy use (7-10). With the aim of promoting healthy diets within planetary boundaries, the EAT-Lancet Commission has proposed the Planetary Health Diet, which advocates a reduction in animal protein foods and an increase in plant protein foods, but this approach has been a subject of debate regarding its potential to increase certain nutrient deficiencies (11, 12). Numerous concerns have indeed been raised about the possible risk of nutrient shortages in diets that are too low in animal protein because animal protein foods contribute significantly to the intake of indispensable nutrients such as iron, calcium and vitamin B12, overt deficiencies of which can cause a variety of adverse health consequences (10, 13-15). Finally, national dietary guidelines in Western countries, such as France, typically recommend increasing consumption of plant-based foods, while occasionally cautioning about the potential nutritional risks of vegan diets (16).

Globally, animal protein foods (such as red and processed meats) and plant protein foods (such as whole grains, legumes and nuts and seeds) have heterogeneous relationships with nutrient adequacy (17) and long-term health outcomes (18-23), although the plant to animal protein ratio in the diet appears central to the sustainability of food systems (7, 24). There is a growing interest in what might be the appropriate proportion of plant protein in the diet (%PP, the percentage of plant protein in total protein intake) that could be consistent with both human and planetary health (25-29). As plant foods are lower in protein than animal foods, and plant proteins are also slightly less digestible and have a lower IAA content than animal proteins, increasing %PP is expected to result in slightly lower intakes of bioavailable protein and IAA, in a context where their current typical intakes far exceed their requirements (30-33). The meta-analysis by Rand et al. (34), which underpins the current estimation of protein requirement, found no differences attributable to the dietary protein source, reporting similar estimates from nitrogen balance studies using predominantly animal, plant or a mixture of both protein sources. In the French adult population, excluding the elderly, we recently showed, using a diet optimization approach, that it is possible to increase %PP from its current low level of one-third to two-thirds without any nutritional risk, thereby reducing diet-related greenhouse gas emissions by almost half, and that the nutritional issues of further increasing %PP are related to nutrients other than protein and IAA (10).

However, the risk of nutrient and protein inadequacy when increasing %PP may be higher in certain populations with elevated or specific physiological requirements, such as the elderly, who may develop anabolic resistance (i.e., a diminished capacity to synthesize muscle protein effectively) and are at a greater risk of developing sarcopenia, a condition that has been associated with insufficient protein and energy intake (35, 36). Accordingly, some European countries (such as France and Germany) have raised the population reference intake (i.e., recommended dietary allowance) for protein from its standard value of 0.83 g/kg/d in young adults to a higher value of 1 g/kg/d in ≥65y adults (37). However, there is widespread debate about the relevance of such a higher estimate of protein requirement, and most scientific committees and health government agencies (such as those in the USA and Europe) still consider the evidence base to be insufficiently convincing (35, 38). Protein and IAA adequacy may constitute an obstacle to increasing %PP in older adults with higher protein requirements, particularly since protein and IAA inadequacy is already more prevalent in older adults, due in part to a greater prevalence of inadequate energy intake and undernutrition (30, 37, 39).

The literature lacks an analysis of the potential to increase %PP in an aging population that considers its integrated impacts on nutrient adequacy and long-term health. We hypothesized that in the elderly, the potential to increase %PP might vary depending on the protein requirement considered, but only marginally, with the adequate %PP range remaining globally similar to that identified in younger adults. This question has been investigated here by modeling and optimizing the diets of French adults aged 65 years and above, taking into account the reference values for nutrients − by distinguishing two levels, standard and high, for protein − and the disease burden risks and consumption habits of different food categories. We characterized modeled diets that departed as little as possible from prevailing diets at all levels of adequate %PP values for nutrient adequacy and long-term health in order to identify nutritional issues (i.e., limiting nutrients) and dietary levers (i.e., effective foods) that could increase %PP in the elderly.

Materials and Methods

Dietary data

The dietary data used for this study were extracted from the French Individual and National Study on Food Consumption Survey 3 (INCA3), the most recent representative cross-sectional survey of the French population conducted in 2014-2015 and described in full detail elsewhere (40). Briefly, participants residing in mainland France were selected following a three-stage stratified random sampling method using the national census database, and weighted to ensure national representativeness. Their dietary data were collected by professional investigators using a standardized and validated dietary software from three unplanned, non-consecutive, 24h dietary recalls spread over a three-week period (two weekdays and one weekend day), with portion sizes estimated using validated photographs (40). The INCA3 study was authorized by the National Commission on Informatics and Liberty, after a favorable opinion from the Advisory Committee on Information Processing in Health Research, and all participants provided informed consent. In the present study, we included the ≥65 y males (*n*=185) and ≥65 y females (*n*=248) not identified as under-reporters for energy intake, using a previously described method (17), resulting in a final sample of 433 older people (Supplemental Figure 1). As in our previous study in younger adults (10), the food items consumed (n=1,533) were gathered in 45 food groups (Supplemental Table 1), with mixed foods being broken down into their ingredients before being gathered. A mean diet was calculated for each sex as the mean of the individual consumptions of each food group.

The nutrient contents of the different food items were extracted from the 2016 food composition database operated by the French Information Centre on Food Quality (CIQUAL) (41). Indeed, the INCA3 food list was matched with the CIQUAL nutrient content database, taking into account the specific characteristics of the foods consumed (e.g., sugar, fat, salt content, cooking methods, etc.). All INCA3 foods were matched with a corresponding CIQUAL descriptor, either a specific descriptor or an "average food", as previously described (40). For each sex, the nutrient content of each food group was then calculated as the mean nutrient content of food items constituting the food group weighted by their mean intake by the sex considered, as previously described (10). All dietary data (food group consumption and nutrient content) related to the total elderly population of each sex (including non-consumers).

Multi-criteria diet optimization

As in our previous study in younger adults (10), we identified the range in the elderly of adequate %PP values – and the corresponding modeled diets – to ensure nutrient adequacy and minimize long-term health risk from chronic non-communicable diseases while not deviating from dietary habits more than necessary. This was achieved by multi-criteria diet optimization under constraints to ensure nutrient adequacy and dietary acceptability. Minimizing long-term health risk (*HR* criterion) was the primary objective and minimizing diet departure (*DD* criterion) the secondary objective.

The *HR* criterion targeted the dietary recommendations for different food group consumptions from the 2019 GBD study based on their associations with chronic disease risk (2), namely the Theoretical Minimum Risk Exposure Levels (TMRELs) for three unhealthy food groups (red meat, processed meat and sweetened beverages) and six healthy food groups (whole grain products, fruit, vegetables, legumes, nuts and seeds, and milk), which are zero and non-zero, respectively. A zero (minimum) *HR* value was obtained when the consumption of each of the three unhealthy food groups was zero and the consumption of each of the six healthy food groups was at or above its TMREL, using the following formula:

$$\text{Min } HR = \sum_{i=1}^{3} \left(\frac{\text{Opt(i)}}{\text{Max(i)}} \times \frac{\text{DALYs(i)}}{\text{DALYs(all)}} \right) + \sum_{j=1}^{6} \left(\max \left[\frac{\text{TMREL(j) - Opt(j)}}{\text{TMREL(j)}} ; 0 \right] \times \frac{\text{DALYs(j)}}{\text{DALYs(all)}} \right)$$

Where i denotes the unhealthy food groups, j denotes the healthy food groups, Opt(i) and Opt(j) are the optimized consumptions of food groups i and j, respectively (in g/d), Max(i) is the upper limit of consumption of food group i (in g/d), TMREL(j) is the TMREL value of food group j (in g/d), DALYs(i) and DALYs(j) are the disability-adjusted life-years (DALYs) associated with excessive or insufficient consumptions of food groups i and j, respectively (in y), and DALYs(all) is the sum of all DALYs(i) and DALYs(j). The Max values used were the maximal recommended consumption of unhealthy foods in line with French dietary guidelines (42): 71g/d for red meat, 25g/d for processed meat and 263 g/d (corresponding to the average portion size) for sweetened beverages. The TMREL and DALYs values used came from the 2019 estimates determined by the GBD (2) and adapted to our study context (by using sex-specific and French DALYs values in ≥65 y elderly, Supplemental Table 2).

The *HR* criterion was thus designed to: (i) range from 0 (best value, achieved when the consumption of each unhealthy or healthy food group is at a level ensuring the lowest health risk) and 1 (worst value, occurring when unhealthy food groups are consumed at their maximum levels and healthy food groups at zero), and (ii) prioritize changes in the food groups contributing the most DALYs during optimization (as within HR, the distance to each food group's target (TMREL value) is weighted by the relative importance of achieving this target compared to other, based on their respective contribution to DALYs). The *HR* criterion thus represents a normalized distance to the consumption targets for both healthy and unhealthy food groups, which are associated with minimal morbidity and mortality risk as established by the GBD. A recent study conducted by our team demonstrated that the *HR* criterion—together with other scores based on the GBD's TMREL—effectively predicts morbidity and mortality from chronic diseases in the French population, including type-2 diabetes, cardiovascular diseases, cancer, and all-cause mortality, with the robustness of these associations confirmed using multiple scoring methods and advanced causal inference models (43).

The *DD* criterion was defined as the sum of the squares of the differences between observed and optimized food group consumption, standardized by their observed standard deviations, using the following formula (10):

$$\text{Min}\, DD = \sum_{k=1}^{n} \left[\frac{\text{Obs(k) - Opt(k)}}{\text{SD(k)}}\right]^2$$

Where k is the number of food groups (n=45), Obs(k) and Opt(k) are respectively the observed and optimized consumptions of food group k (in g/d), and SD(k) is the current standard deviation of the consumption of food group k.

In *DD*, (i) dividing the consumption deviation by its observed standard deviation gave less weight to deviations in food group consumptions with greater inter-individual variability, and (ii) using a quadratic formulation with squared consumption deviations favored the selection of smaller deviations across numerous food groups, rather than larger deviations in just a few (44). To better illustrate the practical meaning of certain *DD* values obtained, they were recalculated using a previously established metric, the diet similarity index, which is more interpretable but less effective for guiding optimization. This index evaluates the consumptions that remain common between the optimized and observed diets, expressed as a percentage of the observed consumptions (45).

As previously explained in detail (10), the optimization process involved two steps, as the two objectives (i.e., the long-term health risk assessed by the *HR* criterion and the effort to change dietary habits assessed by the *DD* criterion) were minimized under a hierarchical optimization approach designed to prioritize health improvement over dietary inertia. In a first step, the adequate %PP range was identified by optimizing the *HR* criterion under all the nutritional and acceptability constraints, with an additional constraint on %PP iteratively parameterized as a grid search to force the %PP value to be equal to x%, with x% ranging from 0% to 100% by 5% steps (or even 1% at the edges of the adequate %PP range). The nutrient-adequate %PP range was that which allowed model convergence (i.e., outside this range, it was impossible to meet both the nutritional and acceptability constraints), and the fully healthy %PP range was the narrower range also ensuring a null *HR* value (i.e., outside this range, there was a conflict between nutrient adequacy and long-term health, as nutrient adequacy could only be ensured via a degraded *HR* value).

In a second step, at each %PP value previously identified as adequate in the main model, we then characterized the corresponding modeled diet (i.e., the modeled consumptions of the 45 food groups) as the most acceptable dietary solution *a priori*, based on the least departure from the current diet. This was achieved by optimizing the *DD* criterion under the constraints that %PP=x% and *HR* was equal to its previously identified minimal value for %PP=x%, always under all the nutritional and acceptability constraints. The minimal dietary changes required to ensure both full health and nutrient adequacy, as estimated in this second step, were also compared to those needed to ensure nutrient adequacy alone, which were estimated by minimizing *DD* under all nutritional and acceptability constraints (i.e., without any additional constraint on *HR*).

This optimization problem was non-linear and performed using the NLP solver of the OPTMODEL procedure of SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA.). Optimization was performed at the population level but separately for males and females because of their specific nutritional constraints. The modeled diets for the total population were then calculated as the means of the modeled diets for males and females.

Nutritional and acceptability constraints

In both optimization process steps, a set of nutritional constraints was applied to ensure that all nutrient intakes in the modeled diets remained or became adequate (if not initially adequate in the observed diets, as for some nutrients) (**Table 1**). The total energy intake was constrained to stay within ±5% of its requirement (estimated at 2,308 and 1,878 kcal/d in ≥65 y males and females, respectively (46)), and 35 other sex-specific nutritional constraints were applied based on the most recent reference values from the French Agency for Food, Environmental and Occupational Health & Safety (47). As previously explained (10), we did not consider vitamin D (because its reference value is too high to be reached using a non-fortified diet alone) but took account of the bioavailability of iron and zinc (using non-linear equations that predict their absorption from certain characteristics of dietary intake and by requiring absorbed amounts that ensure ≤5% deficiency prevalence) and the slightly lower digestibility of plant proteins compared to animal proteins (by applying a 5% penalty to protein intake from plant protein food items in the nutritional constraint on protein requirement). We applied two alternative minimum values for protein intake in the nutritional constraint on protein requirement, corresponding to two estimates of the population reference intake, depending on whether the reference was based on a protein requirement considered as standard (SP, 0.83 g/kg/d as in younger adults <65 y) or high (HP, 1 g/kg/d), and the entire optimization process was performed according to these two options to compare the results. Only protein requirements were considered in the model constraints, but IAA intakes were calculated *a posteriori* using an in-house database of the IAA composition of food groups, as explained previously (10), to check whether their 98% safe intakes were effectively met. For each indispensable IAA, the 98% safe intake was calculated as the estimated average requirement + 2×SD (48), and was increased proportionally to the increase in protein requirement when it was considered to be higher (i.e., multiplied by a 1:0.83 ratio).

Another set of acceptability and dietary constraints was also applied to ensure that food group intakes remained within current consumption limits and French dietary guidelines, respectively (Supplemental Table 3). For each sex, the intake of each food group was bounded between its 5th and 95th percentile of observed consumption (acceptability constraints), except for unhealthy food groups (red meat, processed meat, and sweetened beverages), for which a stricter upper limit was applied according to French dietary guidelines (dietary constraints), and except for certain healthy food groups (nuts and seeds, legumes and milk), for which the upper limit was raised to the TMREL value, which was slightly higher than the 95th percentile value.

Limiting nutrients and contribution of food groups to their intake

For each nutrient, its intake in a given modeled diet deviates from its reference value(s) set as constraint(s)—exceeding the lower bound ensuring adequacy and/or falling below the upper bound preventing excess—when the nutrient is not limiting. Conversely, when the nutrient is limiting, its intake or closely aligns with (one of) its reference value(s). The limiting or non-limiting nature of a nutrient is also reflected in the dual values provided by the optimization process for the nutritional constraints, with these dual values offering the added advantage of enabling the assessment of the strength of the limitation. To better characterize the conflicts between %PP, nutrient adequacy and long-term health, we analyzed the dual values obtained for the nutritional constraints during the first step of the optimization process (i.e., identifying the adequate %PP range, as explained above). These dual values associated with the nutritional constraints during *HR* optimization represented the potential *HR* gain if the limiting bound (lower or upper) of the constraint considered was relaxed by one unit, thus revealing conflicts between nutrient adequacy and long-term health for each %PP value considered. To compare the relative influence of nutrients, their dual values were standardized to represent the potential *HR* gain if the limiting bound was relaxed by 10%, so as to classify nutrients from the most limiting (higher absolute standardized dual value) to the least limiting (lowest absolute standardized dual value).

For each nutrient identified as increasingly limiting as %PP rose or fell towards its maximum or minimum value compatible with nutrient adequacy, we studied the contributions of different food groups to the intake of that particular nutrient in the modeled diets identified throughout the nutrient-adequate %PP range (i.e., in the modeled diets resulting from the second step of identifying the most acceptable dietary solutions, as explained above).

Food groups as dietary levers to further increase %PP

We also analyzed the standardized dual values obtained for the acceptability constraints during the first step of optimization in order to identify those food groups whose consumption limits narrowed the %PP range identified as adequate, i.e., the food groups that are dietary levers for further %PP increases. We also conducted a sensitivity analysis to determine how the acceptability constraints considered influenced the %PP range identified as adequate by comparing the results obtained when these constraints were removed (i.e., model with nutritional constraints only) or not (main model with both nutritional and acceptability constraints).

Results

Modeled diets: main characteristics

Figure 1 shows the composition of the modeled diets and their corresponding health risks (*HR* criterion) and departure from the observed diet (*DD* criterion) throughout the broad %PP range identified as compatible with nutrient adequacy, with the results expressed as mean values for both sexes by considered protein requirement. All the modeled diets identified were very distant from the observed diets (i.e., had high *DD* values), but had much lower *HR* values. In the narrower ~25%-70% %PP range identified as compatible not only with nutrient adequacy but also with full health (i.e., allowing a null *HR* value), all the modeled diets were generally equally distant from the observed diets and those situated within the ~35%-55% %PP range differed by less than 5% in terms of their *DD* values. In this ~35%-55% %PP range, representing the minimal dietary changes required to achieve both nutrient adequacy and full health, the similarity between the modeled and observed diets, recalculated using the diet similarity index, ranged from only 60 to 70%, compared to up to 88% when ensuring nutrient adequacy alone (Supplemental Figure 2). All the fully healthy modeled diets within the ~25%-70% %PP range had in common a similar pattern of change compared to the observed diets, with the removal of unhealthy foods (red meat, processed meat, and sweetened beverages) and a marked increase in healthy foods (whole grain products, fruit, vegetables, legumes, nuts and seeds, and milk) up to or above their minimum risk exposure levels (i.e., TMRELs). Notably, the minimal dietary changes required to ensure nutrient adequacy alone also involved reducing unhealthy food groups and increasing healthy ones, but with smaller amplitudes than when also health considerations were also included (Supplemental Figure 2). Outside the fully healthy ~25%-70% %PP range, *HR* was slightly burdened by insufficient milk consumption at the highest %PP values, and more heavily burdened by excessive red meat consumption and an insufficient consumption of whole grain products, legumes, and nuts at the lowest %PP values (Figure 1).

The detailed plant and animal product contents of the observed and modeled diets are shown in Supplemental Figure 3 and Supplemental Table 4. Overall, in all the modeled diets compared to the observed diet, although energy intake remained relatively stable (by construction), total intakes of both animal and plant products increased, notably due to significant increases in milk, fruit and vegetables up to or above their TMREL values. This led to some mass differences between the modeled and observed diets: when considering the total consumption of solid foods (excluding liquid foods such as milk, sweetened and other beverages), diet mass showed no substantial variation up to the highest %PP values, where it increased by up to +25% (1.77 kg/d compared to 1.42 kg/d in the observed diet; see Supplementary Table 4). The main variations in plant products across the modeled diets, from low to high %PP, were early increases in legumes and nuts that then plateaued (legumes and nuts reached their maximum allowable intakes as early as %PP=25%), and increasing levels of refined grain products and potatoes and starch at the upper end of the nutrient-adequate %PP range. As for variations in animal products as %PP increased, red and processed meats were first readily removed and transiently replaced by poultry and eggs before reaching meat-free diets from PP%=60% or 70% when the protein requirement was considered to be standard or high, respectively. Dairy and seafood were the only remaining animal products at the right end of the nutrient-adequate %PP range. Globally, the composition of the modeled diets varied little according to the protein requirement considered, except that when the protein requirement was considered to be higher, the diets became meat-free at a slightly higher %PP value, and diets at the highest %PP values contained slightly more grain products (Supplemental Table 4).

Range of adequate %PP values

The adequate %PP range compatible with nutrient adequacy was 15–80% (15–75%) in males and 16–74% (16–73%) in females with a standard (high) protein requirement, and the %PP range also compatible with full health (i.e., a null *HR* value) was 23–74% (23–70%) in males and 23–70% (23–69%) in females with a standard (high) protein requirement. Thus, both the nutrient-adequate and fully healthy %PP ranges had slightly lower maximum values in females than in males, and when the protein requirement was considered to be higher (especially in males) by a few percentage points. Of note, the %PP ranges identified as adequate depended on the limits considered for food group consumption, as the sensitivity analysis showed that suppressing all the dietary and acceptability constraints could greatly expand the nutrient-adequate %PP range on both sides (to 6%-96% in males and 8%-94% in females, regardless of the considered protein requirement).

Identified conflicts between %PP, nutrient adequacy and long-term health

The dual value analysis showed that no nutritional constraint was active and limiting for *HR* minimization within the fully healthy %PP range, meaning that there was no conflict between nutrient adequacy and long-term health within this range, allowing a null *HR* value. In contrast, a growing conflict was identified as *HR* deteriorated outside this %PP range, with some nutritional constraints being increasingly active and limiting as %PP increased or decreased toward the maximum or minimum values compatible with nutrient adequacy. The dual values obtained at the highest and lowest nutrient-adequate %PP values are shown in **Table 2** and

Supplemental Table 5, respectively, and the detailed nutrient intakes and their food sources in the modeled diets are shown in Supplemental Table 6 and Supplemental Figures 4 and 5, respectively.

As %PP fell below 23% (i.e., the minimum %PP value compatible with full health in all cases), it was increasingly challenging to maintain a sufficient intake of fiber and non-excessive intakes of saturated fatty acids and sugar (as shown by the opposite sign of their dual values in Supplemental Table 5), which resulted in dietary solutions of increasingly degraded *HR* values. As shown by the food group contributions to nutrient intakes becoming limiting with decreasing %PP, saturated fatty acids approached excess due to increases in meat and dairy, while fiber approached insufficiency due to decreases in whole grain products and legumes (Supplemental Figure 4).

At the other end, as %PP rose above 69-74% (i.e., the maximum %PP value compatible with full health, depending on sex and considered protein requirement), it was increasingly challenging to maintain adequate intakes of various nutrients while staying within the limits imposed for total dietary energy (Table 2). The maximum allowed dietary energy was limiting to further increase %PP under nutrient adequacy, especially when the protein requirement was considered to be high. In all cases (i.e., for each sex and protein requirement considered), the limiting nutrients influenced the dietary solutions identified above %PP=~70%, as it became increasingly challenging to maintain a non-excessive sodium intake and sufficient intakes of iodine, vitamin A and EPA+DHA, together with vitamin B12 (more in males) and bioavailable iron, calcium, α-linolenic acid and riboflavin (more in females), and protein only when a high protein requirement was considered (Table 2). The difficulties encountered in maintaining sufficient intakes of bioavailable iron, riboflavin, vitamins B12 and A, and iodine and calcium were due to the decreases in animal products that were their main contributors, namely red meat, dairy products and eggs (Supplemental Figure 5). EPA+DHA and α-linolenic acid intakes, which were largely insufficient in the observed diets, were rendered sufficient in all the modeled diets by increasing their main contributors, seafood and added fats, respectively, although maintaining sufficient levels became challenging for the highest %PP values (Supplemental Figure 5). Sodium intake, which was dramatically excessive in the observed diets, was reduced to its upper limit in all the modeled diets by eliminating processed meat and reducing refined grain products, with problems in maintaining sodium at a non-excessive level for the highest %PP values because of the increase in whole grain products (Supplemental Figure 5).

Protein and IAA intakes

Maintaining an adequate protein intake at the highest %PP values was only a nutritional issue when the protein requirement was considered high (i.e., 1 g/kg/d), particularly in males, where protein became the most limiting nutrient (Table 2). Thus, over the entire nutrient-adequate %PP range, including meat-free diets, the protein intake was always well above the requirement when it was considered standard, whereas protein intake was just at the required level from %PP=50% when it was considered high (**Figure 2**). Nevertheless, in all cases, the intakes of each IAA were always much higher than their 98% safe intake threshold (**Figure 3**). The relative contribution of food groups to protein intake also differed slightly between cases: when the protein requirement was considered to be higher, meat, and more precisely poultry, made a longer contribution to protein intake as %PP increased, and grain products made a greater contribution at high %PP values (Supplemental Figure 6). Thus, at %PP=70%, the increased protein requirement (HP compared to SP) was met by ~80 g/d more grain products, while legumes, nuts, vegetables, and fruit were already at their upper consumption limits (Supplemental Table 4). As indicated by the dual values for the acceptability constraints (Table 2), these latter food groups (legumes, nuts, vegetables and fruit) were also identified as dietary levers to design more plant-based healthy diets, meaning that their consumption beyond the acceptability limits considered here would permit the design of healthy diets with %PP>~75%. Accordingly, as tested in the sensitivity analysis, removing all food group consumption limits (acceptability and dietary constraints) increased the maximum nutrient-adequate %PP value to ~95% without changing the nutritional issues above this point (in particular, insufficient intakes of vitamin B12, riboflavin and EPA+DHA).

Differences between the results obtained in elderly and younger adults

Figure 4 shows the differences in the adequate %PP ranges identified in the elderly during the present study and in younger adults in a previous study by us (10). Whatever the age or considered protein requirement, a very similar %PP range (~25%-70%) was found to be compatible with both nutrient adequacy and full health. The broader %PP range compatible with nutrient adequacy (but not with full health) had slightly lower maximum %PP values in the elderly than in the young, but only within the food group consumption limits considered and not when these acceptability and dietary constraints were suppressed (as tested in the sensitivity analysis).

Discussion

By gathering a broad range of information on nutrition and health (from reference values for nutrients to nutrient contents, chronic disease risks and consumption habits for food groups), this study was able to establish the ranges of plant protein proportions (%PP) compatible with nutrient-adequate and health-promoting diets in the elderly (≥65y). This was achieved by modeling nearly isoenergetic diets with graded %PP values—constrained to remain within ±5% of estimated energy requirements—that ensured full nutrient adequacy by meeting reference values for an extensive set of 34 nutrients, thereby avoiding any insufficiency or excess in energy or in any nutrient, while also accounting for the bioavailability of protein, IAA, iron, and zinc—an aspect rarely integrated into similar diet modeling approaches. The adequate %PP range was identified by considering the protein requirement as standard (protein reference intake of 0.83 g/kg/d, as in younger adults), according to most national and international scientific committees, or higher (protein reference intake of 1 g/kg/d), considering other opinions (38). Within the nutritionally-adequate adequate %PP range in each scenario, the modeled diets were identified as those deviating from prevailing dietary habits only as much as necessary to minimize chronic disease risk—herein referred to as “health risk”—associated with the overconsumption of unhealthy food groups and underconsumption of healthy food groups in relation to cancer, cardiovascular diseases, and diabetes. This was done by minimizing a health risk score representing the distance to food group consumption targets established by the GBD as associated with minimal risk. Using advanced causal inference models, we recently demonstrated that this score is associated with morbidity and mortality in a longitudinal cohort (43). In this study, we showed that there is no optimal %PP value from a unified nutritional and health perspective, as it was possible to identify a broad spectrum of similarly healthy diets over the ~25%-70% %PP range. Our main finding was that this fully healthy %PP range is remarkably similar regardless of the protein requirement considered and also regardless of age, as we identified the same healthy %PP range in the elderly as previously in younger adults (10). In a context where it is now well established that plant-based diets are more sustainable due to their lower environmental impacts (8, 24, 49-51), our results show interestingly that it is possible to increase %PP in the diet of an aging Western population from its current low level of ~1/3 to ~2/3 while simultaneously reducing the health risk and ensuring full adequacy for protein, IAA, and all other nutrients. A further %PP increase would require the introduction and use of novel foods and/or the consumption of current dietary levers at levels exceeding those currently deemed acceptable.

Age-related differences in the adequate %PP range at standard protein requirement

When considering the same protein requirement in the elderly as in young adults (i.e., a protein reference intake of 0.83 g/kg/d), the same %PP range was identified as compatible with a fully healthy diet (~25%-70%), despite age-related differences in dietary habits that translated into differences in observed diets and some of the constraints applied in diet modeling. The age-related difference in the observed diets was expected to have little influence on the modeled diets, given that the multi-criteria diet optimization problem was conducted in a hierarchical manner, with the health value of the modeled diet (*HR* criterion) being prioritized over its proximity to the observed diet (*DD* criterion). As a result, all of the healthy diets identified in the elderly deviated considerably from the prevailing diets, as was the case in younger adults (10), showing that overcoming dietary inertia is required to achieve healthy diets, regardless of the target %PP value (52, 53). Our fully healthy modeled diets thus shared no more than ~70% of food group consumptions with observed diets, which is consistent with other findings in the literature (45). The model constraints were more influential than the observed diets, and some constraints significantly limited the range of identifiable dietary solutions. There were notably age differences in the limits considered for the consumption levels of each food group, which were constrained to stay between the 5th and 95th percentile of observed values (acceptability constraints). The dual value analysis revealed that the upper limits considered for the consumption of legumes, nuts, vegetables and fruit were limiting for the design of healthy diets with %PP > ~75%, as had also been the case in younger adults (10). In older *versus* younger adults, the lower 95th percentile values for these dietary levers explained that the highest nutrient-adequate %PP value was slightly lower (74% in older adults compared to 77% in younger adults), as this was no longer the case when the acceptability constraints were removed during the sensitivity analysis (with maximum nutrient-adequate %PP values of 94% and 92%, respectively).

Nutritional issues and dietary levers to increase %PP at a standard protein requirement

Therefore, as expected, few age-related differences were found when similar requirements for protein and other nutrients were considered, either in terms of adequate %PP range or in terms of nutritional issues and dietary levers as %PP increased toward its maximum nutrient-adequate value. Regarding nutritional issues, based on the current food repertoire and considered acceptability limits, we found that no diet with %PP > ~75% was able to provide sufficient amounts of a large number of nutrients, namely iodine, vitamin A, riboflavin, vitamin B12, bioavailable iron, calcium, α-linolenic acid and EPA+DHA. This set of limiting nutrients was the same as that previously identified in younger adults (10) and is consistent with the fact that these nutrients are considered problematic in vegetarian diets (3, 49, 54). The upper limit on dietary energy (+5% of the requirement) was also found to be limiting for further increases in %PP, consistent with the fact that nutrient adequacy is also a matter of energy intake (15, 55). Our approach of modeling nearly isoenergetic diets across graded %PP values was designed to prevent energy intake from confounding the interpretation of how %PP interacts with nutrient adequacy and long-term health (56). For instance, in young adults, a lower energy intake explains the increased risk of nutrient inadequacy with more plant-based diets (55). In the elderly, the greater prevalence of insufficient energy intake increases the risk of both nutrient inadequacy and health outcomes such as sarcopenia (35). Here, bioavailable iron was found to be similarly (but not less) limiting in postmenopausal females than previously in younger females (10), but this could be readily explained by the relatively similar thresholds for bioavailable iron. Indeed, the threshold used here for older females (reference value of 1.10 mg/d, as in males) was similar to that previously used for younger females because this value (actually lower than the reference value) was based on the favorable health risk-benefit balance of such flexibility among younger females (44). As for dietary levers, we found that dairy products were key to preventing iodine and calcium shortages while seafood was critical to providing EPA+DHA (with oily fishes as the main source) as well as iodine and vitamin B12, and milk and seafood were the last remaining animal products at the highest %PP values, confirming their importance as healthy, nutrient-dense protein sources (57). Legumes and nuts were also identified as the most effective plant protein sources when designing healthy diets with a high %PP value, according to the dual value analysis of the acceptability constraints which revealed their added value compared to other sources. If dairy products and seafood were still present at the highest %PP levels, it is not because legumes and nuts are inherently unable to replace them, but because the latter had already reached their maximum allowable intake early on (as soon as %PP=25%). When removing all food intake limits in the sensitivity analysis, legumes and nuts further increased and provided solutions for nutrient adequacy, and the maximum nutrient-adequate %PP value reached ~95%. However, it remained impossible to achieve 100% plant-based diets because of the same nutritional issues (vitamin B12, riboflavin and EPA+DHA), thus showing that vegetarian (without seafood) or vegan (without seafood and dairy) diets need to rely on food products other than those presently consumed by the general population, including fortified foods, or dietary supplements (as far as vitamin B12 is concerned) (58-60).

Implications and how to meet a higher protein requirement

In the elderly, considering a higher protein requirement (i.e., 1 g/kg/d instead of 0.83 g/kg/d for the population reference protein intake) did not affect the maximum %PP value compatible with full health and nutrient security.

However, meeting this higher protein reference intake became an active nutritional constraint at high %PP values, influencing the composition of the dietary solutions identified and limiting their health values. This was particularly the case for males, where ensuring a high protein intake became the most influential nutritional constraint from %PP≥73%, while it was also the case for females, but less so than ensuring sufficient intakes of iodine and bioavailable iron. It should be noted that the lower digestibility of plant proteins compared to animal proteins was taken into account in our simulations by penalizing the protein intake (and resulting IAA intakes) from plant-based foods by 5%, which is the average difference in real ileal digestibility between animal and plant proteins (32, 61). Such a penalty ensures an additional safety margin, as the meta-analysis of nitrogen balance studies by Rand et al., which forms the basis for the current protein requirement estimation, found no difference in protein requirement estimates based on whether the protein source was predominantly animal or plant-based (34). It was more difficult to ensure a high protein intake at high %PP levels because of the lower protein density (and to a lesser extent, protein digestibility) of plant products compared to animal products (32, 61, 62), combined with the fact that most healthy plant foods which can make an important (legumes and nuts) or lesser (vegetables and fruit) contribution to protein intake had already reached their considered upper limits of acceptability at such high %PP levels. Meeting an higher protein requirement (1 g/kg/d instead of 0.83 g/kg/d) at high %PP levels was thus possible (explaining why the adequate %PP range was unchanged), but it required a dietary change (explaining why the nutritional constraint of protein requirement was active and influential), namely the addition of ~80 g/d of grain products to provide ~7 g/d more protein. With such an addition, equivalent to two servings (e.g., two slices of bread), grain product consumption remained well below the considered acceptability limit.

Our results therefore support the general view that because of the lower protein density and digestibility of plant products compared to animal products, the natural tendency of plant-based diets, if based on the current food repertoire and theoretical acceptability, is to provide less protein than current animal-based diets. This has led some authors to conclude incorrectly that predominantly plant-based diets are inherently unable to provide enough protein in both young and older French adults (63), but this was actually due to a misspecification in their diet modeling, where the protein requirement was not included as a nutritional constraint like other vitamin, mineral and nutrient requirements, resulting in inadequate protein levels in their %PP≥50% modeled diets (64). Diets rich in plant products naturally tend to drift towards diets insufficient in protein if the protein requirement is not properly considered when designing them, just as diets rich in animal products naturally tend to drift toward diets insufficient in fiber or vitamin C if these requirements are not properly considered. In our study, the increased protein requirement (1 g/kg/d instead of 0.83 g/kg/d) was met passively up to %PP=50%, then actively for %PP≥50%, first by maintaining poultry consumption for longer and then by increasing the consumption of grain products when the modeled diets became meat-free at around %PP=70%. An important contribution of our results to the literature is therefore to demonstrate that even if they are meat-free, carefully designed, high plant-based diets are able to supply sufficient protein to meet the potentially higher requirements of older adults.

Protein quantity and quality considerations in plant-based diets

Because plant protein sources contain less protein and IAA (such as lysine and leucine) and may be less able to stimulate muscle protein synthesis and maintain muscle mass and function (35, 38, 65), much attention has been given in the literature to concerns about the quantity and quality of protein in dietary scenarios of %PP increases in young and older adults (62). Simulation studies have revealed a higher prevalence of inadequacies in protein and lysine when some animal foods are simply replaced by the plant foods currently consumed if they are not sufficiently diversified with grain products as the predominant source, but not when a higher proportion of legumes is used in the substitution scenarios (30-32, 37, 66, 67). Likewise, diet optimization studies have shown that there is considerable room to increase %PP above its current low value while ensuring protein and IAA adequacy (39, 53, 68-70), and that nutrients other than protein and IAA are most likely to be at issue when increasing %PP (10, 31, 68, 71-73). A diet optimization study showed a gradual decline in IAA intakes as %PP increased above 50%, but the results could not be interpreted in terms of IAA adequacy because the intakes were not compared to requirements (74). Furthermore, the risk of protein and IAA inadequacy has been overestimated in some studies using biased assessment methods (33, 75), e.g. by not properly excluding under-reporters, leading to an underestimation of protein and IAA intakes (30), as rigorously acknowledged by the authors thereafter (73), or by requiring all IAA requirements to be met systematically for each meal (39), rather than cumulatively over the day, which is excessively demanding compared to the commonly accepted view (48, 76). Finally, observational and simulation/optimization studies assessing nutrient adequacy in current and more plant-based diets have often considered intakes only, without properly considering the bioavailability of nutrients such as iron and zinc. This is an important limitation because the higher phytate levels in plant-based diets largely reduce iron and zinc bioavailability, which needs to be considered as these nutrients are likely to be the most critical as %PP increases (44, 68, 77, 78). In the present study, by taking into account protein, IAA, iron and zinc bioavailability, we showed that certain nutrients supplied by animal products become critical as %PP increases (such as iodine, iron and calcium), but not protein, unless considering a high protein requirement.

Interestingly, we also showed that protein quality is not an issue when protein quantity is sufficient, in our context of high plant-based diets with diversified plant protein sources and some remaining animal products such as dairy and seafood. Indeed, we found that IAA adequacy was always ensured under protein adequacy, regardless of the protein requirement considered. In other words, the use of a constraint on total protein intake alone was sufficient to ensure full IAA adequacy without the use of additional specific constraints on each IAA intake. Thus, IAA adequacy was ensured passively if protein adequacy was ensured, either passively with a standard protein requirement or actively with a higher one. Because the average protein requirement has been established based on final nitrogen balance using real diets that represent a diverse set of dietary protein sources, it is not surprising that meeting the protein requirement with complementary protein sources results in providing sufficient amounts of each IAA (33, 79, 80). Accordingly, we previously showed that a sufficient protein intake secures adequate IAA intakes in modeled diets with up to %PP=70%, even in modeled diets with minimally diversified plant protein sources (32). Also in line with our results, very low prevalence of inadequate protein and IAA intakes are generally observed with predominantly plant-based diets in Western countries that are diversified in terms of their plant protein sources, and particularly if they contain some animal products, as in lacto-ovo-vegetarian diets (33). Even when overestimated by not excluding under-reporters, the prevalence of IAA inadequacy is found to be much lower than that of protein inadequacy (30), which is consistent with our finding that protein quality is less problematic than protein quantity.

Range for a %PP increase above the current level to enhance diet sustainability

Overall, our results showed that plant-based diets, including meat-free diets, can be fully nutrient-adequate, even in older people when account is taken of their higher protein requirement, if meat is replaced with large amounts of healthy and protein-rich plant foods such as legumes and nuts, and if the diet always includes sufficient quantities of seafood and dairy products to meet certain nutrient reference values such as iodine, calcium, EPA+DHA and vitamin B12 and riboflavin, in line with previous results in the literature (81). It is therefore possible to raise the level of plant proteins in the diet from the current one-third level to two-thirds, without any nutritional risk. A more plant-based diet of this type would also be healthier than the current dominant diet in Western countries, as evidenced by our findings regarding a minimized risk of chronic diseases, including cardiovascular disease, cancer and diabetes, and also by the literature on the expected effects on other age-related illnesses. Indeed, such plant-based diets may promote healthy aging in Western populations (82), where higher %PP levels in older adults, independent of protein intake, have been shown to be associated with a lower risk of frailty (83) and sarcopenia (35, 84) and a better health-related quality of life (85).

Furthermore, more plant-based diets are also better for planetary health as the environmental impacts of the diet diminish as %PP increases (8, 10). However, a %PP of two-thirds seems to be the maximum %PP achievable to eliminate the chronic disease burden of our current diets with complete nutrient adequacy, given the current food repertoire and the acceptability limits considered. If a higher %PP is targeted for environmental or ethical reasons, we found that legumes, nuts, vegetables and fruit appear to act as dietary levers if consumed beyond the acceptability limits considered here, and there is also a need for new products in the food repertoire, including fortified foods, as the availability of protein- and nutrient-rich plant products seems to be crucial to the design of healthy and nutrient-adequate diets with %PP>75%, especially in an aging population with a high protein requirement. Furthermore, a potential barrier to the adoption of more plant-based diets by an elderly population, beyond the cultural shift required in dietary habits, is the increased mass of food to be consumed due to the lower energy density of plant-based products. At the highest %PP levels, modeled diets required up to 25% more solid foods (1.77 kg/d at %PP=70% compared to 1.42 kg/d in the observed diet). However, since 10% of individuals in our population already consume more than 1.77 kg/d of solid foods, this increase appears feasible at the population level, although it may pose challenges for some elderly individuals experiencing appetite loss.

Strengths and limitations

This study had some limitations. First, we modeled diets by distinguishing 45 food groups based on the current food repertoire, each considered as a grouping of foods that are reasonably homogeneous in terms of their nutrient content, health effects and dietary use. However, food grouping remains an arbitrary process that is critical in diet modeling and can always be a matter of debate (42), especially when considering that food repertoire, composition and use can evolve quite rapidly in Western countries, as illustrated by recent changes (86). Nevertheless, our use of a relatively classic food grouping ensured that dietary patterns were represented at an appropriately high level of detail, while our consideration of standard/traditional foods customarily consumed offered a good starting point to assess the current situation before considering changes to food offer or food composition. Second, as shown in the sensitivity analysis, our results regarding the adequate %PP ranges were highly sensitive to the acceptability limits considered for some healthy plant foods that were indeed found to be important dietary levers to increase %PP. We used quite standard acceptability limits, corresponding to the 95th percentile of observed consumption, because we were unable to better account for the actual "acceptability" of unusually high consumption of these dietary levers, a recurring limitation in diet optimization studies (87). Third, our study used many sources of information as background parameters, including reference values for nutrients and target intakes for some food groups based on available epidemiological data (i.e., TMREL values from the GBD 2019 study). Clearly, there are numerous uncertainties in this regard and all these values may be revised in the future (42). Finally, we believe that a strength of our study was our implementation of a conceptual framework that brings together much of the current knowledge on nutrition and health, and the use of advanced analytical methods (including dual values and sensitivity analysis) to analyze the determinants of healthy higher plant protein intake.

Conclusions.

We have shown that in an aging Western population, irrespective of whether protein requirements are considered to be standard or higher than in younger adults, the dominance of animal proteins over plant proteins can be reversed (i.e., %PP can increase from ~1/3 to ~2/3) while ensuring full nutrient adequacy and maximum health improvement. Based on the current food repertoire, the diet must always include sufficient amounts of some animal foods (namely seafood and dairy products) to meet the requirements for nutrients that become limiting as %PP increases: iodine, calcium, EPA+DHA, bioavailable iron, vitamin A, vitamin B12 and riboflavin; and protein (but not IAA) although only if considering a higher protein requirement. Our findings are consistent with previous conclusions that there has been a disproportionate focus on protein and IAA adequacy in the literature on plant-based diets, while other nutrients more specific to animal foods may be far more critical as %PP increases (31, 71). We found that while protein adequacy may be a concern in elderly when considering a high protein requirement, and in this case may need to be carefully considered in the diet design of low animal protein consumption, IAA adequacy is unlikely to be an issue if protein intake is sufficient and diversified between sources. Therefore, even in the elderly, the focus should shift from protein and IAA *per se* to other nutrients carried by protein sources (i.e., the nutrient package (4)), the overall health value of food groups that provide protein, and the efforts required to move away from current unhealthy and unsustainable dietary patterns (79).

Acknowledgments: none.

Author Contributions: HF and FM designed the research; HF conducted the research and analyzed the data; J-FH, EP, AD, JW, EK-G, and FM provided methodological support and help with interpretation of the results; HF wrote the first draft of the manuscript; and all authors provided critical comments on the manuscript. HF had primary responsibility for the final content, and all authors have read and approved the final manuscript.

Potential conflicts of interest: HF has received an INRAE research grant from Roquette. FM has received research grants for AgroParisTech and INRAE PhD fellowships under his direction from Terres Univia and the Ecotone Foundation, under the aegis of the Fondation de France.

Data Sharing: Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval.

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Figures legend

Figure 1. Daily consumption of food categories in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (*HR*) under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value. Results are reported for all the adequate %PP values that ensure nutrient adequacy, which includes those that also ensure a null *HR* value (within the blue box), and those that also have similar minimal diet departure (*DD*) values (within the pink box). The bar charts represent the cumulative consumptions of food categories (black axis on the left) and the curves represent the *HR* and *DD* values (blue and pink axes on the right, respectively). For clarity, the 45 modeled food groups are not represented here but grouped into broader categories. The consumption of water, hot beverages, alcohol and miscellaneous foods are not shown for reasons of clarity. Details on food grouping and consumptions of all food categories are shown in Supplemental Tables 1 and 4, respectively.

Figure 2. Contribution of food categories to protein intake in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (*HR*) under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value. Results are reported for all the adequate %PP values that ensure nutrient adequacy, which includes those that also ensure a null *HR* value (within the blue box), and those that also have similar minimal diet departure (*DD*) values (within the pink box). Sections inside the bars represent the contributions of food categories to protein intake (in g of protein per kg of body weight per day). See Supplemental Table 1 for the detailed composition of food categories.

Figure 3. Intakes of indispensable amino acids (IAA) in observed (obs) and in the closest optimized diets (opt) minimizing long-term health risk under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value. IAA intakes take account of the average 5% lower digestibility of plant proteins compared to animal proteins (see Methods section). Black dashed horizontal lines represent the 98% safe intake for each IAA.

Figure 4. Adequate range of percentage of plant protein (%PP) values for nutrient-adequate and fully healthy diets in French elderly (mean of ≥65 y males and females), considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value, compared to previous findings in younger French adults (mean of 18-64 y males and 18-54 y females) (10). In each studied population/condition, the nutrient-adequate and fully healthy %PP range (box in red) was identified as the one able to ensure minimal long-term health risk (i.e., a null *HR* value) under all nutritional, dietary and acceptability constraints. The wider nutrient-adequate (only) %PP range was identified under all the nutritional, dietary and acceptability constraints ("within acceptability bounds", whiskers in blue), or without the dietary and acceptability constraints ("outside acceptability bounds", whiskers in green). The %PP level in the observed diet (obs) is indicated by a grey line.

Table 1. Nutritional constraints applied in the optimization model in French elderly (≥65 y) males and females[1].

Nutrients	Units (/day)		Lower bounds[2]		Upper bounds[3]	
			Males	Females	Males	Females
Energy intake[4]	kcal		2,193	1,784	2,423	1,972
Retinol	µg		-	-	3,000	3,000
Vitamin A	µg		750	650	-	-
Thiamin (Vitamin B1)	µg/kcal		0.418	0.418	-	-
Riboflavin (Vitamin B2)	mg		1.6	1.6	-	-
Niacin (Vitamin B3)[5]	mg NE/kcal		0.0067	0.0067	900	900
Pantothenic acid (Vitamin B5)	mg		3.77	3.22	-	-
Vitamin B6	mg		1.7	1.6	25	25
Folate (Vitamin B9)	µg		330	330	-	-
Vitamin B12	µg		4	4	-	-
Vitamin C	mg		110	110	-	-
Vitamin D[6]	µg		-	-	100	100
Vitamin E	mg		5.28	4.37	-	-
Vitamin K1	µg		39.47	34.48	-	-
Calcium	mg		950	950	2,500	2,500
Copper	mg		1.07	0.89	5	5
Bioavailable iron[7]	mg		1.10	1.10	-	-
Iodine	µg		150	150	600	600
Magnesium	mg		253.5	194.6	-	-
Manganese	mg		1.99	1.52	-	-
Phosphorus	mg		550	550	-	-
Potassium	mg		3,500	3,500	-	-
Selenium	µg		70	70	300	300
Sodium	mg		1,500	1,500	2,300	2,300
Bioavailable zinc[7]	mg		2.06	1.61	25	25
Water	g		2,500	2,000	-	-
Saturated fatty acids	% EI		-	-	12%	12%
Atherogenic fatty acids	% EI		-	-	8%	8%
Linoleic acid	% EI		4%	4%	-	-
α-linolenic acid	% EI		1%	1%	-	-
Linoleic acid : α-linolenic acid ratio	-		-		5	5
EPA+DHA	g		0.5	0.5	-	-
Sugar (excluding lactose)	g		-		100	100
Protein[8]	g/kg	SP	0.83	0.83	2.3	2.3
		HP	1	1	2.3	2.3
Fiber	g		30	30	-	-

[1] Lower and upper bounds of the nutritional constraints are based on the most recent nutrient reference values from the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) (47).

[2] Lower bounds correspond to the Population Reference Intake (PRI) or the 5th percentile of observed consumption for nutrients without PRI (but Adequate Intake values based on observed intakes): Pantothenic acid (vitamin B5), vitamin E, vitamin K1, copper, magnesium and manganese.

[3] Upper bounds correspond to the Tolerable Upper Intake Level (UL).

[4] Total energy intake was constrained to stay within ±5% of the estimated average energy requirement for the elderly population considered (2,308 kcal for males; 1,878 kcal for females (46)).

[5] 1 mg niacin equivalent (NE) is equal to 1 mg niacin or 60 mg tryptophan.

[6] For vitamin D, a lower bound was not applied as the current reference value is too high to be reached through food intake alone.

[7] For bioavailable iron and zinc, the lower bounds were not based on current reference values but on lower thresholds that ensure ≤5% deficiency prevalence while unlocking the potential for overall healthier diets (44), as in our previous study in younger adults (10).

[8] Two different lower bounds were used for the protein requirement, depending on whether it was considered standard (SP, 0.83 g/kg/d) as in younger adults, or higher (HP, 1 g/kg/d), with optimization being performed separately for each case. Furthermore, to account for the slightly lower average digestibility of plant protein, protein intake from plants was reduced by 5% when calculating the protein and indispensable amino acid intakes.

Atherogenic fatty acids are the sum of lauric, myristic and palmitic acids; DHA, docosahexaenoic acid; EI, energy intake; EPA, eicosapentaenoic acid.

Table 2. Conflicts identified between health and nutrient adequacy or dietary habits as the percentage of plant protein (%PP) in the diet increased toward its maximal nutrient-adequate value in French ≥65 y elderly by sex and protein reference value considered[1].

		Elderly males		Elderly females	
Considered protein requirement		SP (0.83 g/kg/d)	HP (1 g/kg/d)	SP (0.83 g/kg/d)	HP (1 g/kg/d)
Maximal nutrient-adequate %PP value		80%	75%	74%	73%
Conflicts with nutrient adequacy (nutrient and total energy intakes)	Protein		0.091*		0.017
	Sodium	-0.015*	-0.064*	-0.041*	-0.036*
	Iodine	0.018*	0.032*	0.062*	0.056*
	Bioavailable iron		0.018	0.029*	0.023*
	Vitamin B12	0.008			
	Vitamin A	0.005	0.008	0.006	0.006
	Riboflavin	0.012*		0.008	0.005
	Calcium	0.002		0.006	0.005
	α-linolenic acid		0.005	0.002	0.005
	EPA+DHA	0.002	0.001	0.004	0.003
	Total energy	-0.011	-0.040	-0.017	-0.036
Conflicts with dietary habits (food consumption limits)	Legumes	-0.014	-0.022	-0.017	-0.017
	Nuts	-0.007	-0.009	-0.006	-0.006
	Vegetables	-0.005	-0.009	-0.010	-0.010
	Fruit	-0.001	-0.004	-0.002	-0.003

[1] Results of the dual value analysis when minimizing the long-term health risk (*HR*) under all nutritional, dietary and acceptability constraints, in ≥65 y males and females with either a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value. The dual values provided by the optimization process allow the identification of nutrients and dietary habits that become limiting as %PP increases, due to the growing challenge of meeting the reference values of these nutrients within the considered food consumption limits. The dual values also allow for estimating the extent to which this limitation hinders the identification of diets that could be healthier in the long term, as the duality is expressed relative to *HR*.

Dual values indicate the conflicts between the model objective (*HR*) and the model constraints that arose outside the fully healthy %PP range, at the edges of the nutrient-adequate %PP range, where ensuring an adequate nutrient intake (i.e., meeting the nutritional constraints) while respecting food consumption limits (i.e., meeting the acceptability constraints) was limiting for *HR* minimization and made it impossible for the model to converge beyond the nutrient-adequate %PP range. The results given here are the conflicts identified at the maximal nutrient-adequate %PP value (see Supplemental Table 5 for the conflicts identified at its minimal value), as indicated by non-null dual values for (i) the nutritional constraints (on nutrient and total energy intakes), allowing for the identification of nutrients becoming limiting as %PP increases (i.e., nutritional issues), and (ii) the acceptability constraints (on food consumption limits), allowing for the identification of food groups whose consumption limits restrict the nutrient-adequate %PP range (i.e., dietary levers). The reported dual values have been standardized to represent the potential effect on *HR* of a 10% relaxation of the limiting bound, to classify the nutrients/foods from the most limiting (higher absolute value) to the least limiting (lowest absolute value). Limiting nutrients/foods have a positive (negative) dual value if their lower (upper) bound is limiting (e.g., for %PP=75% in elderly males with HP requirement, the dual value for protein indicating that there would be a potential *HR* gain of 0.091 if the lower bound for protein intake was decreased by 10%, i.e., from 1 to 0.9 g/kg/d). Only nutrients with an active constraint (i.e., with a non-null dual value) are presented (i.e., for nutrients not presented here, dual values were always equal to zero, meaning that compliance with these constraints was not limiting).

DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.

*The three most limiting nutrients for each modeled diet (i.e., in a given column).

Supplemental Information

Plant to animal protein ratio in the diet of the elderly: potential for increase and impacts on nutrient adequacy and long-term health – a diet optimization study

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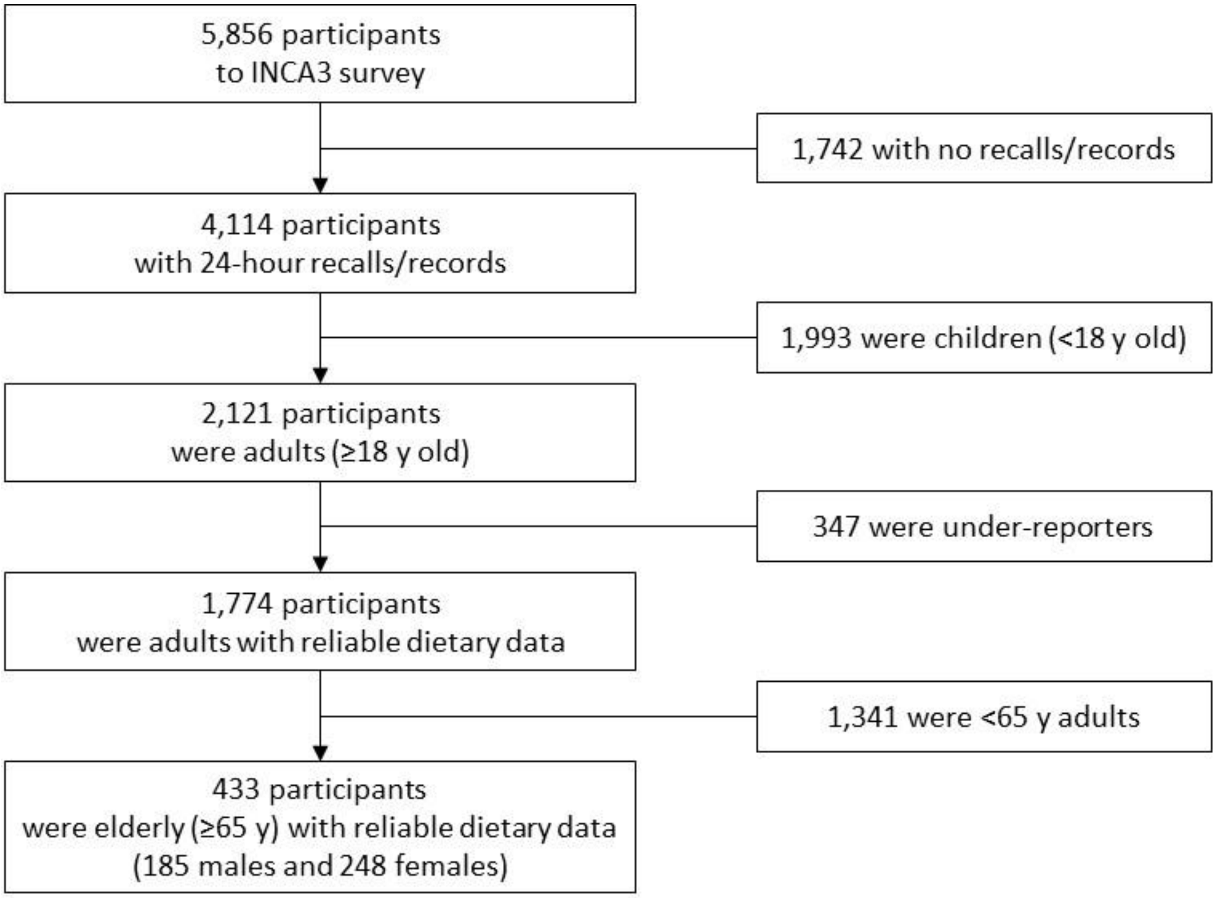
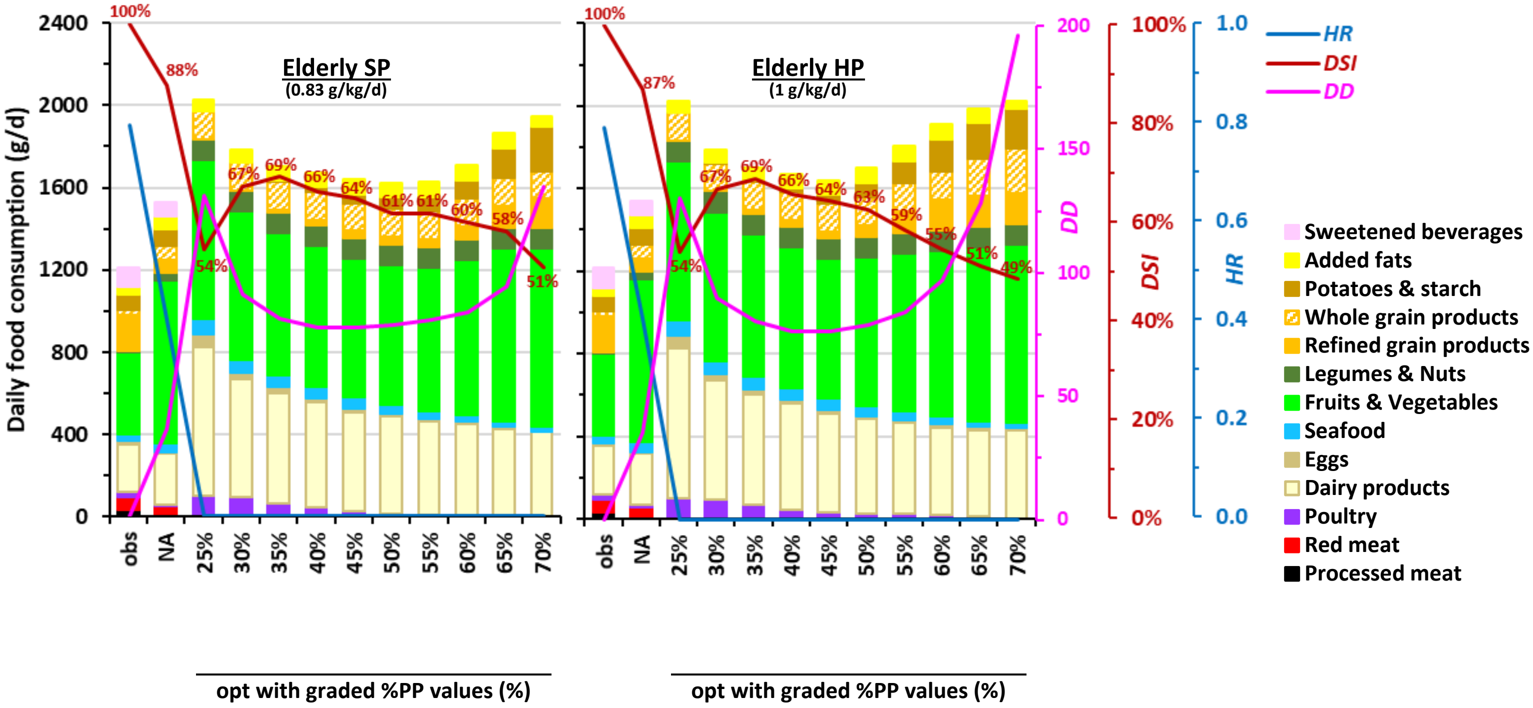
Contents

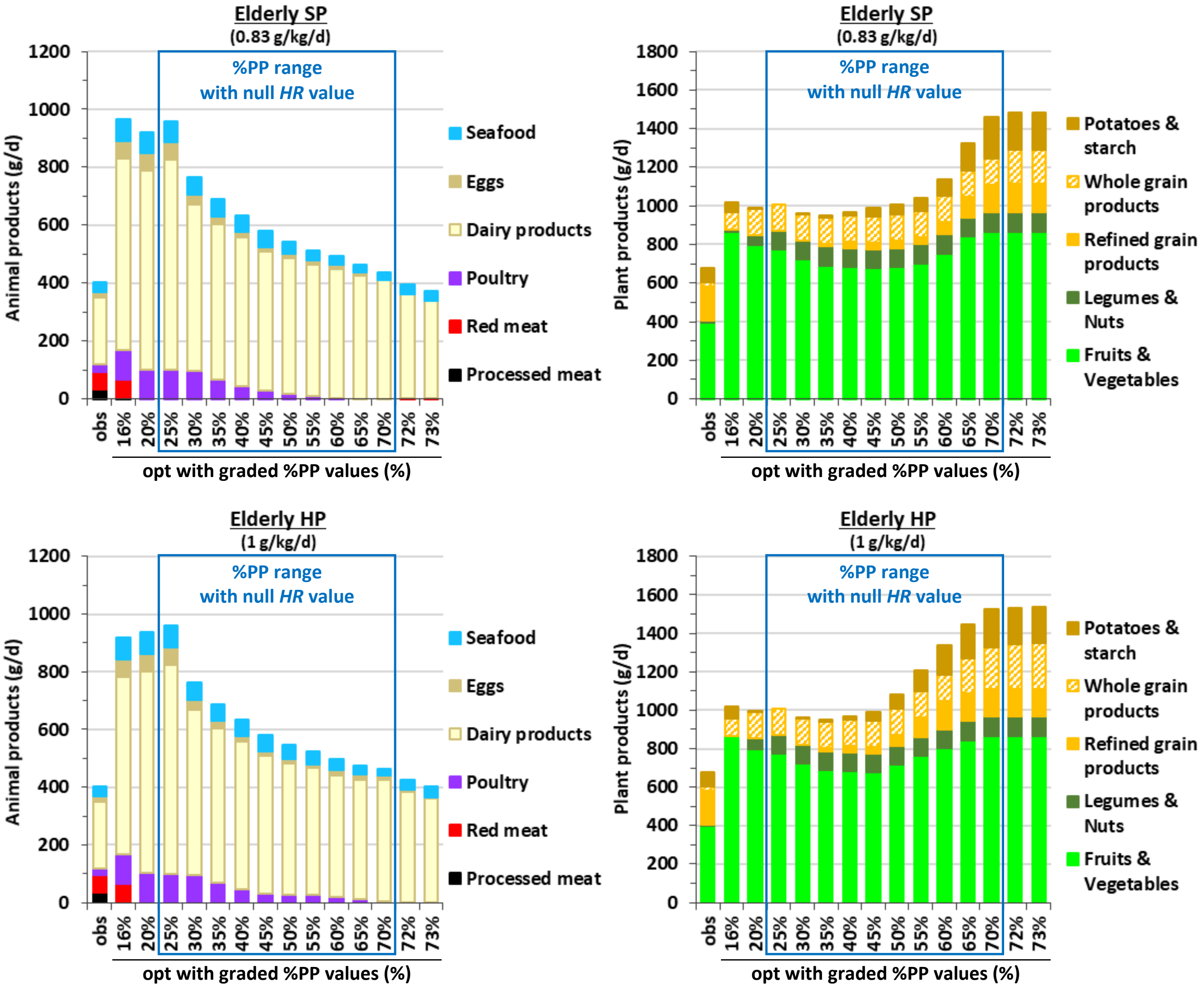


Supplemental Figure 1. Flow chart explaining the sampling of French participants from the third Individual and National Study on Food Consumption Survey (INCA3) for the present study.



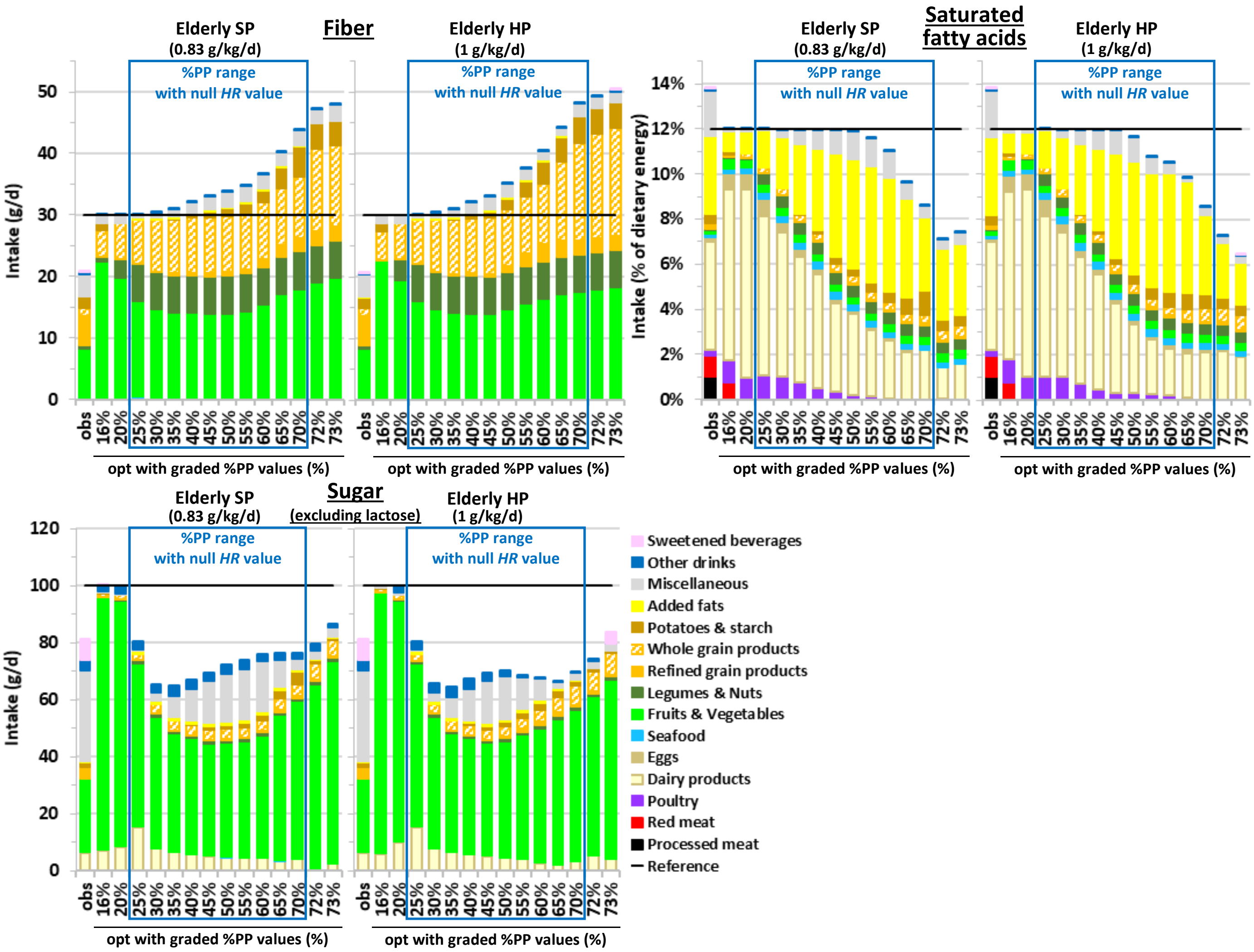
Supplemental Figure 2. Daily consumption of food categories in the observed diet (obs) and in the closest optimized diets being either nutrient-adequate only (NA) or both nutrient-adequate and fully healthy (opt with graded percentage of plant protein in the diet (%PP) value) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

Modeled diets were obtained by minimizing diet departure (*DD*) under nutritional and acceptability constraints only (NA diets), or with additional constraints ensuring a null long-term health risk (*HR*) and a fixed %PP value (optimized diets). To better illustrate the practical meaning of the *DD* values obtained, they were recalculated using a previously established metric that is more interpretable but less effective for guiding optimization: the diet similarity index (*DSI*). This index was calculated as the consumptions that remain common between the optimized and observed diets, expressed as a percentage of the observed consumptions (1). The bar charts represent the cumulative consumptions of food categories (black axis on the left) and the curves represent the *DD*, *DSI* and *HR* values (blue, red and pink axes on the right, respectively). For clarity, the 45 modeled food groups are not represented here but grouped into broader categories. The consumption of water, hot beverages, alcohol and miscellaneous foods are not shown for reasons of clarity. See Supplemental Table 1 for the detailed composition of food categories.



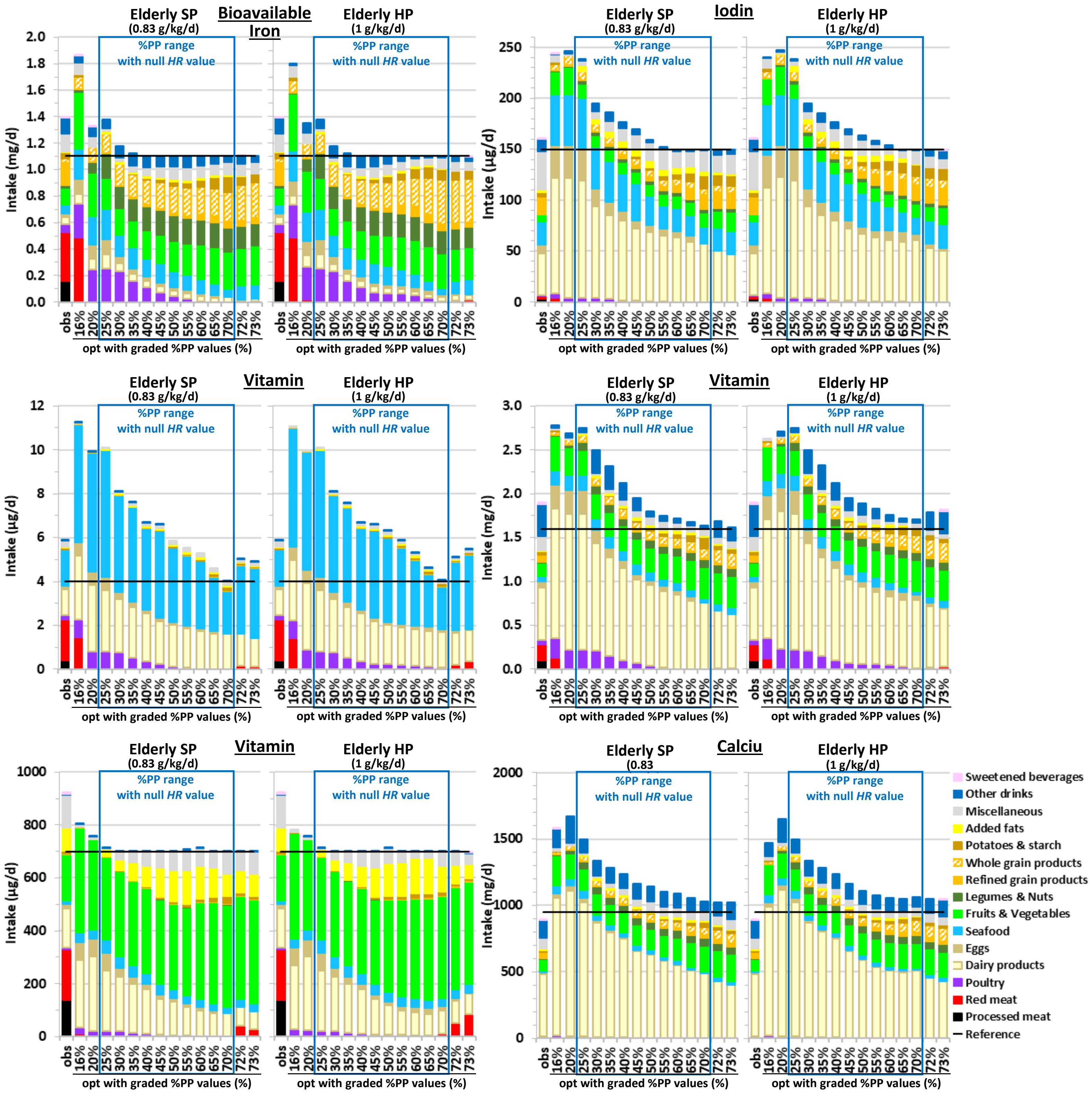
Supplemental Figure 3. Daily consumption of food categories in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (HR) under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

Results are reported for all the adequate %PP values that ensure nutrient adequacy, of which only the ~25%-70% range also ensure a null *HR* value. The bar charts represent the cumulative consumptions of the main animal-based (panels on left) or plant-based (panels on right) food categories. See Supplemental Table 1 for the detailed composition of food categories, and Supplemental Table 4 for the consumptions of food categories not shown here.



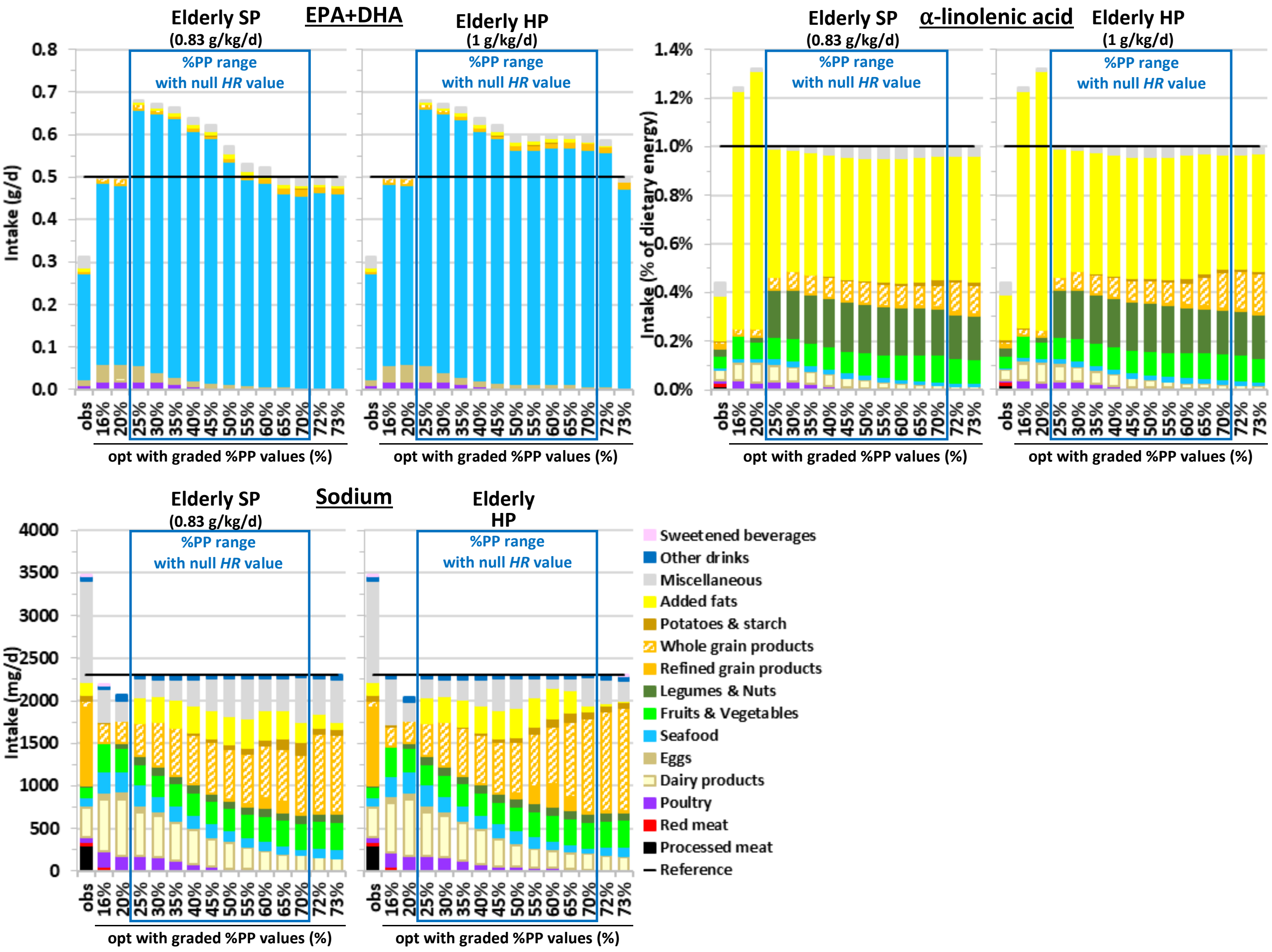
Supplemental Figure 4. Contribution of food categories to the intakes of nutrients that are limiting for a low plant protein percentage in the diet (%PP) in the observed diet (obs) and in the closest optimized (opt) diets minimizing long-term health risk (HR) under imposed %PP value in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

The results are reported for all adequate %PP values ensuring nutrient adequacy and model convergence, of which only the ~25%-70% range ensured a null *HR* value. The line represents the constraint for the selected nutrient (upper bound, except for fiber that is the lower bound). See Supplemental Table 1 for the detailed composition of food categories, and Supplemental Table 6 for the nutrient intakes not shown here.



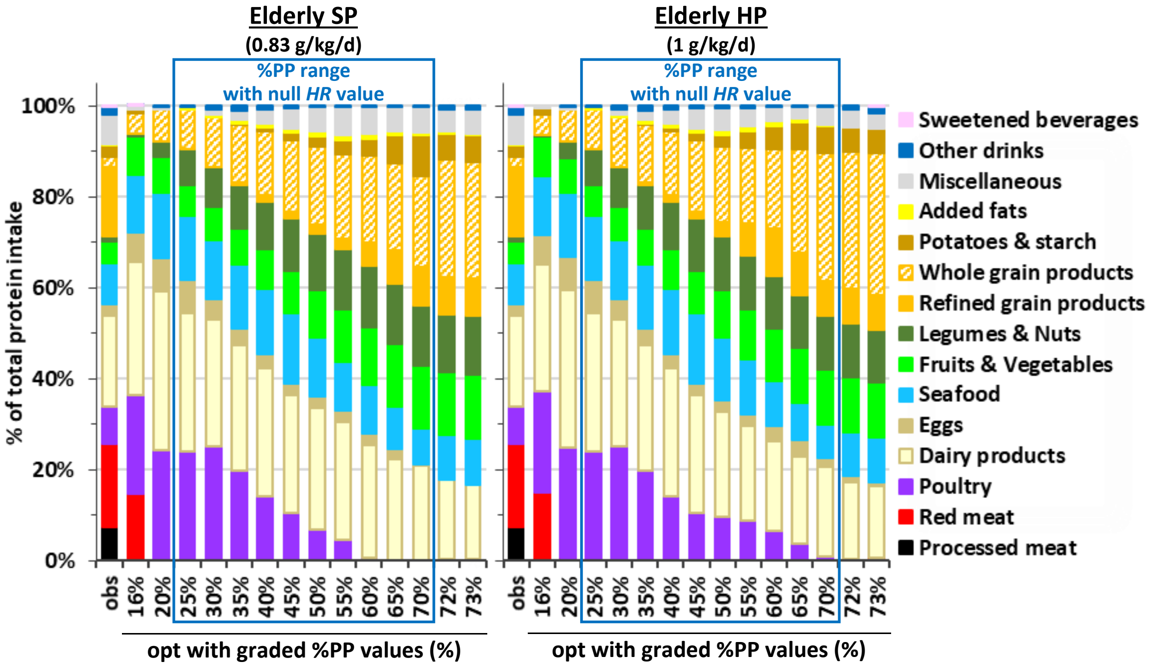
Supplemental Figure 5. Contribution of food categories to intakes of nutrients that are limiting for a high plant protein percentage in the diet (%PP) in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (HR) under imposed %PP value in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

The results are reported for all the adequate %PP values ensuring nutrient adequacy and model convergence, of which only the ~25%-70% range ensured a null *HR* value. The line represents the constraint for the selected nutrient (lower bound, except for sodium that is the upper bound). For bioavailable iron and vitamin A, constraints are represented as the mean between the constraint for males and females. For other nutrients, constraints are similar between sexes. See Table 1 for the detailed values of nutrient constraints, Supplemental Table 1 for the detailed composition of food categories, and Supplemental Table 6 for the nutrient intakes not shown here.



Supplemental Figure 5 (continued). Contribution of food categories to intakes of nutrients that are limiting for a high plant protein percentage in the diet (%PP) in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (HR) under imposed %PP value in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

The results are reported for all the adequate %PP values ensuring nutrient adequacy and model convergence, of which only the ~25%-70% range ensured a null *HR* value. The line represents the constraint for the selected nutrient (lower bound, except for sodium that is the upper bound). For bioavailable iron and vitamin A, constraints are represented as the mean between the constraint for males and females. For other nutrients, constraints are similar between sexes. See Table 1 for the detailed values of the nutrient constraints, Supplemental Table 1 for the detailed composition of food categories, and Supplemental Table 6 for the nutrient intakes not shown here.



Supplemental Figure 6. Relative contribution of food categories to protein intake (in % of total protein intake) in the observed diet (obs) and in the closest optimized diets (opt) minimizing long-term health risk (*HR*) under imposed percentage of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value.

Results are reported for all adequate %PP values ensuring nutrient adequacy and model convergence, of which only the ~25%-70% range ensured a null *HR* value. See Supplemental Table 1 for the detailed composition of food categories.

Supplemental Table 1. Food grouping: food groups and categories gathering food items consumed in the French INCA3 study.

Food category	Food groups (Number of food items per food group)
Processed meat	Processed meats (71)
Red meat	Beef and veal (40) Pork and other meats (39) Offal (19)
Poultry	Poultry (24)
Dairy products	Milk (15) Fresh natural dairy products (18) Fresh sweetened dairy products (39) Sweet milky desserts (22) Cheeses (98)
Eggs	Eggs and egg-based dishes (14)
Seafood	Oily fishes (32) Other fishes (55) Mollusks and crustaceans (21)
Fruit & vegetables	Vegetables (149) Fresh fruits (50) Dried fruits (9) Processed fruits: compotes and cooked fruits (13)
Legumes & nuts	Legumes (16) Nuts, seeds and oleaginous fruits (23)
Refined grain products	Bread and refined bakery products (36) Other refined starches (13)
Whole grain products	Wholemeal and semi-wholemeal bread and bakery products (15) Other complete and semi-complete starches (11)
Potatoes & starch	Starch-based products, sweet/fat processed (61) Salt/fat processed starch products (15) Potatoes and other tubers (20)
Added fats	Animal fats and assimilated fats (4) Butters and light butters (11) Vegetable fats rich in alpha-linoleic acid (4) Vegetable fats low in alpha-linoleic acid (24) Sauces and fresh creams (55)
Miscellaneous foods	Sweet products or Sweet and fatty products (198) Salt (6) Condiments (13) Aromatic herbs, Spices except salt (38) Soups (30) Bouillons (8) Substitutes of animal products (9) Other foods (14)
Sweetened beverages	Sweetened soda type drinks (45) Fruit juices (29)
Other drinks	Hot drinks (22) Drinking water (44) Alcoholic drinks (41)

Supplemental Table 2. Theoretical minimum-risk exposure level (TMREL) and disability-adjusted life-years (DALYs) values used in the optimization model in French elderly (≥65 y) males and females.

		TMREL[1] (g/d)		DALYs[2] (y)	
		Males	Females	Males	Females
Unhealthy foods	Red meat	0	0	73,642	78,188
	Processed meat	0	0	45,673	42,748
	Sweetened beverages	0	0	9,809	9,788
Healthy foods	Whole grains	151	122	108,661	90,608
	Fruit	326	265	50,029	38,119
	Legumes	95	78	48,483	37,982
	Vegetables	301	245	26,334	21,089
	Nuts & seeds	15	12	21,187	15,912
	Milk	431	351	18,617	15,287
	Sum			402,435	349,721

[1] According to the Global Burden of Diseases (GBD) 2019 study, the TMREL values are 0 g/d for red meat, processed meat and sweetened beverages, and 150, 325, 95, 300, 14.5 and 430 g/d, respectively, for whole cereal products, fruit, legumes, vegetables, nuts and seeds, and milk (2). As these TMREL values are overall estimates corresponding to a mean energy intake of 2,300 kcal (2), we used sex-specific values adapted to the particular energy intake of males and females in our French elderly population (centered at the energy requirements of 2,308 kcal/d and 1,878 kcal/d in ≥65 y males and females, respectively (3)).

[2] We used the corresponding (2019) French sex-specific DALYs values associated with excessive/insufficient consumption of unhealthy/healthy foods in the age group of our elderly population, available from the Global Health Data Exchange website (http://ghdx.healthdata.org/gbd-results-tool).

Supplemental Table 3. Dietary and acceptability constraints applied to the consumption of each food group in the optimization model in French elderly (≥65 y) males and females.

Food groups	Males			Females		
	Lower consumption limit (g/d)	Prevailing diet (g/d)	Upper consumption limit (g/d)	Lower consumption limit (g/d)[1]	Prevailing diet (g/d)	Upper consumption limit (g/d)
Unhealthy food groups (dietary constraints)[1]						
Beef and veal	0	38	71*	0	22	71*
Pork and other meats	0	28		0	23	
Offal	0	4		0	5	
Processed meats	0	39	25	0	28	25
Sweetened soda type beverages	0	57	263*	0	26	263*
Fruit juices	0	62		0	44	
Other food groups (acceptability constraints)[2]						
Vegetables	43	199	442	20	180	404
Fresh fruits	0	206	460*	0	168	426*
Dried fruits	0	2		0	2	
Processed fruits: compotes and cooked fruits	0	10		0	27	
Nuts, seeds and oleaginous fruits[3]	0	3	15	0	2	12
Bread and refined bakery products	40	170	422*	28	97	280*
Complete and semi-complete bread and bakery products		14			19	
Other refined starches	0	53	161*	0	32	131*
Other complete and semi-complete starches	0	3		0	5	
Starch-based products, sweet/fat processed	0	7	40	0	8	54
Salt/fat processed starch products	0	1	11	0	1	11
Potatoes and other tubers	0	71	196	0	64	185
Legumes[3]	0	8	95	0	5	78
Poultry	0	26	106	0	25	94
Oily fishes[4]	0	7	39* (26 for oily)	0	7	39* (26 for oily)
Other fishes[4]	0	21		0	23	
Mollusks and crustaceans	0	6	31	0	5	39
Eggs and egg-based dishes	0	17	69	0	16	54
Milk[3]	0	91	431	0	82	351
Fresh natural dairy products	0	45	153	0	75	277
Fresh sweetened dairy products	0	38	125	0	33	127
Sweet milky desserts	0	6	29	0	3	22
Cheeses	0	54	114	0	37	99
Animal fats and assimilated fats[5]	0	0	0	0	0	0
Butters and light butters	0	11	39	0	9	26
Vegetable fats rich in ALA	0	0	36*	0	1	29*
Vegetable fats low in ALA	0	12		0	10	
Sauces and fresh creams	0	20	59	0	16	43
Sweet products or Sweet and fatty products	1	82	283	1	72	172
Salt	0	1	3	0	1	3
Condiments	0	3	19	0	1	9
Aromatic herbs, Spices except salt	0	1	6	0	2	6
Soups	0	180	553	0	208	580
Bouillons	0	9	34	0	22	208
Other foods[5]	3	3	3	2	2	2
Substitutes of animal products[6]	0	3	29	0	6	29
Drinking waters	0	627	-	74	705	-
Hot drinks[7]	0	467	467	0	533	533
Alcoholic drinks[7]	0	276	276	0	67	67
Liquids (sum of Milk, Drinking waters, Sweetened soda type drinks, Fruit juices, Hot drinks, Soups and Bouillons)	612	1,493	2,630	781	1,620	2,485

*These upper consumption limits corresponded to coupled constraints for the groups mentioned (e.g., 71 g/d is the maximum intake for the sum of beef and veal, pork and other meats and offal).

[1] In the dietary constraints, upper bounds were applied to the food groups for which consumption needed to be limited, in line with French dietary guidelines (7).

[2] In the acceptability constraints, lower and upper consumption limits generally represented the 5th and 95th percentiles of consumption, respectively, of the food group in ≥65 y males and females, calculated using data from the third Individual and National Study on Food Consumption French Survey (INCA3), n=433 (185 males, 248 females).

[3] For nuts and seeds, legumes and milk, the upper consumption limits in each sex were raised to their theoretical minimum-risk exposure level (TMREL) values as their 95th percentiles of consumption values were slightly lower (14 g/day and 11 g/day for nuts & seeds, 67 g/day and 34 g/day for legumes and 419 g/day and 341 g/day for milk in males and females, respectively).

[4] For fish, in order to take account of sustainable fish consumption and to limit exposure to contaminants, and in line with French dietary guidelines on fish consumption (8), total fish consumption was limited to 39 g/day and oily fish consumption was limited to 26 g/day.

[5] For animal fats and assimilated fats and other foods, consumptions were imposed as constant and equal to the observed intakes in the modeled diets.

[6] For animal product substitutes, due to the very low value of the 95th percentile of consumption in men, their upper bound was set at the corresponding value in females.

[7] For hot and alcoholic drinks, the upper bound was set at the prevailing consumption level.

Supplemental Table 4. Energy intake and food category consumption in observed (Obs) and modeled diets obtained by minimizing long-term health risk and diet departure under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value[1].

	Obs diet	**Modeled diets**																									
		SP (0.83 g/kg/d)													**HP (1 g/kg/d)**												
%PP	**33%**	**16%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**	**55%**	**60%**	**65%**	**70%**	**73%**	**16%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**	**55%**	**60%**	**65%**	**70%**	**73%**
Energy intake (kcal/day)	2,139	2,198	2,197	2,083	1,992	1,989	1,989	1,989	1,989	1,996	2,034	2,083	2,124	2,198	2,082	2,197	2,083	1,992	1,990	1,989	1,989	1,992	2,036	2,112	2,159	2,198	2,198
Food category consumption (g/day)[2]:																											
Processed meat	34	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Red meat	60	66	0	0	0	0	0	0	0	0	0	0	0	1	66	3	0	0	0	0	0	0	0	0	0	0	2
Poultry	25	100	100	100	95	67	45	30	18	11	2	0	0	0	100	100	100	95	67	45	30	27	25	20	12	2	0
Dairy products	232	663	687	724	574	536	514	480	469	454	448	424	412	338	617	699	724	574	536	514	480	457	440	422	414	424	359
Milk	87	391	391	391	391	391	391	391	391	391	391	391	391	326	391	391	391	391	391	391	391	391	391	391	391	391	340
Eggs	16	61	61	61	34	26	20	15	13	12	12	12	0	0	61	61	61	34	26	20	15	14	14	19	21	13	5
Seafood	35	74	74	74	61	60	55	56	43	34	33	28	24	33	74	74	74	61	60	55	56	49	43	35	28	25	35
Oily fishes	7	9	9	17	20	20	20	19	19	19	19	19	19	18	9	9	17	20	20	20	19	19	20	22	23	24	18
Other fishes	22	30	30	22	19	19	19	18	9	0	0	0	0	0	30	30	22	19	19	19	18	11	7	2	0	0	0
Mollusks & crustaceans	6	35	35	35	22	21	16	19	15	15	14	10	5	15	35	35	35	22	21	16	19	19	16	11	5	1	17
Fruit & Vegetables	397	866	798	772	722	689	682	676	682	700	752	841	866	866	863	800	772	722	689	683	677	717	761	801	843	866	866
Fruit	207	443	443	443	371	330	318	313	318	325	338	418	443	443	440	443	443	371	329	319	314	319	344	378	419	443	443
Vegetables	190	423	355	329	351	359	364	363	364	376	414	423	423	423	423	357	329	351	359	364	363	398	417	423	423	423	423
Legumes & Nuts	9	10	50	100	100	100	100	100	100	100	100	100	100	100	0	55	100	100	100	100	100	100	100	100	100	100	100
Legumes	6	10	49	86	86	86	86	86	86	86	86	86	86	86	0	54	86	86	86	86	86	86	86	86	86	86	86
Nuts	2	0	1	13	13	13	13	13	13	13	13	13	13	13	0	0	13	13	13	13	13	13	13	13	13	13	13
Refined grain products	176	0	0	0	0	16	29	32	36	38	64	103	143	146	0	0	0	0	16	29	32	56	104	146	148	146	146
Whole grain products	21	90	136	137	137	137	137	137	137	137	137	137	137	178	94	136	137	137	137	137	137	137	137	139	178	215	237
Potatoes & starch	76	52	0	0	2	7	21	44	54	68	84	145	213	191	64	0	0	2	8	21	44	73	107	153	177	197	191
Added fats	40	28	29	57	61	65	67	72	73	75	76	72	53	38	26	29	57	61	65	67	72	73	74	76	65	35	20
Miscellaneous foods	298	31	40	11	59	94	124	149	177	193	163	157	202	195	41	39	11	59	93	124	149	149	110	71	71	136	105
Sweetened beverages	94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45
Other drinks	1,337	1,087	1,484	828	1,093	1,098	967	924	912	901	872	784	586	1,130	741	1,305	829	1,094	1,102	965	924	865	794	743	687	600	1,161
Total of solid foods[3]	1,419	1,651	1,584	1,645	1,454	1,406	1,403	1,400	1,411	1,431	1,480	1,628	1,759	1,759	1,615	1,605	1,645	1,454	1,406	1,404	1,401	1,461	1,524	1,591	1,666	1,768	1,726
Relative changes compared to observed diet (%)[2]:																											
Processed meat		-98	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100
Red meat		11	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-99	11	-95	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-97
Poultry		294	294	294	276	165	75	19	-31	-57	-94	-100	-100	-100	294	294	294	276	165	76	20	7	-1	-21	-54	-91	-100
Dairy products		185	196	212	147	131	121	106	102	95	93	83	77	45	165	201	212	147	131	121	106	97	89	82	78	82	55
Milk		351	351	351	351	351	351	351	351	351	351	351	351	276	351	351	351	351	351	351	351	351	351	351	351	351	292
Eggs		277	277	277	107	61	20	-7	-20	-24	-25	-28	-99	-100	277	277	277	107	61	20	-7	-14	-12	16	26	-22	-69
Seafood		113	113	113	76	72	59	61	25	-2	-4	-18	-31	-5	113	113	113	76	72	59	60	42	25	0	-18	-27	0
Oily fishes		29	25	148	189	191	192	182	179	175	175	172	184	160	29	25	148	189	191	192	182	182	199	222	239	250	161
Other fishes		36	37	0	-13	-14	-14	-20	-57	-100	-100	-100	-100	-100	36	37	0	-13	-14	-14	-20	-48	-69	-93	-100	-100	-100
Mollusks & crustaceans		516	516	516	289	265	183	230	160	170	154	72	-19	167	516	516	516	288	263	183	230	226	183	94	-6	-77	196
Fruit & Vegetables		118	101	95	82	74	72	70	72	77	89	112	118	118	117	102	95	82	74	72	71	81	92	102	112	118	118
Fruit		114	114	114	79	59	54	51	54	57	63	102	114	114	112	114	114	79	59	54	51	54	66	82	102	114	114
Vegetables		123	87	74	85	89	92	92	92	98	118	123	123	123	123	88	74	85	90	92	92	110	120	123	123	123	123
Legumes & Nuts		19	473	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	-98	532	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052	1,052
Legumes		63	672	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	-98	760	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267	1,267
Nuts		-100	-67	475	475	475	475	475	475	475	475	475	475	475	-100	-81	475	475	475	475	475	475	475	475	475	475	475
Refined grain products		-100	-100	-100	-100	-91	-84	-82	-80	-78	-63	-42	-19	-17	-100	-100	-100	-100	-91	-83	-82	-68	-41	-17	-16	-17	-17
Whole grain products		335	562	563	563	563	563	563	563	563	563	563	563	766	358	560	563	563	563	563	563	563	563	574	764	943	1,050
Potatoes & starch		-32	-100	-100	-97	-90	-73	-43	-29	-11	10	90	179	150	-16	-100	-100	-97	-89	-73	-43	-4	40	100	132	158	150
Added fats		-30	-26	44	54	64	71	81	85	89	91	82	33	-4	-35	-26	44	54	65	71	81	84	87	92	64	-12	-49
Miscellaneous foods		-90	-87	-96	-80	-68	-58	-50	-41	-35	-45	-47	-32	-35	-86	-87	-96	-80	-69	-58	-50	-50	-63	-76	-76	-54	-65
Sweetened beverages		-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-100	-52
Other drinks		-19	11	-38	-18	-18	-28	-31	-32	-33	-35	-41	-56	-15	-45	-2	-38	-18	-18	-28	-31	-35	-41	-44	-49	-55	-13
Total of solid foods[3]		16	12	16	2	-1	-1	-1	-1	1	4	15	24	24	14	13	16	2	-1	-1	-1	3	7	12	17	25	22

[1] Observed data from the third Individual and National Study on Food Consumption French Survey (INCA3), n=433 (185 ≥65y males, 248 ≥65y females).

[2] For clarity, the 45 modeled food groups are not represented here but grouped into broader categories (see Supplemental Table 1 for details on food grouping). Consumption data on a black background are those having been zeroed, and consumption data on a grey background are those having been raised to their maximal values, as set in the acceptability constraints (see Supplemental Table 3 for details on these consumption limits).

[3] Sum of all food consumptions excluding milk, sweetened beverages, and other drinks.

Supplemental Table 5. Conflicts identified between health and nutritional adequacy or dietary habits as the percentage of plant protein (%PP) in the diet decrease toward its minimal nutrient-adequate value in French ≥65 y elderly by sex[1].

		Elderly males	Elderly females
	Minimal nutrient-adequate %PP value	15%	16%
Conflicts with nutritional adequacy (nutrient and total energy intakes)	Fiber	0.562	0.632
	Sugar excluding lactose	-0.232	-0.201
	Saturated fatty acids	-0.186	-0.090
	Linoleic acid		0.021
	Total energy		-0.147
Conflicts with dietary habits (food consumption limits)	Poultry	-0.100	-0.075
	Red meat	-0.050	-0.032
	Milk	-0.049	-0.025
	Fish	-0.034	-0.028

[1] Results of the dual value analysis when minimizing the long-term health risk (*HR*) under all nutritional, dietary and acceptability constraints, in ≥65 y males and females with either a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value. The results given here are the conflicts identified at the minimal nutrient-adequate %PP value (see Table 2 for conflicts identified at its maximal value), and similar results were found regardless of the protein requirement considered (HP or SP). Non-null dual values are indicated for (i) the nutritional constraints (on nutrient and total energy intakes), allowing for the identification of nutrients becoming limiting as %PP decreases (i.e., nutritional issues), and (ii) the acceptability constraints (on food consumption limits), allowing for the identification of food groups whose consumption limits restrict the nutrient-adequate %PP range. The reported dual values have been standardized to represent the potential effect on *HR* of a 10% relaxation of the limiting bound, to classify the nutrients/foods from the most limiting (higher absolute value) to the least limiting (lowest absolute value). Limiting nutrients/foods have a positive (negative) dual value if their lower (upper) bound is limiting. Only nutrients with an active constraint (i.e., with a non-null dual value) are presented (i.e., for nutrients not presented in this table, dual values were always equal to zero, meaning that compliance with these constraints was not limiting).

Supplemental Table 6. Daily intakes of energy and nutrients in observed (Obs) and modeled diets obtained by minimizing long-term health risk and diet departure under imposed percentages of plant protein in the diet (%PP) in French ≥65 y elderly, considering a standard protein (SP, 0.83 g/kg/d) or high protein (HP, 1 g/kg/d) reference value[1,2].

		Obs	Modeled diets																									
		diet	SP (0.83 g/kg/d)													HP (1 g/kg/d)												
	%PP	33%	16%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	73%	16%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	73%
	Units (/day)																											
Energy intake	kcal	2,139	2,198	2,197	2,083	1,992	1,989	1,989	1,989	1,989	1,996	2,034	2,083	2,124	2,198	2,082	2,197	2,083	1,992	1,990	1,989	1,989	1,992	2,036	2,112	2,159	2,198	2,198
Vitamin A	µg	923	804	756	713	700	700	700	700	700	707	711	700	700	700	782	756	713	700	700	700	700	715	700	700	700	700	700
Thiamin (Vitamin B1)	µg/kcal	0.59	0.55	0.52	0.62	0.63	0.62	0.61	0.61	0.60	0.61	0.61	0.63	0.66	0.62	0.57	0.53	0.62	0.63	0.62	0.61	0.61	0.62	0.63	0.63	0.64	0.66	0.67
Riboflavin (Vitamin B2)	mg	1.90	2.78	2.69	2.75	2.50	2.32	2.12	1.96	1.80	1.75	1.72	1.68	1.64	1.62	2.63	2.71	2.75	2.50	2.32	2.12	1.96	1.89	1.83	1.76	1.72	1.71	1.82
Niacin (Vitamin B3)[3]	mg NE/kcal	0.016	0.020	0.017	0.018	0.019	0.017	0.015	0.014	0.012	0.011	0.011	0.011	0.012	0.012	0.020	0.017	0.018	0.019	0.017	0.015	0.014	0.014	0.013	0.013	0.012	0.012	0.013
Pantothenic acid (Vitamin B5)	mg	5.7	8.2	7.6	8.1	7.4	6.9	6.5	6.2	6.0	6.0	6.0	6.3	6.7	6.4	7.9	7.7	8.1	7.4	6.9	6.5	6.2	6.3	6.5	6.6	6.8	6.9	6.9
Vitamin B6	mg	1.8	2.5	2.0	2.0	1.9	1.8	1.7	1.7	1.7	1.7	1.7	1.9	2.1	2.1	2.4	2.0	2.0	1.9	1.8	1.7	1.7	1.7	1.8	1.9	2.0	2.1	2.1
Folate (Vitamin B9)	µg	331	449	448	493	465	458	455	452	451	457	476	505	526	518	428	453	493	465	458	455	452	469	485	501	519	537	537
Vitamin B12	µg	5.9	11.2	9.9	10.1	8.1	7.6	6.7	6.6	5.9	5.5	5.3	4.6	4.0	4.9	11.1	10.0	10.1	8.1	7.6	6.7	6.6	6.3	5.9	5.3	4.6	4.1	5.5
Vitamin C	mg	108	137	118	143	136	130	130	132	135	140	147	170	181	160	131	118	143	136	130	130	132	139	146	156	168	178	175
Vitamin D	µg	3.3	4.9	4.8	6.1	5.3	5.0	4.8	4.5	4.2	3.9	3.9	3.7	3.2	2.9	4.6	4.9	6.1	5.3	5.0	4.8	4.5	4.2	4.1	4.2	4.1	3.8	2.7
Vitamin E	mg	10	16	16	14	13	14	14	14	14	14	15	15	14	15	16	16	14	13	14	14	14	14	14	15	15	14	13
Vitamin K1	µg	148	323	303	234	234	235	239	239	242	249	267	281	297	326	328	304	234	234	235	239	239	256	266	273	283	299	316
Calcium	mg	896	1,580	1,668	1,497	1,337	1,285	1,239	1,161	1,141	1,102	1,091	1,058	1,032	1,024	1,467	1,647	1,497	1,337	1,285	1,239	1,160	1,113	1,074	1,057	1,052	1,064	1,048
Copper	mg	1.9	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.8	1.9	2.0	2.3	1.9	1.9	1.8	1.8	1.7	1.7	1.7	1.8	1.9	1.9	2.0	2.1	2.4
Bioavailable iron[4]	mg	1.40	1.86	1.33	1.38	1.18	1.12	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.80	1.35	1.38	1.18	1.12	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Oral iron	*mg*	*11*	*14*	*13*	*13*	*12*	*12*	*11*	*11*	*11*	*11*	*11*	*11*	*12*	*13*	*13*	*13*	*13*	*12*	*12*	*11*	*11*	*11*	*12*	*12*	*12*	*12*	*14*
Iron absorption	*%*	*13%*	*14%*	*10%*	*11%*	*10%*	*10%*	*10%*	*10%*	*11%*	*10%*	*10%*	*10%*	*9%*	*9%*	*14%*	*11%*	*11%*	*10%*	*10%*	*10%*	*10%*	*10%*	*10%*	*10%*	*10%*	*9%*	*9%*
Iodine	µg	161	244	246	238	195	186	177	169	159	152	150	150	150	150	239	247	238	195	186	177	169	163	159	154	150	150	150
Magnesium	mg	346	409	408	428	449	442	420	409	384	385	393	409	423	476	389	405	428	449	442	420	409	418	427	429	444	463	533
Manganese	mg	3.2	3.2	3.4	3.4	3.7	3.8	3.8	3.8	3.8	3.9	4.1	4.4	4.7	5.6	3.2	3.4	3.4	3.7	3.8	3.8	3.8	4.0	4.3	4.5	5.0	5.5	6.1
Phosphorus	mg	1,226	1,873	1,822	1,836	1,677	1,576	1,495	1,411	1,352	1,302	1,300	1,318	1,346	1,341	1,806	1,830	1,836	1,677	1,576	1,496	1,411	1,382	1,385	1,401	1,436	1,473	1,446
Potassium	mg	3,283	4,725	4,126	4,128	4,122	3,999	3,854	3,814	3,690	3,738	3,864	4,214	4,547	4,797	4,597	4,118	4,128	4,122	4,004	3,854	3,816	3,963	4,126	4,284	4,453	4,659	4,998
Selenium	µg	129	169	185	154	144	140	134	133	126	123	122	126	129	148	166	183	154	144	140	134	133	132	130	127	125	125	145
Sodium	mg	3,475	2,179	2,063	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,038	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300	2,300
Bioavailable zinc[4]	mg	3.34	4.33	3.97	3.86	3.59	3.40	3.16	2.96	2.79	2.65	2.57	2.44	2.36	2.45	4.21	3.97	3.86	3.59	3.40	3.16	2.96	2.83	2.73	2.65	2.58	2.54	2.60
Oral zinc	*mg*	*9.6*	*15.4*	*12.3*	*12.0*	*10.8*	*10.2*	*9.3*	*8.9*	*8.4*	*8.1*	*7.9*	*7.8*	*7.9*	*8.8*	*15.0*	*12.4*	*12.0*	*10.8*	*10.2*	*9.3*	*8.9*	*8.7*	*8.5*	*8.4*	*8.5*	*8.6*	*9.4*
Zinc absorption	*%*	*35%*	*28%*	*32%*	*33%*	*33%*	*34%*	*34%*	*34%*	*34%*	*33%*	*33%*	*31%*	*30%*	*28%*	*28%*	*32%*	*33%*	*33%*	*34%*	*34%*	*34%*	*33%*	*32%*	*32%*	*31%*	*30%*	*28%*
Water	g	2,394	2,654	2,992	2,419	2,514	2,472	2,336	2,288	2,288	2,296	2,300	2,342	2,250	2,704	2,290	2,834	2,419	2,515	2,474	2,335	2,289	2,283	2,257	2,250	2,253	2,250	2,745
Saturated fatty acids	% EI	14%	12%	12%	12%	12%	12%	12%	12%	12%	12%	11%	10%	9%	8%	12%	12%	12%	12%	12%	12%	12%	12%	11%	11%	10%	9%	7%
Atherogenic fatty acids	% EI	9%	8%	8%	8%	8%	8%	8%	8%	8%	8%	7%	7%	6%	5%	8%	8%	8%	8%	8%	8%	8%	7%	7%	7%	6%	6%	4%
Linoleic acid	% EI	3%	4%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	4%
α-linolenic acid	% EI	0.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
Linoleic / α-linolenic	-	6.9	3.5	3.3	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.6	4.6	3.5	3.3	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.9	4.6	4.2
EPA+DHA	g	0.32	0.50	0.50	0.68	0.68	0.67	0.64	0.63	0.57	0.53	0.52	0.50	0.50	0.50	0.50	0.50	0.68	0.68	0.67	0.64	0.62	0.60	0.60	0.60	0.60	0.60	0.50
Sugar (excluding lactose)	g	81	100	100	81	66	65	67	70	72	74	76	76	76	87	100	100	81	66	65	67	70	70	69	68	66	70	84
Protein[5]	g	84	121	108	109	99	90	83	76	70	65	64	64	65	67	117	108	109	99	90	83	76	74	74	74	74	74	74
Fiber	g	21	30	30	30	31	31	32	33	34	35	37	40	44	48	30	30	30	31	31	32	33	35	38	40	44	48	50

[1] Observed data from the third Individual and National Study on Food Consumption French Survey (INCA3), n=433 (185 ≥65y males, 248 ≥65y females).

[2] In the observed diets, the energy and nutrient intakes on a black background are those outside the range of reference values. In the modeled diets, the intakes on a grey background are those just equal to (one of) their reference values (i.e., equal to the lower or upper bounds of the nutritional constraints). No reference value or nutritional constraint was considered for vitamin D, as its reference value (15 µg/d) is known to be much too high to be reached through food intake alone (5, 7).

[3] 1 mg niacin equivalent (NE) is equal to 1 mg niacin or 60 mg tryptophan.

[4] For bioavailable iron and zinc, lower bounds were not based on current reference values but on lower threshold values ensuring ≤5% prevalence of deficiency.

[5] To account for the slightly lower average digestibility of plant protein, protein intake from plants was reduced by 5% when calculating total protein intake.

Atherogenic fatty acids are the sum of lauric, myristic and palmitic acids; DHA, docosahexaenoic acid; EI, energy intake; EPA, eicosapentaenoic acid.

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