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Emmanuelle Kesse-Guyot[1], Hélène Fouillet[2], Julia Baudry[1], Alison Dussot[2], Brigitte Langevin[5], Benjamin Allès[1], Pauline Rebouillat[1], Joséphine Brunin[1,6], Mathilde Touvier[1], Serge Hercberg[1,3], Denis Lairon[4], François Mariotti[2], Philippe Pointereau[5]

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

[2] UMR PNCA, AgroParisTech, INRAE, Université Paris-Saclay, 75005, Paris, France

[3] Département de Santé Publique, Hôpital Avicenne, 93017 Bobigny, France

[4] Aix Marseille Université, INSERM, INRAE, C2VN, 13005 Marseille, France

[5] Solagro, 75, Voie TOEC, CS 27608, F-31076 Toulouse Cedex 3, France

[6] ADEME, Agence de l'Environnement et de la Maîtrise de l'Energie), 49004 Angers, France

Correspondence: Email: e.kesse@eren.smbh.univ-paris13.fr

Equipe de Recherche en Epidémiologie Nutritionnelle (EREN)

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

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Abstract *300 words*

Background: Diet-related greenhouse gas emissions (GHGe) mainly comes from animal-sourced foods. As progressive changes are more acceptable for a sustainable food transition, we aimed to identify nutritionally adequate and culturally acceptable optimized diets ensuring a gradual reduction in GHGe, using observed diet from a large sample of French adults, while considering the mode of food production (organic *vs* conventional farming) and the co-production link between milk and beef.

Material and method: Based on the consumption of 257 organic and conventional foods among 29,413 participants (75% women, age: 53.5±14.0y) of the NutriNet-Santé study, we modelled optimal diets according to GHGe reduction scenarios in 5% steps, from 0 to 50% with nutritional, acceptability, and coproduct constraints, for men, premenopausal and menopausal women separately.

Results: Gradual GHGe decrease under these constraints led to optimal diets with an overall decrease in animal foods, with marked reductions in dairy products (up to -83%), together with a stable but largely redistributed meat consumption in favor of poultry (up to +182%) and pork (up to +46%) and at the expense of ruminant meat (down to -92%). Amounts of legumes increases dramatically (up to +238%). The greater the reduction in diet-related GHGe, the lower the cumulative energy demand (about -25%) and land use (about -43%). The proportion of organic food increased from ~30% in the observed diets to ~70% in the optimized diets.

Conclusion: Our results suggest that meeting both nutrient reference value and environmental objectives of up to 50% GHGe reduction requires the reduction of animal foods together with important substitutions between animal food groups, which result in drastic reductions in beef and dairy products. Further research is required to explore alignment with long-term health value and conflict with acceptability, in particular for even greater GHGe reductions.

1. Introduction

The current environmental crisis, beyond the irreversible damage to natural resources, is characterized by climate change and global warming (defined as the increase of both air and sea surface temperature over a long period of time (>30 years)). Thus, anthropogenic global warming in 2017 was +1°C compared to pre-industrial levels (1850-1900), *i.e.* about 0.2°C per decade (1).

Food systems are responsible for about 30% of global greenhouse gas emissions (GHGe) (2) and are major users of fresh water, therefore largely contributing to climate change (3). Unless action is taken in the next decades, various prospective scenarios have estimated that, by 2050, unsustainable diets will lead to an additional 80% rise in GHGe compared to the current situation (4). To mitigate climate change below 1.5°C, some scenarios have documented that halving agricultural carbon footprint by 2050 would be necessary (5) and this would require strong dietary changes on a global scale (6).

The scientific literature about GHGe related to dietary patterns, based on optimization-based modelling and observational data, is growing and is consistently reporting that plant-based diets exhibit lower GHGe compared to those rich in animal products (7–10). Plant-based dietary patterns can also help to prevent chronic diseases (3,11–14), underlying co-benefits of plant-based diets for climate mitigation and human health promotion. Clark et al. (14) have documented, based on metadata, that beneficial foods for health, apart from fish, generally exhibit lower environmental pressures, encompassing GHGe, acidification, eutrophication, land and water use. Conversely, some foods which could be detrimental for health, such as red meat and processed meat (associated with increased risk for various health outcomes, including mortality and morbidity due to coronary heart diseases, stroke, diabetes and colorectal cancer), are also the highest contributors to diet-related GHGe and large variations in GHGe exist across food groups (14).

However, the question of how to achieve changes in dietary behavior including a reduction in meat consumption and more generally animal-based food has not been resolved (15). Indeed, food choices are diverse and based on multiple influencing factors which may constitute barriers (15,16). Thus, the strategies accompanying the transitions towards greater sustainability and in particular lower GHGe should be multiple and adapted to different types of consumers (17). We may hypothesize that among traditional high meat consumers, a first step of the transition can be based on intra-food group substitutions, especially due to cultural traits that hinder large reduction in meat consumption (18,19). For instance, in France, a previous study modelled a gradual reduction in GHGe and showed that a 30% reduction was possible without drastically deviating from the current diets while respecting nutritional constraints and diet cost (20). Among the gaps in existing studies we can mention the following. First, most modelling studies used GHGe as constraints or objective function (10) but few have considered other environmental indicators in their analysis - as descriptors, constraints or objective - despite the fact that some conflicts are known to occur among the different environmental dimensions, which are related to the general organization of the food system, such as energy demand and land occupation (21). Besides, few studies have distinguished conventional and eco-friendly production systems, as the data are generally based on life cycle assessment (LCA) for generic foods. Although organic farming has not been systematically related to lower GHGe, energy demand is lower while land use is higher compared to conventional agriculture (22,23). In a previous work based on observational data distinguishing between organic and conventional diets, we observed that diets with high GHGe were higher in animal-based food, more caloric and nutritionally less healthy (24). Thus, the role of various food systems on environmental pressure has not been yet considered enough (25). Finally, food systems also include some important structural determinants of food production, such as the fact that co-productions rules are often operating, as for milk and beef meat productions, but is rarely considered (26–28).

We can hypothesize that transitions to sustainable diets will require to activate all the levers and substitution is one of them. Thus, the objective of this study was to test whether the possibility to reduce GHGe of production by 50% as defined in the Paris agreement (29) in a set of culturally acceptable diets. We modelled dietary pattern characteristics with gradual decreasing GHGe under nutritional, coproduction and acceptability constraints and to relate these dietary patterns to other environmental indicators while considering two different food production systems, organic and conventional.

2. Methods

2.1 Population

The population included adults participating in the ongoing web-based prospective NutriNet-Santé cohort initiated in France in May 2009 (and on-going) whose aim is to investigate relationships between nutrition and health (30). Participants are recruited on a voluntary basis 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). At baseline and every year thereafter, participants provide data about their sociodemographic and economic status, anthropometrics, lifestyles and dietary intakes through self-administered questionnaires. They are also regularly invited to fill in complementary questionnaires.

2.2 Sociodemographic and lifestyle characteristics

Participants completed regularly validated questionnaires about sociodemographic and lifestyle features (31,32), thus data from the sociodemographic questionnaires that were the closest to the dietary questionnaire were used. Sociodemographic and lifestyle characteristics encompassed gender, age, education (<high school diploma, high school diploma, and post-secondary graduate), smoking

status (former, current, or never-smoker), and physical activity assessed using the International Physical Activity questionnaire (33).

2.3 Dietary data assessment

The present study is based on dietary data collected through a self-administered validated semi-quantitative food frequency questionnaire (FFQ), administered from June to December 2014. This questionnaire has been enriched by a five-point ordinal scale for each of the 264 food and beverage items to evaluate the share of organic food consumption (under official labels) (34). Organic production is one of the official signs of quality and origin in France. This method is governed by a European regulation since 1991, with the overall objectives of ensuring respect of the environment, biodiversity and animal welfare (35) recently updated (EU regulations 2018/848 and 2020/464 coming into force in January 2022. More specifically, for each item, participants were asked 'How often was the product of organic origin?' with the following answer modalities: "never", "rarely", "half-of-time", "often" or "always". This questionnaire developed within the frame of the BioNutriNet project has been extensively described elsewhere (22). Organic food consumption was estimated by allocating the respective weights: 0, 25, 50, 75 and 100 to the modalities. For clarity purpose, food and beverage items were grouped into 16 food groups as presented in **Appendix A**. Nutrient intake were calculated using a published food composition database (36).

2.4 Environmental pressure indicators

Environmental indicators were assessed using the DIALECTE tool, established by Solagro (Toulouse, France) (37), whose aim is to evaluate environmental impacts of French farming systems using attributional life cycle analysis (LCA) without considering land use change. The perimeter of LCA was restricted to the agricultural production phase (conditioning, transport, processing, storage or recycling stages were not considered). Upstream processes were therefore included in the assessment, such as input production or energy supply. Three environmental indicators were considered at the farm level: the GHGe measured as kg of CO_2 equivalents (CO_2eq), the cumulative energy demand (CED) in MJ, and the land occupation expressed in m^2 for >60 raw products (24). The original database has been completed by other data sources that have been previously listed (24), to obtain environmental pressures in organic and conventional of 92 raw agricultural products covering the 264 food items. Data have been published elsewhere (24). Environmental pressures of the FFQ food items as consumed were retrieved from the 92 raw agricultural products by using a set of conversion coefficients (economic allocation (accounting for co-products) and cooking and edibility coefficients.

Coproduct factors for ruminant products

We considered a meat to carcass weight ratio of 68% (38), and further yields of 90% during distribution (due to 10% distribution losses) and 68% during consumption (due to 32% losses by cooking, bones and wastes) (38).

In 2010 in France, 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight) (5) were produced, of which 41% was from dairy herd, i.e., 0.62 million tons of beed (39). Thus, 1L of milk corresponded to 10g of beef when applying the equation (1):

$$(1)\ \ 25 \text{ million tons of Milk (L)} = 1.52 \text{ million tons of beef} \times 41\% \times 68\%_{carcass\ yield} \times 90\%_{distribution\ yield} \times 68\%_{preparation\ yield}$$

Furthermore, we considered that 8L of milk are required to make 1kg of cheese and 1L of milk to make 1kg of fresh dairy products, using the average figures from French processing chains.

2.6 Diets modelling and optimization

As nutrient requirements vary according to population subgroups, participants were grouped as men, premenopausal women and menopausal women and diets were modeled for each subgroup to account for differences in iron intake requirements. Postmenopausal women were considered to have a low iron requirement and premenopausal women have a high iron requirement (the highest reference value, i.e. the reference covering 97.5% of the women requirements; of note most women (80%) have much lower requirements). Data related to observed food consumption as well as attributes of food items, *i.e.* nutritional composition, environmental pressures and production mode (conventional or organic), were used to define optimized diets being nutritionally adequate, acceptable, and more sustainable.

Nutritional adequacy was ensured by a set of nutritional constraints by considering, in particular, nutrient bioavailability for iron and zinc, as described in **Appendix B**.

The list of constraints was as follows:

- Nutritional constraints on total energy and 31 nutrients, with upper and/or lower bounds based on nutrient reference intakes. Lower bounds were taken as recommended dietary allowance (population reference intake) or adequate intake, or lower bound of reference intake range for the French population (40) as mostly derived from the EFSA opinion (41). For some nutrients, when the adequate intake was based on the observed average intake, the lower bound was set as the value of the 5th percentile. Reference intakes also included upper levels, as tolerable upper intakes for vitamins and minerals, when identified, and upper bound of reference intake range.
- Acceptability constraints on some food groups, with upper bounds set as the population-specific 95th percentiles for 37 *ad-hoc* food groups. Additional moderation constraints on some food groups (dairy products ≤2 portions/d, fish ≤2 portions/week with 1 of fatty fish, and red meat <500 g/week), to comply with national public health moderation recommendations for animal products, as prescribed in French food-based dietary guidelines (42).
- Co-production constraint limiting the consumption of milk to a proportion of that of beef, using the factor between milk and beef defined above in Eq. (1).
- Environmental constraint for a given (from 0 to -50 % by 5% decrement) reduction in GHGe compared to the observed situation. For each food, during diet optimization, the model selected the production option (conventional or organic) exhibiting lower GHGe.

The objective corresponded to the maximization of acceptability, i.e. minimizing the total departure (D) from the observed diet (initial condition), as follows:

$$\text{Min D}=\sum_{i}^{257}\left[\frac{Obs_i-Opt_i}{SD_i}\right]^2$$

where Obs_i and Opt_i denote the daily consumption of food item (i) in the observed and optimized diets, respectively and SD_i is the standard deviation of the observed daily consumption of food item (i).

The climatic improvement approach was examined using scenarios of 5% gradual decreases in GHGe, by using a GHGe constraint in each scenario from 0% (basal model: GHGe ≤ Observed situation) to -50%.

The optimization process was performed using the procedure SAS/OR ® *optmodel* (version 9.4; SAS Institute, Inc.) using the *nlp* non-linear optimization algorithm (since the objective and some nutritional constraints were non-linear) and *multistart* option (to ensure that solutions were not only local optimums).

During diet optimization, we estimated the standardized dual values (i.e., the dual values associated with each constraint that has been standardized by its limiting bound), which represent the potential gain in objective for a 100% relaxation of each constraint's limiting bound. This allowed to identify the active (*vs.* inactive) constraints and compare their relative influences on the results. To conduct this sensitivity analysis even further, some alternative models were also tested, with either introducing some flexibility in some constraints (like the bioavailable zinc and iron nutritional constraints) or the suppression of some other (like the co-production constraint).

Consumptions of food groups, animal- and plant-based products, nutrient intakes, percentage of organic production mode per food group, monetary cots, environmental pressures (GHGe, cumulative energy demand and land occupation) and the pReCiPe, as previously described (22), were calculated for each optimized diet.

The pReCiPe (partial ReCiPe), a synthetic estimate of environmental impact based on GHGe, cumulative energy demand and land occupation, which enables to consider potential trade-offs between indicators (43), was calculated as follows:

$$pReCiPe = 0.0459\ \times GHGe + 0.0025\ \times CED + 0.0439\ \times LO$$

with GHGe, in kg of CO_2eq/d, CED, in MJ/d and LO, in m^2/d. The higher the pReCiPe, the higher the environmental impact.

2.7 Statistical analysis

For the present study, we considered participants of the NutriNet-Santé study who had completed the Org-FFQ between June and December 2014 (N=37,685), with no missing covariates (N=37,305), not detected as under- or over-energy reporter (N=35,196), living in mainland France (N=34,453), and with available data regarding the place of purchase for the computation of the dietary monetary cost, leading to a final sample of 29,413 participants. The sociodemographic, lifestyle and dietary characteristics were presented by subgroup (men, premenopausal and menopausal women).

Dietary consumptions per subgroup were presented as observed mean (SD) or optimized values for scenarios for the main 16 food groups and further specifically detailed among both animal and plant-based foods.

All statistical analyses were performed using SAS (version 9.4; SAS Institute, Inc., Cary, NC, USA).

3. Results

3.1 Sample characteristics.

The sociodemographic characteristics of the sample are presented in **Table 1**. The sample included in the present analysis was constituted of 7,416 men, 9,710 premenopausal women and 12,287 menopausal women. The mean age was 53.5y (SD=14.0). Most of the sample was postgraduate (64%) and few individuals were current smokers (11%) or exhibited a low physical activity level (19%). For each population (men, premenopausal and menopausal women), the food group consumptions for the observed diet and the optimized diet under each model and by each scenario of GHGe reduction are presented in **Appendix C**.

3.2 Overall dietary changes

The overall food group composition of optimized diets meeting the set of nutritional, acceptability, moderation and coproduct constraints without (basal scenario, 0% reduction in GHGe) or with gradual GHGe reduction (following scenarios, up to 50% of the observed pressures), are presented in **Figure 1**. In the basal scenario (0% reduction in GHGe, where the optimized diet was the closest diet to the observed diet that meet the nutritional, acceptability, moderation and coproduct constraints), nutrient constraints resulted in decreases in butter (up to -80% vs observed diet), dairy products (up to -64%), extra-foods (up to -75%), non-alcoholic beverages (up to -54%) and fish (up to -45%) and in contrast increases in soya-based food (up to +390%), eggs (up to +140%) and mixed dishes (up to +156%), with also some sex-specific effects (whole starchy foods 45% decrease in men but 70% increase in women, starchy foods and vegetable oils 54% and 145% respectively increase in men). In the following scenarios, as detailed in the **Appendix D** , fulfilment of the environmental constraints of gradual up to 50% decrease in GHGe was ensured by gradual further increases in soya-based food in women (up to +68% vs basal scenario) and eggs in all groups (up to +24%) and by gradual further decreases in extra-foods in all groups (up to -68%), whole grains & starchy foods, mixed dishes and dairy products in men (-95%, -32% and -32% respectively), in meat and vegetables oils in women (up to -27% and -29%, respectively).

3.3 Animal-based foods consumption

Figure 2 presents the detailed intakes of animal-based foods in observed diets and in the optimized diets for the basal (0% reduction in GHGe) and following (up to 50% gradual decrease in GHGe) scenarios. Compared to the observed diets, in the basal scenario meeting the nutritional requirements, all optimized diets (whatever the population) were characterized by a reduction in total animal products (up to -44%), with suppression of milk and reductions in dairy products and cheese (up to -66% and -30%, respectively) and fish (up to -45%, to be reduced to its maximal recommendation), and in contrast increases in eggs and poultry (up to +140% and +182%, respectively). Moreover, in the basal scenario compared to the observed situation, so as to ensure the nutrient requirements and animal-based food dietary guidelines, ruminant meat increased (up to +30% in postmenopausal women) while pork meat decreased (up to -89% in men). These trends for ruminant and pork meats were then reversed during the following scenarios of up to 50% reduction in GHGe, which were systematically characterized by concomitant and gradual decrease in ruminant meat (up to -91% compared to the basal model with no GHGe decrease) and increase in pork (up to +964%). The GHGe 50% reduction was also ensured, to a lesser extent, by some sex-specific effects in line with those already observed in the basal scenario, namely a further dairy products reduction in men and a further egg increase in women.

Finally, compared to the observed diets, ensuring both nutritional needs, acceptability, moderation and coproduction constraints and 50% GHGe reduction was achieved by strong reductions in the consumptions of fish and ruminant meat (up to -23 g/d and -52 g/d) together with strong reductions in the consumptions of milk and dairy products (up to -65 g/d and -115 g/d), while the consumptions of poultry, eggs and pork increased (up to +46 g/d, +18 g/d and +18 g/d). Overall, if the total meat consumption remained relatively similar between the observed and optimized diets, it was strongly redistributed between meat types, as the contribution of poultry to total meat consumption greatly increased from 18%-24% in observed diets to 43%-50% in optimized diets, while the contribution of pork more moderately increased from 39%-42% to 46%-54% and the contribution of ruminant meat greatly decreased from 34%-41% to 3%-5%.

3.4 Plant-based foods consumption

Figure 3 presents the detailed intakes of plant-based foods in the observed and optimized diets for the basal (0% reduction in GHGe) and following (up to 50% gradual decrease in GHGe) scenarios. Compared to the observed diets, in the basal scenario meeting the nutritional requirements, all optimized diets were characterized by strong increases in legumes (up to +238%, i.e., +45g/d) and decreases in soups, soya-based food and fruits in all groups (up to -97%, -81% and -34%, i.e., -73 g/d and -3.6 g/d and -91 g/d respectively). Whole grains and starchy foods decreased in men (-63%, i.e. -59 g/d) but increase in women (up to +52%, i.e. 34 g/d). These effects were similar or even slightly further strengthened in the following scenarios of up to 50% GHGe reduction. Indeed, whole grains and starchy foods decreased in premenopausal women, increased in menopausal women and were almost totally suppressed in men. The 50% GHGe reduction was also achieved by a reduction in potatoes (up to -69%, i.e., -21 g/d).

3.5 Environmental and cost characteristics

The evolution of environmental and monetary cost indicators across the different scenarios is presented in **Table 2.** Compared to the observed situation, the basal scenario meeting the nutrient reference values (without GHGe reduction) yielded an increase in almost all these indicators (energy demand and land occupation, pReCiPe and monetary cost of the diet). In the following scenarios of gradual GHGe reduction, all these indicators then gradually decreased and reached lower values than those observed for the environmental indicators, but not for the diet monetary cost. Indeed, compared to the observed situation, in the last scenario of 50% GHGe reduction, the energy demand was lowered by up to -29%, land occupation by -48% and pReCiPe by -47%, while the monetary cost of the diet increased between +9% and +20%.

The share of organic food, starting from 26-32% in the observed diets, increased greatly and rapidly from the basal scenario and then stabilized around 65-70% in all optimized diets. As detailed in the

Appendix E, while animal foods were consumed mostly as non-organic, plant-based food were consumed as organic in optimized diet.

3.6 Nutrient characteristics

The nutrient intakes according to the observed and optimized diets are presented in **Table 3** Notably, in all optimized diets, the intakes of fibers and bioavailable zinc, which were insufficient in the observed diets, were leveled up to their reference value and were then kept unchanged. We found similar results for the intakes of bioavailable iron and vitamin B12, except that while they also increased in all the optimized compared to observed diets, they nevertheless decreased among optimized diets along with GHGe reductions. The intake of phytates was also gradually decreased as GHGe was reduced, allowing meeting reference values for bioavailable iron and zinc. Calcium intake increased in all optimized diets, except in menopausal women.

3.7 Active constraints and sensitivity analysis

Analysis of the standardized dual values showed that the most limiting constraints were, in descending order, bioavailable zinc, EPA+DHA (eicosapentaenoic acid + docosahexaenoic acid), energy intake, sodium and saturated fatty acids in men and bioavailable zinc, EPA+DHA and sodium in women. The redistribution between ruminant meat and pork across modeling scenarios was driven by the compromise between satisfying the nutritional constraints for bioavailable zinc and iron and sodium requirements and the environmental constraint of GHGe reduction, as tested by alternative models where we allowed some flexibility in the requirements for each of these nutrients one by one (data not shown).

The sensitivity analysis also showed that the nutritional constraints for bioavailable zinc and iron were determinant for the distribution between meat and whole grains products having a phytate content that limit the zinc and iron bioavailabilities. Indeed, as shown in **Appendix F**, we verified that allowing some flexibility for bioavailable zinc led to meat reduction together with whole grains and starch foods increase (in men: 110 g/d *vs.* 2 g/d of whole grains and starch foods with *vs.* without flexibility, respectively, under the 50% reduction in GHGe scenario).

Moreover, as shown in **Appendix G**, the constraint on livestock co-products had little influence on the modeling results that were fairly similar with or without considering this constraint.

4. Discussion

In the present diet optimization study, the minimal changes in current French diets necessary to first meet nutrient reference values and then reduce GHGe by up to 50% were characterized by an overall decrease in the consumption of foods of animal origin with notably suppression of milk and strong reductions in dairy products and cheese, together with a stable but largely redistributed meat consumption in favor of poultry and pork and against ruminant meat, as well as marked increases in the consumptions of legumes. It should be noted that strong dietary changes were induced as soon as the first, basal stage consisting in modelling diets meeting nutrient reference values (under

acceptability and moderation constraints), without any reduction in GHGe (which were however constrained to avoid any increase). From this first stage, the consumption of animal products decreases and the model opted for organic plant products, which are more efficient than non-organic ones to limit GHGe. During the second stage, GHGe reductions by up to 50% mainly resulted from a redistribution between meat types against ruminant meat, within total consumptions of meat and animal products remaining relatively stable. Noteworthy, the model selects the most efficient farming practice for each food (organic or not) thus the entire optimized consumption of each food item is either organic or conventional which does not reflect the reality of consumer behavior.
Notably, in addition to food behaviors, a major challenge to improve the sustainability of food systems is the reduction of losses and waste (44). The lack of quantitative data about waste for each food did not allow us to consider this dimension in our models. This is all the more complex, as waste occurs at each link of the food system chain and depends on both the production and processing methods

This study, by considering environmental pressures associated with food production while accounting for farming practices, as well as numerous detailed food items, allowed intra-group substitutions by favoring less emitter foods. This brings new insights since nowadays most French consumers are unlikely to be ready to follow drastic plant-based diets such as vegetarian or vegan diets, that would represent a radical change in eating habits for the highest consumers of animal products, and would require steps over time. In the meantime, small, low-impact dietary changes for a large proportion of the population are probably more acceptable than substantial changes as strong changes may need more time (45) . Overall, our results are coherent with literature findings comparing emissions from observed diets more or less rich in animal products, which have documented lower emissions for diets richer in plant foods (7,46–48). However, such observed diets do not necessarily meet the nutritional requirements.

Optimization modelling enables to identify environmental-friendly diets in line with nutrient requirements, (e.g. by avoiding counter-productive effects such as increase in consumption of sweet and fat products) (15). Scientific literature using diet optimization for exploring potential GHGe reduction under nutrient constraints is plentiful (7–10,48). Overall, from these studies, it appears that a drastic and specific reduction of ruminant meat as well as dairy products consumption is the main lever for GHGe reduction from diet, which is in line with our results. We indeed found that dairy products and ruminant meat have to be drastically decreased, without being totally suppressed, which is somewhat different from the results of a recent diet optimization study that identified the need to completely eliminate ruminant meat while maintaining dairy products (excluding butter and cheese) to comply with the 2030 and 2050 GHGe reduction targets (being much stronger than those modelled here) in the Netherlands (49). However this study, as well as most of the others, did not take into account nutrient bioavailability in nutrient constraints and did not include coproduction constraints, whereas these important parameters may shape the modelling results and the order of magnitude of potential decreases and increases according to food groups (9). Herein, as previously done (26–28), we have considered and controlled the bioavailability of iron and zinc using validated equations for their absorption. We have shown that considering the bioavailability of iron and zinc was crucial for the concomitant variations in meat and whole grains products, whereas considering beef-milk coproduction had little influence in our context.

A wide heterogeneity exists in terms of methodological aspects across modelling studies (50). First, the number of food items can vary greatly and we worked with a relatively large number of food items (~250) (9), with the notable feature of allowing the choice (or a mix) between two modes of production (organic or conventional) for each food item. Second, contrary to what has been most often done, we have considered constraints on food groups but not on food items so as to allow intra-group substitutions. These acceptability constraints based on the 95th percentile of each population, including participants with healthier diets than the general population, allowed stronger increases in some food groups. Finally, we have adopted a quadratic rather than a linear formulation for the objective function of diet departure to minimize, so as to favor more numerous but smaller changes rather than fewer but larger changes during optimization (51). All these methodological choices have provided levers for optimized diets, since we had a wide inventory of food items and since intra-group substitutions were favored by different means as modeled here.

In our particular context, under all the considered nutritional and acceptability constraints and by accounting for the influence of anti-nutritional factors like phytate on zinc and iron bioavailabilities, total meat was maintained relatively stable, because of a decrease in whole grains and starchy foods (and thus a decrease in phytate), although it was qualitatively remodeled in disfavor of ruminant meat so as to reduce GHGe. In line with our results, a diet optimization study among old Dutch adults with 50% reduction in GHGs found unchanged total meat consumption with an increased contribution of poultry and pork and a decreased contribution of beef (52).

Several options regarding plant foods merit further discussion. In the optimized diets, non-alcoholic beverages (including coffee and tea) were strongly reduced (up to -54%), as they are poor in nutrients and represent important environmental pressures at the post-production stage. However, as culturally deeply entrenched in our usual diets, such drops could be an important limitation and all the more so since positive health effects have been reported (53). It should be noted that whole grains and starchy foods, whose beneficial role on health is well-documented (54), were lowered in optimized diets (almost in men), and this may be ascribed to their phytates content limiting the iron and zinc bioavailability. Such a prominent role in optimized solutions raises the issue related to nutritional constraints relying on nutritional references which are based on calculated physiological requirements as for zinc, for instance, reliable biomarkers are lacking (55). Thus, while we have defined the nutrient constraints according to the French nutritional references and the literature equations for bioavailability, the methods of definition may be highly conservative and slightly lower intakes may not result in clear adverse effect on health, such as over-deficiency. Of note, the nutritional reference for fiber (i.e. >30g/d) favors the increase in foods with high content such as legumes, while reducing the ruminant meat for reducing GHGe required a reduction in phytate intake to allow sufficient absorption of iron and zinc, which in turn has favored the reduction of starchy foods. This was clearly illustrated by an alternative model allowing flexibility on zinc, with which whole grains foods did increase. Moreover, in the optimized diets, fish consumption was limited by an upper value. Fish and seafood are the major supplier of EPA and DHA that should be consumed at the highest level of their reference value. This reflects the fact that EPA+DHA is a limiting constraint for more sustainable diets and suggest that other and presumably better sustainable diets might be identified when introducing other new sources of these fatty acids.

Finally, the proportion of organic foods drastically increased (in weight) from ~30% in the observed diets to ~70% in all the optimized diets, which explained the monetary cost increase of optimized diets (56). At the individual diet level, we previously reported that regular organic food consumers exhibit diets with a lower impact regarding GHGe, land use and energy demand but dietary patterns (i.e. plant-based patterns) prevailed on the mode of production in this association (22). However, at the food item level, organic farming may play a substantial role in reducing GHGe, depending on the food considered (23,57,58). Our results illustrate that when optimizing diets by selecting specific products like in the present study, rather than by only substituting some conventional by organic products at constant diet, as some consumers can do, organic foods can greatly help to the reduction of GHGe, as previously shown in our observational studies (59). The consumption of organic foods increases from the first step (i.e. 0% reduction in GHGe corresponding to modeling diet with GHGe ≤ observed value) which means that the foods preferentially selected to respect the nutritional constraints are more efficient as organic to maintain GHGe. However, due to modeling, one food is selected 100% as organic or 100% as conventional what does not reflect the reality of behaviors. This is interesting as an increased consumption of organic foods can have beneficial consequences on two levels. First, on the environmental level as organic production systems also exhibit improved energy efficiency (60), better biophysics and biological quality of soils (57,61) and are valuable for plant and animal biodiversity (57,60,61). Second, on the sanitary level, as high plant-based diets based on organic agriculture may lead to much lower exposure to pesticide residues (22,62,63), motivating the promotion of plant products produced without synthetic pesticides in the new French food-based dietary guidelines (64).

As regards the obtained solutions, optimized diets exhibited high consumption of fruits and vegetables (>500g/d), low consumption of red meat (<500g/week), processed meat (<150g/week), sweet products, low intake in salt and moderated consumption of dairy products, in line with the French food-based guidelines (42). Importantly, consumption of legumes among menopausal women was somewhat low and the consumption of whole grains and starchy foods was very low in men. As scientific literature has documented a notable beneficial role of plant-food diets, beyond fiber intake which are controlled in the present study, for health and environment (3), further steps of the transition, probably further away from the observed diets would require to introduce a higher plant versus animal food ratio. For instance, in the same cohort we previously described low emitting dietary patterns (GHGe for production lower than about 2.2 kg CO_2 eq) that were richer in plant-based food than the present solution but nutritional adequacy was not assessed (24). Higher shares of healthy plant protein such as whole grains and lower consumption of animal protein as red meat are considered as part of a healthy diet as documented by epidemiological data (65,66) and may be warranted for a full sustainable transition together with GHGe. Finally, the nutritional values of highly plant-based diets should be tested in the future by deleting or relaxing acceptability constraints, considering alignment with healthy eating patterns as defined from epidemiological data or by using hierarchical optimization as we did in a recent study (67). Finally, it has been previously documented that healthier diets are often more expensive (68). In line with this, the optimized diets were more expensive than the observed diet, constituting a potential barrier for some consumers. Without appropriate policies, this may jeopardize food security due to inaccessibility and potential low availability for vulnerable populations.

Some limitations of our work should be highlighted. First, the NutriNet-Santé cohort included volunteers who were probably more concerned by health and diet issues than the general population, limiting extrapolation to the general population as these participants exhibit diet rich in plant-based food. For instance, lowering energy intake is a well-known lever for reducing GHGe (69,70) but in this population including “small eaters”, energy intake increased in the basal model to reach the requirement. Second, post-farm environmental pressures for organic agriculture are lacking, thus life cycle assessments were limited to farm activities which have most impacts in the food system. Therefore, our scenarios may be insufficient to meet the global climatic objective, since some steps following food production were not considered. Concerning environmental indicators, LCA were used while it is recognized that some ecosystem services related to agroecological practices are misestimate by this method (25). Third, beyond GHGe, we considered two other environmental pressures for descriptive purpose, those three allowing an acceptable representativeness of the overall environmental impact (43), but other dimensions such as water use or biodiversity should be studied. However, in further works, it would be very important to consider water use in particular in the context of vegetable and fruit and the production of corn, mainly for feeding monogastric livestock breeding. We observed a decrease in land occupation with the gradual reduction in GHGe. Reallocation of released land may induce important fluctuations in GHGe which are the results of carbon balance of managed forests, agricultural soil organic carbon stocks soil and reallocation (grassland, deforestation, afforestation, artificialization etc.)(71). But, an important factor that was not considered is land use reallocation since this analysis used attributional LCAs. Thus, the change in the type of meat consumed would have also an effect on the demand for arable land and therefore on carbon stocks and on GHGs (72). Notably, in addition to food behaviors, a major challenge to improve the sustainability of food systems is the food losses and waste reduction (44). The lack of quantitative data about waste for each food did not allow us to consider this important dimension in our models. This is all the more complex, as waste occurs at each link of the food system chain and depends on both the type production and level of processing. The reallocation of permanent grasslands is also an issue We have also assumed, as in most diet optimization studies (9), that the most acceptable diets are those the closest to the observed diets. While this classical assumption makes it possible to define a simple and very restrictive metric of cultural acceptability, it is known to account only very imperfectly for true acceptability as stronger dietary changes may occur, at least in certain segments of the population. Besides, this study integrates many strengths such as the level of detail for food consumption, the detailed and reliable consideration of the updated nutritional recommendations (including bioavailability of the micronutrients of concern in our context, iron and zinc, which is seldom done), the consideration of different food production methods and the corresponding environmental indicators.

In conclusion, this study in adults provides detailed results on the possible dietary changes that can be implemented to mitigate GHGe up to 50% with minimal departure from the observed diet. We were here able to identify more sustainable diets, being nutritionally adequate and culturally acceptable, and from which meat was not excluded. Because the present optimized nutrition model preferentially allowed intra-category substitutions, the plant/animal food ratio was not noticeably altered. Although adequate according to a large set of lower and upper nutrient reference values, the modelled diets may be sub-optimal for long-term health, which may benefit from further decrease in red meat and higher increases in whole grains. Furthermore, reducing the consumption of foods of animal origin, particularly beef and lamb, as well as milk and dairies, is necessary not only for environmental or health reasons but also for animal welfare considerations. Lastly, future research will be needed to document even greater reductions as this 50% is unlikely to be sufficient and further research focusing on specific subgroups, e.g. according to age or socioeconomic status would be of interest to fine-tune the optimized diet.

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5. The authors’ contributions are as follows:

EKG, BA, MT, and SH conducted the study.

EKG, JB, BL, SH, DL and PP conducted the research and implemented databases.

EKG, HF, AD, and FM conducted the diet optimization.

EKG performed statistical 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.

6. Conflict of Interest

No author declared conflict of interest.

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Figure 1: Overall composition (g/d) of the observed and optimized diets according to the modelling scenario and population group (color figure)

Main food groups intakes (g/d) in the observed diets and in the diets being nutritionally, culturally and environmentally optimized so as to ensure gradual reduction in greenhouse gas emissions (GHGe) from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal women, C: menopausal women.

Figure 2: Composition in animal-based foods in the observed and optimized diets according to the modelling scenario and population group (color figure)

Detailed animal foods intakes (g/d) in the observed diets and in the diets being nutritionally, culturally and environmentally optimized so as to ensure gradual reduction in greenhouse gas emissions (GHGe) from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal women, C: menopausal women.

Figure 3: Composition in plant-based foods in the observed and optimized diets according to the modelling scenario and population group (color figure)

Detailed plant-based foods intakes (g/d) in the observed diets and in the diets being nutritionally, culturally and environmentally optimized so as to ensure gradual reduction in greenhouse gas emissions (GHGe) from 0 to 50%. Abbreviations: Obs, observed diet. A: men, B: premenopausal women, C: menopausal women.