Nutritionally adequate and environmentally respectful diets are possible for different diet groups: an optimized study from the NutriNet - Santé cohort

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NutriNet-Santé cohort is registered at: https://clinicaltrials.gov/ct2/show/NCT03335644

Data availability: Data described in the manuscript, code book, and analytic code will be made available upon request pending application and approval. Researchers from public institutions can submit a collaboration request including information on the institution and a brief description of the project to collaboration@etude-nutrinet-sante.fr. All requests will be reviewed by the steering

committee of the NutriNet-Santé study. If the collaboration is accepted, a data access agreement will be necessary and appropriate authorizations from the competent administrative authorities may be needed. In accordance with existing regulations, no personal data will be accessible.

Abbreviations:

AS, adequation sub-score

cDQI, Diet Quality Index

CED, cumulative energy demand

GHGe, greenhouse gas emissions

LO, land occupation

M1, model 1

MF, Final Model

MS, moderation sub-score

Obs, observed situation

PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake

pReCiPe, partial ReCiPe

sPNNS-GS2: simplified Programme National Nutrition Santé guidelines score; observed diet;

PF, plant-based food

SFA, saturated fatty acids

Abstract

Background: While research has shown that vegetarian diets have a low environmental impact, few studies have examined the environmental impacts and nutritional adequacy of these diets together, although vegetarian diets can lead to nutritional issues.

Objectives: Our objective is to optimize and compare six types of diets with varying degrees of plant foods (lacto-, ovolacto- and pescovegetarian and diets with low-, medium- and high meat content) under nutritional constraints.

Methods: Consumption data in 30,000 participants are derived from the French NutriNet-Santé cohort using a food-frequency questionnaire. Diets are optimized by a non-linear algorithm minimizing the diet deviation while meeting multiple constraints at both the individual and population levels: non-increase of the cost and environmental impacts (as pReCipe accounting for greenhouse gas emissions, cumulative energy demand and land occupation, distinguishing production methods: organic and conventional), under epidemiological, nutritional (based on nutrient reference values), and acceptability (according to the diet type) constraints.

Results: Optimized diets were successfully identified for each diet type, except that it was impossible to meet the EPA+DHA requirements in lacto- and ovolactovegetarians. In all cases, meat consumption was redistributed or reduced and the consumption of legumes (including soy-based products), wholegrains, and vegetables were increased, while some food groups, such as potatoes, fruit juices and alcoholic beverages, were entirely removed from the diets. The lower environmental impacts (as well as individual indicators) observed for vegetarians can be attained even when nutritional references were reached except for long-chain omega 3 fatty acids.

Conclusions: A low-meat diet could be considered as a target for the general population in the context of sustainable transitions, although all diets tested can be overall nutritionally adequate, except for 3-n fatty acids, when planned appropriately.

Keywords: plant-based diets, diet optimization, vegetarians, meat consumers, nutritional references, sustainable diet, healthy diets

Introduction

Currently, westernized diets (i.e. characterized by high levels of sugar, saturated fat and salt) are associated with nutrition-related chronic diseases while, the healthiness of diets rich in plant-based foods is now well documented (1,2). Thus, worldwide, a total of 11 million deaths and 255 life years are attributable to dietary factors (2).

Moreover, current dietary patterns have significant detrimental effects on the environment as the production of current Western diets is a major contributor to greenhouse gas emissions (GHGe) and cause permanent damage to natural resources, many of which have already reached planetary limits (3). In that context, three pillars have been defined to limit the environmental impacts of food systems: improving agricultural practices, reducing waste and losses, changing dietary patterns and promote consumption of local and seasonal products (4,5). As regards dietary patterns, numerous observational and modelling studies have documented that diets richer in plant products have reduced environmental pressures compared to diets containing meat, with ruminant meat being a major determinant of emissions (6–13), regardless of the functional unit considered (10). A recent literature review (9) noted that compared to Western diets, an ovolactovegetarian diet resulted in a 35% reduction in GHGe, a 42% reduction in land use and a 28% reduction in water use. Vegan diets, compared to current western diets, performed even better, -49% and -49.5% for GHGe and land use respectively, but were associated with a higher water use (+17%).

There is thus an overall improvement towards better environmental indicators when increasing plant-based food consumption, from omnivorous to vegetarian and finally, vegan diets, with the exception of water use in vegan diets. For example, we documented, in an observational study, that the pReCiPe (a synthetic indicator integrating GHGe, energy demand and land use) was 61% lower in vegetarians compared to meat eaters (14).

However, these results are often derived from observational studies (comparison of different populations according to their types of diets) or from simulation studies, in particular from studies using substitution scenarios. Such observed or modelled diets may not be adequate from a nutrient point of view. For instance, a recent study comparing 11 typical diets representing habitual dietary habits showed that typical diets were not necessarily nutritionally adequate or environmentally-friendly (15). Furthermore, the different sustainability dimensions are rarely considered together, in particular because the economic dimensions is often lacking (9), although potential conflicts may arise between dimensions. While the lower environmental pressures associated with plant-based diets are well documented, meatless diets or diets devoid of any animal products may not provide adequate intake of some key nutrients provided by animal sources (16–18). To address the question of nutrient security, diet optimization is particularly suitable as it allows to impose meeting the nutritional references. However, studies have generally insufficient numbers of individuals following rarely adopted alternative diets (11). Although interesting from an environmental point of view, the vegan diet, characterized by a total exclusion of animal products, exhibits (in case of no dietary supplement) low or no intakes for nutrients mainly provided by animal products, such as EPA, DHA and vitamin B12, but also potentially calcium, iodine and bioavailable iron and zinc (19–21). For instance, a scenario study conducted in the Netherlands (22) showed that entirely replacing meat and dairy by plant-based foods drastically lowered environmental pressures (more than 40 %) but led to inadequate intakes of zinc, thiamin, vitamins A and B12, and calcium. Also, a 30 % reduction in animal foods led to improvement of saturated fatty acids, sodium, fiber and vitamin D intakes, and environmental pressures were lowered by 14 % leading the authors to suggest that replacing a part of animal foods was interesting concomitantly for environment and health.

Thus, the objectives of the present study are to identify for a spectrum of diets observed in a French cohort study, ranging from meat-rich diets to vegetarian diets, nutritionally adequate diets (by imposing the respect of nutritional constraints) and to compare optimized diet to the observed situation. Second, we analyze their environmental pressures and costs. We run sequential models to describe the trade-offs between nutritional, environmental and economic dimensions. Vegan diets is not considered in this study because some animal-specific nutrient requirements cannot be met through diet alone.

Methods

Population

This study is conducted on a sample of adults from the web-based prospective nutritional NutriNet-Santé cohort (23). The participants are volunteers recruited from the general French population. This study is conducted in accordance with the Declaration of Helsinki, and all procedures were approved by the Institutional Review Board of the French Institute for Health and Medical Research (IRB Inserm 0000388FWA00005831) and the National Commission on Informatics and Liberty (Commission Nationale de l'Informatique et des Libertés, CNIL 908450 and 909216). Electronic informed consent was obtained from all participants. The NutriNet-Santé study is registered in ClinicalTrials.gov (NCT03335644).

Sociodemographic and lifestyle data

Sociodemographic characteristics, including age, education (<high school diploma, high school diploma, and post-secondary graduate), lifestyles, i.e. smoking status (former, current, or never-smoker) and physical activity assessed using the International Physical Activity questionnaire (24) as well as anthropometrics (25), are collected using pre-validated questionnaires each year (26,27). We reported data closest to the FFQ (2014).

Dietary data collection and diet definition

The dietary data were collected in 2014 via a self-administered semi-quantitative food frequency questionnaire (FFQ), aiming to distinguish organic (under official label) and conventional food consumption (28). This tool is based on a previously validated 264 items food frequency questionnaire (29) improved by a five-point scale to evaluate the mode of production of food (30). For each food item, participants reported the frequency of food consumed as organic by ticking the following modalities: “never”, “rarely”, “half-of-time”, “often” or “always” in response to the question ‘How often was the product of organic origin?’. Weight was allocated to each modality, i.e. 0, 25, 50, 75 and 100%, respectively. Nutrient intakes were calculated using a published food composition table (31). Six groups of individuals with varying proportions of animal products are formed, corresponding to six diet types. Meat includes red meat, poultry, offal and processed meat.

Pescovegetarians are defined as participants consuming less than 1g/d of meat but consuming fish. Ovolactovegetarians are those consuming less than 1g/d of meat and seafood but consuming eggs, and lactovegetarians those consuming less than 1g/d of egg, meat and seafood but consuming dairies. Low, medium and high consumers of meat are defined as those having a total meat intake <50g/d, 50g/d to 100g/d and >100g/d, respectively.

To depict the overall quality of observed and modeled diets, the cDQI (comprehensive Diet Quality Index), the PANDiet (Diet Quality Index Based on the Probability of Adequate Nutrient Intake) and the sPNNS-GS2 (simplified Programme National Nutrition Santé-Guidelines Score 2) dietary indexes are computed.

The cDQI (range 0-85) is based on food group consumption and has been recently developed to assess the quality of the diet (32). It is composed of a vegetal sub-score (up to 55 points) and an animal sub-score (up to 30 points). For each sub-score, the components provide 0 to 5 points based on increasing thresholds for beneficial components and decreasing thresholds for non-beneficial components. Intermediate points are allocated for intermediate consumptions (32).

The PANDiet score is based on the probability of adequacy for 27 nutrients and fibers, based on nutrient intake or bioavailability, and the probability of moderation for 6 nutrients. In addition penalty values are given for 12 nutrients in the case of exceeding upper limits of intakes (33). The PANDiet score ranges from 0 to 100 points (a higher score reflects better adherence to the French nutrient-based recommendations and adequate nutrient intake (34)).

The healthiness of diet is estimated using the sPNNS-GS2 (35), a validated index aiming to estimate the adherence to the official French food-based dietary guidelines (36). The sPNNS-GS2 (theoretical range: $-\infty$ to 14.25), consists of 6 adequacy components and 7 moderation components, based on epidemiological evidence. The components are weighted according to the level of evidence for the associations with health and a penalty on energy intake is also given. The sPNNS-GS2 includes components related to fruit and vegetables, legumes, whole grain, nuts, fish, red meat, processed meat, sweet products, sweet beverages, added lipids, alcohol, dairy products, and salt. Scoring and computation have been extensively described elsewhere (35).

Environmental pressure data

Environmental indicators related to food-production are computed using life cycle analysis (LCA) using the DIALECTE database developed by Solagro (37), distinguishing organic and conventional farming. We considered GHGe (kg of CO_2 equivalents (CO_2eq)), cumulative energy demand (MJ), and land occupation (m^2). Downstream steps, including conditioning, transport, processing, storage or recycling stages, are not included in the perimeter of the LCA. Extensive details have been described elsewhere (38). Nuts are excluded from the analysis as environmental indicators are not available.

As regards environmental impacts, the pReCiPe (partial ReCiPe), a synthetic estimate of overall environmental impact based on GHGe, cumulative energy demand and land occupation per kg of diet, is computed. The pReCiPe, standardized by the consumption quantities, enables to consider potential trade-offs between indicators (39), and is calculated as follows (1):

$$(1)\quad pReCiPe = \frac{\sum_{i=1}^{n} 0.0459 \times Qte_i \times GHGe_i + 0.0025 \times Qte_i \times CED_i \times + 0.0469 \times Qte_i \times LO_i}{\sum_{i=1}^{n} Qte_i}$$

Where i is the number of foods consumed and Qte_i is the quantity of i which is consumed.

$GHGe_i$, in kg of CO_2eq/d, CED_i, in MJ/d and LO_i, in m^2/d are the GHGe, CED and LO to produce 1 kg of the food i. A greater pReCiPe reflects a higher environmental impact.

Economic data

A price database for each food item, accounting for the place of purchase collected concomitantly with food consumption and the type of farming method (organic or conventional), is computed based on the Kantar Wordpanel purchase database® (40) including 20,000 representative households and an *ad-hoc* collection in short food-supply chains (28).

Coproduct factor linking milk to beef

We consider a coproduct factor linking milk to beef as milk production is not possible without meat production. This is of particular interest in the present work since some types of vegetarian diets include dairy product intake. To do so, we use the following information:

- 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight) were produced in 2010 in France (41),
- 41% of beef was from dairy herd corresponding to 0.62 million tons of beef (42).

Postulating a meat to carcass weight ratio of 68%, 10% distribution losses, 32% losses at the consumer level (cooking, bones and wastes) (43), we apply the following equation (2):

(2) 25 million tons of milk (L) = 1.52 million tons of beef $\times$ 41% $\times$ $68\%_{carcass\ yield}$ $\times$

$$90\%_{distribution\ yield} \times 68\%_{preparation\ yield}$$

Leading to 1L of milk corresponding to 10g of beef.

In this study, the coproduction constraint linking beef and milk consumption is considered at the whole population level, i.e. accounting for all types of diets and their repartition.

Weighting of nutritional reference values

Due to significantly different physiological needs, the French nutritional reference values are established separately for males and females (34). Furthermore, a distinction is made between females with high and low iron requirements. We therefore derive new nutritional reference values, based on an average individual, consisting of 50% males and 50% females. In addition, for females, we further consider that 50% of females have low requirements and 50% have high iron requirements. The reference values for each nutrient for this average individual are therefore defined as the weighted average requirements of males, females with high and low iron (**Supplementary Table 1**).

Optimization model

Optimized diets are derived from each of the 6 observed diet types, using food item attributes, including nutritional composition, environmental indicators (GHGe, CED and LO to compute pReCiPe) and individual cost (as organic and conventional).

The optimized diets are identified using the procedure SAS/OR ® *optmodel* (version 9.4; SAS Institute, Inc.). A non-linear optimization algorithm with multistart is used to select a solution that is not only a local minimum, by modelling the 6 diet types concomitantly (to apply a beef-milk co-production constraint at the population level).

The objective function that we use aimed at minimizing the total deviation (TD) from the 6 observed diets, as follows (3):

$$(3)\ \text{Min TD} = \sum_{j}^{6}\sum_{i}^{257}\left[\frac{Opt_{i,j}-Obs_{i,j}}{SD_{i,j}}\right]^2$$

Where $Opt_{i,j}$ and $Obs_{i,j}$ respectively denote the optimized and observed daily consumptions of the food item (i) for the diet group (j), with $SD_{i,j}$ being its standard deviation in the observed situation.

A first model is computed under nutritional, epidemiological and coproducts constraints only (described below) – M1. As environmental pressures increase, a second model is performed imposing an additional environmental constraint which leads to increase in cost (from 3 to 6.4%). Thus, the final model includes both constraints, enforcing the cost of the diet and the pReCiPe below the observed values – MF.

The set of constraints was as follows:

-Nutritional references

The nutritional constraints, which include daily energy intake and a set of nutrients, are based on the upper and/or lower ANSES 2016 reference values (34). Lower bounds are defined as either recommended dietary allowance (population reference intake), adequate intake, or lower bound of reference range for the intake in the French population (34).

For adequate intake, based on observed mean intake, the lower limit is set at the 5^{th} weighted percentile value of the overall population. Upper bounds are defined as the maximum tolerable intakes for vitamins and minerals or the upper limit of the reference intake range. For zinc and iron, bioavailability is considered using published formula (**Supplementary Material**) (44,45). The reference values are shown in **Supplementary Table 1**.

Since no optimized diets could be found for lactovegetarian and ovolactovegetarian diets, we lower the constraint on EPA+DHA to half of the value (i.e. 0.25g/d).

-Epidemiological thresholds

To comply with official French dietary guidelines (36) the model imposes:

- Consumption of red meat ≤500g/week
- Consumption of processed meat ≤150g/week
- Consumption of fish = 2 portions/week, including one portion of fatty fish
- Consumption of fruit and vegetables ≥5 portions /day.

-Coproducts constraint

The optimization procedure is based on a double indexing considering the consumption of each food *i* and the indexed sub-populations *j* so that beef consumption of the three meat-consumers populations stayed in line with the dairy products consumption of the six diet groups. We keep the observed occurrence of the diets, which were 1.09%, 1.03%, 1.59%, 16.08%, 31.01% and 49.2% for lacto, ovolacto, pescovegetarians and low, medium, and high consumers of meat, respectively.

-Acceptability constraint

Acceptability constraints are defined at the consumed food group level, with upper bounds set at the weighted 95th percentiles values for each food group in each diet.

-Additional constraints for environmental pressures and cost

In the final model (MF), an environmental constraint imposes an optimized pReCiPe ≤ its observed value and a diet-related monetary cost ≤ its observed value.

For mean of observed food group consumption, nutrients intake as well as 5th and 95th percentiles (see below) values according to diet are also weighted so as to respect the male/female distribution/ratio defined above.

Statistical analysis

The baseline situation is based on data of the participants of the NutriNet-Santé study who had completed the FFQ between June and December 2014 (N=37,685), with no missing covariates (N=37,305), who are not under-energy reporters (N=35,196), living in mainland France (N=34,453) and with information as regards the place of purchase for the computation of the dietary monetary cost (N= 29,413). Finally, 87 vegans are removed from the sample for a total 29,326 individuals (**Supplementary Figure 1**). The sociodemographic, lifestyle characteristics of the six initial groups are estimated as mean (SD) or percentage. The observed and optimized diets, for each group, are described as food group consumption, nutrients intakes, dietary indexes, environmental pressures (GHGe, CED LO and pReCiPe), and monetary cost of the diet.

All statistical analyses are performed using SAS® (version 9.4; SAS Institute, Inc., Cary, NC, USA) and figures were performed developed using R version 3.6.

Results

Characteristics of the baseline study sample (weighted data)

The average age was 54.5 (SD=14.1) years old. High consumers of meat (>100g/day) were the most numerous (49%). The proportion of vegetarians of any type was 3.7%. The characteristics of the diet types are presented in **Table 1**. Low meat consumers had the lowest daily energy intake, while high meat consumers had the highest. The highest sPNNS-GS2 was observed in pescovegetarians and the lowest in high meat-eaters. The organic ratio was highest in lactovegetarians (62%) and lowest in high meat-eaters (23%) (**Table 2**). Many of the observed nutrient intakes were not in line with the nutrient references, whichever the diet considered (**Supplementary Table 2**). Note that in the observed situation, high and medium meat diets were too rich in saturated fatty acids and sodium. Conversely, total energy intake was rather low in all diet groups. Most diets did not provide enough EPA+DHA and bioavailable iron, and the intake of fiber was too low in all meat-eater groups.

Environmental impact of vegetarians was ¼ of that of high meat-eaters (**Table 2**). Low meat-eaters had an intermediate environmental impact. The highest diet cost was observed for the lactovegetarian diet, followed by the ovolactovegetarian and high meat diets.

Optimization of diets according to nutritional, epidemiological and coproducts constraints

The first model (M1) (**Figure 1**) (namely, without the environmental and price constraints and with the nutritional, dietary guideline and coproduct constraints) led to a restructuring of diets. In particular, milk and alcohol were excluded and intake of fruit juice was strongly reduced in all diets. Beef consumption increased for low and medium meat diets whereas pork consumption decreased and poultry and egg consumption increased for all meat diets. Dairy product consumption decreased for all diets except the lactovegetarian diet, where it increased.

For all diets, there was a large increase in the consumption of dried fruits, legumes, soy-based food, wholegrain products, vegetable oil, prepared dishes and beverages, while vegetable consumption increased only moderately. Overall, the consumption of other fat and dressing decreased in favor of vegetable oil consumption. Moreover, fruit and potatoes consumption decreased in all diets. In model M1, compared to the observed situation, the pReCiPe was increased from 17% (ovolactovegetarian diet) to 63% (medium meat diet).

Of note, no organic foods were selected (as the nutritional values used were the same for both farming system) (**Table2**).

Optimization of diets according to nutritional, epidemiological, coproducts constraints, pReCiPe and cost

In model MF, the addition of constraints on pReCiPe and diet cost (≤ observed values), led to some redistributions within only a few food groups (**Figure 1**, **Supplementary Supplemental Tables 3 and 4**) as strong changes were observed when imposing nutritional adequacy (M1). In particular, with regard to meat, compared to the model M1, a reduction of beef consumption was observed for the benefit of pork. Consumption of vegetables slightly increased while consumption of vegetable oil decreased, except for the high meat diet. In addition, consumption of potatoes was further reduced. Changes in individual environmental indicators are also presented (**Supplementary Figure 2**). Regarding nutrient intakes (**Table 3 and Supplementary Table 5**), by construction, the nutritional references were reached, except EPA+DHA in non-fish eaters who were at their lower target value (i.e. 0.25g). The percentage of proteins of plant origin fluctuated from 31% (high meat diet) to 76% (lactovegetarian diet) (**Table 3)**. The overall nutritional quality of the diet, as assessed by the different scores (**Table 2 and Figure 2**), varied from 53.14 (lactovegetarian diet) to 62.99 (pescovegetarian diet) for the cDQI, 74.68 (high meat diet) to 82.84 (pescovegetarian diet) for the PANDiet and, 6.08 (high meat diet) to 11.25 (lactovegetarian diet) for the sPNNS-GS2 in model MF. The nutritional and health constraints induced changes in nutritional profiles. In particular, saturated fatty acids decreased in high meat consumers and increased in ovo and lactovegetarians, while a strong increase of animal-based proteins in lactovegetarians and an increase of plant-based proteins in all diet groups, especially in small and medium meat diets, was observed. Strong increases of fiber, vitamin B12, and bioavailable iron and zinc were observed as well as a reduction of sodium in high meat consumers. High meat consumers benefited the most from the nutritional constraints with a 962% increase in sPNNS-GS2 while low meat consumers showed a 63% increase (**Table 2 and Supplementary Table 5)**.

Regarding the cDQI, which considers the quality of animal and vegetable products, the lacto- and ovolactovegetarian diets had the lowest scores and the pescovegetarian group had the highest score.

A reduction of diet monetary cost was observed in the final optimized model, ranging from -6% in medium meat diet to -26% in pescovegetarian diet. The lowest cost was observed for low meat consumers and the highest for lactovegetarians (**Table 2 and Supplementary Table 5**).

In model MF, that included the pReCiPe and cost constraints, organic foods were selected, but their proportion in the diet was much lower than in the observed situation, ranging from 5.9% in high meat diet to 8.80% in pescovegetarian diet.

Some limiting nutrients (elevated dual value) differed according to the diet (**Supplementary Table 6**), but bioavailable zinc and EPA+DHA were limiting in all diets.

Discussion

Using a multicriteria approach, we were able to identify optimized diets that comply with the French nutritional references, in line with the dietary recommendations, while maintaining constant diet monetary cost and environmental impact, for all the six diets studied.

Nutrient adequacy and diet quality

The scientific literature documenting potentially inadequate intakes of certain nutrients, in particular iron, zinc, vitamin A, and B6, among individuals following vegetarian diets and in particular in vegans is plentiful (16–18). In the present work, we were able to identify vegetarian diets with adequate nutrient intakes, similar to the diets of meat-eaters. One important exception was the intake of EPA+DHA in vegetarian diets excluding fish, for which we had to halve the target, since the principal vector (seafood) is not part of these diets. However, it should be born in mind, that due to missing values for some environmental indicators, nuts, which provide omega-3 ALA, were not considered in the optimization procedure.

In addition, the obtained diets appeared to be healthy, since they were in line with the PNNS guidelines in terms of food consumption. Adherence to the PNNS-GS has been indeed associated with long-term health benefits (46–48). This suggests that adequacy to most nutritional references is conceivable with meat-free diets but implies a high degree of restructuring within and between food groups, as illustrated by drastic modifications when compared to observed diets. However, such drastic modifications were also noted for the high-meat diet in order to reach the nutritional references.

It should be also noted that plant-based foods contain anti-nutritional factors that may result in lower bioavailability or digestibility of certain nutrients (49). We accounted for the bioavailability of iron and zinc using validated equations but similar considerations could be made for some other nutrients such as proteins. However, even when considering a lower digestibility of plant-based proteins, total protein intake remains higher when compared to recommended allowance (33).

In the present study, we also found that both observed and optimized low meat diets were both the healthiest and the cheapest as compared to diets of medium or high meat-eaters. Their PANDiet and PNNS-GS2 score levels were higher than those observed among medium and high consumers of meat in the observational settings. This is in line with previous studies documenting higher quality of plant-based diets compared to diets rich in meat (9,50,51).

Optimized food consumption

In the optimized diets, the rearrangement of the diets was characterized by an increase in legumes and soy-based products, and a decrease in dairy products. This is consistent with the literature documenting that legumes are an effective lever for transition towards sustainable diets (6,52). In addition, meat consumption was drastically reduced in high meat diet. Some food groups such as milk, fruit juice and alcoholic beverages were completely or almost completely removed from the diets, suggesting that these food groups were not the best vectors of micronutrients such as calcium or fibers. Our findings suggest that these diets should be carefully addressed to avoid micronutrient deficiencies. Among meat-eaters, poultry consumption increased while beef and pork decreased. In any case, for modelled diets for meat-eaters, total optimized beef and pork consumption reached levels below 75g per day, from 15g for low consumers to ≈70 for high consumers, in order to meet nutritional and epidemiological constraints. Thus, our results suggest that optimized diets of low meat consumers may comply with different sustainability dimensions, including nutritional/health, acceptability (as vegetarian diets would not be necessarily well accepted in the general French population), environmental and economic sustainability. This is of particular interest since low-meat diet might be accepted by a greatest number of people since vegetarian diets remain relatively uncommon in European countries (53). In Interestingly, the consumption of beef and pork in this group was close to the threshold recommended by the Eat-Lancet diet (52). Similarly, the consumption of wholegrain products, dairy products, vegetable oils, potatoes, poultry, vegetables and fish were within the target values of the Eat-Lancet diet. However, the consumption of pulses (including soy-based products as defined in the Eat-Lancet diet) were very high in our study but we considered soy-based beverages which contain a lot of water. Soy-based foods may be optimized diet of this group of low consumers of meat was also in line with the Mediterranean diet, whose sustainability has been consistently recognized (10,54,55). However, some adverse health effects of soy foods have been suspected (56). Thus, the models may need to be revised if the level of evidence increases.

Resources and environment

In the observed diets, a great variability was observed according to the diets with regard to the food production related environmental pressures and impact (which accounted for differential role of modes of production (organic or conventional)). The pReCiPe, reflecting environmental impact, was -73% lower for the lactovegetarian diet compared to the high meat diet. Of note, low meat consumers exhibited an intermediate level for the pReCiPe.

In previous observational studies, vegans and vegetarians exhibited far lower GHGe related to diet than consumers of meat (57–59). For instance, in a small study carried out in Italy, vegetarian and vegan diets had 34% and 40% lower GHGe, respectively, than omnivorous diets (57). Also, in a work by Scarborough et al., conducted in the EPIC-Oxford cohort study (58), medium meat-eaters, low meat-eaters, fish-eaters, vegetarians and vegans showed GHGe reduced by 22%, 35%, 46%, 47%, and 60%, compared to high meat-eaters.

Such findings based on observed situations, are consistent with the scientific literature, based on different scenarios, documenting that diets including small amounts or no animal products exert lower environmental pressures (7–9,13,60,61) than those of meat eaters, in particular with regard to GHGe, due to the large impact of animal food production (62). It is noteworthy that these estimates vary greatly, between -45% (61) and -70% (13), depending on the type of study (scenarios of substitutions or observational data), the choice of the substitutions made within the scenarios, and the baseline diet (particularly the level of meat consumption) within the observational studies. However, variations in environmental pressures and impacts associated with diet types may not be fully aligned with nutrient adequacy, as vegetarian diets with their lower impacts may be associated with some intake inadequacies. Optimization models have been widely used to identify sustainable or environmentally friendly diets (61), but such analysis has not been conducted by diet type. We identified only one modeling study using this type of modeling for various diet types. However, the study was not conducted in adults (63). This approach is very useful, however, because it allows us to highlight nutritional issues and identify dietary levers under nutritional constraints.

Multicriteria analysis

In our study, applying nutritional constraints led to an overall increase in environmental impact compared to the observed situation. This seems, although not strictly comparable, consistent with some studies documenting potential lack of alignment between dietary guidelines and environmental objectives (64). However, some studies have shown the opposite in specific countries such as Spain (65) and France (46). Concerning, monetary cost, findings are inconsistent. Some authors showed that diets following European dietary guidelines are more expensive than current diets (46,65,66) while one study argued that the Mediterranean diet can be inexpensive (67), and finally another study has found that the Western diet is expensive (68). We have shown here the ability to combine the sustainability dimensions to design healthy diets with costs and environmental impact below or equal to the observed situation.

Considering low meat consumers' diet, which corresponds to "flexitarian" diets (69), as of particular interest since, plant and animal farming have complementary and indispensable roles in healthy and sustainable food systems (5,70). Such a low meat diet has also been described as more sustainable than diet with elevated consumption of meat from a health perspective (71). Diets derived from the first model did not include organic foods because no constraints were set on this parameter and nutritional composition did not consider potential differences related to farming methods. In the final model, under cost and environmental impact constraints, some organic foods were introduced because they had lower environmental pressures as previously published (38). However, because conventional foods are overall cheaper than organic foods, the cost-constrained model favors conventional foods first. Thus, the proportions of organic food in the final diets were much lower than in the observed situation. This shows that among nutritionally adequate alternatives, those that modulate environmental and price pressures favor conventional foods, when toxicity aspects (e.g., exposure to synthetic pesticides) are not considered in the model.

In addition, the proportion of organic food was the highest for the low meat diet compared to the other studied diets, while the diet monetary cost was the lowest. Compared to the observed situation, at similar dietary monetary cost, organic foods were less represented as energy intake was far higher in modelled diets than the observed level due to the constraint. This is worth underlining since, compared to conventional farming, organic farming exhibits several benefits and notably contribute to an agroecological management of resources and environment preservation (72). It would be important to consider such factors in future diet modelling studies as well as indicators such as biodiversity, or water pollution (72–74) or toxicity. Frequencies and quantities of pesticide residues are indeed far more important in conventionally produced plant-based foods (75).We previously documented that plant-rich diets including only conventionally grown produce can lead to a strong increase in to pesticide residue exposure (76).

Limitations and strengths

Our study has limitations which should be emphasized. First, LCA were restricted to the production stage since post farm data were not available for the whole organic system. While the production is the main cause of environmental pressures (3), it would be also important to consider the pressures up to the plate. In addition, it is well documented that LCA misestimates some ecosystem services in particular for agroecological practices (77). In particular, nuts were excluded from the present analysis because environmental indicators were not available for these products even though they may be important vector of certain nutrients, especially for vegetarian diets. Second, our environmental analysis encompassed three major indicators (39) which, although important, did not allow to conduct a comprehensive analysis, in particular we did not have data on biodiversity loss. Finally, participants were volunteers, and therefore more concerned by nutritional and health issues. Thus, the observed diet (starting point of the optimization) was healthier, especially richer in plant foods, than that of the general population (28,78).

Nonetheless, the strengths of our study are multiple. We used a multicriteria approach including various parameters, including nutrition, consideration of coproduct factors, health, environment and sanitary indicators and we distinguished the organic farming system from the standard conventional farming system. Finally, the list of foods was highly detailed, allowing to select food items of particular nutritional interest. We also used a wide set of nutritional reference values,, including bioavailability for zinc and iron, which may be a nutritional issue in plant-based diets (79).

A wide range of proposals have been described to implement sustainable diets (52). Among these, actions should include the mobilization of consumers and more generally a transformation of the food systems by involving all the stakeholders. Policies should encompass measures aiming to guiding choices (by promoting sustainable dietary guidelines), but also policy measures aiming to restrict unhealthy choices (by providing economic support to sustainable system) and tax incentives and discouraging measures.

Conclusion

In this optimization study, it appears that vegetarian (including pescovegetarian) diets, which are more respectful of the environment and natural resources, can meet nutritional references, even for nutrients provided mostly by animal-based food sources (except for long-chain omega 3 fatty acids among non-fish eaters), but this requires appropriate food choices. Given the potential lack of acceptability of meatless diets by a large part of the population, a diet characterized by low meat consumption (29g/d including beef, pork and poultry, which corresponds to ≈1 serving/week) and a high amounts of vegetables, fruits, wholegrain products and legumes may be an acceptable trade-off for the general population, as it is close to the dietary guidelines, has a low monetary cost and has half of the environmental that the diet of high-meat eaters.

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Alexandre De Sa (dietitian), Rebecca Lutchia (dietitian)

The authors' contributions are as follows:

EKG, BA, BL, SH, DL, PP and JB, led the BioNutriNet project on which the data used.

EKG conducted the diet optimization and BA, HF, CB, CC and JB provided conceptual assistance in the context of SISAE project.

EKG wrote the statistical script, conducted analyses and drafted the manuscript.

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

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

Conflict of Interest

No author declared conflict of interest.

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Table 1: Description of the weighted sample, by diet group, NutriNet-Santé Study (n=29,326, 2014)[1]:

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
% of the sample	1.09	1.03	1.59	16.08	31.01	49.2
% Females	50	50	50	50	50	50
Age (y)	43 (14)	46 (14)	53 (13)	55 (15)	55 (14)	55 (14)
Body mass index (kg/m²)	21.99 (3.84)	22.93 (6.40)	22.29 (3.26)	23.04 (3.79)	24.15 (4.03)	25.32 (4.68)
Education (%)						
< High-school diploma	11.6	13.8	15.2	23.8	21.9	19.7
High school diploma	18.6	12.2	16.5	14.2	12.9	13.5
Postgraduate	69.8	74.1	68.3	62.0	65.2	66.9
Occupation (%)						
Unemployed	11.3	7.3	5.2	3.4	3.5	4.6
Retired	14.0	15.9	28.7	40.9	43.9	39.5
Employee, manual worker	18.6	17.4	16.5	13.5	11.0	10.6
Intermediate professions	12.3	13.1	14.6	13.9	12.7	13.4
Managerial staff, intellectual profession	25.8	28.7	24.6	21.1	22.7	24.4
Never employed	13.0	15.1	7.9	5.3	4.5	5.6
Self-employed, farmer	5.0	2.5	2.6	1.9	1.8	1.8
Physical activity level (%)						
Missing data	9.7	10.4	10.5	9.6	8.6	6.9
Low	15.7	18.1	20.2	17.1	10.9	12.1
Moderate	36.4	36.2	34.2	33.3	41.7	38.6
High	38.2	35.3	35.1	40.0	38.8	42.3
Tobacco status (%)						
Never smoker	55.0	46.4	44.1	44.6	46.5	48.3
Former smoker	36.8	39.6	44.9	44.0	44.4	42.6
Current smoker	8.2	14.1	11.1	11.4	9.2	9.1

Energy intake (kcal/d)	2073 (647)	1993 (582)	1964 (686)	1741 (573)	1845 (526)	2298 (650)
cDQI	47.06 (6.13)	50.03 (6.68)	54.98 (7.42)	51.71 (8.25)	48.28 (8.68)	45.40 (8.36)
PANDiet	72.54 (6.19)	68.92 (7.57)	70.65 (7.68)	68.53 (8.11)	66.99 (7.54)	62.09 (7.08)
sPNNS-GS2	5.64 (1.97)	5.58 (2.07)	5.72 (2.28)	5.05 (2.49)	3.70 (2.66)	0.57 (3.25)

Abbreviations: cDQI, Diet Quality Index, sPNNS-GS2, simplified Programme National Nutrition Santé-guidelines score

[1]All data are weighted as explained in the method section.

[2]Values are mean (SD) or % as appropriate. P-values across groups based on Chi^2 or ANOVA tests were <0.001 (not tabulated).

Table 2: Environmental and cost analysis for observed and modelled diets by diet group[1]

	pReCiPe[2]			Cost €/d			Organic (%)		
	Obs	**M1**	**MF**	**Obs**	**M1**	**MF**	**Obs**	**M1**	**MF**
Lactovegetarian	0.10 (0.04)	0.12	0.10	9.04 (4.98)	7.88	8.13	62 (29)	0	8.11
Ovolactovegetarian	0.12 (0.04)	0.14	0.12	8.09 (3.81)	6.79	7.00	59 (29)	0	6.77
Pescovegetarian	0.11 (0.04)	0.13	0.11	8.94 (4.77)	6.21	6.58	56 (31)	0	8.80
Low-meat	0.17 (0.07)	0.23	0.17	6.70 (2.89)	5.93	6.27	42 (31)	0	8.43
Medium-meat	0.24 (0.09)	0.39	0.24	6.95 (2.50)	6.21	6.53	30 (26)	0	6.14
High-meat	0.38 (0.18)	0.45	0.38	8.77 (2.91)	6.74	6.98	23 (23)	0	5.90

Abbreviations: M1, model 1; MF, Final Model; Obs, observed situation; pReCiPe, partial ReCiPe

[1]Values are means (SD) or optimized values

[2]The pReCiPe (partial ReCiPe) is a synthetic estimate of overall environmental impact based on greenhouse gas emissions (GHGe), cumulative energy demand (CED) and land occupation (LO) per kg of diet calculated as follows (1):

$$(1)\quad pReCiPe = \frac{\sum_{i=1}^{n} 0.0459\times Qte_i\times GHGe_i\ + 0.0025\times Qte_i\times CED\ _i\times + \ 0.0469\ \times Qte_i\times LO_i}{\sum_{i=1}^{n} Qte_i}$$

Where i is the number of foods consumed and Qtei is the quantity of i which is consumed. GHGei, in kg of CO2eq/d, CEDi, in MJ/d and LOi, in m2/d are the GHGe, CED and LO to produce 1 kg of the food i. A greater pReCiPe reflects a higher environmental impact.

Table 3: Nutritional analysis and quality indexes for each modelled diet [1]

	Lactovegetarian	Ovolactovegetarian	Pescovegetarian	Low-meat	Medium-meat	High-meat
Nutrients						
Energy Intake (Kcal/d)	2317	2312	2158	2127	2151	2300
SFA (g/d)	23.63	29.51	25.62	28.12	28.69	30.67
Animal protein (g/d)	24.97	33.72	28.94	43.96	61.09	83.55
Plant protein (g/d)	79.14	68.09	63.90	51.31	43.19	38.12
% Protein from PF	76.02	66.88	68.82	53.86	41.42	31.33
DHA+EPA (g/d)	0.25	0.25	0.50	0.50	0.50	0.50
Selenium (µg/d)	99.82	99.28	91.51	85.61	81.71	89.46
Potassium (g/d)	4772	4430	4266	3854	3839	3976
Calcium (mg/d)	1410	1415	1334	1473	1420	1426
Vitamin A (µg/d)	1260	1348	1190	1123	1302	1868
Vitamin B6 (mg/d)	2.95	2.93	2.68	2.29	2.38	2.54
Vitamin B9 (µg/d)	788.17	701.50	648.48	510.47	506.24	503.65
Vitamin B12 (µg/d)	4.49	4.85	5.22	6.45	7.74	12.76
Bioavailable zinc (mg/d)	3.58	3.66	3.53	3.71	3.95	4.34
Bioavailable iron (mg/d)	2.01	1.95	1.91	1.95	2.15	2.54
Fiber (g/d)	50.92	44.73	45.70	35.20	32.88	30.00
Sodium (mg/d)	2300	2300	2300	2300	2300	2300
Dietary Indexes						
cDQI	53.14	56.04	62.99	60.13	61.35	61.06
PANDiet	82.47	71.02	82.84	82.18	79.18	74.68
AS	91.87	92.46	95.20	95.21	95.03	95.37
MS	73.06	49.58	70.47	69.16	63.32	54.00

PNNS-GS2	11.25	8.75	10.75	8.25	7.75	6.08

Abbreviations: AS, adequation sub-score; cDQI, diet quality index; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; MS, moderation sub-score; sPNNS-GS2: simplified Programme National Nutrition Santé guidelines score; PF, plant-based food; SFA, saturated fatty acids.

[1]Values are optimized values of the final model under nutritional, cost and pReCiPe Constraints

Figure 1: Food group consumption for each observed and optimized diets, by diet group[1,2]

Abbreviations: M1, first model; MF, final model; Obs, observed diet; SFF, sweet and fat foods.

[1]Food group consumption (g/d) in the observed diets (red) and in the modelled diets are nutritionally, culturally and environmentally optimized so as to ensure gradual increase in the proportion of energy intake from plant-based foods. M1 (green) is the first model under nutritional, epidemiological and coproduction constraints. MF (blue) is the final model including constraints on pReCiPe and cost (below the observed values).

[2]Dairy products include yogurts, fresh cheese and cheese and milk consumed with tea/coffee; fish includes seafood, cereals include breakfast cereals with no added sugar, bread semolina, rice and pasta; fruits include fresh fruit, fruit in syrup and compote, dried fruit and seeds; potatoes include potatoes and other tubers; soy-based foods include tofu, soy meat substitute and vegetable patties, soy yogurt, soy milk; vegetables include all vegetables and soups; oil includes all vegetable oils; other fats include fresh cream and butter; prepared dishes include sandwich, dishes such as pizza, hamburger, ravioli, panini, salted pancake; sweet and fat foods (SFF) include croissants, pastries, chocolate, biscuits, milky desserts, ice cream, honey and marmalade, cakes, chips, salted oilseeds, salted biscuits; and beverages include fruit nectar, syrup, soda (with or without sugar), plant-based beverages (except soy-based drinks).

Figure 2: Dietary scores for observed and optimized diets, by diet group

Abbreviations: cDQI, diet quality index; M1, first model; MF, final model; Obs, observed diet; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; sPNNS-GS2, simplified Programme National Nutrition Santé-Guidelines Score 2