How to best reshape diets to be healthier with lower or no ruminant meat, and implications for environmental pressures

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Highlights

- Nutritionally adequate and healthy diets without ruminant meat were identified
- Direct or gradual removal scenarios, including nutrient bioavailability, were studied.
- Ruminant and total red meat were replaced by poultry meat
- Fruit, vegetables and whole grain products also increased, leading to healthier diets
- Such modeled diets led to reductions in indicators of climate change and land use

Abstract

Shifts in dietary patterns are important for both health and the environment, and ruminant meat has been highlighted as a critical cornerstone in this respect. Here, nonlinear and multi-objective diet optimization based on the consumption of French adults (INCA3, n=1 125, 18-64 years old) have been used to model transitions towards nutritionally adequate and healthy dietary patterns under scenarios of either the direct removal or gradual reduction (in 10% steps) of ruminant meat, without or with preserving at best dietary habits, respectively. This has led to identify the nutritional issues when designing diets low in ruminant meat, and the dietary levers that make them nutritionally adequate and healthy. Overall, our main finding is that ruminant meat could readily be replaced by poultry. Such a gradual transition from ruminant meat to poultry should be accompanied by an in-depth restructuring to achieve a healthy diet, involving the early removal of processed meat and non-ruminant red meat and a gradual increase in healthy plant-based foods such as fruits and vegetables (reaching 800 g/d at the final step) and whole grain products (reaching 330 g/d). In terms of its expected environmental impacts, this transition would result in a gradual improvement in greenhouse gas emissions and land use (up to -29% and -36%, respectively), without changing cumulative energy demand but requiring an increase in water use (up to +47%). Finally, reducing ruminant meat forms part of a transitional feature that consists in replacing all red meat with poultry, which could result in healthy and nutritionally adequate dietary patterns aligned with reductions in greenhouse gas emissions.

Keywords: nutrition; healthy dietary pattern; diet optimization; ruminant meat reduction; environmental pressures; greenhouse gas emissions

Introduction

A reduction of environmental pressures and the revision of food systems is essential in our response to climate change (Campbell et al., 2017; Crippa et al., 2021). Livestock farming, particularly of ruminants, is a well-documented and significant contributor to food-related greenhouse gas emissions (GHGe) (Clune et al., 2017; Poore and Nemecek, 2018; Temme et al., 2015). Furthermore, food products associated with marked increases in disease risks – red and processed meats – are often associated with the most damaging environmental impacts that go beyond the potential ecosystem services offered by some livestock systems (Clark et al., 2019). Consistent evidence in the scientific literature (Fresán and Sabaté, 2019; Tilman and Clark, 2014), including systematic reviews (Hallström et al., 2015; Jarmul et al., 2020; Nelson et al., 2016), has indicated that a dietary pattern containing more plant-based foods (*e.g.*, fruits and vegetables, legumes, nuts, whole grain products) and less animal-based foods (especially red meat and dairy products) and total energy is both healthier and associated with lower pressures on the environment and natural resources. Most studies that have tried to identify sustainable diets have been based on either observed consumptions or food substitution scenarios (Auestad and Fulgoni, 2015; Perignon et al., 2016; van Dooren, 2018). Thus, these studies offer no assurance that the diets identified will be nutritionally adequate, i.e., provide enough of the substances that are needed in order to live and grow (Aleksandrowicz et al., 2016; Jones et al., 2016; Ridoutt et al., 2017). Mathematical optimization techniques can help to identify dietary patterns that will both improve nutrient adequacy and reduce environmental impacts (van Dooren, 2018; Wilson et al., 2019). In Western countries, part of the population has started to reduce, or is considering reducing, their consumption of animal products (and particularly meat) for environmental reasons (Allès et al., 2017; Lea et al., 2006). Average total meat intakes remain high in Europe at present, ranging from 75 g/d (Sweden) to 233 g/d (Germany) in adults (Cocking et al., 2020). Reducing

meat consumption would be entirely consistent with the results of some diet optimization studies (Kramer et al., 2017; Macdiarmid et al., 2012; Wilson et al., 2019). These studies tried to define diets with less environmental impact)(Barré et al., 2018; Kesse-Guyot et al., 2021). Because beef is by far the greatest contributor to greenhouse gas emissions, and climate change is among the most urgent environmental issues, reducing beef intake is on the agenda of numerous programs and is gaining in popularity as a strategy (*FAO*, 2021). However, few studies in the literature have evaluated how diets low in ruminant meat should be composed to render them nutritionally adequate and healthy in the context of a possible in-depth revision of the overall diet. Our first objective was to analyze the intrinsic importance of ruminant meat in the dietary-nutritional system. The second objective was to design diets involving a gradual reduction in ruminant meat consumption in order to identify the most salient nutritional problems and potential and effective dietary levers to overcome these issues during a transition of reduction towards total removal. Showing scenarios of gradual reduction, beyond scenarios of direct removal, is useful to show trajectories of dietary changes and their impacts. Finally, it was relevant to assess *a posteriori* the changes in environmental pressures that would be associated with the modeled diets (compared to observed diets), notably GHGe reductions and other environmental footprint indicators.

Methods and materials

Population and data assessment

This study used food consumption data on males (*n*=564, 18-64 years old) and pre-menopausal females (*n*=561, 18-54 years old) classified as non-under-reporters in the latest representative French national study (INCA3) that has been fully described elsewhere (Dubuisson et al., 2019) (see lifestyle and sociodemographic characteristics in Supplemental Figure 1). In brief, participants were selected according to a three-stage random sampling design (geographic units, dwellings, and then individuals) and the weight of individuals was calculated to improve representativeness by region, size of the urban area, occupation and socio-professional category of the household's reference person, household size,

education level, gender, and age. Food and beverages consumption data were collected over 3 non-consecutive days (2 weekdays and 1 weekend day) using the 24-hour recall method. Portion sizes consumed were estimated using a picture booklet of food portions and household measurements. Food items (*n*=1 533) were categorized into 48 food groups (Supplemental Table 2), for which the nutrient composition was detailed using the 2016 food composition database from the French Information Centre on Food Quality (CIQUAL, 2017). Mixed foods were broken down into ingredients and then gathered into food groups. Categorization within meats distinguished between poultry, beef and veal, pork and other non-ruminant meats, lamb, non-ruminant offal, ruminant offal, non-ruminant processed meat, ruminant processed meat. The nutrient content of each food group was calculated, for each gender, as the mean nutrient content of food items constituting the food group weighted by their mean intake in the considered gender (Dussiot et al., 2021).

The selected age ranges had previously been used to establish the nutritional references applied in the present study for each gender (*Anses*, 2021).

The French Life Cycle Assessment (LCA) Database for food items as consumed, AGRIBALYSE® 3.0.1 (*ADEME*, 2020), developed by the French Agency for the Environment and Energy Management (ADEME) were used to assess differences in environmental pressures (food-related GHGe, land use, water use, and cumulative energy demand) associated to the modeled diets (compared with observed diets). Overall, the method is based on the international LCA standards: ISO 14040 (*ISO*, 2006a) and ISO 14044 (*ISO*, 2006b), LEAP guidelines (*FAO*, 2022) and product environmental footprint (PEF) (*European Commission*, 2018). The perimeter is from the agricultural upstream to the finished product, by integrating from now on the French productions but also the imports for most of the food consumed in France. For the agricultural step, each inventory considers all the processes and inputs necessary for the production of an agricultural product within the boundaries of "cradle to field/workshop". The perimeter chosen is consistent with those defined in GESTIM (Gac et al., 2011) and ecoinvent® (Nemecek and Kägi, 2007). The SHARP database was used to complete some of the missing GHGe data (Mertens et al., 2019). Climate change (kg CO2 eq) referred to Global Warming Potentials over a 100-

year time horizon. The indicator is potential global warming due to emissions of greenhouse gases to air. The main contributors are generally the combustion of fossil fuels such as coal, oil, and natural gas (*IPCC*, 2013). The water footprint has been estimated using the guidelines of The Water Footprint Network (Aldaya et al., 2012). Water use (m3 water use related to local scarcity of water) is an indicator of the relative amount of water used, based on regionalized water scarcity factors estimated using blue water. Land occupation (m2) is a measure of the surface of terrestrial land involved in the production processes for a specific time duration. The methodological approach (representativeness, system definition and allocation) for the evaluation of environmental impact indicators has been extensively described elsewhere (*ADEME*, 2020; Colomb et al., 2015; Koch and Salou, 2014) (see summary in Supplemental Method 1).

Multi-criteria diet optimization

Modeled diets were identified by multi-criteria optimization under constraints, the aim being to obtain a maximal health profile with minimal deviation from the current diet, under the constraint of covering all gender-specific nutrient references and remaining within current consumption limits, where the decision variables were the daily consumption of food groups. Diet modeling and optimization was conducted using SAS software and its NLP algorithm for nonlinear optimization under the OPTMODEL procedure (SAS Institute®, Inc., Cary, NC, USA, version 9.4). As previously described (Dussiot et al., 2021), the health profile was estimated using the *Healthy Dietary Pattern* (*HDP*) criterion, which sets dietary objectives based on epidemiological studies that have evaluated associations between food group consumption and chronic disease risk (*Anses*, 2016) as used to prepare French dietary guidelines (Mariotti et al., 2021). It aimed to limit the consumption of red meat such as beef and veal, pork and other meats (including game, rabbit, and horse meat), and offal, and also that of processed meats and soft drinks, while promoting the consumption of vegetables, fruits and whole grain products. The *HDP* criterion was expressed and maximized as follows:

$$HDP = \sum_{i=1}^{3} \left[\frac{Opt(i)}{P95(i)}\right] - \sum_{j=1}^{3} \left[\frac{Opt(j)}{Max(j)}\right]$$

where i denotes the food groups to be increased (vegetables, fruits, and whole grain products), j denotes the food groups to be decreased (red meat, processed meat and soft drinks), Opt(i) and Opt(j) are the gender-specific optimized intakes of food groups i and j, respectively (in g/d), P95(i) is the current 95th gender-specific percentile intake of food group i (in g/d), and Max(j) is the upper limit of intake for food group j (in g/d). The upper limit of intakes for red meat, processed meat and soft drinks were 71, 25, and 263 g/d, respectively, as defined by the French Agency for Food, Environmental, and Occupational Health Safety (ANSES) (Mariotti et al., 2021).

To also evaluate how the modeled diets deviated from current diets, the *Diet Departure* (*DD*) criterion was used in order to account for dietary inertia (Kramer et al., 2018). The *DD* criterion was expressed and minimized as follows:

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

where k is the number of food groups, Obs(k) and Opt(k) are the observed and optimized gender-specific consumptions of food group k (in g/d), respectively, standardized by dividing by SD(k), the current gender-specific standard deviation of the consumption of food group k. At each step of the gradual reduction in ruminant meat consumption, *DD* was calculated with reference to consumption at the previous step, so that only efforts made progressively throughout the transition would be considered.

As some food groups were considered to be more easily substitutable, they were grouped together in *DD* so that their substitutions would not be weighted in *DD*. Such non-penalized substitutions were between different kinds of fruits (fresh/dried/processed), breads (refined/whole grain), other starch-based products (refined/whole grain), vegetable fats (low/high in α-linolenic acid), meat (poultry/red meat, excluding offal), soft drinks (drinks with added sugar/fruit juices), fish (oily/lean), fresh dairy products (natural/sweetened), and soups/bouillons.

The optimization procedure consisted in maximizing *HDP* while minimizing *DD* without specific weighting (1:1), as previously performed by us (Dussiot et al., 2021) and before that by the ANSES (Mariotti et al., 2021).

Nutritional and acceptability constraints

Using a set of nutritional constraints related to 33 nutrients (Supplemental Table 3), nutritionally adequate modeled diets were identified. These gender-dependent constraints with lower and/or upper bounds were based on all the latest reference values from ANSES (*Anses*, 2021). The reference values for nutrients comprise different types of values. One type is the "recommended dietary allowance" (or "population reference intake"), which is the value that covers the nutritional requirement of ~98% of the population. Nutritional requirements are based on experimental estimates in human studies using various criteria (such as metabolic, physiological, or losses/balance estimates) reviewed by expert committees. Another type of value is the "adequate intake", as a default value, which stands for a nutrient intake that appears associated with adequacy at the population level, based on epidemiological relations, where these have been shown. Expert committees from health organizations have reported in details on nutrient reference value, such as Anses, which relied on other expert reviews such as those of Efsa (*Anses*, 2021). One exception was vitamin D, for which no lower constraint was set because the reference value is known to be far too high to be reached in diet optimization (Dussiot et al., 2021; Mariotti et al., 2021). Total energy intake was also constrained at within ±5% of the estimated mean energy requirement of French adults.

To account for the lower digestibility of plant proteins, a 5% penalty was applied to protein intake from plant protein food items, as previously described (de Gavelle et al., 2018). For iron and zinc, the reference values were based on bioavailable iron and zinc calculated from dietary intakes and the equations available regarding their absorption (Armah et al., 2013; Hallberg and Hulthén, 2000; Miller et al., 2007)(Supplemental Method 2). Regarding the nutrient constraints for bioavailable iron and zinc, it was appropriate to use threshold values lower than the current reference values, corresponding to a deficiency prevalence of 5% in each gender (Supplemental Table 3), because such flexibility would

enable the identification of diets being apparently healthier overall, with a better balance in terms of Disability Adjusted Life Years (DALYs) averted due to less chronic diseases despite a higher prevalence of iron-deficiency anemia (Dussiot et al., 2021). Flexibility was introduced by adding variables to the *HDP* and *DD* terms of the objective function goal that would minimize any violation of the relaxed constraints related to bioavailable iron and zinc.

Furthermore, acceptability constraints were used to maintain the food groups consumption in the modelled diet within the observed, gender-specific range (Supplemental Table 4). The acceptability constraints included lower and upper values corresponding to the 5^{th} or 95^{th} gender-specific percentiles of consumption for all food groups, except those with an upper limit set as a dietary constraint (red meat, processed meat, soft drinks, total fish, and oily fish). In the same way as for the *DD* criterion, the most substitutable food groups in the acceptability constraints (see above) were grouped in order to define their lower and upper bounds as the 5^{th} or 95^{th} gender-specific percentiles of their total consumption. Some dietary constraints were also applied to the food groups included in the *HDP* criterion whose consumption was to be reduced: red meat (beef and veal/pork and other meats/offal), processed meat and soft drinks (sugar-sweetened beverages and fruit juice) were limited to the maximum values used in the *HDP* criterion of 71 g/d, 25 g/d, and 263 g/d, respectively (Mariotti et al., 2021). Moreover, in order to take account of French dietary guidelines on fish consumption (*Anses*, 2008), two additional constraints were added in order to limit total fish consumption to 39 g/d and oily fish consumption to 26 g/d.

Analyzing the optimization solutions led to estimate the dual values associated with each constraint, *i.e.*, the potential gain in the objective function that would result from relaxing the limiting bound of the considered constraint by one unit. All constraints were standardized on the value of their limiting bounds, so that the standardized dual values (representing the effect of a 100% relaxation of the limiting bound) could be compared numerically with each other, and the limiting constraints for nutrient and food group intakes could be classified from the most to the least limiting, as previously explained (Dussiot et al., 2021).

Diet optimization scenarios

A preliminary optimization model consisted of maximizing the *HDP* criterion only, without forcing a reduction in ruminant meat (direct scenario). Then a multi-criteria optimization on both *HDP* and *DD* was used to model a gradual transition towards diets containing less and less ruminant meat (as a gradual scenario involving iterative reductions of 10%). Both the direct and gradual scenarios included compliance with all nutritional, acceptability and dietary constraints. The gradual scenario included an additional constraint for a gradual reduction in total ruminant meat (beef and veal, lamb, ruminant offal, and ruminant processed meat), which was forced to be equal to 100%-x% of its previous value in a stepwise manner from x=0% to 100% (by successive steps of 10% increments in x, until the diets were devoid of ruminant meat). In addition, under the gradual scenario, a constraint for the non-degradation of *HDP* was added so that it could only increase or remain the same as the previous step. As a complementary analysis, the two scenarios (direct and gradual) were run again while adding a coproduction constraint linking ruminant meat and dairy products, by considering that 10 g of beef corresponded to 1 L milk, 1 L milk to 1 kg fresh dairy products and 8 L milk to 1 kg cheese, as previously described (Kesse-Guyot et al., 2021).

Results

Direct optimization scenario

In the observed INCA3 diets, total and ruminant meat consumption differed by gender and averaged 132 g/d and 46 g/d, respectively. Under the direct scenario (optimizing *HDP* only without a specific constraint for ruminant meat reduction, and under nutritional and acceptability constraints only), ruminant meat was removed and replaced by poultry: completely in males and almost completely in females (-93%) (**Figure 1**). This meat substitution contributed to improving the *HDP* between the modeled and observed diets (-2.5 to +2.9 on average for both genders), together with concomitant increases in fruits (+191% to +219% depending on the gender) and vegetables (+128% to +142%), and the considerable replacement of refined grain products with whole grain products (Figure 1).

Compared to the increases in these plant-protein sources, the consumption of seafood and dairy products remained relatively stable (+24% to +77%, and +9% to +18%, respectively), but there had been an internal redistribution within seafood products (in favor of oily fish and shellfish/crustaceans). Egg consumption also increased (+336% to +409%).

Gradual optimization scenario

Under the gradual scenario (optimizing both *HDP* and *DD* under all the nutritional and acceptability constraints and the constraint for gradual reduction in ruminant meat), modeled diets could be identified at each step of ruminant meat reduction in both genders (**Figure 2** and Supplemental Tables 5, 6 and 7). Major dietary changes occurred very early (from the first step, to reach diets with full nutrient adequacy), then more gradually during the first half of the transition, before slowing down during the second half, with diets being much similar overall within a 50% to 100% reduction in ruminant meat (Figure 2).

The amount of total meat decreased at the first step (-26% to -34%, depending on gender, at the 10% ruminant meat reduction step compared to the observed diet) and then remained relatively constant throughout, at a relatively high amount (∼100g per day). There was an internal redistribution within meats, marked by a strong and early increase in poultry consumption by both males and females (+42 to +50% from the 10% ruminant meat reduction step), and drastic reductions or the removal of pork and other meats as well as processed meats (Supplemental Table 8). Meat intake consisted almost exclusively of poultry in much larger quantities than in the observed diets, as from the 20% ruminant meat reduction step. Regarding internal redistribution within ruminant meats, the consumption of mainly beef and veal was kept and then reduced as from the 10% reduction step, and ruminant offal was kept at a relatively high level compared to its observed consumption by both genders (Figure 2 and Supplemental Table 8).

The most notable improvements in the *HDP* criterion were achieved early in the transition and at low *DD* costs, as two-thirds of the potential *HDP* gain were achieved after only half of the total *DD* (Supplemental Figure 2). From the point where the *HDP*/*DD* yield was falling sharply, little additional

HDP gain was achieved by subsequent dietary changes that mainly consisted in a gradual reduction of ruminant meat consumption. The *HDP* criterion finally almost reached its maximum possible value, indicating that all unhealthy foods had been removed and all healthy foods had reached their maximum values defined in the acceptability constraints.

Impact of the beef-milk co-production constraint

Addition of the beef-milk co-production constraint had little influence on the results, regardless of the scenario considered (Supplemental Figures 3, 4 and 5). Indeed, the coproduction constraint was never active (*i.e.*, had no influence on the results) at any step in the transition among males, but became active in females from the 90% step and finally problematic at the 100% step where the model no longer converged (Supplemental Figures 4 and 5), in particular because the food vectors of calcium intake other than dairy products were no longer sufficient. More specifically, the coproduction constraint became limiting in females for a ruminant meat consumption of 4 g per day or less (data not shown).

Nutritional adequacy and changes in food group contributions to nutrient intakes throughout transition

Sodium, linoleic acid, α-linolenic acid, docosahexaenoic (DHA) and eicosapentaenoic (EPA) acids, and sugar (excluding lactose), which were excessively or insufficiently provided by the observed diets, rose to adequate intakes in all the modeled diets, but they were nevertheless identified as limiting nutrients (*i.e.*, maintaining their adequacy was costly for the objective criteria *HDP* and *DD)* in both genders in all modeled diets (**Table 1**). In addition, some nutrients with inadequate observed intakes were also identified as being limiting in the modeled diets in both genders but only during the first part of the transition, when ruminant meat intake was only partly reduced: vitamins A and C, iodine, saturated fatty acids, and fiber (Table 1 and Supplemental Figures 6, 7and 8). In terms of relative importance, sodium was always the most binding nutrient regardless of gender and the degree of ruminant meat reduction, often followed by that of sugar (excluding lactose) (Supplemental Table 9).

By contrast, B vitamins (especially B6 and B12), protein, selenium, bioavailable iron and zinc were never limiting, and their intakes were maintained above reference/target values throughout the transition to ruminant meat-free diets (Supplemental Table 3).

In the observed diet, ruminant meat contributed notably to the intakes of bioavailable iron (20-25%, depending on gender), vitamin B12 (20-25%), bioavailable zinc (19-25%), protein (11-15%), vitamin B6 (8-11%), vitamin A (4-5%), and selenium (2-3%). As consumed in the INCA3 survey, ruminant meat (and particularly ruminant offal) contained higher levels of these nutrients than other types of meat (Supplemental Table 10). Although small in absolute amounts, preserving ruminant offal mitigated the decrease in the contribution of red meat to adequate levels of vitamins A and B12 (**Figure 3**). Under the ruminant meat-free diets that were obtained at the last step of the transition, animal or plant-based food groups other than ruminant meat (mainly poultry, seafood, dairy products, eggs, fruit and vegetables and whole grain products) contributed to maintaining intakes above current reference/target values for selenium (82-96% higher than its reference value, depending on gender), vitamin B12 (64-67% higher), protein (59-63% higher), bioavailable zinc (43-81% higher), vitamin B6 (26-43% higher), bioavailable iron (13-33% higher) and vitamin A (2-4% higher) (Figure 3 and Supplemental Figure 8). Therefore, during the later steps of the transition marked by a marked reduction in ruminant meat, more than half of bioavailable iron and zinc were supplied by plant-based food groups, although the absorption of non-heme iron and zinc was hampered by the increase in phytate levels (due to the increase in whole grain products). For selenium and vitamins A and B6, gradual increases in plant food groups also helped to maintain adequate intakes until a ruminant meat-free diet was achieved (Figure 3 and Supplemental Figure 8).

Improvement in the environmental footprint of the modeled diets

Compared to observed diets, ruminant meat-free diets at the final transition step would emit fewer GHGe (-29% on average for both genders) and enable less land use (-36%), but would consume more water (+47%) with a slightly higher energy demand (+5%) (**Figure 4**).

Discussion

Because it was modeled in order to obtain the healthiest dietary pattern (using the *HDR* criterion), the direct scenario revealed that ruminant meat could be removed from the diet without jeopardizing nutritional adequacy. Under both scenarios, the direct removal or gradual reduction of ruminant meat involved the removal of red meat and its replacement with poultry (up to ∼100 g/d) alongside marked increases in fruits, vegetables and whole grain products. Such healthier modeled diets, virtually free of unhealthy foods and almost maximal in terms of healthy foods up to their acceptability limits, were associated with reductions of about one third in related GHGe (-29%) and land use (-36%) when compared to current diets.

More specifically, maximizing *HDR* directly without taking account of dietary inertia (direct scenario) led to identifying in both genders modeled diets containing no ruminant meat that were more nutritionally adequate than the observed diets. The modeled diets were relatively distant from current diets, and poultry was almost the only meat consumed (but three times more than observed levels). This scenario showed that ruminant meat could readily be removed when the diet was optimized based on a health objective only. As the observed diets were typical current Western diets rich in animal products and particularly meat (132 g/d), removing ruminant meat, and red meat more broadly, could have implications in terms of cultural acceptability (Dagevos, 2021; Tyszler et al., 2016). Here, the modeling of healthy dietary patterns by successive steps of a 10% reduction in ruminant meat enabled the analysis of a gradual departure from diets that preserved the best dietary habits in order to depict progressive attitudinal shifting. As an effect of the health criterion, non-ruminant red meat (pork and processed meat) was drastically reduced at a very early stage, and further meat redistribution then consisted in a gradual replacement of the remaining beef and veal with poultry. Within the red meat category, offal was largely maintained (-16% at the final step compared to the observed diet), indicating a nutritional leverage effect of offal, particularly because of its high vitamin A, iron, and zinc contents, as previously shown (Barré et al., 2018). Taken together, limiting nutrients proved to be not directly related to the contribution of red meat, and partial substitution with poultry

offered a solution. Indeed, poultry did not fully replace red meat in terms of quantity, and the final diets contained a quarter less meat overall.

Given that the reductions in red and processed meats were driven by the *HDP* criterion, it was expected that the modeled diets would favor poultry, which was in line with the literature which had shown that poultry is a healthier alternative to red and processed meats (Papier et al., 2021; Papp et al., 2021). Notably, during the first step of the gradual scenario, reducing red and processed meats in favor of poultry resulted in a lower and more adequate intake of saturated fatty acids (SFA) (-17% compared to the observed diet).

Reducing meat consumption and shifting primarily to poultry would be entirely consistent with some diets modeled during studies designed to define diets with concomitant human and environmental health benefits (Walker et al., 2019). In our study, ruminant meat-free modeled diets were associated with a ∼30% reduction in GHGe. This was in line with the literature which had shown lower GHGe levels with diets higher in plant-based foods (Chai et al., 2019; Clune et al., 2017; Jarmul et al., 2020), and reported ∼35% lower GHGe from ovolactovegetarian diets than most current omnivore diets (Fresán and Sabaté, 2019). Our findings should also be compared with the corpus of diet optimization studies that specifically explored potential GHGe reductions under nutritional constraints (Perignon et al., 2017; van Dooren, 2018; Wilson et al., 2019). However, as expected, the literature on modeling reductions in overall meat consumption (not just of a ruminant type) has indicated more marked GHGe effects (Chai et al., 2019; Ferrari et al., 2020; Tyszler et al., 2016). Using diet optimization, a French study concluded that moderate GHGe reductions (≤30 %) were compatible with nutritional adequacy and affordability, but the shift in food groups was limited to those required to meet nutrient reference values (Perignon et al., 2016) whereas in the present study the objective of a higher compliance with health-related dietary patterns was also included. A recent optimization study of Dutch dietary patterns showed that modeled diets involving no change in total meat consumption (but with reduced beef consumption offset by increased contributions from both poultry and pork) could be associated with a 50-60%

reduction in GHGe (Grasso et al., 2021). Starting from a high level of GHGe with the observed diet, it would have expected a greater reduction with the modeled diets than that found here. There could be several possible reasons for this, one being that environmental effects were here assessed *a posteriori* in an impact analysis, unlike the other studies where a reduction in GHGe was a direct goal or constraint of the optimization model. Thus in our study, the modeled diets used dietary levers on the health dimension, and some other emitting food groups markedly increased, such as poultry (+201% at the 100% step compared to the observed diet), fruits (+205%) and vegetables (+135%).

Finally, all environmental pressures (land use and cumulative energy demand) displayed similar patterns of change during the transition towards ruminant meat reduction, except for water use (Meier and Christen, 2013; Tom et al., 2016). The increase in water use along the reduction of ruminant meat plateaued at 50% reduction, as did the increase in fruit and vegetables in the dietary pattern. Therefore, increases in some food groups such as fruits and vegetables, considered as lumped groups, in the modeled diets may not meet all environmental requirements in a context of rising temperatures and drought, or where changes to agricultural practices are required.

Our study had certain strengths and limitations. In terms of its strengths, our multi-criteria approach to diet optimization considered a broad range of nutrients, including bioavailable iron and zinc, and the relative digestibility of protein. Our findings were also relatively generalizable to the Western context, as the study was based on observed diets in French adults with similar background intakes – although somewhat higher in meat – and similar reference values when compared to other Western countries (Mariotti et al., 2021). Using gradual scenarios of reduction also offers a precise analysis of the trajectory of changes and the impact of ruminant meat reduction on diet characteristics, which proved to be not always linear. Regarding the limitations, our results were closely dependent on the underlying model assumptions and parameterization (such as the definition of food groups and the acceptability values considered). The sample was taken from a representative survey and the sample size was large enough to offer good precision

regarding the initial diets and avoid the bias of a non-representative population structure; however, a larger sample size would have been useful to address the variability of dietary patterns in the population and study subgroups of populations that might be expected to offer some contrast, such as groups of different ages. The number of food groups also greatly influenced the model by smoothing the nutritional contents of the groups and thus masking any specific features of certain contributors within each group at a more detailed level. Potential influence of food grouping and the level of details in food subgroups within the food structure have been recognized in diet modeling research (Mariotti et al., 2021). However, a certain level of aggregation in the dietary structure (48 food groups were used here) is useful in representing the contribution of food groups to nutrient intake in accordance to the way the food subgroups are actually consumed. This limitation also applied to assessing the environmental impact of the diet; environmental data do not include all the externalities associated with foods such as indicators on biodiversity, and the LCAs were based on generic production methods that did not take account of any diversity of practices, being limited to the French consumption context. Lastly, the present findings can be generalized to other developed countries, which have rather similar background diets, but they are not readily transportable to developing countries, in terms of feasibility, inasmuch as it may represent a high departure from usual observed diets that are not secured enough by the simple acceptability constrains that have been used in this study and mostly concern western countries.

Conclusions

Taking ruminant meat as a cornerstone, this study has identified a route for diet modification that offers dual benefits regarding health and the environment. Using diet modeling, it was shown that ruminant meat could be removed completely to achieve healthy and nutritionally adequate diets. Our main findings are that ruminant meat could be simply replaced by poultry, as could other red meats. Such a reduction in ruminant meat consumption would be accompanied by an in-depth restructuring of the diet towards a healthy dietary pattern that would rapidly be devoid of processed meats and

non-ruminant red meat, and with a gradual increase in healthy, plant-based foods. This transition would also result in marked reduction (30%) in food-related GHGe, a factor which is often central to the rationale for reducing ruminant production. By addressing the cornerstone question of the place of beef in sustainable diets in high income countries, our study provides a clear and detailed analysis of beef alternatives in healthy diets modelled in proximity to prevailing diets, and a thorough assessment of the resulting expected changes in environmental pressures. To our view, this work makes an important contribution to a major topic in the field of food system sustainability.

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

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References

AGRIBALYSE 3.0, the French agricultural and food LCI database, methodology for food products (collective expertise report), 2020. . ADEME, Paris, France.

Aldaya, M.M., Chapagain, A.K., Hoekstra, A.Y., Mekonnen, M.M., 2012. The Water Footprint Assessment Manual, 0 ed. Routledge. https://doi.org/10.4324/9781849775526

Aleksandrowicz, L., Green, R., Joy, E.J.M., Smith, P., Haines, A., 2016. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. PLOS ONE 11. https://doi.org/10.1371/journal.pone.0165797

Allès, B., Baudry, J., Méjean, C., Touvier, M., Péneau, S., Hercberg, S., Kesse-Guyot, E., 2017. Comparison of Sociodemographic and Nutritional Characteristics between Self-Reported Vegetarians, Vegans, and Meat-Eaters from the NutriNet-Santé Study. Nutrients 9, 1023. https://doi.org/10.3390/nu9091023

AR5 Climate Change 2013: The Physical Science Basis — IPCC, 2013. . The Intergovernmental Panel on Climate Change (IPCC).

Armah, S.M., Carriquiry, A., Sullivan, D., Cook, J.D., Reddy, M.B., 2013. A Complete Diet-Based Algorithm for Predicting Nonheme Iron Absorption in Adults. The Journal of Nutrition 143, 1136–1140. https://doi.org/10.3945/jn.112.169904

Auestad, N., Fulgoni, V.L., 2015. What current literature tells us about sustainable diets: emerging research linking dietary patterns, environmental sustainability, and economics. Advances in Nutrition 6, 19–36. https://doi.org/10.3945/an.114.005694

Barré, T., Perignon, M., Gazan, R., Vieux, F., Micard, V., Amiot, M.-J., Darmon, N., 2018. Integrating nutrient bioavailability and co-production links when identifying sustainable diets: How low should we reduce meat consumption? PLOS ONE 13. https://doi.org/10.1371/journal.pone.0191767

Campbell, B., Beare, D., Bennett, E., Hall-Spencer, J., Ingram, J., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society 22. https://doi.org/10.5751/ES-09595-220408

CFS Voluntary Guidelines on Food Systems and Nutrition, 2021. . Food and Agriculture Organization of the United Nations, Roma, Italy.

Chai, B.C., van der Voort, J.R., Grofelnik, K., Eliasdottir, H.G., Klöss, I., Perez-Cueto, F.J.A., 2019. Which Diet Has the Least Environmental Impact on Our Planet? A Systematic Review of Vegan, Vegetarian and Omnivorous Diets. Sustainability 11, 4110. https://doi.org/10.3390/su11154110

CIQUAL, 2017. The ANSES-CIQUAL food composition table [WWW Document]. URL https://ciqual.anses.fr/# (accessed 6.22.21).

Clark, M.A., Springmann, M., Hill, J., Tilman, D., 2019. Multiple health and environmental impacts of foods. Proceedings of the National Academy of Sciences 116, 23357–23362. https://doi.org/10.1073/pnas.1906908116

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. Journal of Cleaner Production 140, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082

Cocking, C., Walton, J., Kehoe, L., Cashman, K., Flynn, A., 2020. The role of meat in the European diet: current state of knowledge on dietary recommendations, intakes and contribution to energy and nutrient intakes and status. Nutrition Reviews 33, 181–189. https://doi.org/10.1017/S0954422419000295

Colomb, V., Amar, S.A., Basset-Mens, C., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., Van Der Werf, H., 2015. AGRIBALYSE, the French LCI database for agricultural products: high quality data for producers and environmental labelling. OCL Oilseeds and fats crops and lipids 22, D104. https://doi.org/10.1051/ocl/20140047

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2, 198–209. https://doi.org/10.1038/s43016-021-00225-9

Dagevos, H., 2021. Finding flexitarians: Current studies on meat eaters and meat reducers. Trends in Food Science & Technology 114, 530–539. https://doi.org/10.1016/j.tifs.2021.06.021

de Gavelle, E., Huneau, J.-F., Mariotti, F., 2018. Patterns of Protein Food Intake Are Associated with Nutrient Adequacy in the General French Adult Population. Nutrients 10, 226. https://doi.org/10.3390/nu10020226

Dubuisson, C., Dufour, A., Carrillo, S., Drouillet-Pinard, P., Havard, S., Volatier, J.-L., 2019. The Third French Individual and National Food Consumption (INCA3) Survey 2014–2015: Method, design and participation rate in the framework of a European harmonization process. Public Health Nutrition 22, 584–600. https://doi.org/10.1017/S1368980018002896

Dussiot, A., Fouillet, H., Wang, J., Salomé, M., Huneau, J.-F., Kesse-Guyot, E., Mariotti, F., 2021. Modeled healthy eating patterns are largely constrained by currently estimated requirements for bioavailable iron and zinc—a diet optimization study in French adults. The American Journal of Clinical Nutrition. https://doi.org/10.1093/ajcn/nqab373

Ferrari, M., Benvenuti, L., Rossi, L., De Santis, A., Sette, S., Martone, D., Piccinelli, R., Le Donne, C., Leclercq, C., Turrini, A., 2020. Could Dietary Goals and Climate Change Mitigation Be Achieved Through Optimized Diet? The Experience of Modeling the National Food Consumption Data in Italy. Frontiers in Nutrition 7.

Fresán, U., Sabaté, J., 2019. Vegetarian Diets: Planetary Health and Its Alignment with Human Health. Advances in Nutrition 10, S380–S388. https://doi.org/10.1093/advances/nmz019

Gac, A., Cariolle, M., Deltour, L., Dollé, J.B., Espagnol, S., Flénet, F., Guingand, N., Lagadec, S., Gall, A.L., Lellahi, A., Malaval, C., Ponchant, P., Tailleur, A., 2011. GES'TIM – des apports pour l'évaluation environnementale des activités agricoles. Innovations Agronomiques 17, 83.

Grasso, A.C., Olthof, M.R., van Dooren, C., Broekema, R., Visser, M., Brouwer, I.A., 2021. Protein for a Healthy Future: How to Increase Protein Intake in an Environmentally Sustainable Way in Older Adults in the Netherlands. The Journal of Nutrition 151, 109–119. https://doi.org/10.1093/jn/nxaa322

Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs) - version 6.3., 2018. . European Commission.

Hallberg, L., Hulthén, L., 2000. Prediction of dietary iron absorption: an algorithm for calculating absorption and bioavailability of dietary iron. The American Journal of Clinical Nutrition 71, 1147–1160. https://doi.org/10.1093/ajcn/71.5.1147

Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2015. Environmental impact of dietary change: a systematic review. Journal of Cleaner Production 91, 1–11. https://doi.org/10.1016/j.jclepro.2014.12.008

ISO 14040. Management environnemental — Analyse du cycle de vie — Principes et cadre, 2006a.

ISO 14044. Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices, 2006b.

Jarmul, S., Dangour, A.D., Green, R., Liew, Z., Haines, A., Scheelbeek, P.F., 2020. Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of `sustainable diets'. Environmental Research Letters 15, 123014. https://doi.org/10.1088/1748-9326/abc2f7

Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., Shapiro, L.F., 2016. A Systematic Review of the Measurement of Sustainable Diets123. Adv Nutr 7, 641–664. https://doi.org/10.3945/an.115.011015

Kesse-Guyot, E., Rebouillat, P., Brunin, J., Langevin, B., Allès, B., Touvier, M., Hercberg, S., Fouillet, H., Huneau, J.-F., Mariotti, F., Lairon, D., Pointereau, P., Baudry, J., 2021. Environmental and nutritional analysis of the EAT-Lancet diet at the individual level: insights from the NutriNet-Santé study. Journal of Cleaner Production 296, 126555. https://doi.org/10.1016/j.jclepro.2021.126555

Koch, P., Salou, T., 2014. AGRIBALYSE®: Rapport Méthodologique – Version 1.1. ADEME, FRANCE.
Kramer, G.F., Tyszler, M., Veer, P.V., Blonk, H., 2017. Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. Public Health Nutrition 20, 1699–1709. https://doi.org/10.1017/S1368980017000349
Lea, E.J., Crawford, D., Worsley, A., 2006. Consumers' readiness to eat a plant-based diet. European Journal of Clinical Nutrition 60, 342–351. https://doi.org/10.1038/sj.ejcn.1602320
Livestock Environmental Assessment and Performance (LEAP) Partnership, 2022. . Food and Agriculture Organization of the United Nations.
Macdiarmid, J.I., Kyle, J., Horgan, G.W., Loe, J., Fyfe, C., Johnstone, A., McNeill, G., 2012. Sustainable diets for the future: Can we contribute to reducing greenhouse gas emissions by eating a healthy diet? The American Journal of Clinical Nutrition 96, 632–639. https://doi.org/10.3945/ajcn.112.038729
Mariotti, F., Havard, S., Morise, A., Nadaud, P., Sirot, V., Wetzler, S., Margaritis, I., 2021. Perspective: Modeling Healthy Eating Patterns for Food-Based Dietary Guidelines-Scientific Concepts, Methodological Processes, Limitations, and Lessons. Advances in Nutrition 12, 590–599. https://doi.org/10.1093/advances/nmaa176
Meier, T., Christen, O., 2013. Environmental Impacts of Dietary Recommendations and Dietary Styles: Germany As an Example. Environ. Sci. Technol. 47, 877–888. https://doi.org/10.1021/es302152v
Mertens, E., Kaptijn, G., Kuijsten, A., van Zanten, H., Geleijnse, J.M., van 't Veer, P., 2019. SHARP-Indicators Database towards a public database for environmental sustainability. Data in Brief 27, 104617. https://doi.org/10.1016/j.dib.2019.104617
Miller, L.V., Krebs, N.F., Hambidge, K.M., 2007. A Mathematical Model of Zinc Absorption in Humans As a Function of Dietary Zinc and Phytate. The Journal of Nutrition 137, 135–141. https://doi.org/10.1093/jn/137.1.135
Nelson, M.E., Hamm, M.W., Hu, F.B., Abrams, S.A., Griffin, T.S., 2016. Alignment of Healthy Dietary Patterns and Environmental Sustainability: A Systematic Review12. Advances in Nutrition 7, 1005–1025. https://doi.org/10.3945/an.116.012567
Nemecek, T., Kägi, T., 2007. Life Cycle Inventories of Agricultural Production Systems. Ecoinvent v2.0.
Opinion of the French Food Safety Agency on the benefits/risks of fish consumption (Collective expertise report), 2008. . French Agency for Food, Environmental and Occupational Health Safety (Anses), Paris, France.
Papier, K., Knuppel, A., Syam, N., Jebb, S.A., Key, T.J., 2021. Meat consumption and risk of ischemic heart disease: A systematic review and meta-analysis. Critical Reviews in Food Science and Nutrition 0, 1–12. https://doi.org/10.1080/10408398.2021.1949575
Papp, R.-E., Hasenegger, V., Ekmekcioglu, C., Schwingshackl, L., 2021. Association of poultry consumption with cardiovascular diseases and all-cause mortality: a systematic review and dose response meta-analysis of prospective cohort studies. Critical Reviews in Food Science and Nutrition 0, 1–22. https://doi.org/10.1080/10408398.2021.1975092
Perignon, M., Masset, G., Ferrari, G., Barré, T., Vieux, F., Maillot, M., Amiot, M.-J., Darmon, N., 2016. How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. Public Health Nutrition 19, 2662–2674. https://doi.org/10.1017/S1368980016000653
Perignon, M., Vieux, F., Soler, L.-G., Masset, G., Darmon, N., 2017. Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. Nutrition Reviews 75, 2–17. https://doi.org/10.1093/nutrit/nuw043
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216
Ridoutt, B.G., Hendrie, G.A., Noakes, M., 2017. Dietary Strategies to Reduce Environmental Impact: A Critical Review of the Evidence Base. Advances in Nutrition 8, 933–946. https://doi.org/10.3945/an.117.016691

Temme, E.H., Toxopeus, I.B., Kramer, G.F., Brosens, M.C., Drijvers, J.M., Tyszler, M., Ocké, M.C., 2015. Greenhouse gas emission of diets in the Netherlands and associations with food, energy and macronutrient intakes. Public Health Nutrition 18, 2433–2445. https://doi.org/10.1017/S1368980014002821

The nutritional guideline update for vitamins and minerals (Collective expertise report), 2021. . French Agency for Food, Environmental and Occupational Health Safety (Anses), Paris, France.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. https://doi.org/10.1038/nature13959

Tom, M.S., Fischbeck, P.S., Hendrickson, C.T., 2016. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. Environ Syst Decis 36, 92–103. https://doi.org/10.1007/s10669-015-9577-y

Tyszler, M., Kramer, G., Blonk, H., 2016. Just eating healthier is not enough: studying the environmental impact of different diet scenarios for Dutch women (31–50 years old) by linear programming. The International Journal of Life Cycle Assessment 21, 701–709. https://doi.org/10.1007/s11367-015-0981-9

Updating of the PNNS guidelines: Revision of the food-based dietary guidelines, French Agency for Food, Environmental and Occupational Health Safety (Anses). ed, 2016. , Collective Expertise Report. Maisons-Alfort, France.

van Dooren, 2018. A Review of the Use of Linear Programming to Optimize Diets, Nutritiously, Economically and Environmentally. Frontiers in Nutrition 5, 48. https://doi.org/10.3389/fnut.2018.00048

Walker, C., Gibney, E.R., Mathers, J.C., Hellweg, S., 2019. Comparing environmental and personal health impacts of individual food choices. Science of The Total Environment 685, 609–620. https://doi.org/10.1016/j.scitotenv.2019.05.404

Wilson, N., Cleghorn, C.L., Cobiac, L.J., Mizdrak, A., Nghiem, N., 2019. Achieving Healthy and Sustainable Diets: A Review of the Results of Recent Mathematical Optimization Studies. Advances in Nutrition 10, S389–S403. https://doi.org/10.1093/advances/nmz037

How to best reshape diets for health with less or no ruminant meat and associated high environmental pressures

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TABLES AND FIGURES

TABLE 1. Daily intakes of limiting nutrients in observed and modeled diets optimized to be healthier (direct scenario, "Direct") or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

			Males											
Nutrient [2]	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario** [3]										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
Vitamin A	µg·d^{-1}	804	750 [4]	750	750	752	781	795	789	777	766	759	779	750	-
Vitamin C	mg·d^{-1}	**98** [5]	159	110	124	143	159	168	168	169	169	168	168	110	-
Calcium	mg·d^{-1}	1065	950	1007	1017	1024	1030	1030	1020	1018	1012	1007	1001	950	2500
Iodine	µg·d^{-1}	175	164	150	150	150	150	150	150	150	152	154	154	150	600
Sodium	mg·d^{-1}	**3938**	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	1500	2300
Water	g·d^{-1}	2780	2684	2634	2690	2753	2801	2790	2500	2511	2520	2507	2500	2500	-
Saturated fatty acids	%EI·d^{-1}	**14%**	10%	12%	12%	12%	11%	11%	11%	11%	10%	10%	10%	-	12%
Atherogenic fatty acids [6]	%EI·d^{-1}	8%	6%	7%	7%	7%	7%	7%	7%	7%	7%	7%	6%	-	8%
Linoleic acid	%EI·d^{-1}	**3%**	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	-
α-linolenic acid	%EI·d^{-1}	**0%**	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	-
EPA+DHA [7]	g·d^{-1}	**0.33**	0.50	0.50	0.50	0.50	0.50	0.50	0.65	0.50	0.50	0.50	0.50	0.50	-
Sugar (excluding lactose)	g·d^{-1}	**102**	100	100	100	100	100	100	100	100	100	100	100	-	100
Fiber	g·d^{-1}	**23**	47	30	32	34	36	37	37	38	39	39	38	30	-

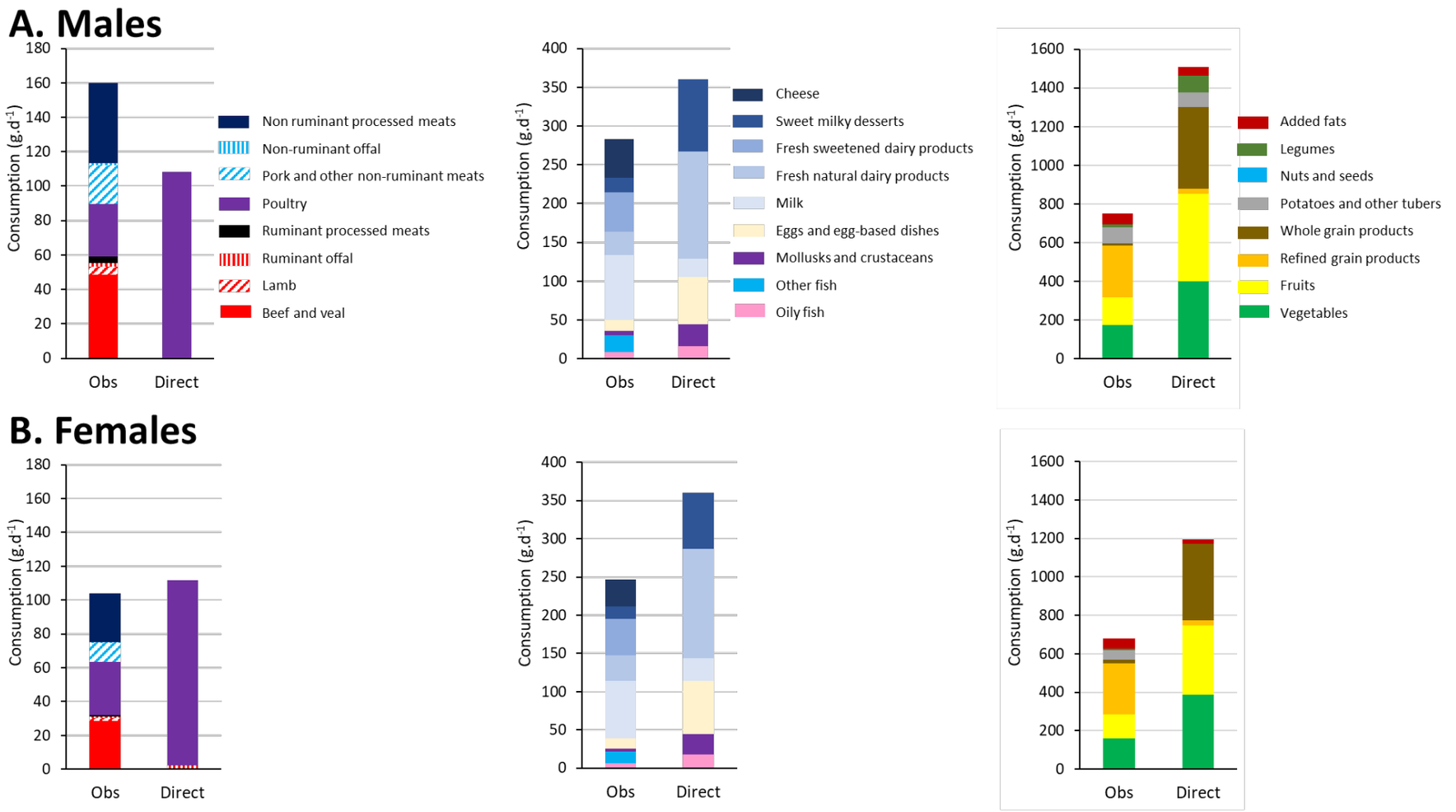
[1] Dietary inertia was modeled using the *Diet Departure* criterion.
[2] Only limiting nutrients (*i.e.*, nutrients whose constraint was active in at least one step of the transition in males or females, thus constraining the identified dietary solution) are represented here. See Supplemental Table 3 for the other nutrients considered in the model.
[3] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[4] In the modeled diets, the nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[5] In the observed diet, the nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[6] Atherogenic fatty acids, lauric and myristic and palmitic acids.
[7] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.

TABLE 1 cont. Daily intakes of limiting nutrients in observed and modeled diets optimized to be healthier (direct scenario, "Direct") or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

			Females											
Nutrient [2]	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario** [3]										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
Vitamin A	µg·d^{-1}	**608** [4]	650 [5]	650	679	718	764	788	791	791	774	682	663	650	-
Vitamin C	mg·d^{-1}	**84**	123	110	110	124	142	137	145	144	144	142	141	110	-
Calcium	mg·d^{-1}	**892**	950	980	986	1002	1009	971	1000	996	993	987	981.8	950	2500
Iodine	µg·d^{-1}	**145**	150	150	150	150	150	150	150	152	155	155	153	150	600
Sodium	mg·d^{-1}	**3100**	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	1500	2300
Water	g·d^{-1}	2422	2923	2446	2470	2511	2544	2206	2214	2218	2216	2205	2198		
Saturated fatty acids	%EI·d^{-1}	**15%**	8%	12%	12%	12%	11%	11%	11%	11%	11%	11%	11%	-	12%
Atherogenic fatty acids [6]	%EI·d^{-1}	**9%**	5%	8%	8%	7%	7%	7%	7%	7%	7%	7%	7%	-	8%
Linoleic acid	%EI·d^{-1}	**3%**	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	-
α-linolenic acid	%EI·d^{-1}	**0%**	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	-
EPA+DHA [7]	g·d^{-1}	**0.22**	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	-
Sugar (excluding lactose)	g·d^{-1}	80	100	100	92	100	100	100	100	98	98	99	99	-	100
Fiber	g·d^{-1}	**19**	41	30	31	33	35	34	35	36	36	36	36	30	-

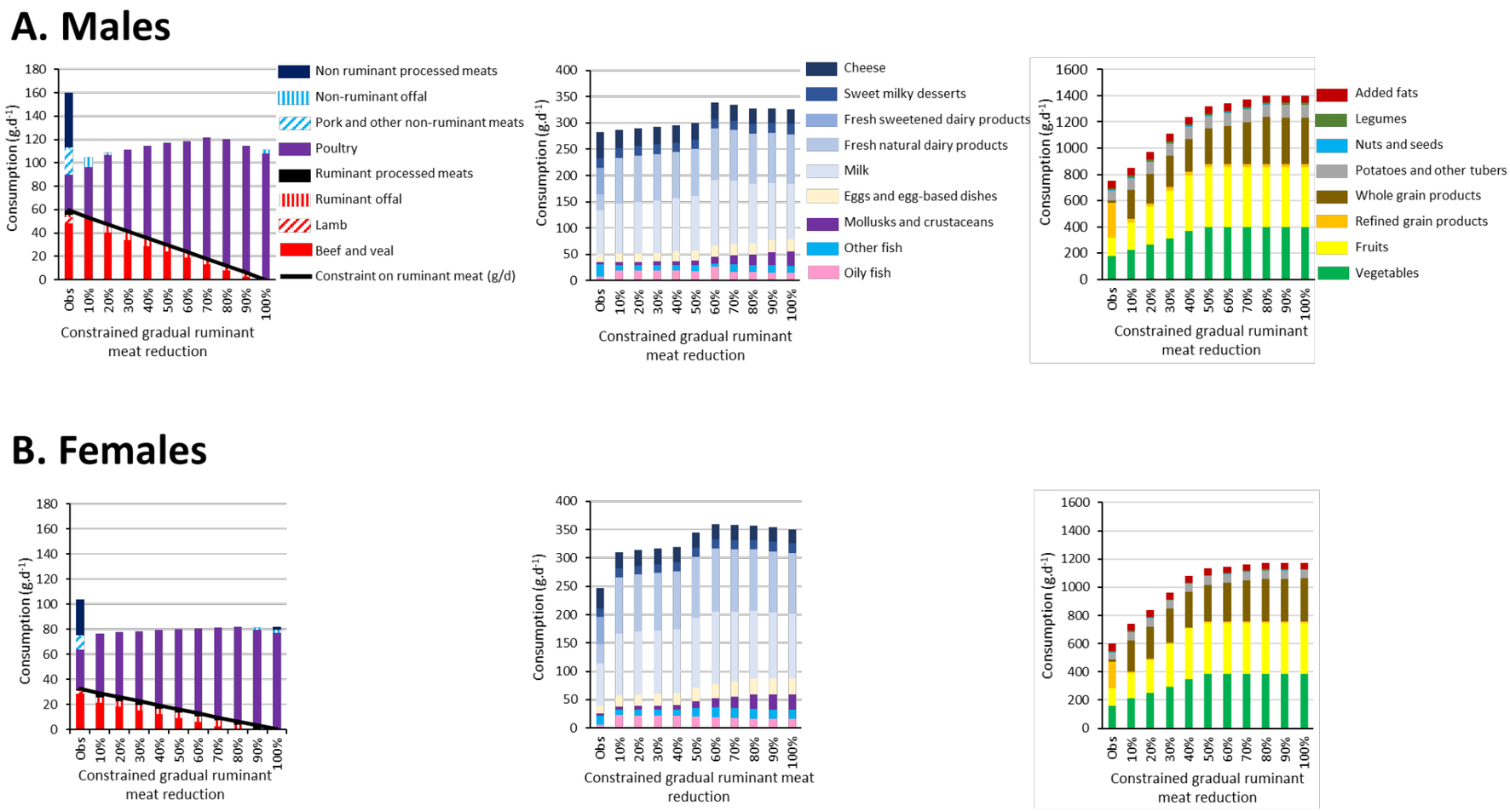
[1] Dietary inertia was modeled using the *Diet Departure* criterion.
[2] Only limiting nutrients (*i.e.*, nutrients whose constraint was active in at least one step of the transition in males or females, thus constraining the identified dietary solution) are represented here. See Supplemental Table 3 for the other nutrients considered in the model.
[3] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[4] In the observed diet, the nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[5] In the modeled diets, the nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[6] Atherogenic fatty acids, lauric and myristic and palmitic acids.
[7] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.

FIGURE 1. Average daily consumption of plant- or animal-based food groups in observed (Obs) and modeled diets optimized to be healthier (direct scenario, "Direct") in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)



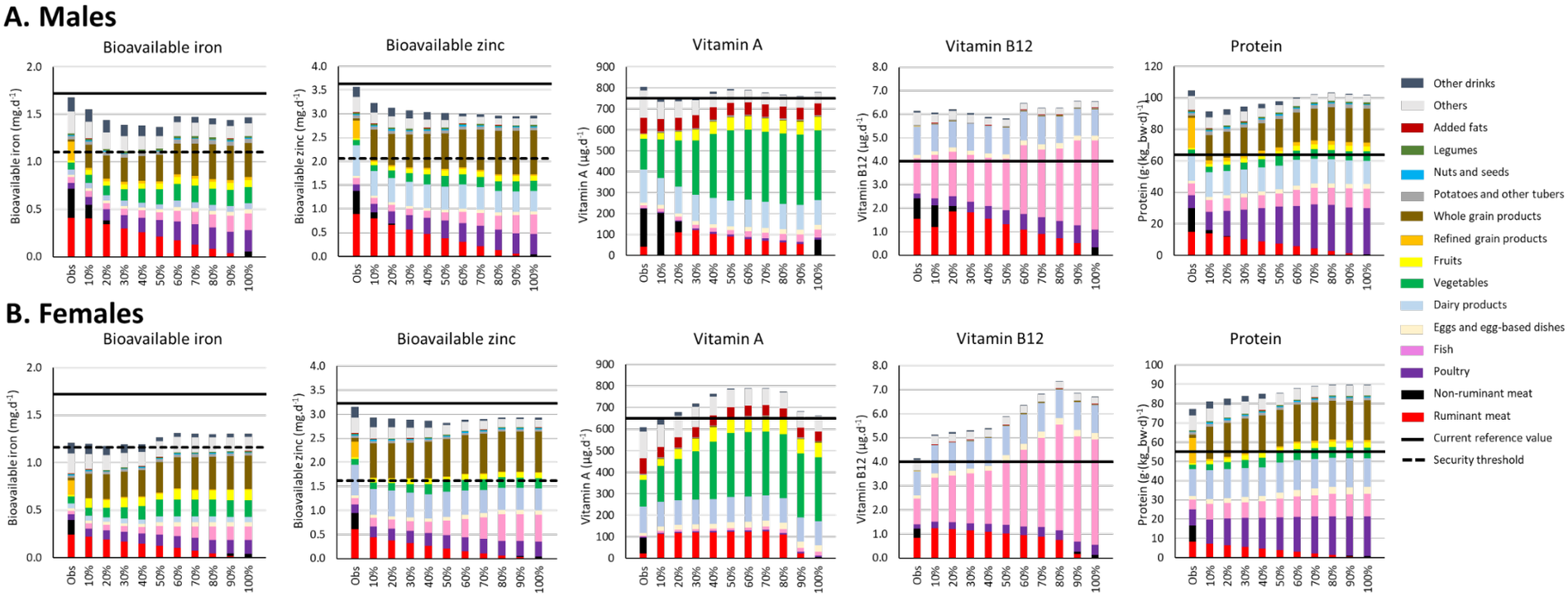
For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 3.

FIGURE 2. Average daily consumption of plant- or animal- based food groups in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)



Dietary inertia was modeled using the Diet Departure criterion. In each x% modeled scenario, total ruminant meat consumption was reduced by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 3.

FIGURE 3. Contribution of food groups to bioavailable iron and zinc, vitamins A and B12, and protein in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)



Dietary inertia was modeled using the Diet Departure criterion. In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 3.

Iron and zinc are shown as bioavailable amounts that take account of their absorption, and likewise protein intake accounts for the lower digestibility of plant proteins (see Methods for detailed information). For each nutrient, the current reference values and security thresholds (for bioavailable iron and zinc) are represented by solid and dashed lines, respectively (see Methods for detailed information on how "flexibility" was allowed on bioavailable iron and zinc using goal variables, and Table 1 and Supplemental Table 3 for detailed values on the current references and security thresholds).

The Figures show nutrients that are largely provided by meat in the observed diets.

FIGURE 4. Contribution of food groups to different Agribalyse indicators (greenhouse gas emissions, land use, water deprivation, and cumulative energy demand) in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2.

For each indicator, the total is represented by a line. We used the French LCA Database for food items as consumed (AGRIBALYSE®).

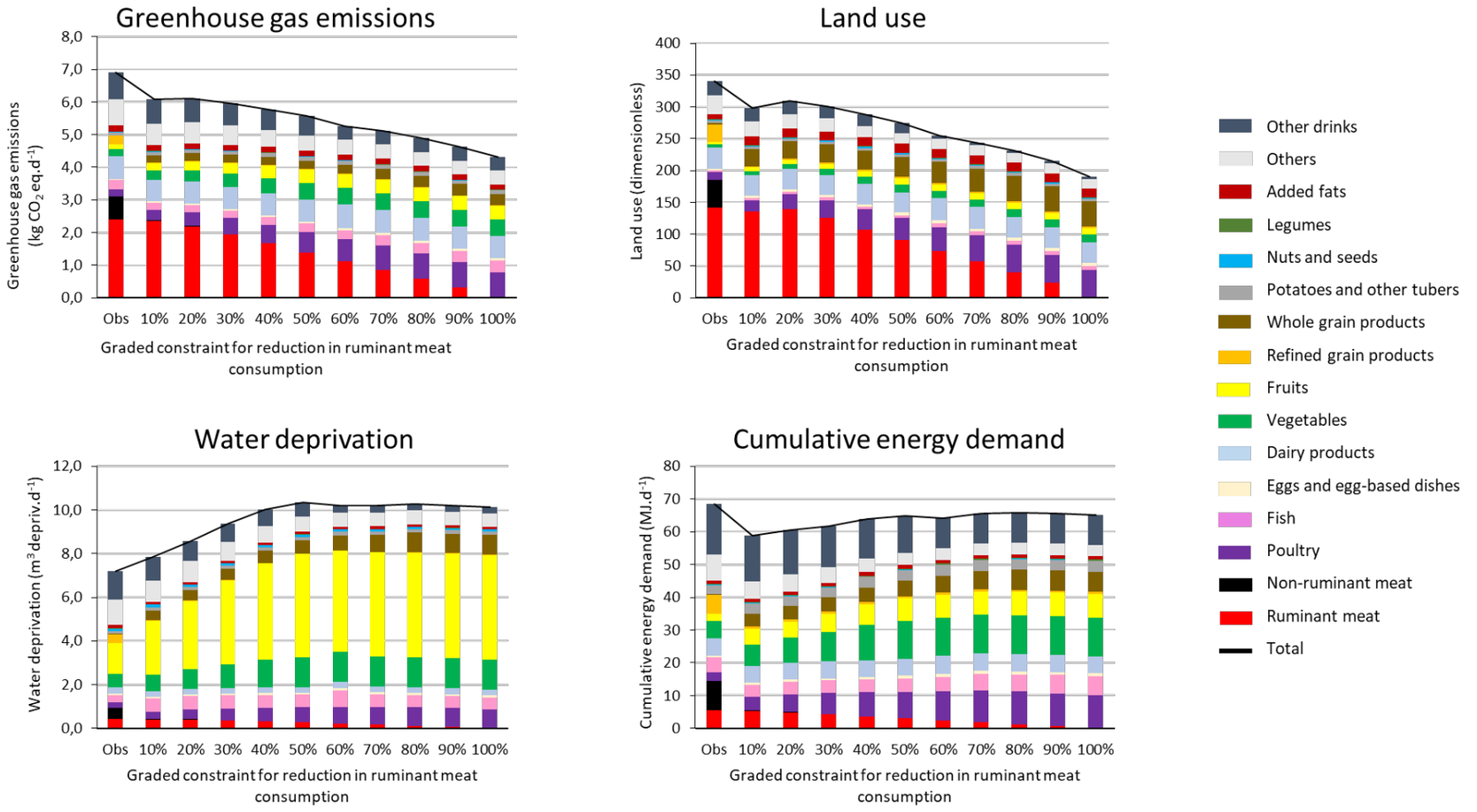
Greenhouse gas emissions are linked to the rise in average global temperatures and expressed in carbon dioxide equivalent (kg CO2 eq).

Land use refers to the use and transformation of land and is dimensionless.

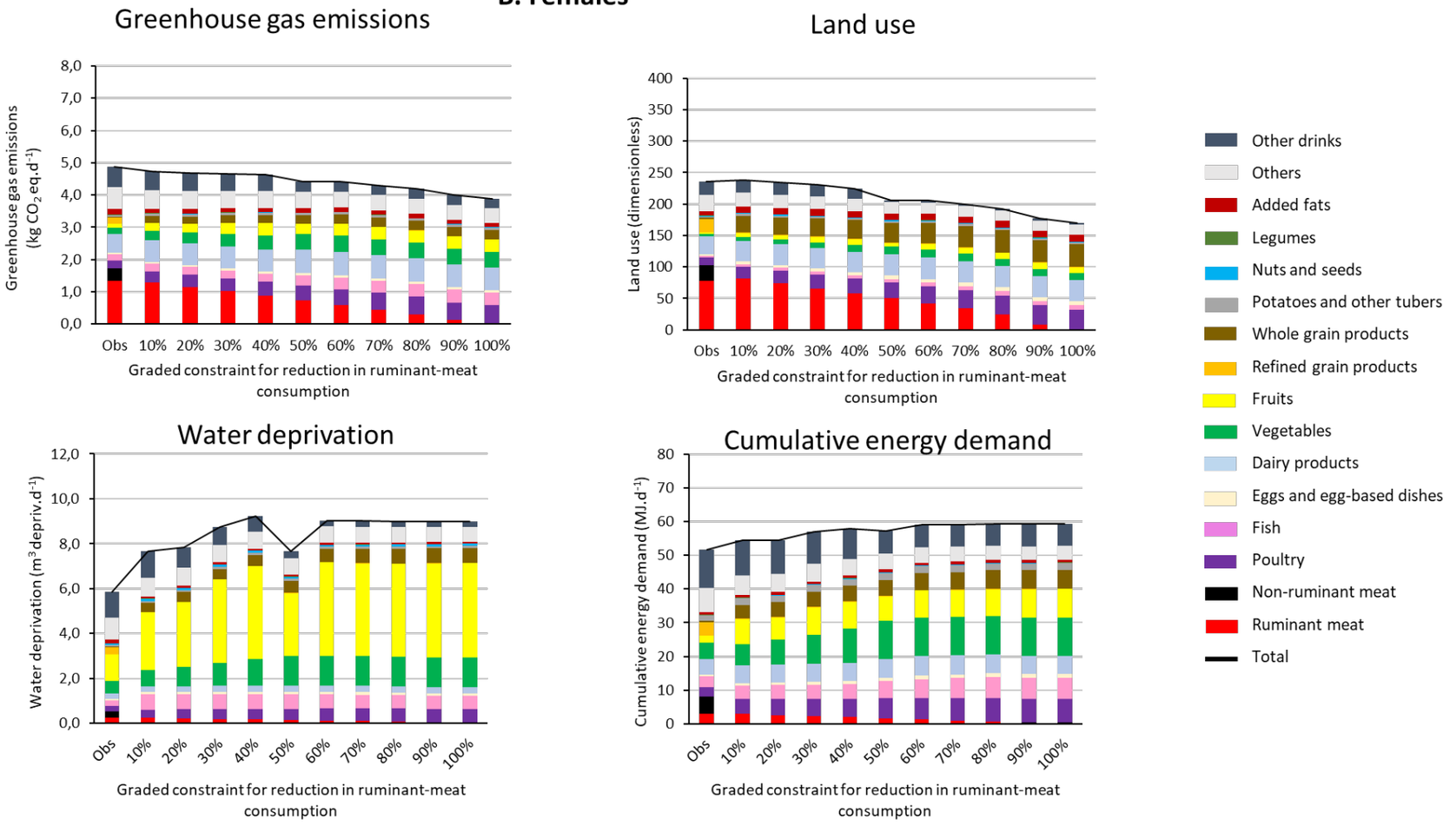
Water deprivation is related to the local scarcity of water and expressed in cubic meters of water (m3 depriv).

Cumulative energy demand is the use of non-renewable fossils resources such as coal, oil, and gas and expressed in MJ.

A. Males


Greenhouse gas emissions
Greenhouse gas emissions (kg CO_2 eq.d^{-1})
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant meat consumption
Land use
Land use (dimensionless)
400
350
300
250
200
150
100
50
0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant meat consumption
Water deprivation
Water deprivation (m^3deprivation.d^{-1})
12,0
10,0
8,0
6,0
4,0
2,0
0,0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant meat consumption
Cumulative energy demand
Cumulative energy demand (MJ.d^{-1})
80
70
60
50
40
30
20
10
0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant meat consumption
Other drinks
Others
Added fats
Legumes
Nuts and seeds
Potatoes and other tubers
Whole grain products
Refined grain products
Fruits
Vegetables
Dairy products
Eggs and egg-based dishes
Fish
Poultry
Non-ruminant meat
Ruminant meat
Total

B. Females


Greenhouse gas emissions
Greenhouse gas emissions (kg CO_2 eq.d^{-1})
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant-meat consumption
Land use
Land use (dimensionless)
400
350
300
250
200
150
100
50
0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant-meat consumption
Water deprivation
Water deprivation (m^{3}depriv.d^{-1})
12,0
10,0
8,0
6,0
4,0
2,0
0,0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant-meat consumption
Cumulative energy demand
Cumulative energy demand (MJ.d^{-1})
80
70
60
50
40
30
20
10
0
Obs 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Graded constraint for reduction in ruminant-meat consumption
Other drinks
Others
Added fats
Legumes
Nuts and seeds
Potatoes and other tubers
Whole grain products
Refined grain products
Fruits
Vegetables
Dairy products
Eggs and egg-based dishes
Fish
Poultry
Non-ruminant meat
Ruminant meat
Total

How to best reshape diets for health with less or no ruminant meat, and associated high environmental pressures

Dussiot *et al.*

ONLINE SUPPLEMENTARY MATERIAL

SUPPLEMENTAL TABLE 1. Lifestyle and sociodemographic characteristics of the sample of adults (*n* = 1125) extracted from the French national INCA3 study, 2014-2015

	Males (*n* = 564)	**Females (*n* = 561)**
Age, %		
< 25y	9%	8%
25-35y	16%	25%
35-50y	38%	52%
50-65y	37%	15%
Level of education, %		
< High-school diploma	34%	23%
High-school diploma	21%	21%
Post-secondary education	44%	56%
Body Mass Index, %		
< 18.5 $kg.m^{-2}$	2%	4%
18.5-24.99 $kg.m^{-2}$	49%	59%
25-29.99 $kg.m^{-2}$	38%	24%
> 30 $kg.m^{-2}$	11%	12%
Alcohol consumption, %		
Non-drinker	30%	54%
Moderate drinker [1]	70%	46%
Heavy drinker [2]	-	-

[1] <20g/d for females and <30 g/d for males

[2] >20g/d for females and >30 g/d for males (Dubuisson et al., 2019; “Anses,” 2017)

SUPPLEMENTAL TABLE 2. Summary of food groups formed for food categorization and different Agribalyse indicators (greenhouse gas emissions, land use, water deprivation and cumulative energy demand)

Food category (Number of food items per category)	**Food group (Number of food items per group)**	**Proportion of food group within the category**	**Main types of foods (Proportion of foods within the group)**	**Greenhouse gas emissions (kg CO_2 eq.d^{-1})**	**Land use (dimension -less)**	**Water use (m^3 depriv. d^{-1})**	**Energy demand ($MJ.d^{-1}$)**
Fruits and vegetables (244)	Vegetables (149)	61%	Raw vegetables (~ 40%) Cooked vegetables (~	1.28	29.58	3.44	29.30
	Fresh fruit (50)	20%	Raw fruit (100%)	0.90	22.06	10.41	15.21
	Dried fruit (9)	4%	Dried fruits (70%) Chestnuts (30%)	2.50	65.82	24.36	104.94
	Processed fruit: compotes and cooked fruit (13)	5%	Compote (40%) Fruit in syrup (40%)	0.72	7.38	3.33	22.22
	Nuts and seeds (23)	9%	Nuts (~ 50%) Seeds (~ 40%)	5.02	507.19	34.95	54.32
Starches (171)	Bread and refined bakery products (36)	21%	Breads (~ 50%) Rusks (~ 20%)	0.81	88.32	0.97	20.50
	Whole-meal and semi-refined bread and bakery products (15)	9%	Breads (~ 50%) Rusks (~ 30%)	1.04	133.63	0.90	20.04
	Other refined starches (13)	8%	Rice (~ 30%) Pasta (~ 20%)	1.38	138.28	2.46	23.32
	Other complete and semi-complete starches (11)	6%	Wheat (50%) Quinoa (20%)	0.94	106.85	2.99	16.77
	Potatoes and other tubers (20)	12%	Potatoes (~ 50%) Other tubers (~ 20%)	1.17	44.56	1.59	33.86
Legumes (16)	Legumes (16)	100%	Dried beans (~ 50%) Lentils (15%)	0.73	63.66	1.07	20.81

Food category (Number of food items per category)	**Food group (Number of food items per group)**	**Proportion of food group within the category**	**Main types of foods (Proportion of foods within the group)**	**Greenhouse gas emissions (kg CO_2 eq.d^{-1})**	**Land use (dimension-less)**	**Water use (m^3 depriv.d^{-1})**	**Energy demand ($MJ.d^{-1}$)**
Meats, Processed meats, Fish products, Eggs (315)	Poultry (24)	8%	Chicken (~ 30%) Duck (~ 20%)	7.23	401.43	7.85	92.53
	Beef and veal (40)	13%	Beef (~ 65%) Veal (~ 35%)	44.04	2526.48	7.57	99.31
	Pork and other non-ruminant	8%	Pork (~ 60%)	14.47	912.21	9.76	171.03
	Lamb (13)	4%	Lamb (~ 100%)	58.14	5139.21	14.18	114.21
	Non-ruminant offal (6)	2%	Chicken (~ 50%)	1.61	74.95	1.41	32.89
	Ruminant offal (13)	4%	Beef and veal (~ 85%)	30.71	1808.49	5.99	83.31
	Ruminant processed meat (69)	22%	Sausages,"andouilles" (~ 35%) "Rillettes", "pâtés", "terrines", "foie gras" (~ 35%)	8.30	490.86	6.15	107.06
	Non-ruminant processed meat (2)	1%	Merguez (50%), Grisons cured beef (50%)	47.52	3460.97	9.94	97.20
	Oily fish (32)	10%	Salmon (~ 30%) Mackerel (~ 20%)	4.97	132.88	28.05	93.15
	Other fish (55)	17%	Tuna (~ 15%) Trout (~ 10%)	9.49	54.48	4.78	148.57
	Mollusks and crustaceans (21)	7%	Mollusks excluding cephalopods (40%) Crustaceans (~ 30%)	5.66	142.94	2.05	84.47
	Eggs and egg-based dishes (14)	4%	Whole eggs (~ 65%) Egg yolks (~ 20%)	2.85	215.26	4.59	40.10

Food category (Number of food items per category)	Food group (Number of food items per group)	Proportion of food group within the category	Main types of foods (Proportion of foods within the group)	Greenhouse gas emissions (kg CO_2 eq.d^{-1})	Land use (dimension-less)	Water use (m^3 depriv.d^{-1})	Energy demand (MJ.d^{-1})
Milk and dairy products (192)	Milk (15)	8%	Semi-skimmed cow's milk (40%) Whole cow's milk (25%)	1.60	81.69	0.46	11.35
	Fresh natural dairy products (18)	9%	Yoghurts, fermented milks and dairy Cottage cheese, "Faisselles", Petit	2.81	135.04	1.14	25.94
	Fresh sweetened dairy products (39)	20%	Yoghurts, fermented milks and dairy Cottage cheese, "Faisselles", Petit	2.08	98.83	1.57	25.98
	Sweet milky desserts (22)	11%	Cream desserts (~ 60%) Other sweet desserts (~ 25%)	3.80	98.64	2.15	32.76
	Cheese (98)	51%	-	5.95	309.36	2.25	32.81
Added fats (98)	Animal fats and assimilated fats (4)	4%	Lard, bacon, duck or goose fat	1.46	68.90	1.01	23.80
	Butter and low-fat butter (11)	11%	Butter (55%) Low-fat butter (45%)	15.16	471.86	9.72	55.53
	Vegetable fats rich in α-linoleic acid (4)	4%	Vegetable oils (100%)	1.95	418.18	1.30	22.48
	Vegetable fats low in α-linoleic acid (24)	24%	Vegetable oils (33%) Vegetable fats (margarine type)	2.28	196.86	6.14	25.92

Food category (Number of food items per category)	Food group (Number of food items per group)	Proportion of food group within the category	Main types of foods (Proportion of foods within the group)	Greenhouse gas emissions (kg CO_2 eq.d^{-1})	Land use (dimension-less)	Water use (m^3 depriv.d^{-1})	Energy demand (MJ.d^{-1})
Others (447)	Starch-based products, sweet/fat processed (61)	36%	Breakfast cereals (~ 50%) Cookies (~ 20%)	3.74	163.03	3.53	32.07
	Salt/fat processed starch products (15)	9%	Savory cookies (~ 50%) Crisps: 4 foods (~ 20%)	2.05	180.01	1.03	32.05
	Sauces and fresh creams (55)	56%	Hot sauces (80%) Cold sauces	4.47	227.70	4.06	37.00
	Sweet products or sweet and fatty products (198)	100%	Pastries (~ 15%) Cookies (~ 10%)	4.69	134.41	8.01	35.44
	Salt (6)	100%	-	0.63	3.38	0.76	12.73
	Condiments (13)	100%	Olives or similar (~ 50%) Vinegar products (~ 20%)	0.34	22.29	2.22	6.81
	Aromatic herbs, spices except salt (38)	100%	Aromatic herbs (~ 65%) Spices (35%)	0.81	80.07	2.82	15.90
	Soups (30)	79%	Vegetable soups (with or without cheese) (85%) Soups with eggs, poultry or fish (15%)	1.03	46.39	1.07	25.85
	Bouillons (8)	21%	Broths with meat (75%) Vegetable broths only (25%)	0.11	2.09	0.30	13.46
	Substitutes for animal products (9)	100%	Soy products (~ 90%) Almond drink (~ 10%)	0.66	28.38	2.66	14.29
	Other foods (14)	100%	Fish eggs (~ 40%) Vinegars (25%)	1.34	79.31	1.65	27.58

Food category (Number of food items per category)	Food group (Number of food items per group)	Proportion of food group within the category	Main types of foods (Proportion of foods within the group)	Greenhouse gas emissions (kg CO_2 eq.d^{-1})	Land use (dimension-less)	Water use (m^3 depriv.d^{-1})	Energy demand (MJ.d^{-1})
Other drinks (181)	Drinking water (44)	100%	-	0.25	1.48	0.16	5.70
	Sweetened soda-type drinks (45)	61%	-	0.47	8.85	1.65	10.90
	Fruit juices (29)	39%	-	0.38	11.84	3.58	7.80
	Hot drinks (22)	100%	Coffee and related products (~ 60%) Tea and herbal teas (~ 30%)	0.47	32.60	1.00	5.64
	Alcoholic drinks (41)	100%	-	1.11	16.32	0.53	22.48

The French LCA Database for food items as consumed AGRIBALYSE® was used here (*ADEME*, 2020).
Greenhouse gas emissions are linked to the increase in the average global temperatures and expressed in carbon dioxide equivalent (kg CO_2 eq).
Land use refers to the use and transformation of land and is dimensionless.
Water deprivation is related to the local scarcity of water and is expressed in cubic meters of water (m^3 depriv).
Cumulative energy demand is use of non-renewable fossils resources such as coal, oil, and gas and expressed in MJ.

Online Supplementary Material

SUPPLEMENTAL TABLE 3. Daily intakes of nutrients under the observed and modeled diets optimized to be healthier (direct scenario, "Direct") or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reductions in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

Males														
Nutrient	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario [2]**										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**		
Retinol	$\mu g \cdot d^{-1}$	573	332	506	464	418	393	376	371	359	348	342	362	-	3000
Vitamin A	$\mu g \cdot d^{-1}$	805	750 [3]	750	750	752	781	795	789	777	766	759	779	750	-
Thiamin	$\mu g \cdot (kcal \cdot d)^{-1}$	0.54	0.54	0.50	0.51	0.53	0.55	0.56	0.56	0.56	0.57	0.56	0.56	0.42	-
Riboflavin	$mg \cdot d^{-1}$	2.2	2.1	2.1	2.1	2.1	2.1	2.1	1.9	2.0	2.0	2.0	2.0	1.6	-
Niacin [4]	$\mu g \cdot d^{-1}$	20	10	20	20	20	20	20	20	20	20	20	20	6.7	-
Pantothenic acid	$mg \cdot d^{-1}$	6.9	7.8	6.7	6.8	6.9	7.1	7.2	7.1	7.2	7.2	7.2	7.2	3.8	-
Vitamin B6	$mg \cdot d^{-1}$	2.1	2.5	2.0	2.1	2.2	2.3	2.4	2.4	2.5	2.5	2.4	2.4	1.7	25
Folate	$\mu g \cdot d^{-1}$	347	545	378	395	418	443	460	463	471	479	477	477	330	-
Vitamin B12	$\mu g \cdot d^{-1}$	6.2	5.7	6.1	6.2	6.0	5.9	5.8	6.5	6.3	6.3	6.6	6.5	4.0	-
Vitamin C	$mg \cdot d^{-1}$	**98** [5]	159	110	124	143	159	168	168	169	169	168	168	110	-
Vitamin D [6]	$\mu g \cdot d^{-1}$	3.5	3.6	3.4	3.4	3.4	3.4	3.4	3.8	3.4	3.3	3.3	3.2	-	100
Vitamin E	$mg \cdot d^{-1}$	13	18	15	15	16	16	17	17	17	17	17	17	5.3	-
Vitamin K1	$\mu g \cdot d^{-1}$	118	240	146	163	183	205	218	221	219	219	219	219	39	-
Calcium	$mg \cdot d^{-1}$	1065	950	1007	1017	1024	1030	1030	1020	1018	1012	1007	1001	950	2500
Copper	$mg \cdot d^{-1}$	2.1	2.8	2.0	2.2	2.3	2.3	2.4	2.3	2.4	2.4	2.5	2.4	2.0	5
Bioavailable Iron	$mg \cdot d^{-1}$	1.68	1.69	1.55	1.44	1.39	1.38	1.37	1.48	1.47	1.46	1.44	1.47	1.10	-
Iodine	$\mu g \cdot d^{-1}$	175	164	150	150	150	150	150	150	150	152	154	154	150	600
Magnesium	$mg \cdot d^{-1}$	409	542	463	471	483	495	499	453	469	484	484	484	254	-

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[3] In the modeled diets, the nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[4] 1 mg niacin equivalent (NE) is equal to 1mg niacin or 60 mg tryptophan.
[5] In the observed diet, nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[6] One exception was vitamin D, for which we did not set any lower constraint; based on previous works, the reference value is known to be much too high to permit a solution from diet optimization (Dussiot et al., 2021; Mariotti et al., 2021).

SUPPLEMENTAL TABLE 3 cont. Daily intakes of nutrients under the observed and modeled diets optimized to be healthier (direct scenario, “Direct”) or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

Males														
Nutrient	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario [2]**										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
Manganese	$mg \cdot d^{-1}$	3.6	6.6	4.5	4.6	4.8	5.0	5.1	5.0	5.2	5.5	5.5	5.5	2.0	-
Phosphorus	$mg \cdot d^{-1}$	1483	1751	1424	1459	1490	1528	1562	1620	1653	1679	1664	1654	550	-
Potassium	$mg \cdot d^{-1}$	3736	4513	3963	4054	4215	4396	4466	4196	4236	4247	4233	4220	3500	-
Selenium	$\mu g \cdot d^{-1}$	146	141	123	127	130	133	135	129	134	136	137	137	70	300
Sodium	$mg \cdot d^{-1}$	**3938 [3]**	2300 [4]	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	1500	2300
Bioavailable zinc	$mg \cdot d^{-1}$	3.57	2.90	3.23	3.13	3.08	3.04	3.01	3.01	2.99	2.96	2.95	2.96	2.06	25
Water	$g \cdot d^{-1}$	2780	2684	2634	2690	2753	2801	2790	2500	2511	2520	2507	2500	2500	-
Saturated fatty acids	$\%EI \cdot d^{-1}$	**14%**	10%	12%	12%	12%	11%	11%	11%	11%	10%	10%	10%	-	12%
Atherogenic fatty acids [5]	$\%EI \cdot d^{-1}$	8%	6%	7%	7%	7%	7%	7%	7%	7%	7%	7%	6%	-	8%
Linoleic acid	$\%EI \cdot d^{-1}$	**3%**	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	-
α-linolenic acid	$\%EI \cdot d^{-1}$	**0%**	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	-
Linoleic acid / α-linolenic acid ratio	-	**8**	**4**	4	4	4	4	4	4	4	4	4	4	-	5
EPA+DHA [6]	$g \cdot d^{-1}$	**0.33**	0.50	0.50	0.50	0.50	0.50	0.50	0.65	0.50	0.50	0.50	0.50	0.50	-
Sugar excluding lactose	$g \cdot d^{-1}$	**102**	100	100	100	100	100	100	100	100	100	100	100	-	100
Protein [7]	$g \cdot d^{-1}$	103	109	91	93	94	96	98	100	102	103	102	102	64	179
Fiber	$g \cdot d^{-1}$	**23**	47	30	32	34	36	37	37	38	39	39	38	30	-

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[3] In the observed diet, nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[4] In the modeled diets, nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[5] Atherogenic fatty acids, lauric and myristic and palmitic acids.
[6] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.
[7] Intakes (mg/d) were converted to mg/kg body weight/day for a mean body weight of 77.4 kg for males. To account for the slightly lower average digestibility of plant protein, protein intake from plants was reduced by 5% when calculating total protein intake, as previously described in the Methods section (L122-L123).

SUPPLEMENTAL TABLE 3 cont. Daily intakes of nutrients under the observed and modeled diets optimized to be healthier (direct scenario, “Direct”) or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

Females														
Nutrient	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario [2]**										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
Retinol	$\mu g \cdot d^{-1}$	395	268	386	389	389	387	393	389	390	375	285	267	-	3000
Vitamin A	$\mu g \cdot d^{-1}$	**608 [3]**	650 [4]	650	679	718	764	788	791	791	774	682	663	650	-
Thiamin	$\mu g \cdot (kcal \cdot d)^{-1}$	0.56	0.54	0.55	0.55	0.55	0.57	0.56	0.56	0.56	0.56	0.56	0.56	0.42	-
Riboflavin	$mg \cdot d^{-1}$	1.7	1.8	1.9	1.9	1.9	1.9	1.7	1.8	1.8	1.8	1.7	1.7	1.6	-
Niacin [5]	$\mu g \cdot d^{-1}$	20	20	20	20	20	20	10	20	20	20	20	20	6.7	-
Pantothenic acid	$mg \cdot d^{-1}$	5.3	7.0	6.1	6.2	6.4	6.5	6.1	6.4	6.5	6.5	6.4	6.4	3.2	-
Vitamin B6	$mg \cdot d^{-1}$	**1.5**	2.0	1.8	1.8	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.6	25
Folate	$\mu g \cdot d^{-1}$	**280**	410	358	363	385	410	403	426	429	430	423	421	330	-
Vitamin B12	$\mu g \cdot d^{-1}$	4.1	6.5	5.1	5.2	5.3	5.4	5.9	6.4	6.8	7.3	6.8	6.7	4.0	-
Vitamin C	$mg \cdot d^{-1}$	**84**	123	110	110	124	142	137	145	144	144	142	141	110	-
Vitamin D [6]	$\mu g \cdot d^{-1}$	2.9	3.6	3.5	3.5	3.5	3.5	3.6	3.6	3.5	3.4	3.4	3.4	-	100
Vitamin E	$mg \cdot d^{-1}$	11	14	13	13	14	14	15	15	15	15	15	15	4.4	-
Vitamin K1	$\mu g \cdot d^{-1}$	111	232	146	161	181	203	252	217	217	217	217	217	35	-
Calcium	$mg \cdot d^{-1}$	**892**	950	980	986	1002	1009	971	1000	996	993	987	982	950	2500
Copper	$mg \cdot d^{-1}$	1.6	2.6	2.0	2.1	2.2	2.2	2.1	2.2	2.3	2.4	2.2	2.2	0.89	5
Bioavailable Iron	$mg \cdot d^{-1}$	1.21	1.51	1.2	1.18	1.19	1.2	1.27	1.31	1.3	1.3	1.3	1.31	1.16	-
Iodine	$\mu g \cdot d^{-1}$	**145**	150	150	150	150	150	150	150	152	155	155	153	150	600
Magnesium	$mg \cdot d^{-1}$	330	483	435	441	455	461	401	426	435	442	442	442	195	-

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[3] In the observed diet, nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[4] In the modeled diets, nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[5] 1 mg niacin equivalent (NE) is equal to 1mg niacin or 60 mg tryptophan.
[6] One exception was vitamin D, for which we did not set any lower constraint; based on previous works, the reference value is known to be much too high to permit a solution from diet optimization (Dussiot et al., 2021; Mariotti et al., 2021).

SUPPLEMENTAL TABLE 3 cont. Daily intakes of nutrients under the observed and modeled diets optimized to be healthier (direct scenario, “Direct”) or to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

Females														
Nutrient	**Unit**	**Observed diet**	**Modeled diet**										**Lower bound**	**Upper bound**
			Direct scenario	**Gradual scenario [2]**										
				10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
Manganese	$mg \cdot d^{-1}$	3.1	5.8	4.4	4.5	4.7	4.8	4.4	4.7	4.8	4.9	4.9	4.9	1.5	-
Phosphorus	$mg \cdot d^{-1}$	1128	1 558	1321	1340	1378	1411	1435	1490	1506	1514	1508	1510	550	-
Potassium	$mg \cdot d^{-1}$	**2906 [3]**	3 825	3781	3743	3939	4038	3601	3834	3819	3813	3815	3811	3500	-
Selenium	$\mu g \cdot d^{-1}$	120	135	116	119	121	124	135	124	126	128	128	127	70	300
Sodium	$mg \cdot d^{-1}$	**3100**	2300 [4]	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	1500	2300
Bioavailable zinc	$mg \cdot d^{-1}$	3.15	2.98	2.93	2.91	2.88	2.86	2.81	2.88	2.90	2.93	2.93	2.92	1.61	25
Water	$g \cdot d^{-1}$	2422	2 923	2446	2470	2511	2544	2206	2214	2218	2216	2205	2198	2000	-
Saturated fatty acids	$\%EI \cdot d^{-1}$	**15%**	8%	12%	12%	12%	11%	11%	11%	11%	11%	11%	11%	-	12%
Atherogenic fatty acids [5]	$\%EI \cdot d^{-1}$	9%	5%	8%	8%	7%	7%	7%	7%	7%	7%	7%	7%	-	8%
Linoleic acid	$\%EI \cdot d^{-1}$	**3%**	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	-
α-linolenic acid	$\%EI \cdot d^{-1}$	**0%**	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	-
Linoleic acid / α-linolenic acid ratio	-	**7**	**4**	4	4	4	4	4	4	4	4	4	4	-	5
EPA+DHA [6]	$g \cdot d^{-1}$	**0.22**	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	-
Sugar excluding lactose	$g \cdot d^{-1}$	80	100	100	92	100	100	100	100	98	98	99	99	-	100
Protein [7]	$g \cdot d^{-1}$	76	99	81	82	84	85	86	88	89	90	90	90	55	152
Fiber	$g \cdot d^{-1}$	**19**	41	30	31	33	35	34	35	36	36	36	36	30	-

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled diet of the gradual scenario, total ruminant meat consumption was reduced by x% of its observed value.
[3] In the observed diet, nutrient intakes not complying with nutritional constraints (*i.e.*, not between the lower and upper bounds) are shown in bold.
[4] In the modeled diets, nutrient intakes that were limiting (*i.e.*, equal to their lower or upper bounds) are shown in white on a black background.
[5] Atherogenic fatty acids, lauric and myristic and palmitic acids.
[6] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.
[7] Intakes (mg/d) were converted to mg/kg body weight/day for a mean body weight of 77.4 kg for males. To account for the slightly lower average digestibility of plant protein, protein intake from plants was reduced by 5% when calculating total protein intake, as previously described in the Methods section (L122-L123).

SUPPLEMENTAL TABLE 4. Summary of constraints and criteria for each food group in the diet optimization model for males and females

		Males				Females			
			Constraint				Constraint		
Food group	**Optimization Objective (*HDP* criterion)**	**Observed consumption (g/d)**	**Lower limit [1] (g/d)**	**Upper limit (g/d)**	**Joint upper limit (g/d)**	**Observed consumption (g/d)**	**Lower limit (g/d)**	**Upper limit (g/d)**	**Joint upper limit (g/d)**
Vegetables	Maximization	176	20	400	-	160	18	387	-
Fresh fruits	Maximization	128	0	-	454 [2]	107	0	-	359
Dried fruits		1	0	-		1	0	-	
Processed fruit: compotes and cooked fruit		13	0	-		15	0	-	
Nuts, seeds and oleaginous fruit	Maximization	3	0	20	-	2	0	14	-
Bread and refined bakery products	Maximization	168	27	-	-	115	10	-	-
Complete and semi-complete bread and bakery products	Maximization	11	0	-	-	15	0	-	-
Other refined starches	Maximization	98	0	-	-	72	0	-	-
Other complete and semi-complete starches	Maximization	4	0	-	-	4	0	-	-
Potatoes and other tubers	Maximization	79	0	264	-	49	0	196	-
Legumes	Maximization	13	0	86	-	6	0	43	-
Poultry	Maximization	30	0	108	-	31	0	109	-
Beef and veal	Minimization	48	0	-	71	28	0	-	71
Pork and other non-ruminant meats	Minimization	22	0	-		11	0	-	
Lamb	Minimization	5	0	-		2	0	-	
Non-ruminant offal	Minimization	1	0	36		0	0	36	
Ruminant offal	Minimization	2	0			1	0		
Non-ruminant processed meats	Minimization	46	0	-	25	29	0	-	25
Ruminant processed meats	Minimization	4	0	-		1	0	-	

Oily fish [3]		8	0	26	-	6	0	26	-
Other fish [3]		22	0	110	-	15	0	80	-
Mollusks and crustaceans		5	0	28	-	4	0	26	-
Eggs and egg-based dishes		14	0	61	-	14	0	70	-
Milk		84	0	343	-	75	0	322	-
Fresh natural dairy products		31	0	138	-	33	0	143	-
Fresh sweetened dairy products		50	0	179	-	48	0	168	-
Sweet milky desserts		19	0	93	-	16	0	73	-
Cheeses		49	0	131	-	36	0	94	-
Animal fats and assimilated fats		1	0	0	-	0	0	0	-
Butter and light butter		10	0	33	-	10	0	30	-
Vegetable fats rich in α-linoleic acid		0	0	-	32	0	0	-	30
Vegetable fats rich in α-linoleic acid		12	0	-		10	0	-	
Sauces and fresh creams		35	0	118	-	32	0	100	-
Sweet products or sweet and fatty products		103	9	251	-	83	9	215	-
Drinking water		1007	182	-	-	929	75	-	-
Sweetened soda-type drinks	Minimization	141	0	-	263	140	0	-	263
Fruit juices		80	0	-		67	0	-	
Hot drinks		494	0	494	-	507	0	507	-
Salt		1	0	4	-	1	0	4	-
Condiments		4	0	29	-	3	0	21	-
Aromatic herbs, Spices except salt		2	0	7	-	2	0	6	-
Soups		71	0	434	-	75	0	381	-
Bouillons		5	0	21	-	4	0	25	-
Substitutes for animal products		3	0	29	-	5	0	29	-
Other foods		4	4	4	-	2	2	2	-
Alcoholic drinks		216	0	216	-	59	0	59	-
Bread and bakery products		178	-	354	-	130	-	316	-
Other starches		102	-	276	-	76	-	188	-
Liquids		2098	1061	3777	-	1857	738	3087	-

Online Supplementary Material

[1] Lower and upper limits correspond to the 5th or 95th percentiles of consumption for all food groups except those with an upper limit set as a dietary constraint (red meat, processed meat and soft drinks).
[2] The most substitutable food groups were grouped together to define their lower and upper bounds as the 5th or 95th percentiles of their total consumption.
[3] In order to consider the French dietary recommendations for fish consumption, two additional constraints were added to limit total fish consumption to 39 g/d and oily fish consumption to 26 g/d (*Anses*, 2008).

SUPPLEMENTAL TABLE 5. Absolute changes to daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females) [2]

	Males										
	Observed diet	Modeled diet with gradual meat reduction (%) [3]									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Diet composition, g/d											
Vegetables	176	223	263	309	366	400	400	400	400	400	400
Fruits	142	212	289	369	424	453	453	453	453	453	453
Nuts and seeds	3	3	3	3	3	3	3	3	3	3	3
Refined grain products	266	27	27	27	27	27	27	27	27	27	27
Whole grain products	14	220	227	238	252	269	290	319	355	354	353
Potatoes and other tubers	79	89	89	90	94	95	98	97	96	96	96
Legumes	13	15	14	14	14	14	14	14	14	14	14
Poultry	30	43	59	70	79	88	95	104	108	108	108
Beef and veal	48	53	40	34	29	24	19	13	8	2	0
Pork and other non-ruminant meats	22	0	0	0	0	0	0	0	0	0	0
Lamb	5	0	0	0	0	0	0	0	0	0	0
Non-ruminant offal	1	8	2	0	0	0	0	0	0	0	3
Ruminant offal	2	0	7	8	7	6	5	5	4	3	0
Non-ruminant processed meats	46	0	0	0	0	0	0	0	0	0	0
Ruminant processed meats	4	0	0	0	0	0	0	0	0	0	0
Oily fishes	8	20	19	19	19	19	26	16	16	15	15
Other fishes	22	10	10	10	10	11	6	15	14	14	13
Mollusks and crustaceans	5	5	6	7	8	9	14	17	19	25	28
Eggs and egg-based dishes	14	16	17	17	18	19	22	22	22	23	23
Milk	84	96	97	99	102	104	124	119	113	109	105

Fresh natural dairy products	31	87	88	88	88	89	98	97	96	95	94
Fresh sweetened dairy products	50	0	0	0	0	0	0	0	0	0	0
Sweet milky desserts	19	19	20	19	18	18	18	19	19	19	20
Cheeses	49	34	34	33	32	32	31	30	29	28	27
Added fats	23	31	31	32	33	33	33	33	33	33	33
Others	253	158	155	140	122	112	109	107	104	103	101
Other drinks	1938	1777	1709	1644	1577	1490	1144	1138	1131	1126	1124

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] Data are averages.

[3] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, the 48 modeled food groups are not shown here. The remaining food groups were grouped as "others" (11 groups) and "other drinks" (5 groups). Detailed food categories are presented in Supplemental Table 2.

SUPPLEMENTAL TABLE 5 cont. Absolute changes to daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females) [2]

	Females										
	Observed diet	Modeled diet with gradual meat reduction (%) [3]									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Diet composition, g/d											
Vegetables	176	223	263	309	366	400	400	400	400	400	400
Fruits	142	212	289	369	424	453	453	453	453	453	453
Nuts and seeds	3	3	3	3	3	3	3	3	3	3	3
Refined grain products	266	27	27	27	27	27	27	27	27	27	27
Whole grain products	14	220	227	238	252	269	290	319	355	354	353
Potatoes and other tubers	79	89	89	90	94	95	98	97	96	96	96
Legumes	13	15	14	14	14	14	14	14	14	14	14
Poultry	30	43	59	70	79	88	95	104	108	108	108
Beef and veal	48	53	40	34	29	24	19	13	8	2	0
Pork and other non-ruminant meats	22	0	0	0	0	0	0	0	0	0	0
Lamb	5	0	0	0	0	0	0	0	0	0	0
Non-ruminant offal	1	8	2	0	0	0	0	0	0	0	3
Ruminant offal	2	0	7	8	7	6	5	5	4	3	0
Non-ruminant processed meats	46	0	0	0	0	0	0	0	0	0	0
Ruminant processed meats	4	0	0	0	0	0	0	0	0	0	0
Oily fishes	8	20	19	19	19	19	26	16	16	15	15
Other fishes	22	10	10	10	10	11	6	15	14	14	13
Mollusks and crustaceans	5	5	6	7	8	9	14	17	19	25	28

Eggs and egg-based dishes	14	16	17	17	18	19	22	22	22	23	23
Milk	84	96	97	99	102	104	124	119	113	109	105
Fresh natural dairy products	31	87	88	88	88	89	98	97	96	95	94
Fresh sweetened dairy products	50	0	0	0	0	0	0	0	0	0	0
Sweet milky desserts	19	19	20	19	18	18	18	19	19	19	20
Cheeses	49	34	34	33	32	32	31	30	29	28	27
Added fats	23	31	31	32	33	33	33	33	33	33	33
Others	253	158	155	140	122	112	109	107	104	103	101
Other drinks	1938	1777	1709	1644	1577	1490	1144	1138	1131	1126	1124

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] Data are averages.

[3] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, the 48 modeled food groups are not shown here. The remaining food groups were grouped as "others" (11 groups) and "other drinks" (5 groups). Detailed food categories are presented in Supplemental Table 2.

SUPPLEMENTAL TABLE 6. Relative changes to daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Males									
	Observed diet	Modeled diet with gradual meat reduction (%) [2]								
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Differences to observed diets, % [3]										
Δ Vegetables	-	27%	49%	76%	108%	128%	128%	128%	128%	128%	128%
Δ Fruits	-	49%	103%	160%	198%	219%	219%	219%	219%	219%	219%
Δ Nuts and seeds	-	9%	6%	3%	2%	0%	-4%	-6%	-8%	-10%	-11%
Δ Refined grain products	-	-90%	-90%	-90%	-90%	-90%	-90%	-90%	-90%	-90%	-90%
Δ Whole grain products	-	1422	1470	1546	1644	1759	1903	2104	2354	2344	2340
Δ Potatoes and other tubers	-	13%	13%	14%	18%	20%	24%	23%	21%	21%	21%
Δ Legumes	-	9%	8%	7%	7%	6%	5%	4%	3%	2%	2%
Δ Poultry	-	42%	94%	129%	159%	188%	212%	241%	256%	256%	256%
Δ Beef and veal	-	10%	-17%	-30%	-40%	-51%	-61%	-73%	-84%	-95%	-100%
Δ Pork and other non-ruminant meats	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Lamb	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Non-ruminant offal	-	539%	61%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	135%
Δ Ruminant offal	-	-100%	201%	231%	183%	147%	111%	92%	69%	47%	-100%
Δ Non-ruminant processed meats	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Ruminant processed meats	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Oily fishes	-	135%	131%	128%	125%	120%	209%	95%	90%	81%	78%
Δ Other fishes	-	-56%	-55%	-54%	-53%	-51%	-72%	-33%	-38%	-38%	-40%
Δ Mollusks and crustaceans	-	1%	15%	33%	53%	82%	175%	237%	292%	414%	459%
Δ Eggs and egg-based dishes	-	14%	18%	23%	28%	33%	54%	57%	58%	61%	65%

Δ Milk	-	14%	16%	18%	21%	25%	48%	42%	35%	29%	26%
Δ Fresh natural dairy products	-	184%	188%	189%	188%	190%	220%	218%	214%	211%	209%
Δ Fresh sweetened dairy products	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Sweet milky desserts	-	-1%	2%	-1%	-6%	-9%	-6%	-4%	-2%	0%	2%
Δ Cheeses	-	-30%	-31%	-33%	-34%	-36%	-37%	-39%	-42%	-43%	-45%
Δ Added fats	-	35%	36%	37%	41%	43%	42%	42%	41%	41%	41%
Δ Others	-	-38%	-39%	-45%	-52%	-56%	-57%	-58%	-59%	-60%	-60%
Δ Other drinks	-	-8%	-12%	-15%	-19%	-23%	-41%	-41%	-42%	-42%	-42%

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

[3] The percentage increase or decrease at each step is relative to the observed diet. For clarity, the 48 modeled food groups are not shown here. The remaining food groups were grouped as "others" (11 groups) and "other drinks" (5 groups). Detailed food categories are presented in Supplemental Table 2.

SUPPLEMENTAL TABLE 6 cont. Relative changes to daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Females									
	Observed diet	Modeled diet with gradual meat reduction (%) [2]								
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Differences to observed diets, % [3]										
Δ Vegetables	-	35%	57%	83%	117%	142%	142%	142%	142%	142%	142%
Δ Fruits	-	43%	87%	147%	191%	191%	191%	191%	191%	191%	191%
Δ Nuts and seeds	-	31%	29%	27%	25%	24%	22%	20%	18%	16%	14%
Δ Refined grain products	-	-95%	-95%	-95%	-95%	-95%	-95%	-95%	-95%	-95%	-95%
Δ Whole grain products	-	1040%	1094%	1140%	1188%	1258%	1331%	1424%	1471%	1480%	1494%
Δ Potatoes and other tubers	-	17%	19%	19%	19%	21%	21%	20%	19%	18%	17%
Δ Legumes	-	23%	23%	22%	22%	22%	21%	21%	20%	19%	19%
Δ Poultry	-	50%	64%	77%	90%	103%	115%	128%	139%	142%	146%
Δ Beef and veal	-	-25%	-36%	-47%	-58%	-69%	-79%	-91%	-100%	-100%	-100%
Δ Pork and other non-ruminant meats	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Lamb	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Non-ruminant offal	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	263%	306%
Δ Ruminant offal	-	376%	402%	413%	417%	424%	423%	435%	376%	-9%	-100%
Δ Non-ruminant processed meats	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-92%
Δ Ruminant processed meats	-	243%	221%	201%	183%	168%	154%	142%	130%	119%	-100%
Δ Oily fishes	-	272%	267%	262%	256%	230%	206%	189%	167%	169%	172%
Δ Other fishes	-	-38%	-34%	-33%	-32%	-1%	15%	13%	13%	8%	4%
Δ Mollusks and crustaceans	-	54%	78%	104%	139%	223%	329%	450%	606%	606%	606%
Δ Eggs and egg-based dishes	-	43%	48%	53%	58%	77%	91%	94%	97%	102%	107%

Δ Milk	-	45%	47%	48%	49%	63%	69%	64%	58%	54%	51%
Δ Fresh natural dairy products	-	202%	205%	207%	210%	227%	236%	233%	230%	228%	226%
Δ Fresh sweetened dairy products	-	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	-100%
Δ Sweet milky desserts	-	-5%	-3%	-2%	0%	3%	5%	6%	7%	8%	9%
Δ Cheeses	-	-21%	-22%	-23%	-24%	-25%	-26%	-28%	-29%	-30%	-31%
Δ Added fats	-	16%	15%	15%	15%	16%	16%	17%	17%	17%	17%
Δ Others	-	-19%	-23%	-28%	-32%	-34%	-37%	-40%	-42%	-43%	-45%
Δ Other drinks	-	-5%	-9%	-13%	-17%	-42%	-42%	-42%	-43%	-43%	-43%

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

[3] The percentage increase or decrease at each step is relative to the observed diet. For clarity, the 48 modeled food groups are not shown here. The remaining food groups were grouped as "others" (11 groups) and "other drinks" (5 groups). Detailed food categories are presented in Supplemental Table 2.

SUPPLEMENTAL TABLE 7. Absolute daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Males										
	Observed	Modeled diet with gradual meat reduction (%) [2]									
Diet composition, g/d	**diet**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Vegetables	176	223	263	309	366	400	400	400	400	400	400
Fresh fruits	128	194	283	369	424	453	441	450	449	448	447
Dried fruits	1	18	6	0	0	0	0	3	4	5	6
Processed fruits: compotes and cooked fruits	13	0	0	0	0	0	13	0	0	0	0
Nuts, seeds and oleaginous fruits	3	3	3	3	3	3	3	3	3	3	3
Bread and refined bakery products	168	27	27	27	27	27	27	27	27	27	27
Complete and semi-complete bread and bakery products	11	104	101	99	95	92	84	82	79	77	77
Other refined starches	98	0	0	0	0	0	0	0	0	0	0
Other complete and semi-complete starches	4	116	126	139	157	177	206	237	276	276	276
Potatoes and other tubers	79	89	89	90	94	95	98	97	96	96	96
Legumes	13	15	14	14	14	14	14	14	14	14	14
Poultry	30	43	59	70	79	88	95	104	108	108	108
Beef and veal	48	53	40	34	29	24	19	13	8	2	0
Pork and other non-ruminant meats	22	0	0	0	0	0	0	0	0	0	0
Lamb	5	0	0	0	0	0	0	0	0	0	0
Non-ruminant offal	1	8	2	0	0	0	0	0	0	0	3
Ruminant offal	2	0	7	8	7	6	5	5	4	3	0
Non-ruminant processed meats	46	0	0	0	0	0	0	0	0	0	0
Ruminant processed meats	4	0	0	0	0	0	0	0	0	0	0
Oily fishes	8	20	19	19	19	19	26	16	16	15	15

Online Supplementary Material

	Males										
	Observed	Modeled diet with gradual meat reduction (%) [2]									
Diet composition, g/d	**diet**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Other fishes	22	10	10	10	10	11	6	15	14	14	13
Mollusks and crustaceans	5	5	6	7	8	9	14	17	19	25	28
Eggs and egg-based dishes	14	16	17	17	18	19	22	22	22	23	23
Milk	84	96	97	99	102	104	124	119	113	109	105
Fresh natural dairy products	31	87	88	88	88	89	98	97	96	95	94
Fresh sweetened dairy products	50	0	0	0	0	0	0	0	0	0	0
Sweet milky desserts	19	19	20	19	18	18	18	19	19	19	20
Cheeses	49	34	34	33	32	32	31	30	29	28	27
Animal fats and assimilated fats	1	1	1	1	1	1	1	1	1	1	1
Butters and light butters	10	8	8	8	8	8	8	8	8	8	8
Vegetable fats rich in alpha-linoleic acid	0	22	22	22	23	24	24	24	24	24	24
Vegetable fats low in alpha-linoleic acid	12	0	0	0	0	0	0	0	0	0	0
Starch-based products, sweet/fat processed	22	17	16	15	13	12	12	11	11	10	10
Salt/fat processed starch products	4	2	2	2	2	2	2	2	2	2	2
Sauces and fresh creams	35	30	28	27	25	24	22	21	20	19	19
Sweet products or Sweet and fatty products	103	97	96	85	71	64	62	62	61	60	60
Salt	1	0	0	0	0	0	0	0	0	0	0
Condiments	4	2	2	2	2	1	1	1	1	1	1
Aromatic herbs, Spices except salt	2	2	2	2	2	2	2	2	2	2	2
Soups	71	0	0	0	0	0	0	0	0	0	0
Bouillons	5	0	0	0	0	0	0	0	0	0	0
Substitutes of animal products	3	4	4	4	3	3	4	4	4	4	4
Other foods	4	4	4	4	4	4	4	4	4	4	4
Drinking waters	1007	981	977	974	969	964	962	958	953	949	948
Sweetened soda type drinks	141	0	0	0	0	0	0	0	0	0	0
Fruit juices	80	86	52	36	28	23	21	19	17	16	14
Hot drinks	494	494	464	443	402	342	0	0	0	0	0
Alcoholic drinks	216	216	216	191	179	161	161	161	161	161	161

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

SUPPLEMENTAL TABLE 7 cont. Absolute daily food group consumptions in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Females										
	Observed	Modeled diet with gradual meat reduction (%) [2]									
Diet composition, g/d	**diet**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Vegetables	160	215	251	292	347	387	387	387	387	387	387
Fresh fruits	107	125	196	265	331	202	329	332	331	328	326
Dried fruits	1	52	35	40	29	7	30	27	28	32	33
Processed fruits: compotes and cooked fruits	15	0	0	0	0	150	0	0	0	0	0
Nuts, seeds and oleaginous fruits	2	3	3	3	3	3	3	3	3	3	3
Bread and refined bakery products	115	10	10	10	10	10	10	10	10	10	10
Complete and semi-complete bread and bakery products	15	122	124	124	122	120	117	116	115	116	119
Other refined starches	72	0	0	0	0	0	0	0	0	0	0
Other complete and semi-complete starches	4	98	106	115	126	142	159	178	188	188	188
Potatoes and other tubers	49	58	59	59	59	60	60	59	59	58	58
Legumes	6	7	7	7	7	7	7	7	7	7	7
Poultry	31	47	52	56	60	64	68	72	75	76	77
Beef and veal	28	21	18	15	12	9	6	3	0	0	0
Pork and other non-ruminant meats	11	0	0	0	0	0	0	0	0	0	0
Lamb	2	0	0	0	0	0	0	0	0	0	0
Non-ruminant offal	0	0	0	0	0	0	0	0	0	2	2
Ruminant offal	1	4	4	4	4	4	4	4	4	1	0
Non-ruminant processed meats	29	0	0	0	0	0	0	0	0	0	2
Ruminant processed meats	1	4	4	3	3	3	3	3	3	3	0
Oily fishes	6	22	22	22	21	20	18	17	16	16	16

	Females										
	Observed	Modeled diet with gradual meat reduction (%) [2]									
Diet composition, g/d	**diet**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Other fishes	15	10	10	10	10	15	18	17	17	17	16
Mollusks and crustaceans	4	6	7	8	9	12	16	21	26	26	26
Eggs and egg-based dishes	14	20	20	21	22	24	26	27	27	28	28
Milk	75	109	111	111	112	123	127	123	119	116	114
Fresh natural dairy products	33	99	100	101	102	108	111	110	109	108	107
Fresh sweetened dairy products	48	0	0	0	0	0	0	0	0	0	0
Sweet milky desserts	16	15	15	16	16	16	17	17	17	17	17
Cheeses	36	28	28	27	27	27	26	26	25	25	25
Animal fats and assimilated fats	0	0	0	0	0	0	0	0	0	0	0
Butters and light butters	10	7	7	7	7	6	6	6	6	6	6
Vegetable fats rich in alpha-linoleic acid	0	17	17	17	17	17	17	18	18	18	18
Vegetable fats low in alpha-linoleic acid	10	0	0	0	0	0	0	0	0	0	0
Starch-based products, sweet/fat processed	19	18	17	17	16	16	15	15	14	14	14
Salt/fat processed starch products	2	2	2	2	2	2	2	2	2	1	1
Sauces and fresh creams	32	27	26	24	23	22	20	20	19	18	18
Sweet products or Sweet and fatty products	83	69	69	68	67	67	66	65	64	63	62
Salt	1	0	0	0	0	0	0	0	0	0	0
Condiments	3	2	2	2	2	2	2	2	2	2	2
Aromatic herbs, Spices except salt	2	2	2	2	2	2	2	2	2	2	2
Soups	75	57	49	41	35	32	28	26	24	22	21
Bouillons	4	0	0	0	0	0	0	0	0	0	0
Substitutes of animal products	5	6	6	6	6	6	5	5	5	5	5
Other foods	2	2	2	2	2	2	2	2	2	2	2
Drinking waters	929	914	912	910	908	905	902	901	899	897	896
Sweetened soda type drinks	140	0	0	0	0	0	0	0	0	0	0
Fruit juices	67	141	67	46	36	30	26	23	20	18	17
Hot drinks	507	507	507	469	406	0	0	0	0	0	0
Alcoholic drinks	59	59	59	59	59	59	59	59	59	59	59

SUPPLEMENTAL TABLE 8. Relative changes to total and detailed daily meat consumption by type (non-ruminant processed meats, non-ruminant offal, pork and other non-ruminant meats, poultry, ruminant processed meats, ruminant offal, lamb, beef and veal) in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Males										
	Observed diet	**Modeled diet with gradual meat reduction (%) [2]**									
		10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Max. allowed meat consumption, g/d	-	53	47	41	36	30	24	18	12	6	0
Modeled meat consumption, g/d	59	53	48	42	36	30	24	18	12	6	0
Differences to observed diets, % [3]											
Meat consumption	-	-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%	-90%	-100%
Poultry	-	42%	94%	129%	159%	188%	212%	241%	256%	256%	256%
Beef and veal	-	10%	-17%	-30%	-40%	-51%	-61%	-73%	-84%	-95%	-100%
Pork and other meats	-	-100%	-	-	-	-	-	-	-	-	-
Pork and other non-ruminant meats	-	-100%	-	-	-	-	-	-	-	-	-
Lamb	-	-100%	-	-	-	-	-	-	-	-	-
Offal	-	128%	151%	112%	82%	58%	36%	23%	9%	-5%	-16%
Non-ruminant offal	-	539%	61%	-100%	-100%	-100%	-100%	-100%	-100%	-100%	135%
Ruminant offal	-	-100%	-	-	-	-	-	-	-	-	-
Processed meat	-	-100%	-	-	-	-	-	-	-	-	-
Non-ruminant processed meats	-	-100%	-	-	-	-	-	-	-	-	-
Ruminant processed meats	-	-100%	-	-	-	-	-	-	-	-	-

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

[3] The percentage increase or decrease at each step is relative to the observed diet.

SUPPLEMENTAL TABLE 8 cont. Relative changes to total and detailed daily meat consumption by type (non-ruminant processed meats, non-ruminant offal, pork and other non-ruminant meats, poultry, ruminant processed meats, ruminant offal, lamb, beef and veal) in observed and modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Females										
	Observed diet	**Modeled diet with gradual meat reduction (%) [2]**									
		10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Max. allowed meat consumption, g/d	-	29	26	23	20	16	13	10	7	3	0
Modeled meat consumption, g/d	33	29	26	23	20	16	13	10	7	3	0
Differences to observed diets, % [3]											
meat consumption	-	-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%	-90%	-100%
Poultry	-	50%	64%	77%	90%	103%	115%	128%	139%	142%	146%
Beef and veal	-	-25%	-36%	-47%	-58%	-69%	-79%	-91%	-100%	-100%	-100%
Pork and other meats	-	-100%	-	-	-	-	-	-	-	-	-
Pork and other non-ruminant meats	-	-100%	-	-	-	-	-	-	-	-	-
Lamb	-	-100%	-	-	-	-	-	-	-	-	-
Offal	-	201%	218%	225%	227%	232%	231%	239%	201%	91%	49%
Non-ruminant Offal	-	-100%	-	-	-	-	-	-	-	263%	306%
Ruminant offal	-	-87%	-88%	-88%	-89%	-90%	-90%	-91%	-91%	-92%	-92%
Processed meat	-	-87%	-88%	-88%	-89%	-90%	-90%	-91%	-91%	-92%	-92%
Non-ruminant processed meats	-	-100%	-	-	-	-	-	-	-	-	-92%
Ruminant processed meats	-	243%	221%	201%	183%	168%	154%	142%	130%	119%	-100%

SUPPLEMENTAL TABLE 9. Standardized dual values showing the relative influences of the limiting constraints in modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Males									
	Modeled diet with gradual meat reduction (%) [2]									
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Dual values of nutrient constraints [3]										
Vitamin A	1.92	0.20	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Vitamin C	0.41	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Iodine	2.19	0.21	0.22	0.26	0.34	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Sodium	**-7.36** [4]	**-1.38**	**-1.30**	-1.74	**-1.65**	**-1.42**	**-1.42**	**-1.68**	**-1.39**	**-1.20**
Water	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	0.02
Saturated fatty	-2.57	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
α-linolenic acid	4.09	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
EPA+DHA [5]	[0.001-0.01]	0.02	[0.001-0.01]	0.02	0.02	0.03	0.03	0.03	0.03	0.02
Sugar excluding	[0.001-0.01]	-0.03	-1.04	**-1.89**	-1.22	-0.05	-0.05	-0.04	-0.05	-0.05
Fiber	1.11	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

[3] Standardized dual values representing the potential effect on the objective function of a 100% relaxation of the limiting bound of the constraint considered, in order to classify the nutritional constraints from the most to the least limiting (*i.e.*, active). Limiting constraints have a positive (negative) value if the lower (upper) bound is binding. Only nutrients with a limiting constraint (*i.e.* a non-null dual value) are presented here. Dual values are indicated as [0.001-0.01] when values are between 10^{-3} and 10^{-2}.

[4] For each step, the most limiting constraint (*i.e.*, with the highest absolute value) is shown in bold.

[5] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.

SUPPLEMENTAL TABLE 9 cont. Standardized dual values showing the relative influences of the limiting constraints in modeled diets optimized to be healthier while taking account of dietary inertia [1] during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males and females (INCA3 survey, *n*=564 males and *n*=561 females)

	Females									
	Modeled diet with gradual meat reduction (%) [2]									
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Dual values of nutrient constraints [3]										
Vitamin A	1.96	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Vitamin C	0.76	0.28	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Iodine	6.73	0.17	0.14	0.20	0.90	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Sodium	**-7.43** [4]	**-1.18**	**-1.33**	**-1.48**	**-1.59**	**-1.21**	**-1.21**	**-1.25**	**-0.90**	**-0.80**
Water	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Saturated fatty acids	-4.03	-0.15	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
α-linolenic acid	3.94	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	0.09	0.09	0.09	0.08	0.08	0.07
EPA+DHA [5]	[0.001-0.01]	0.03	0.03	0.03	0.05	0.03	0.03	0.03	0.02	0.02
Sugar excluding lactose	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]
Fiber	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]	[0.001-0.01]

[1] Dietary inertia was modeled using the *Diet Departure* criterion.

[2] In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.

[3] Standardized dual values representing the potential effect on the objective function of a 100% relaxation of the limiting bound of the constraint considered, in order to classify the nutritional constraints from the most to the least limiting (*i.e.*, active). Limiting constraints have a positive (negative) value if the lower (upper) bound is binding. Only nutrients with a limiting constraint (*i.e.* a non-null dual value) are presented here. Dual values are indicated as [0.001-0.01] when values are between 10^{-3} and 10^{-2}.

[4] For each step, the most limiting constraint (*i.e.*, with the highest absolute value) is shown in bold.

[5] DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid.

SUPPLEMENTAL TABLE 10. Amounts of energy and certain nutrients (largely contributed by meat), in the meat food groups calculated as the weighted average of the consumption of these food items in males (INCA3 survey, *n*=564) [1]

	Males						
	Energy *kcal*	**Vitamin A** *µg*	**Riboflavin** *mg*	**Vitamin B6** *mg*	**Vitamin B12** *µg*	**Iron** *mg*	**Heme iron** *mg*
Nutrient content */100g of food*							
Poultry	169	11.0	0.2	0.5	0.7	1.2	0.3
Beef and veal	174	4.1	0.2	0.4	2.2	2.5	1.6
Pork and other non-ruminant meats	207	3.2	0.3	0.4	1.0	1.5	0.9
Non-ruminant offal	148	2391.1	1.1	0.3	11.1	10.0	2.6
Non-ruminant processed meats	246	325.3	0.3	0.3	1.1	1.9	0.7
Lamb	193	2.5	0.2	0.2	2.1	1.6	0.7
Ruminant offal	142	1526.0	0.5	0.3	13.6	2.2	1.1
Ruminant processed meats	283	69.4	0.2	0.2	1.5	2.0	0.4

[1] Data were calculated from the data extracted from the CIQUAL table *("CIQUAL," 2016)*. See Methods for detailed information.

	Males						
	Non-heme iron	**Selenium**	**Sodium**	**Zinc**	**Saturated fatty acids**	**Atherogenic fatty acids** [1]	**Protein**
	mg	*µg*	*mg*	*mg*	*g*	*g*	*g*
Nutrient content *per 100g of food*							
Poultry	0.9	14.3	179.2	1.6	2.0	1.5	26.9
Beef and veal	0.8	7.5	74.4	5.4	3.3	2.1	26.1
Pork and other non-ruminant meats	0.6	10.7	67.2	2.5	5.0	3.2	26.1
Non-ruminant offal	7.4	32.1	442.3	5.0	1.5	0.9	25.3
Non-ruminant processed meats	1.3	11.1	913.5	2.2	7.0	4.4	18.6
Lamb	0.9	8.6	69.7	4.3	3.8	2.3	26.4
Ruminant offal	1.2	16.0	200.7	2.5	2.2	1.3	19.4
Ruminant processed meats	1.6	5.0	927.0	3.2	12.0	6.6	19.9

[1] Atherogenic fatty acids, lauric and myristic and palmitic acids.

SUPPLEMENTAL TABLE 10 cont. Amounts of energy and certain nutrients (largely contributed by meat), in the meat food groups calculated as the weighted average of the consumption of these food items in females (INCA3 survey, *n*=561)

	Females						
	Energy *kcal*	**Vitamin A** *µg*	**Riboflavin** *mg*	**Vitamin B6** *mg*	**Vitamin B12** *µg*	**Iron** *mg*	**Heme iron** *mg*
Nutrient content */100g of food*							
Poultry	163	11.1	0.2	0.5	0.6	1.1	0.3
Beef and veal	184	3.5	0.2	0.4	2.2	2.6	1.7
Pork and other non-ruminant meats	213	1.8	0.2	0.3	0.8	1.2	0.8
Non-ruminant offal	150	4.6	0.2	0.1	5.6	7.7	3.1
Non-ruminant processed meats	232	248.6	0.3	0.3	0.9	1.7	0.6
Lamb	194	2.1	0.2	0.2	2.1	1.7	0.8
Ruminant offal	176	2832.9	1.1	0.5	18.3	4.1	2.0
Ruminant processed meats	282	68.9	0.2	0.3	1.5	2.0	0.4

Data were calculated from the data extracted from the CIQUAL table *("CIQUAL," 2016)*. See Methods for detailed information.

	Females						
	Non-heme iron	**Selenium**	**Sodium**	**Zinc**	**Saturated fatty acids**	**Atherogenic fatty acids** [1]	**Protein**
	mg	*µg*	*mg*	*mg*	*g*	*g*	*g*
Nutrient content *100g of food*							
Poultry	0.9	16.3	178.2	1.6	1.6	1.3	26.7
Beef and veal	0.9	7.1	77.7	5.5	3.8	2.4	26.0
Pork and other non-ruminant meats	0.4	13.4	54.2	2.5	5.4	3.3	26.7
Non-ruminant offal	4.6	31.8	704.8	5.1	1.3	0.9	27.7
Non-ruminant processed meats	1.0	10.5	880.7	2.2	6.5	4.0	18.4
Lamb	0.9	8.6	68.7	4.4	3.8	2.4	26.3
Ruminant offal	2.1	22.8	208.8	3.3	2.6	1.5	25.5
Ruminant processed meats	1.6	5.1	932.1	3.3	11.9	6.6	20.0

[1] Atherogenic fatty acids, lauric and myristic and palmitic acids.

Online Supplementary Material

SUPPLEMENTAL METHOD 1 Description of the methodological approach for the evaluation of environmental impact indicators

The environmental pressures associated with diets were estimated using indicators resulting from the matching of the 2497 foods items consumed in France with those of the French Agribalyse® 3.0.1 database developed by the French Agency for the Environment and Energy Management (ADEME) (Colomb et al., 2015).

Environmental indicator estimates were based on the Life Cycle Assessment (LCA) method whose scope is "from field to plate". The perimeter of the indicators covered each process in the value chain: production of raw materials, transport, processing, packaging, distribution and retailing, preparation by the consumer and disposal of packaging. These processes were split into two phases: 1) production and 2) post-farm. Of note, losses and waste (other than non-edible parts) at home, as well as transport from the retailer to the household, were not considered.

Overall, the method was based on international LCA standards: ISO 14040 (“iso.org,” 2006b) and ISO 14044 (“iso.org,” 2006a), LEAP guidelines (*FAO*, 2022) and PEF (European Commission, 2018) and the finalized indicators were given per kg of product and detailed by process.

For the agricultural phase of plant products, all upstream processes (notably input production) excluding storage or drying were included except for the ingredients in processed foods. In the case of animal products, all operations including production, transport and the storage of feed, the fattening of animals, milking, the construction and maintenance of buildings and machinery were considered. The scope chosen was consistent with those defined in GESTIM (Gac et al., 2011) and ecoinvent® (Nemecek and Kägi, 2007).

The LCI (life cycle inventory) data from AGRIBALYSE v3.0.1 covered the period 2005-2009, except for perennial crops (2000-2010). The variety of production systems was considered by applying coefficients based on the share of systems in national production. The allocation rules were varied and based on international recommendations as described by ISO 14040/14044 standards (“iso.org,” 2006a; “iso.org,” 2006b). In particular, allocations were developed in order to distribute organic nitrogen fertilizers and mineral fertilizers (P and K) between crop sequences. Biophysical allocations were used for animal production (milk versus meat). The biophysical models used for animal production and allocations by type of production are presented in the full report (Koch and Salou, 2020) according to AFNOR-BPX 30-323 (*AFNOR*, 2011) and in compliance with the ISO 14044 standard (“iso.org,” 2006b) following three rules in descending order: 1) avoid allocation, 2) : biophysical allocation and 3) economic allocation.

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A characterization method recommended by the European Commission (Environmental Footprint 3.0) translated the input and output flows of the inventory into impacts. For the background data (inputs in construction, raw materials, etc.) the ecoinvent® database was used to assess indirect emissions (off-field emissions). The full methodology and methodological choices have been described elsewhere (Koch and Salou, 2020).

The pathway from commodities to foods for consumption introduced coefficients relative to the edible share and economic allocations between co-products. The recipes were broken down into ingredients, and for feasibility reasons a threshold of 95% of the ingredients was applied. Similarly, in terms of the origins of the ingredients, a threshold of 70% coverage was used, followed by a standardization step. The methodology and methodological adaptations as a whole have been described elsewhere (Asselin-Balençon et al., 2020) and post-farm estimates were aligned with the PEF guidelines (European Commission, 2018).

A total of 14 midpoint indicators were available: climate change, ozone depletion, particulate matter, ionizing radiation (effects on human health), ecotoxicity, photochemical ozone formation (effects on human health), acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, land use, water use, resource use, minerals and metals and resource use, and fossils.

Concerning the indicators for foods consumed, and according to the guidelines of the PEF method (European Commission, 2018), a quality indicator (DQR) was provided and the AGRIBALYSE 3.0 database was reviewed and criticized by RIVM and GreenDelta as well as by French agricultural and agri-food technical institutes and "Peter Koch Consulting".

SUPPLEMENTAL METHOD 2. Description of the methodological approach to predict the absorption of iron and zinc from dietary intakes.

Because the absorption of iron and zinc is dependent on dietary factors, the requirements were based on bioavailable iron and zinc calculated from dietary intake using equations that predict their absorption.

We first of all considered heme iron (mainly present in red meat) and non-heme iron (present in other animal-based and plant-based foods)(Moretti, 2017). The following equation was used to determine the absorption of heme iron (Hallberg and Hulthén, 2000):

$$\text{Log Absorption (\%)} = 1.9897 - 0.3092 \times \log(\text{SF})$$

where SF is serum ferritin, which was set at 15 µg/L (*Anses*, 2021). A serum ferritin value of 15 µg/L corresponds to a lack of iron reserves and higher intestinal absorption, without any further functional impact (Walters et al., 1973). This value, when compared to 30 µg/L, enables a better estimate of iron absorption at marginal levels of iron intake.

For non-heme iron, we applied the following equation (Armah et al., 2013):

$$\text{Ln Absorption (\%)} = 6.294 - 0.709 \ln(\text{SF}) + 0.119 \ln(\text{C}) + 0.006 \ln(\text{MFP} + 0.1)$$
$$-0.055 \ln(\text{T}+0.1) - 0.247 \ln(\text{P}) - 0.137 \ln(\text{Ca}) - 0.083 \ln(\text{NH})$$

where SF is serum ferritin, which was also set at 15 µg/L, C is vitamin C (mg), MFP is meat, fish, and poultry (g), T is tea (number of cups), P is phytate (mg), Ca is calcium (mg), and NH is non-heme iron (mg).

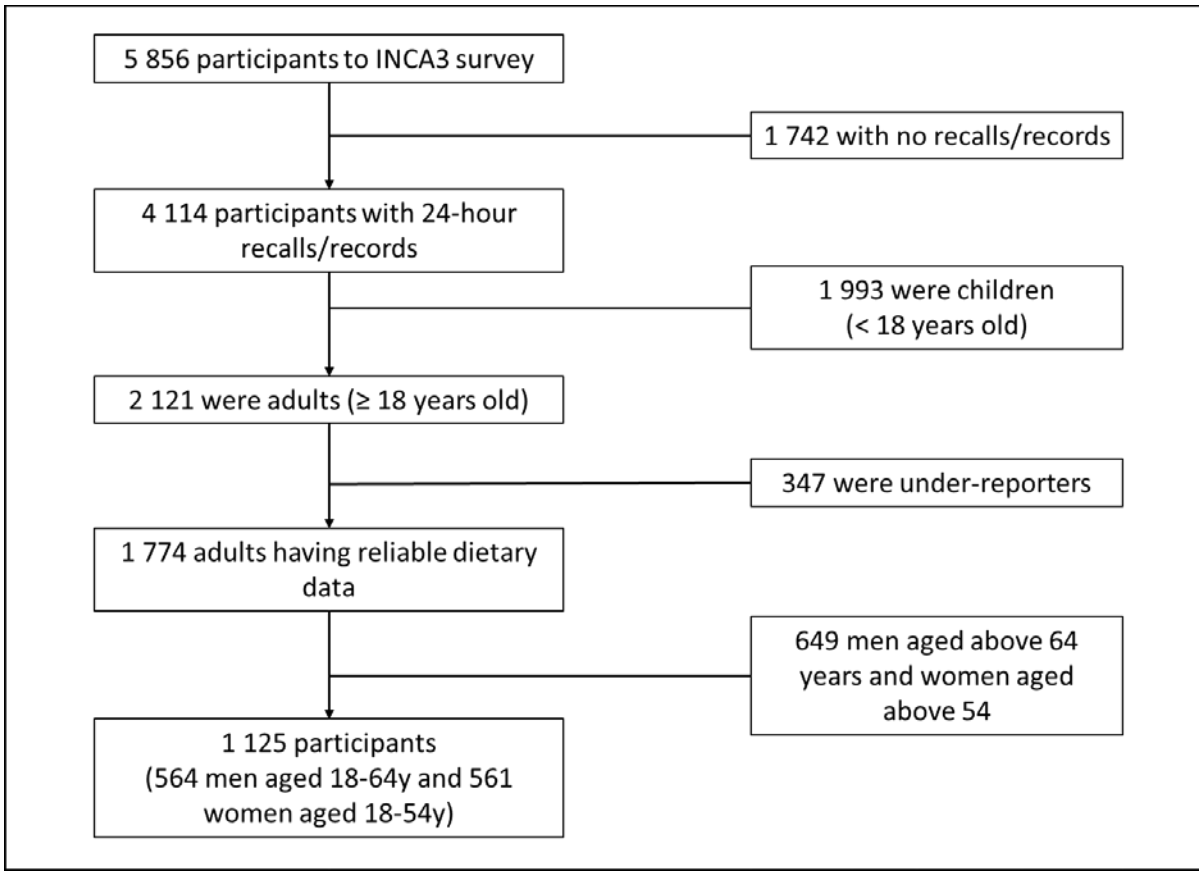
For zinc absorption, we used the following equation (*EFSA*, 2014):

$$\text{TAZ} = 0.5 \times \left\{ 0.033 \times \left(1 + \frac{\text{TDP}}{0.68}\right) + 0.091 + \text{TDZ} - \sqrt{\left(0.033 \times \left(1 + \frac{\text{TDP}}{0.68}\right) + 0.091 + \text{TDZ}\right)^2 - 4 \times 0.091 \times \text{TDZ}} \right\}$$

where TAZ is bioavailable zinc (mmol), TDZ is dietary zinc (mmol) and TDP is dietary phytate (mmol).

Online Supplementary Material

SUPPLEMENTAL FIGURE 1. Flow chart which explains the sampling of French participants from the third Individual and National Study on Food Consumption Survey (INCA3) for the present study



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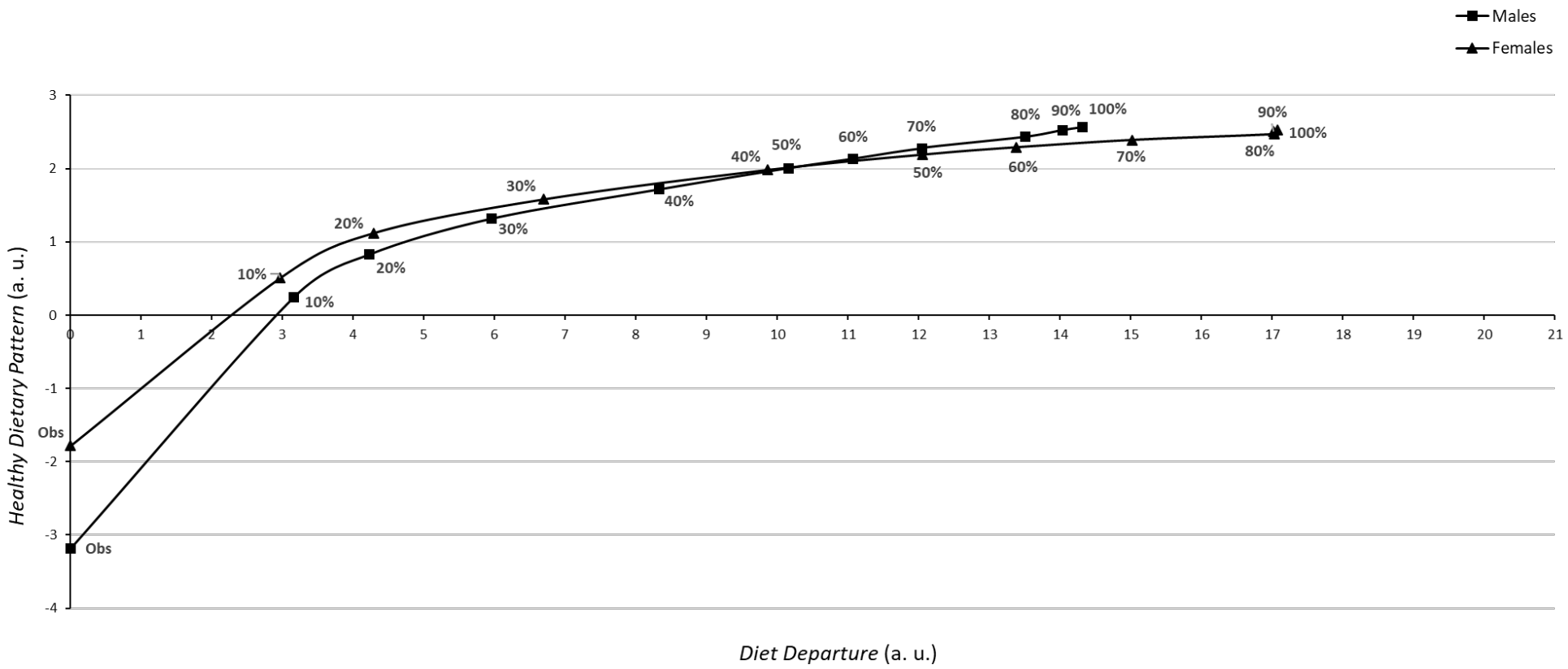
SUPPLEMENTAL FIGURE 2. Values of the *Healthy Dietary Pattern* (*HDP*) and *Diet Departure* (*DD*) criteria of the objective function of the initial observed diets and the diets modeled during a gradual reduction of ruminant meat consumption, in males and females

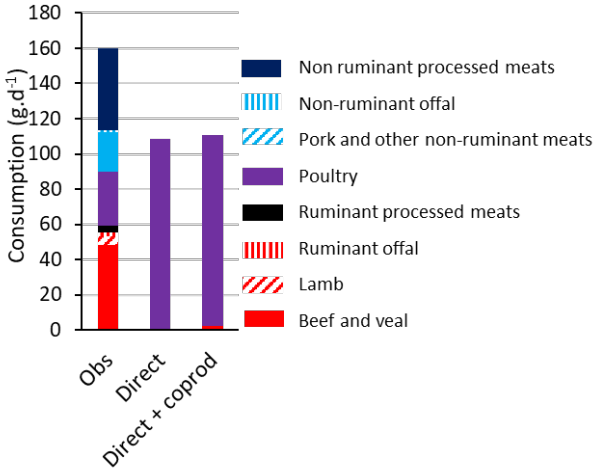


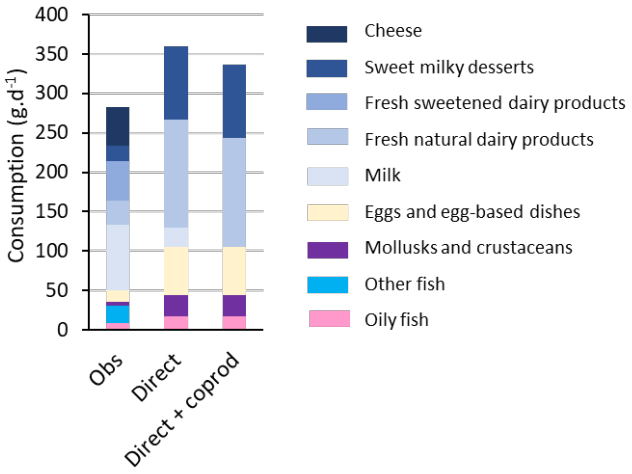
In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value.
a.u., arbitrary unit.

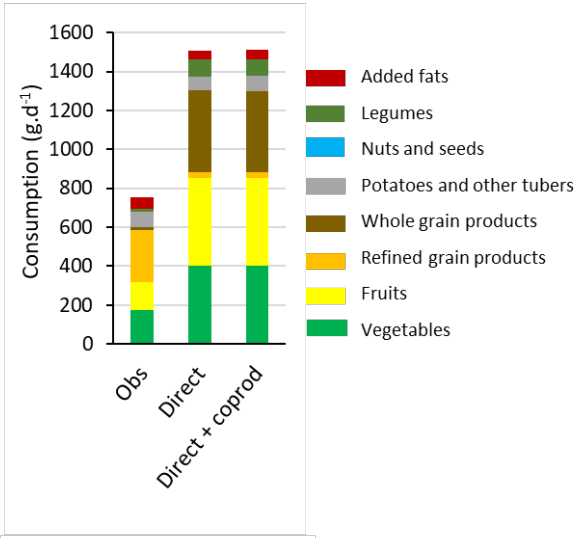
Online Supplementary Material

SUPPLEMENTAL FIGURE 3. Average daily consumption of plant- or animal-based food groups in observed (Obs) and modeled diets optimized to be healthier (direct scenario, “Direct”) or to be healthier with a coproduction link (direct scenario with a coproduction link, “Direct + coprod”) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

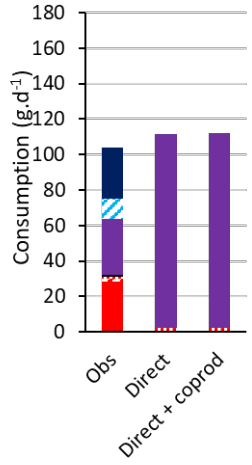
A. Males

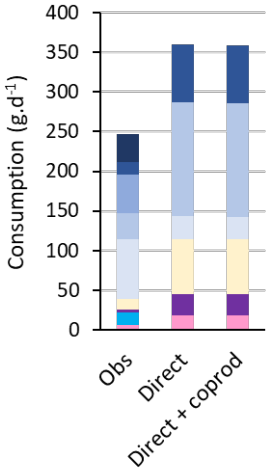


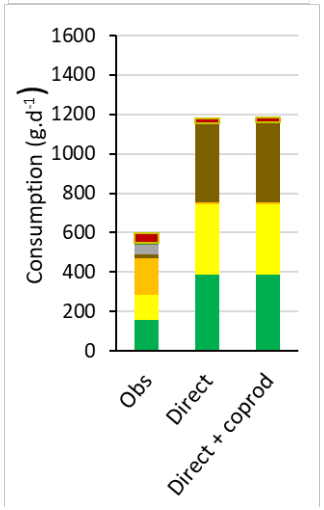




B. Females







Online Supplementary Material

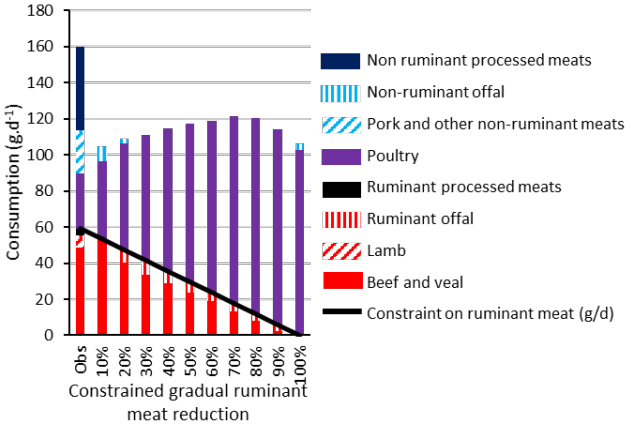
For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2. Here, coproduct factors were added for ruminant products based on the fact that 10 g beef corresponds to 1 L milk, 1 L milk to 1 kg fresh dairy products and 8 L milk to 1 kg of cheese, as previously described (Kesse-Guyot et al., 2021).

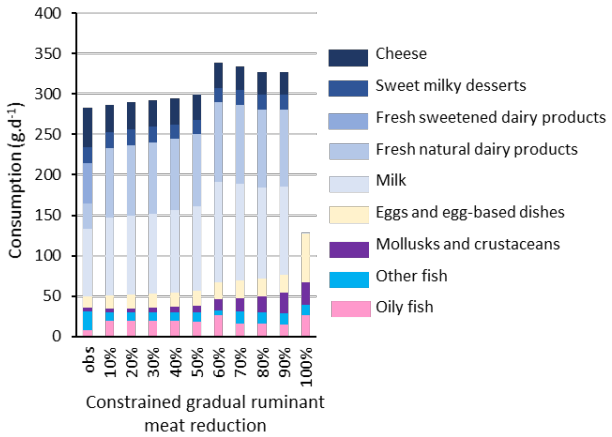
Online Supplementary Material

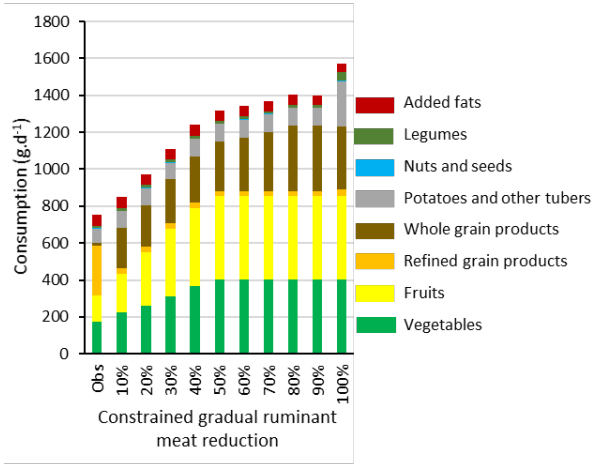
SUPPLEMENTAL FIGURE 4. Average daily consumption of plant- or animal- based food groups in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) with a coproduction link in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

Online Supplementary Material

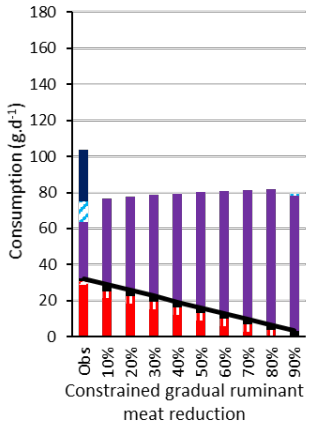
A. Males

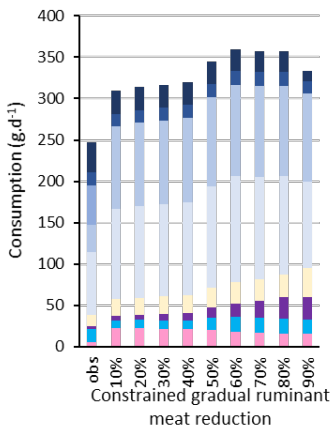


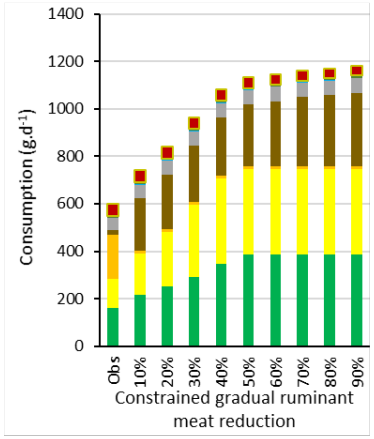




B. Females







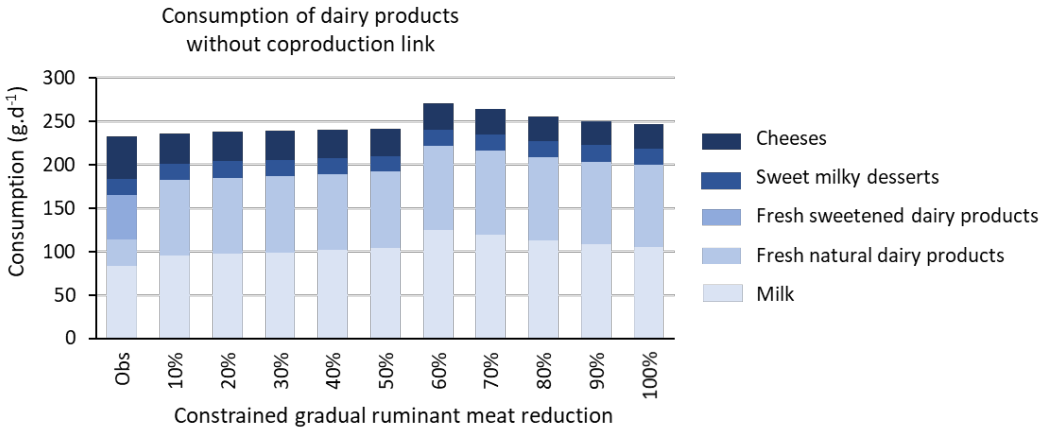
Online Supplementary Material

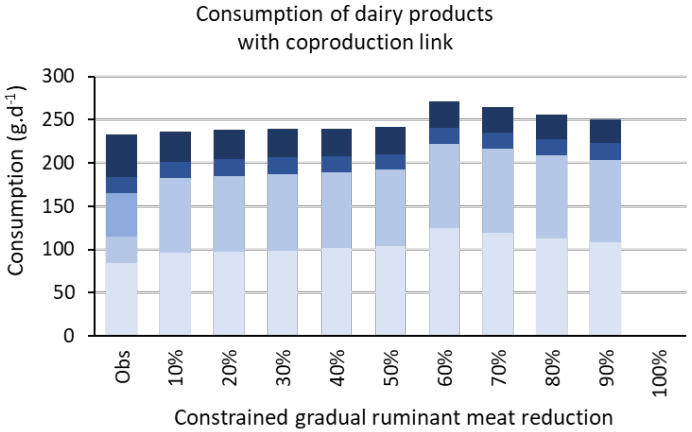
Dietary inertia was modeled using the *Diet Departure* criterion. In each x% modeled scenario, total ruminant meat consumption was reduced by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2. Here, coproduct factors were added for ruminant products based on the fact that 10 g beef corresponds to 1 L milk, 1 L milk to 1 kg fresh dairy products and 8 L milk to 1 kg of cheese, as previously described (Kesse-Guyot et al., 2021). In women, modeled diets could be identified up to the 90% step of the meat reduction transition. Beyond this step, a modeled diet could no longer be identified.

Online Supplementary Material

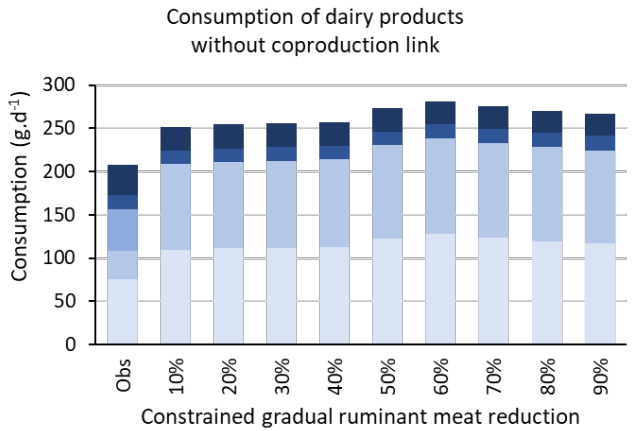
SUPPLEMENTAL FIGURE 5. Focus on the average daily consumption of dairy products in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) with a coproduction link in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

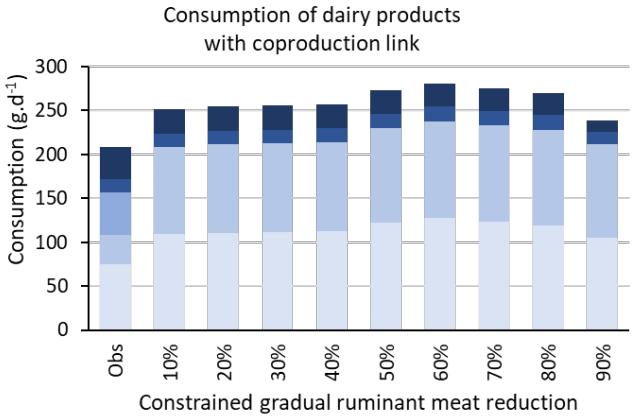
A. Males





B. Females





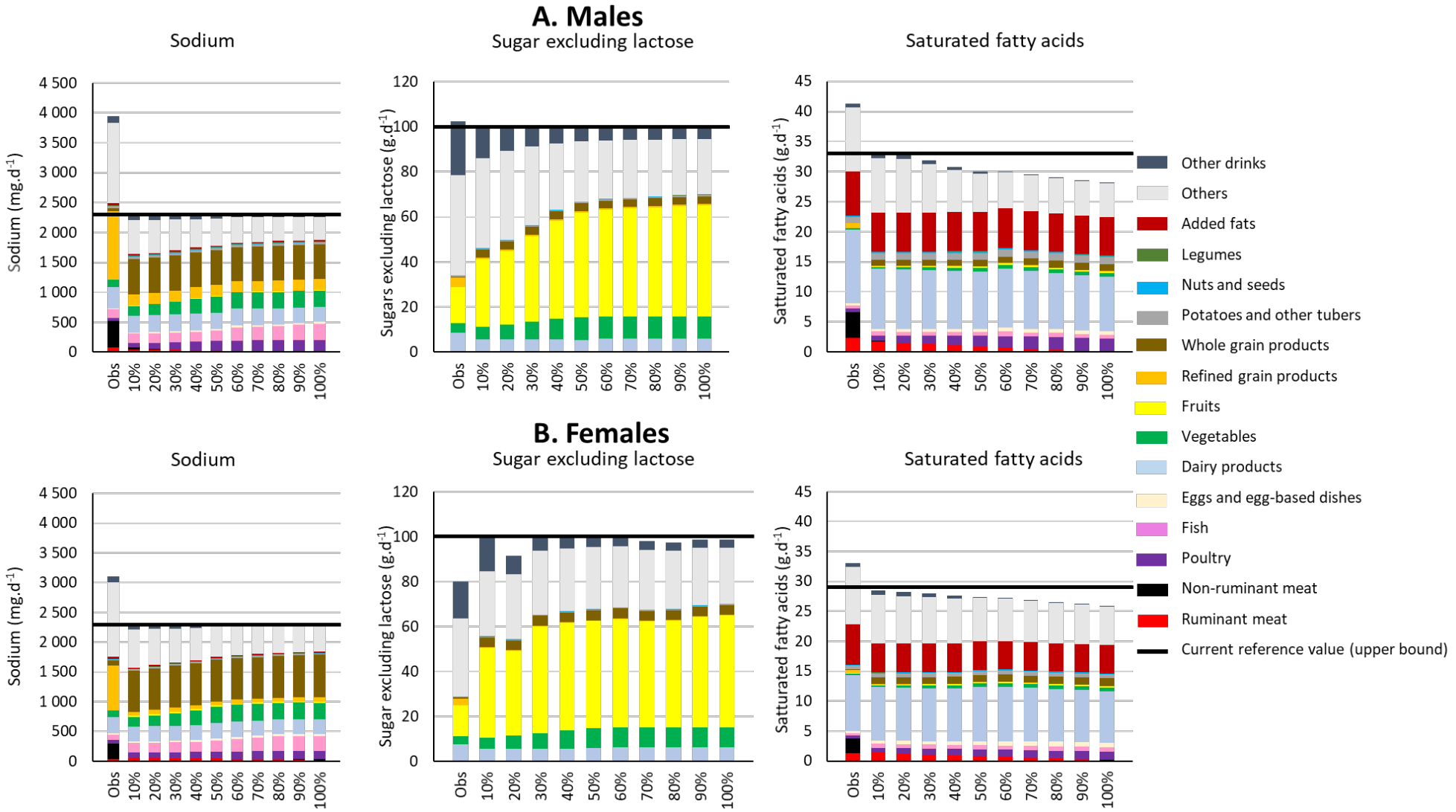
Online Supplementary Material

Dietary inertia was modeled using the *Diet Departure* criterion. In each x% modeled scenario, total ruminant meat consumption was reduced by x% of its observed value. Here, coproduct factors were added for ruminant products based on the fact that 10 g beef corresponds to 1 L milk, 1 L milk to 1 kg fresh dairy products and 8 L milk to 1 kg of cheese, as previously described (Kesse-Guyot et al., 2021). In women, modeled diets could be identified up to the 90% step of the meat reduction transition. Beyond this step, a modeled diet could no longer be identified.

Online Supplementary Material

SUPPLEMENTAL FIGURE 6. Contribution of food groups to sodium, sugar excluding lactose, and saturated fatty acids in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

Online Supplementary Material



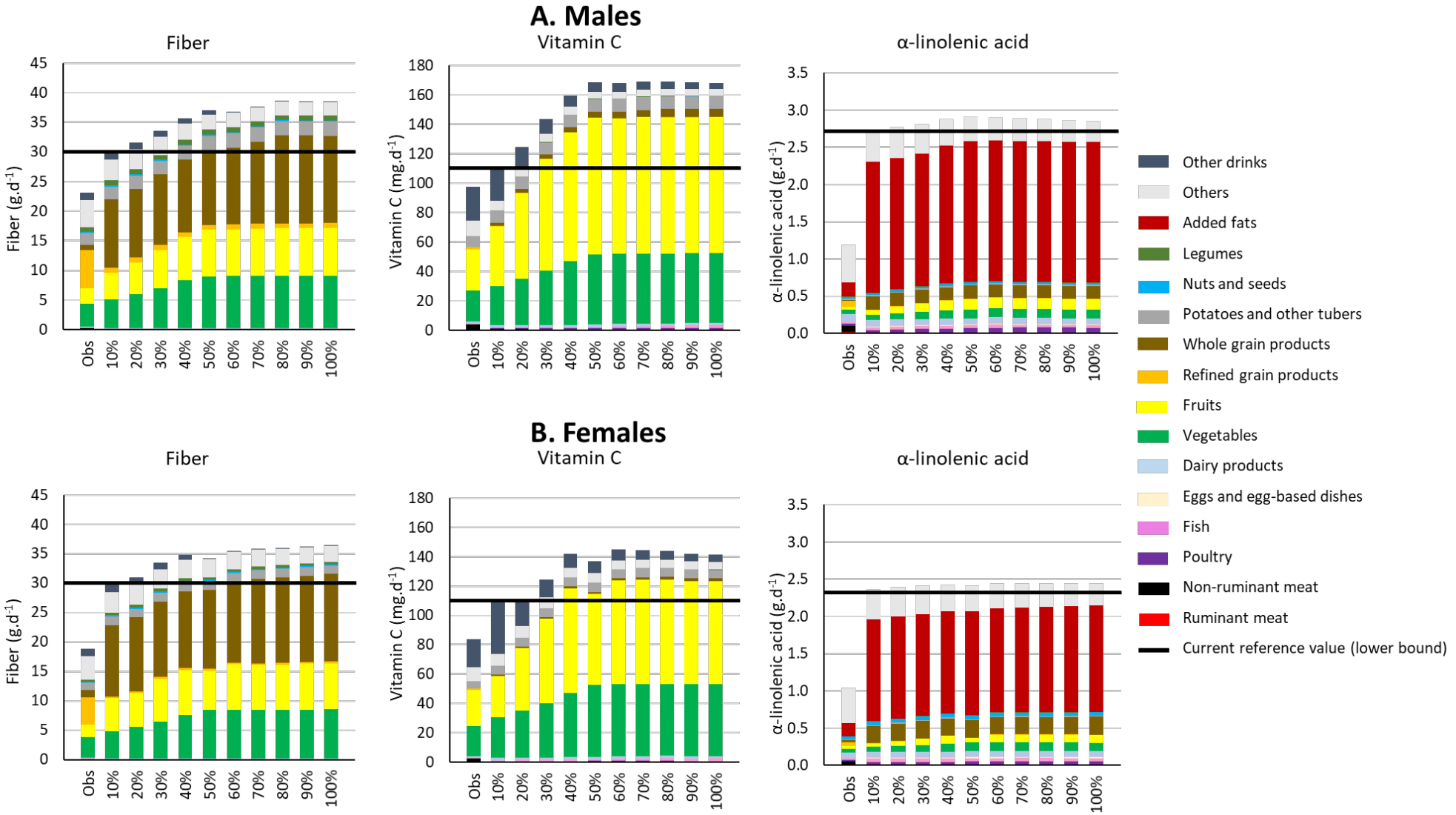
Online Supplementary Material

Dietary inertia was modeled using the *Diet Departure* criterion. In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2. For each nutrient, the current reference value is represented by a horizontal line.

Online Supplementary Material

SUPPLEMENTAL FIGURE 7. Contribution of food groups to fiber, vitamin C, and α-linolenic acid in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

Online Supplementary Material



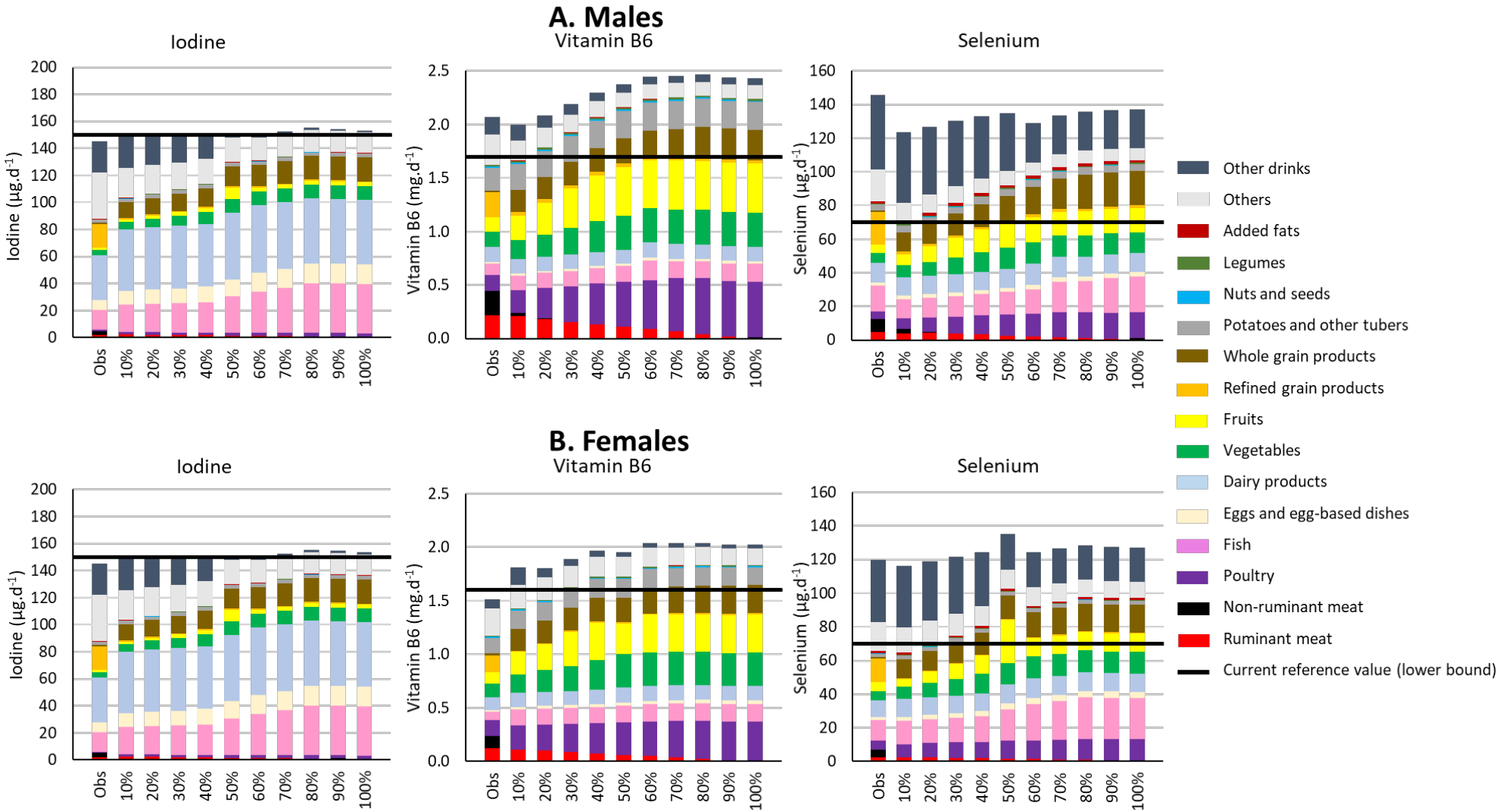
Online Supplementary Material

Dietary inertia was modeled using the *Diet Departure* criterion. In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2. For each nutrient, the current reference value is represented by a horizontal line.

Online Supplementary Material

SUPPLEMENTAL FIGURE 8. Contribution of food groups to iodine, vitamin B6, and selenium in observed (Obs) and modeled diets optimized to be healthier while taking account of dietary inertia during a gradual transition towards diets containing less ruminant meat (gradual scenario, by iterative steps of 10% reduction in ruminant meat up to 100%) in males (panel A) and females (panel B) (INCA3 survey, *n*=564 males and *n*=561 females)

Online Supplementary Material



Online Supplementary Material

Dietary inertia was modeled using the *Diet Departure* criterion. In each x% modeled scenario, total ruminant meat consumption was decreased by x% of its observed value. For clarity, all 48 modeled food groups are not shown here. Those not shown are presented in Supplemental Table 7 and detailed food categories are presented in Supplemental Table 2. For each nutrient, the current reference value is represented by a horizontal line.

References

AGRIBALYSE 3.0, the French agricultural and food LCI database, methodology for food products (collective expertise report), 2020. . ADEME, Paris, France.

Armah, S.M., Carriquiry, A., Sullivan, D., Cook, J.D., Reddy, M.B., 2013. A Complete Diet-Based Algorithm for Predicting Nonheme Iron Absorption in Adults. The Journal of Nutrition 143, 1136–1140. https://doi.org/10.3945/jn.112.169904

Asselin-Balençon, A., Broekema, R., Teulon, H., Aasvang, G.M., Houssier, J., Moutia, A., Rousseau, V., Wermeille, A., Colomb, V., 2020. AGRIBALYSE v3.0 : the French agricultural and food LCI database. Methodology for the food products.

BP X30-323-5 (Afnor EDITIONS), 2011.

Colomb, V., Amar, S.A., Mens, C.B., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., Werf, H.M.G. van der, 2015. AGRIBALYSE®, the French LCI Database for agricultural products: high quality data for producers and environmental labelling. OCL 22, D104. https://doi.org/10.1051/ocl/20140047

Dubuisson, C., Dufour, A., Carrillo, S., Drouillet-Pinard, P., Havard, S., Volatier, J.-L., 2019. The Third French Individual and National Food Consumption (INCA3) Survey 2014–2015: Method, design and participation rate in the framework of a European harmonization process. Public Health Nutrition 22, 584–600. https://doi.org/10.1017/S1368980018002896

Dussiot, A., Fouillet, H., Wang, J., Salomé, M., Huneau, J.-F., Kesse-Guyot, E., Mariotti, F., 2021. Modeled healthy eating patterns are largely constrained by currently estimated requirements for bioavailable iron and zinc – a diet optimization study in French Adults. The American Journal of Clinical Nutrition. https://doi.org/10.1093/ajcn/nqab373

European Commission, 2018. Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs) - version 6.3.

Online Supplementary Material

Gac, A., Cariolle, M., Deltour, L., Dollé, J.B., Espagnol, S., Flénet, F., Guingand, N., Lagadec, S., Gall, A.L., Lellahi, A., Malaval, C., Ponchant, P., Tailleur, A., 2011. GES'TIM – des apports pour l'évaluation environnementale des activités agricoles. Innovations Agronomiques 17, 13.

Hallberg, L., Hulthén, L., 2000. Prediction of dietary iron absorption: an algorithm for calculating absorption and bioavailability of dietary iron. The American Journal of Clinical Nutrition 71, 1147–1160. https://doi.org/10.1093/ajcn/71.5.1147

ISO 14040. Management environnemental — Analyse du cycle de vie — Principes et cadre [WWW Document], 2006a. . iso.org. URL https://www.iso.org/obp/ui/fr/#iso:std:iso:14040:ed-2:v1:fr (accessed 10.3.22).

ISO 14044. Management environnemental — Analyse du cycle de vie — Exigences et lignes directrices [WWW Document], 2006b. . iso.org. URL https://www.iso.org/obp/ui/fr/#iso:std:iso:14044:ed-1:v1:fr (accessed 10.3.22).

Kesse-Guyot, E., Fouillet, H., Baudry, J., Dussiot, A., Langevin, B., Allès, B., Rebouillat, P., Brunin, J., Touvier, M., Hercberg, S., Lairon, D., Mariotti, F., Pointereau, P., 2021. Halving food-related greenhouse gas emissions can be achieved by redistributing meat consumption: Progressive optimization results of the NutriNet-Santé cohort. Science of The Total Environment 789, 147901. https://doi.org/10.1016/j.scitotenv.2021.147901

Koch, P., Salou, T., 2020. AGRIBALYSE®: Rapport Méthodologique- Volet Agriculture- Version 3.0. ADEME, Angers, France.

Livestock Environmental Assessment and Performance (LEAP) Partnership, 2022. . Food and Agriculture Organization of the United Nations.

Mariotti, F., Havard, S., Morise, A., Nadaud, P., Sirot, V., Wetzler, S., Margaritis, I., 2021. Perspective: Modeling Healthy Eating Patterns for Food-Based Dietary Guidelines-Scientific Concepts, Methodological Processes, Limitations, and Lessons. Advances in Nutrition 12, 590–599. https://doi.org/10.1093/advances/nmaa176

Online Supplementary Material

Moretti, D., 2017. Plant-Based Diets and Iron Status, in: Vegetarian and Plant-Based Diets in Health and Disease Prevention. pp. 715–727.

Nemecek, T., Kägi, T., 2007. Life Cycle Inventories of Agricultural Production Systems Ecoinvent v2. 0, 361.

Opinion of the French Food Safety Agency on the benefits/risks of fish consumption (Collective expertise report), 2008. . French Agency for Food, Environmental and Occupational Health Safety (Anses), Paris, France.

Scientific Opinion on Dietary Reference Values for zinc, 2014. . European Food Safety Authority (EFSA), Parma, Italy.

The ANSES-CIQUAL food composition table [WWW Document], 2016. URL https://ciqual.anses.fr/# (accessed 6.22.21).

The nutritional guideline update for vitamins and minerals (Collective expertise report), 2021. . French Agency for Food, Environmental and Occupational Health Safety (Anses), Paris, France.

The Third Individual and National Survey on Food Consumption (INCA3 Survey), 2017. . French Agency for Food, Environmental and Occupational Health Safety (Anses), Public Expert Report 24. https://www.anses.fr/en/system/files/NUT2014SA0234Ra.pdf [cited 2021 Jun 22]

Walters, G.O., Miller, F.M., Worwood, M., 1973. Serum ferritin concentration and iron stores in normal subjects. Journal of Clinical Pathology 26, 770–772.