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Alignment between greenhouse gas emissions reduction and adherence the EAT-Lancet diet: A modeling study based on the NutriNet-Santé cohort

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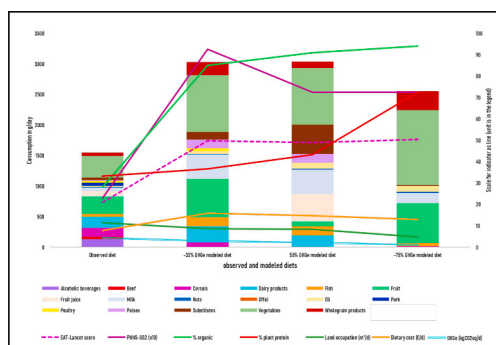
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HIGHLIGHTS

- Low GHGe modeled diets differ from observed diets to a greater extent the greater the reduction.
- Modeled diet with a 75% reduction in GHGe needs to lower the iron and zinc bioavailability cut-off.
- Modeled diet with a 33% reduction in greenhouse gases is the best complying with the French recommendations.
- Modeled diet with a 75% reduction in GHGe led to a 141% improved EAT score. Land use decreased by 57% compared with the observed value. The diet contained 94% organic food.
- While adherence to the EAT-Lancet diet could lead to a reduction in GHGe, other levers may be also efficient.

GRAPHICAL ABSTRACT



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ABSTRACT

The potential of the EAT-Lancet reference diet, which promotes a healthy diet within planetary limits, to reduce greenhouse gas emissions (GHGe) remains understudied. This study examines the role of nutritional and acceptability constraints in reducing GHGe through diet optimization, and tests the alignment between GHGe reduction and the EAT-Lancet score.

The study used data from 29,413 NutriNet-Santé participants to model French diets and evaluate their environmental, nutritional, economic, and health impact. The Organic Food Frequency Questionnaire was used to assess organic and conventional food consumed, and the Dialecte database was used to estimate the diet

Abbreviations: GBD, global burden of diseases; GHGe, greenhouse gas emissions; P, percentile; TMREL, theoretical minimum-risk exposure levels.

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Sustainable diet
Healthy diet

environmental impacts. Quality of diets were also evaluated based using the PNNS-GS2 (Programme National Nutrition-Santé 2 guidelines score).

When testing minimizing GHGe under strict nutritional and acceptability constraints, it was possible to reduce GHGe up to 67 % (from 4.34 in the observed diet to GHGe = 1.45 kgeqCO₂/d) while improving the EAT score by 103 % with 91 % of the food as organic. Greater reductions required relaxation of some constraints.

When testing maximizing EAT score under gradual reduction in GHGe, the adherence to the EAT-Lancet diet was not significantly affected by the gradual reduction in GHGe. To maximize EAT score with 75 % reduction in GHGe (1.09 kgeqCO₂/d), less strict constraints on the bioavailability of iron and zinc are necessary. The EAT score improved by 141 %, while land occupation decreased by 57 %, compared to the observed value. The diet contained 94 % of organic foods.

There was some alignment between the degree of adherence to the EAT-Lancet diet and the reduction in GHGe, but other diets may also lead to a strong reduction in GHGe. Thus, GHGe can be greatly reduced by dietary choices, but require profound reshaping of diets which must be coupled with changes in other areas of the food chain.

1. Introduction

In 1990, the Intergovernmental Panel on Climate Change (IPCC) released its first report on the risks of global warming and climate disruption caused by human activities (Intergovernmental Panel on Climate Change, 1992). The report highlighted the immediate consequences of our actions. Twenty-five years later, in 2015, the Paris Agreement was signed by 196 Parties at the United Nations COP 21, with the goal to limit the increase in the earth's surface temperature to well below 2 °C compared to the pre-industrial era (European Commission. Climate Action - European Commission, 2016). This significant agreement is the first universal climate agreement and is reflected in France by the “National Low-Carbon Strategy” (Stratégie Nationale Bas-Carbone, SNBC) (Ministère de la Transition Écologique et de la Cohésion des Territoires, 2024) requiring a 75–80 % decrease in emissions from 1990, equivalent to reducing them by a factor of 4 by 2050 corresponding by the IPCC objective (IPCC, 2018). However, the SNBC also specifies a 46 % reduction for the agricultural sector.

Achieving the Paris Agreement goals requires to drastically curb our greenhouse gas emissions (GHGe) very soon. The food system plays an important role in climate change caused by humans, responsible for 34 % of yearly emissions (Crippa et al., 2021; Clark et al., 2018; Clark et al., 2020). Notably, a significant 39 % of these emissions stem from the agricultural phase, primarily due to nitrous oxide and methane emissions (Crippa et al., 2021). To effectively reduce emissions from food systems, change in eating habits is a major lever (HLPE, 2014). The global food system is a significant contributor to GHGe and massive transformation of the global food system is needed to achieve the Paris target, including change in dietary behaviors. Scientific research has consistently advised transitioning to a diet based on plant foods, regardless of the study area. Replacing animal meat, particularly beef, with unprocessed plant-based options is an effective lever to reduce diet-related emissions (Poore and Nemecek, 2018; Aleksandrowicz et al., 2016; Garnett, 2011; Hallström et al., 2016; Tilman and Clark, 2014; Steenson and Buttriss, 2021; Jarmul et al., 2020). Besides the impact of food systems on the environment, many current diets are harmful to human health. The Global Burden of Diseases report reveals that 11 million deaths were due to dietary factors (including excesses of red and processed meat) in its latest report (with a 95 % uncertainty interval of 10–12 million) and 255 million DALYs (with a 95 % uncertainty interval of 234–274 million) (GBD 2019 Risk Factors Collaborators, 2020).

In that context, the EAT-Lancet International Commission created a worldwide reference diet in 2019. Its goal is to promote the planet's health and guarantee food security (Willett et al., 2019; Almaraz et al., 2023). The EAT-Lancet guidelines encourage moderate consumption of fish, eggs, poultry, and dairy products, and discourage the intake of sugary, fatty foods, refined cereals, beef, pork, and lamb. This diet emphasizes a high proportion of minimally processed plant-based foods, including legumes, nuts, and whole grain products. There is a growing body of evidence on the potential health benefits, nutritional values or

environmental impacts of the EAT-Lancet diet (Tulloch et al., 2023). The EAT-Lancet diet's health and nutritional benefits have not been examined with the Paris Agreement's goals. Most strategies aimed at reducing GHGe are believed to positively impact public health (Gao et al., 2018; Hamilton et al., 2021) but nutritional consequences are debatable (Leonard et al., 2024).

Therefore, the overall objective of the present work is to explore consistency or conflict between improvement toward the EAT-Lancet diet and greenhouse gas emissions reduction under nutritional constraints. First, we explore the maximum achievable GHG reduction according to several sets of constraints. Then, we aim to maximize the EAT score under a gradual decrease in GHGe to explore alignment. The optimized diets are then described in terms of nutritional, environmental, economic and health values using the adherence to the French food-based dietary guidelines using the *Programme National Nutrition Santé-Guidelines Score* (PNNS-GS2).

2. Methods

2.1. Population

This analysis is based on a sample of adults involved in the ongoing web-based prospective NutriNet-Santé cohort study. The study aims to investigate relationships between nutrition and health (Herberg et al., 2010). 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 909,216). Electronic informed consent was obtained from all participants. The NutriNet-Santé study is registered in [ClinicalTrials.gov](https://clinicaltrials.gov) (NCT03335644).

2.2. Dietary data assessment

The dietary data were collected in 2014 using a self-administered validated semi-quantitative food frequency questionnaire (FFQ) covering the prior year (Baudry et al., 2019). The questionnaire includes a five-point ordinal scale for each of the 264 food and beverage items, allowing for evaluation of their production methods - whether organic (with an official label) or conventional (Baudry et al., 2015). Participants responded to the question ‘How often was the product of organic origin?’ by the following modalities: “never”, “rarely”, “half-of-time”, “often” or “always”. Organic food consumption was estimated by allocating the respective weights: 0, 25, 50, 75 and 100 % to the modalities. To improve clarity and hamper high consumption of specific foods, food and beverage items were grouped into 46 food categories specifically defined for this optimization modeling (see Supplemental Table 3). The nutritional composition of each item was determined by

combining the published NutriNet-Santé food composition table (>3500 items) (Nutrinet-Santé, 2013) with the FFQ-items as the weighted mean of the nutritional content of all corresponding foods. Weights were the frequencies of consumption in the overall NutriNet-Santé population.

2.3. Sociodemographic and lifestyle characteristics

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 (Hagströmer and Oja, 2006) were collected using yearly questionnaires (Vergnaud et al., 2011; Touvier et al., 2010). The data the closest to the dietary questionnaire were used.

2.4. EAT-lancet adherence score

We constructed an EAT-Lancet score based on the universal healthy diet definition (Willett et al., 2019) created in 2019. Supplemental Table 1 presents the components and cut-offs of the EAT-Lancet diet for 14 food groups, including wholegrain grains, vegetables, fruits, and dairy products, among others. The intake of added sugars is considered for the sweetener's component. In order to accurately reflect adherence to the EAT-Lancet diet, we analyzed the deviation from the cut-off value. As cheese is the primary dairy product consumed in France (rather than liquid), we adjusted the cut-off value from 500 g/d to 150 g/d. To calculate the EAT-Lancet diet score based on the daily intake for each food group, we used the following Eq. (1):

$$ELD - I_j = \frac{100 \times \left\{ \sum_{\text{component } i=1}^{14} \frac{a_i \times \left(\frac{\text{cut-off}_i - \frac{\text{consumption}_{ij} \times 2500}{\text{Energy intake}_j}}{\text{cut-off}_i} \right)}{14} \right\}}{14} \quad (1)$$

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

where i referred to one of the 14 food groups and j is the individual. $a_i = 1$ for component to limit and $a_i = -1$ for component to promote.

2.5. PNNS-GS2 (Programme National Nutrition Santé-Guidelines Score)

The PNNS-GS2 (theoretical range: $-\infty$ to 14.25) has been developed based on the 2017 dietary guidelines and validated against socio-demographic and biological data (Chaltiel et al., 2019). Guidelines, components, scoring, and weights are detailed in Supplemental Method 1. It is based on 13 components: seven refer to healthy foods: fruits and vegetables, nuts, legumes, whole-grain food, milk and dairy products, fish and seafood and added fat and six components refer to food categories whose intakes should be limited: red meat, processed meat, sweet food, sweet-tasting beverages, alcoholic beverages. Penalties were also applied to overconsumption.

2.6. Environmental pressure indicators

Life cycle assessment (LCA) at farm level from the DIALECTE database developed by Solagro (Pointereau and Langevin, 2012) were used to compute food-related environmental indicators. This database specifically covers conventional and organic farms. GHGe (the indicator calculated in this study is the Global Warming Potential (GWP) over a 100-year time horizon (GWP₁₀₀) in kg of CO₂ equivalents (CO₂eq), cumulative energy demand (MJ), and land occupation (m²) were

computed at the farm perimeter excluding downstream steps such as conditioning, transport, processing, storage or recycling stages.

Data and detailed computation have been extensively described elsewhere (Seconda et al., 2018). Economic allocation (accounting for coproducts), as well as cooking and edibility coefficients were applied to 92 raw agricultural products, to estimate production environmental pressure for the 264 food items.

2.7. Price of the food

An average price was calculated for both organic and conventional food items, considering the place of purchase from the Kantar World-panel purchase database®. This database includes data from 20,000 representative households and an additional collection from short food-supply chains (Baudry et al., 2019).

2.8. Coproduction constraint

We conducted a sensitivity analysis by imposing a coproduction constraint in order to comply with a reasonable ratio between milk or derivatives, and beef.

To do so, we used the following figures and data:

- 25 million tons of milk and 1.52 million tons of beef (expressed in carcass weight) were produced in 2010 in France (Couturier et al., 2016),
- 41 % was from dairy herd corresponding to 0.62 million tons of beef (France Agrimer, 2012).

Postulating a meat to carcass weight ratio of 68 %, 10 % distribution losses, 32 % losses at the consumer level (cooking, bones and wastes) (Idèle, 2016), and that 1 L of milk corresponded to 10 g of meat, we applied the following equation:

$$1 \text{ L milk} \Leftrightarrow 100 \text{ g of beef}$$

2.9. Weighting of nutritional reference

The nutritional reference values are established separately for men and women since they have significantly different physiological requirements (French Agency for Food, Environmental and Occupational Health Safety (Anses). Actualisation Des repères du PNNS : élaboration Des références Nutritionnelles [Internet], 2016). In addition, a subsequent distinction is made between women with high vs low iron requirements. It is estimated that about 20 % of menstruating women have high iron requirements (French Agency for Food, Environmental and Occupational Health Safety (Anses). Actualisation Des repères du PNNS : élaboration Des références Nutritionnelles [Internet], 2016). In this study, to improve clarity, we defined an average individual constituted of 50 % men and 50 % women, reflecting the French distribution. In addition, for women, we considered 50 % postmenopausal women and 50 % non-menopausal women with low and high iron requirement respectively. The assignment of high iron requirements to all menstruating women allows to mimic the strictest situation. Reference values, established separately for men and women, for each nutrient were defined as the weighted mean and are presented in Supplemental Table 2.

For mean, 5th, 95th and 99th percentiles (Supplemental Table 3) values based on observed food item intakes distributions, we calculated weighted averages after calculation of individual weights so that the

proportions defined above were respected.

2.10. Statistical analysis and modeling

In this study, we focused on individuals from the NutriNet-Santé study who filled out the Org-FFQ questionnaire between June and December 2014. We excluded those with incomplete information ($N = 37,305$) and those who were identified as under- or over-energy reporters ($N = 35,196$), as well as those not residing in mainland France ($N = 34,453$). We also used data about the cost of their dietary purchases (as previously published), requiring data about the place of purchase, resulting in a final sample size of 29,413 participants (Kesse-Guyot et al., 2020). The sociodemographic and lifestyle characteristics of the three initial populations (men, premenopausal and menopausal women) and of the average individual were estimated as mean (SD) or percentage.

Optimized nutritionally adequate diets were developed from initial conditions based on 46 observed food categories consumptions, their distribution, nutritional composition, cost and environmental pressures (Listed in Supplemental Table 3). The output variables of the models are the optimized consumptions and the percentage as organic and various models were computed by varying the number and types of constraints.

2.10.1. Constraints

Nutritional constraints on daily energy intake and a set of nutrients were defined according to the upper and/or lower reference values. Lower bounds were defined as recommended dietary allowance (population reference intake), adequate intake, or lower bound of reference range for the intake in the French population (French Agency for Food, Environmental and Occupational Health Safety (Anses). *Actualisation Des repères du PNNS : élaboration Des références Nutritionnelles [Internet]*, 2016) according to the 2021 EFSA opinion (EFSA, 2021). For adequate intake based on observed mean intake, the lower limit was set at the weighted 5th percentile value. Upper bounds were defined as the upper limit of the reference intake range or the maximum tolerable intakes for vitamins and minerals when available otherwise. For zinc and iron, bioavailability was considered using published formula (Armah et al., 2013; Miller et al., 2007) as explained in Supplemental Method 2. The nutritional constraints are presented in Supplemental Table 2. A lower limit based on deficiency intake has been defined for bioavailable zinc and iron.

Several acceptability constraints were used at the food category level. To consider that a consumption level is acceptable, we have used the weighted 95th or 99th percentile values as the maximum limits of consumption and the weighted 5th percentile value as the minimum limit of consumption.

A coproduction factor between beef and milk (defined above) has also been tested.

2.10.2. Optimization strategy

1) Minimizing GHGe under various set of constraints

In a preliminary analysis, we search to analyze to what extent deviating from the current diet may enable emissions to be reduced further by introducing different sets of constraints. Thus, we modeled different diets aiming to minimize GHGe (Eq. 1) under different nutritional constraints based on nutritional references and more or less strict acceptability constraints. The constraints of these models are depicted in Table 1. The objective function was defined according to the following formula (Eq. (2)):

$$\text{Min GHGe} = \sum_i^{46} C_{\text{organic } i} \times \text{GHGe}_{\text{organic } i} + C_{\text{conventional } i} \times \text{GHGe}_{\text{conventional } i} \quad (2)$$

where i is the food category, GHGe and C denote greenhouse gas

Table 1

Indicators for models minimizing greenhouse gas emissions (GHGe) according to different set of constraints^a.

	Obs	Modeling diets				
	Obs	G1	G2	G3	G4	G5
Constraints						
Nutritional references		✓	✓	✓	✓	✓
Acceptability cut-off						
Lower				>P5 th		
Upper			<P95 th	<P95 th	<P99 th	<P99 th
Relaxing Fe and Zn						✓
Objective function						
Minimizing GHGe	–	✓	✓	✓	✓	✓
GHGe (kgCO ₂ eq/d)	4.34	0.46	2.99	3.18	1.45	0.72
Eat-Lancet score	20.93	38.22	47.28	46.19	40.82	41.46
Number of EAT-Lancet components achieved (/14)	10.09	7	9	9	8	8
PNNS-GS2	2.28	0.75	7.25	7.25	6.75	5.25
Proportion of organic food in the diet	0.28	0.88	0.92	0.93	0.91	0.94
% plant-based proteins	33.18	48.80	31.85	33.60	53.66	78.16
Land occupation (m ² /d)	11.36	3.83	9.20	9.80	6.13	4.24
Dietary cost (€/d)	7.70	7.74	13.66	9.80	11.40	8.68
Diet deviation	0	58.59	67.60	60.76	129.04	10,115.85

Abbreviations: GHGe, greenhouse gas emissions; Obs, observed situation; P: percentile.

^a G1 to G5 denote the models aiming at minimizing GHGe under several set of constraints as described.

emissions and consumption value in the food categories (i), as organic and conventional. To this end, a series of models were developed to describe solutions that minimize GHGe emissions from food 1) under nutritional constraints (G1, 2) under nutritional and several acceptability constraints (threshold for consumption of food category at P5, P95 or P99) (G2 to G4) and then 3) relaxing constraints on bioavailable iron and zinc (G5).

2) Maximizing EAT-Lancet diet under gradual reduction in GHGe

The main analysis consists of maximizing the EAT-Lancet diet score under nutritional and acceptability constraints and an additional constraint pertaining to gradual reduction in GHGe lower in order to test whether and how diet-related GHGe can be divided by 4 from the observed situation. The first step was to reach GHGe lower or at the observed value under nutritional and acceptability constraints (M1). Next, models were performed by adding a gradual constraint for the reduction of GHGe (M2 to M5). Going beyond a factor 3 reduction required a relaxation of iron and zinc to permit convergence of the model (M6 and M7) as previously done (Dussiot et al., n.d.).

Finally, a sensitivity analysis was conducted by reanalyzing the data but by imposing a coproduction constraint to comply with a reasonable ratio between milk, derivatives, and beef (M3* and M5*).

2.10.3. Description variables

The optimized diets identified were described for the average individual by the following indicators:

1) environmental pressures (GHGe and land occupation),

- 2) indicators encompassing EAT-Lancet diet score, health risk score
- 3) dietary consumption by combined food groups ($n = 28$, see Supplemental Table 3)
- 4) diet deviation using the following formula (Eq. (3)):

$$\sum_i^{46} \left[\frac{Opt_i - Obs_i}{SD_i} \right]^2 \quad (3)$$

where Opt_i and Obs_i denote the daily consumption of the food category (i) in the modeled and observed diets, respectively and SD_i was the standard deviation of the daily consumption of food group (i) over the wholegrain population in the observed condition.

All statistical analyses were performed using SAS® (version 9.4; SAS Institute, Inc., Cary, NC, USA) and figures were drawn using R version 3.6. Diet optimization was performed using the procedure SAS/OR® *opt model* (version 9.4; SAS Institute, Inc.) using a non-linear optimization algorithm with multi-start option to warrant that identified solutions were not only local optima. For each model, we analyzed the “standardized dual values” to identify the limiting constraints of the model (compared to the inactive variables) and evaluate their respective influences. The standardized dual value corresponds to the potential gain in objective function in case of a 100 % relaxation of the limiting bound of the constraint (Bazaraa and Shrali, 2021).

We conducted a sensitivity analysis for the model G3 and G5 indicated G3* and G5* respectively, reducing GHGe by a 3 and 4 factor, and by imposing a coproduction constraint in order to comply with a realistic ratio between milk or derivatives, and beef.

3. Results

The characteristics of the sample are presented by sex in Supplemental Table 4. The population initially included 29,413 participants (75 % women), with a mean age of 53.5y. In the observed situation, mean EAT-Lancet scores were 31.55 (SD = 39.02) and 21.67 (SD = 35.51) among women and men, respectively.

Daily dietary GHGe were 3.75 (SD = 2.21) and 4.94 (SD = 3.00) kgCO₂eq/d among women and men respectively and 4.34 kgCO₂eq/d in the weighted sample.

Compared to individuals in the whole NutriNet-Santé cohort in 2014, those included in the present study, i.e. who completed the FFQ, were less often women (74 % vs. 79 %), were also more likely to be retired (36 % vs. 14 %), older (53.20 ± 14.07 year vs. 44.62 ± 14.20 year) and

more often have obtained a master degree (34 % vs. 33 %). An extensive description of the EAT-Lancet adherence in the NutriNet-Santé cohort and association with environmental pressures have been published before (Berthy et al., 2023; Kesse-Guyot et al., 2021a).

3.1. Achievable GHGe reductions depending on nutritional and acceptability constraints

The initial step involved determination of the maximum GHGe reductions achievable while meeting the nutrient reference values (with or without relaxing constraints pertaining to bioavailable iron and zinc intake), depending on the acceptability constraints considered. Varying the acceptability cut-offs (G1 to G4) produce variations in results, as follows (Table 1). The achievable GHGe reductions ranged from –31 % (G2) when limiting food group consumption at the 95th percentile, to –67 % when using instead the 99th percentile (G4) and up to –89 % without any acceptability constraint (G1) (Table 1). The G4 model consists of dairy products, milk, oil, pulses, sugared-sweetened beverages, soya-based food, vegetables, wholegrain products, and low quantities of fish and sweet and fat products. It does not include any meat, eggs, fruit, potatoes, or snacks (Fig. 1 and Supplemental Table 5). Further GHGe reduction was attainable by relaxing the bioavailable iron and zinc constraints allowed (G5: GHGe = 0.72 kgCO₂eq/d, i.e. –83 % compared to the observed diets), with less dairy products and vegetables and more wholegrain products and fruit juice. This had an EAT score of 41.46 (i.e., +98 % compared to the observed value).

Compared with the observed values, all these GHG reductions, as soon as the nutritional constraints were introduced, were concomitant with decreases in land use while the PNNS-GS2 reflecting a healthy diet and the percentage of organic food increased. The cost of the diet did not linearly follow the reduction in GHGs.

The standardized dual value analysis uncovered that the limiting nutritional factors were bioavailable zinc, energy, sodium, linoleic to alpha-linolenic acid ratio, sugar, and bioavailable iron, in descending order.

3.2. Gradual reductions in GHGe while maximizing adherence to the EAT-lancet

The characteristics of diets maximizing the EAT-Lancet score under different imposed GHGe reductions and other constraints are shown in

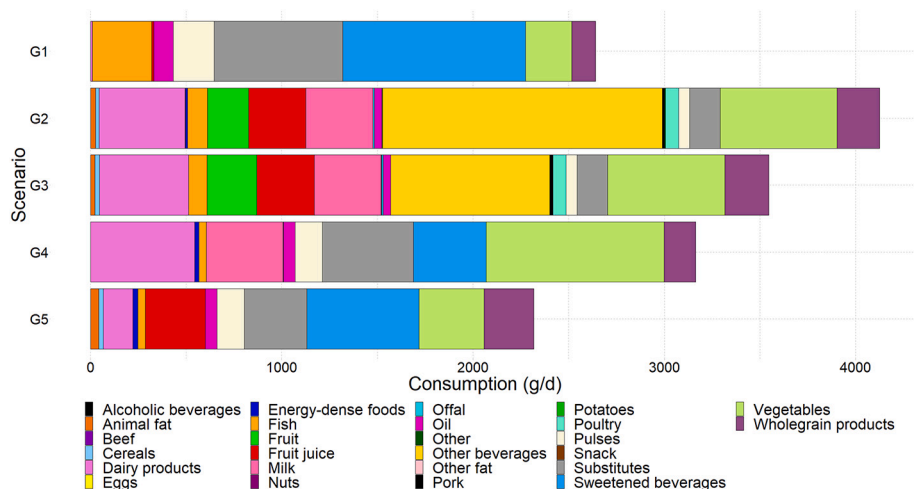


Fig. 1. Composition (g/d) of the observed and optimized scenarios modeling diets minimizing the greenhouse gas emissions^{1,2}.

Abbreviations: Obs, observed diet.

¹Food group consumption (g/d) in the observed diets and in the modeled diets being nutritionally, culturally and environmentally optimized so as to ensure gradual increase in the proportion of energy intake from plant-based foods.

²G1 to G5 denote the models aiming at minimizing GHGe under several set of constraints (see Table 1).

Table 2
Indicators for models maximizing EAT-Lancet diet score according to gradual reduction in greenhouse gas emissions³.

	Obs	Modeling diets						
		M1	M2	M3	M4	M5	M6	M7
Constraints								
Nutritional references		✓	✓	✓	✓	✓	✓	✓
Maximum acceptability cut-off (P99 th)		✓	✓	✓	✓	✓	✓	✓
Relaxing Fe and Zn							✓	✓
Maximal GHGe value		Obs	Obs / 1.5	Obs / 2	Obs / 2.5	Obs / 3	Obs / 3.5	Obs / 4
Objective function								
Maximization of the EAT-Lancet diet	-	✓	✓	✓	✓	✓	✓	✓
GHGe (kgCO ₂ eq/d)	4.34	4.1	2.89	2.17	1.74	1.45	1.24	1.09
EAT-Lancet score	20.93	50.09	49.75	48.87	47.72	42.43	50.51	50.34
Number of EAT-Lancet components achieved (/14)	10.09	8	9	7	8	8	10	11
PNNS-GS ^b	2.28	6.58	9.25	7.25	8.75	6.75	8.58	7.25
Proportion of organic food in the diet	0.28	0.80	0.85	0.91	0.91	0.91	0.89	0.94
% plant protein	33.18	34.39	36.56	43.33	53.92	54.12	62.02	72.43
Land occupation (m ² /d)	11.36	11.53	8.63	8.33	7.93	6.21	5.70	4.84
Dietary cost (€/d)	7.7	16.97	15.88	14.7	12.66	11.5	12.78	12.91
Diet deviation		135.05	116.92	160.25	158.68	150.93	141.51	109.60

Abbreviations: GHGe, greenhouse gas emissions; Obs, observed situation.

^a M1 to M7 denote the models aiming at maximizing the EAT-Lancet with gradual reduction in GHGe from the observed value up to a factor 4 reduction.

^b See supplemental method for computation. Maximal PNNS-GS2 is 14.25.

Table 2. To achieve convergence beyond a 3-factor reduction, the thresholds for bioavailable iron and zinc have been lowered.

The modeled diets consistently showed higher EAT-Lancet score than the observed value (ranging from +103 to 141 %). The EAT-lancet score gradually decreased in the models that required a reduction in GHGe (M2 to M5) but were highest (+141 %) when iron and zinc constraints were relaxed (M6 and M7). Compared to the observed situation, it is thus possible to improve the EAT-Lancet score while reducing dietary-related GHGe by up to a 4-factor (i.e. 1.09 kgeqCO₂/d) but some nutritional constraints need to be relaxed.

Interestingly, land occupation decreased concomitantly with the reduction in GHGe (from 11.53 to 4.84 m²/d) but the PNNS-GS2 reflecting compliance with food-based dietary recommendations, was maximum for the 1.5-factor reduction in GHGe (GHGe = 2.9 kgeqCO₂/d and PNNS-GS2 = 9.25/14.25) and then rises again.

The food group compositions for models gradually reducing GHGe are presented in Fig. 2 and Supplemental Table 6. The gradual reduction in GHGe maximizing the EAT-Lancet (as objective function) score under nutritional and acceptability constraints are marked by no consumption of alcoholic beverages, animal fat, beef, eggs, offal, refined cereals, other beverages, other fat, pork, potatoes, poultry, energy-dense foods, and snack. In addition, from model M1 to M5, dairy products, vegetable oil, soya-based foods and wholegrain products increased, while fruit decreased. In the following models (M6 and M7), relaxing iron and zinc constraints, certain specificities emerged, namely a high consumption of fruits, vegetables and wholegrain products, while dairy products other than milk were eliminated.

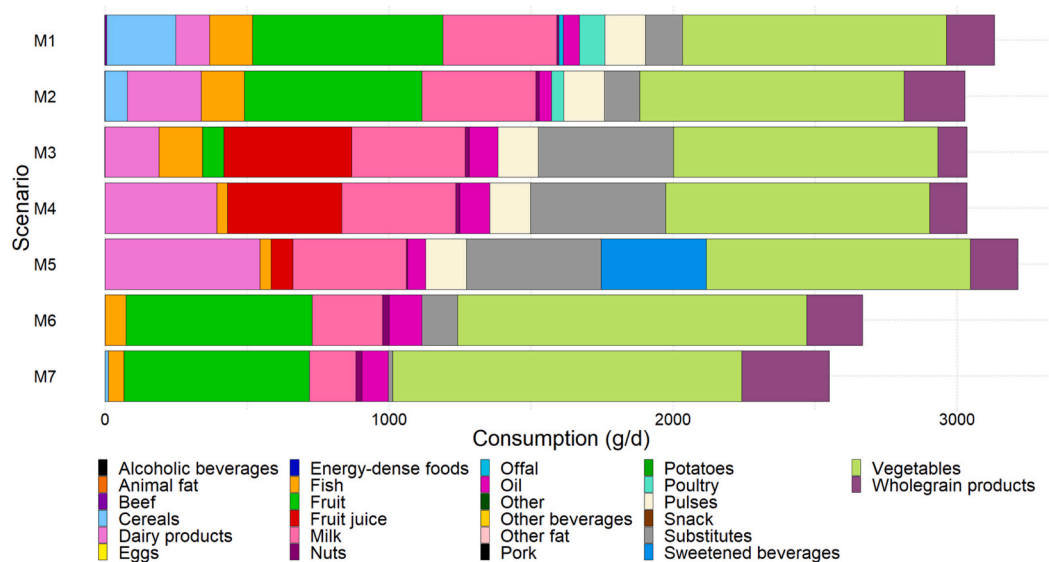


Fig. 2. Composition (g/d) of the modeled diets modeling maximizing the EAT-Lancet score with gradual reduction in greenhouse gas emissions¹.

¹M models aim at maximizing Eat-Lancet score under several set of constraints (acceptability constraints at 99th percentile of food groups consumptions and nutritional constraints except for M6 and M7 with relaxed constraints pertaining to bioavailable iron and zinc). M1 imposed GHGe at observed value. The M2 to M7 models also require an additional reduction in GHGe emissions by a factor from 1.5 to 4 by 0.5 increment.

4. Discussion

In this study we could show how much diets could comply with the reference diet Eat-Lancet with associated predefined reduction in GHGe.

We found that it is possible to reduce diet-related emissions by 75 % only if the nutritional references for iron and zinc are relaxed. There is some alignment between the degree of adherence to the EAT-Lancet diet and the reduction in greenhouse gas emissions, but other levers, less consistent with this reference diet, may lead to a greater reduction in greenhouse gas emissions.

4.1. Optimal reduction of GHGe

When considering both nutritional and acceptability constraints, GHGe can be reduced to a minimum of 1.45 kg eqCO₂ per day, equivalent to 66 %. To achieve a reduction of 75 %, it is necessary to relax the constraints related to bioavailable iron and zinc, but it has been shown that such a flexibility can have long-term health benefits (Dussiot et al., n.d.) as also illustrated by PNNS-GS2 values that are not impaired in these models. However, it is important to consider the potential impact of climate change on the concentration of iron and zinc in food (Frumkin and Haines, 2019; Myers et al., 2017), which may require further examination in the future. In the future, it is conceivable that lower GHGe could be achieved by introducing novel foods in the diet, or changing farming practices for less emitting ones (Mazac et al., 2022). Low-emitting diets are typically meat-free but can include certain unhealthy products such as sugared-sweetened beverages and energy-dense foods. As expected under nutritional constraints, EAT score and PNNS-GS2 markedly improved whatever the set of constraints, compared to the observed situation.

Other studies have shown that it is possible to reduce greenhouse gas emissions by 30 % without significantly affecting acceptability and while complying with nutritional references (Perignon et al., 2016; Nordman et al., 2023; Kramer et al., 2017). However, in the French study based on INCA3 data, reducing GHGe by 70 % or more would make it impossible to meet nutritional requirements (Perignon et al., 2016). Our study also shows that the acceptability constraints considered can play a significant role in limiting the achievable GHGe reductions. Therefore, to minimize the carbon footprint of diets, it will be necessary to shift away from current dietary patterns by drastically reducing meat products and increasing plant-based diet up to the 99th observed percentile of consumption.

Studies have shown that plant-foods are on average lower emitting as organic than conventional (Chiriaco et al., 2022). For instance, a study conducted in Qatar suggests that adopting a local, organic plant-based diet can contribute to reducing carbon emissions (Vicente-Vicente and Piore, 2021). However, while the carbon footprint of organic plant-based diets is reduced the cost of the diet may be higher than non-organic alternatives (Chiriaco et al., 2022; Giampieri et al., 2022).

4.2. Optimal EAT-lancet adherence for reduction in GHGe

A high number of observational studies have documented a reduction in GHGe associated with greater adherence to the EAT-Lancet diet, with a magnitude of 50 % between the most adherent individuals compared with the least adherent (Kesse-Guyot et al., 2021a; Cacau, 2021; Colizzi et al., 2023; Montejaño Vallejo et al., 2022; Tepper et al., 2022). In addition, we previously observed that EAT-lancet score greatly varied for the diet less emitting, suggesting other less levers to reduce GHGe (Kesse-Guyot et al., 2021a).

Furthermore, a scenario study based on food purchases data in Spain (Cambeses-Franco et al., 2022) showed that the EAT-Lancet diet emits less than the traditional Spanish diet (2.13 kgCO₂eq/d versus 3.62 kgCO₂eq/d) (Cambeses-Franco et al., 2022).

Diet optimization is an adequate approach to explore the potential alignments, conflicts and complex relationships between several

indicators while ensuring nutritional adequacy of the modeled diets (Gazan et al., 2018; van Dooren, 2018). However, most of the optimization studies aiming at reducing GHGe have been conducted using optimization under multiple constraints related to nutritional, often acceptability and sometimes epidemiological constraints (Wilson et al., 2019). In these studies, the objective function frequently denotes the minimization of the deviation from the observed diet under gradual constraints of GHG reductions and does not allow comparison of the adherence level to a reference diet. In our model, the levels of adherence to the EAT-Lancet, and the PNNS-GS2 as illustrative indicator, are overall not worsened by the gradual reduction in GHGe, which is consistent with literature on the alignments of certain diets for both health and environment (Tilman and Clark, 2014; Jarmul et al., 2020; Willett et al., 2019; Laine et al., 2021; Nelson, 2016). Of note, the EAT score was suggestively lower for a reduction by a factor of 3, under the strict constraints on iron and zinc. The model converged, but the latter constraints contribute to maintaining high consumption levels of some emitting foods, such as dairy products.

We do not find any study that has concomitantly explored the potential reduction in GHGe according to the adherence to the EAT-Lancet diet while this diet has been defined to comply with planetary boundaries.

For example, a recent Danish study reported findings of models based on a set of constraints relating to GHGe, nutritional references and health (epidemiological constraints) while minimizing the distance to the observed diets (Nordman et al., 2023), which is close to the objective of our study. In this study, some epidemiological health-related constraints, such as compliance to certain recommendations (excluding processed meat), were considered, but no overall dietary index was provided to estimate improvement. In addition, this study did not impose any constraints on sodium, and the maximum reduction to be achieved in greenhouse gas emissions was 30 %. The authors reported that it is possible to identify a diet complying with nutritional references, epidemiologic optimal consumption and low GHGe (reduction of 31 % in GHGe while minimizing deviation from the observed regime) but stronger reduction complying with the Paris Agreement was not tested. In addition, in this study, the health impacts of the modeled diets are difficult to interpret and compare to ours, as there is no composite indicator, and processed meat was not considered a health constraint. Finally, these diets are not interpreted in light of the adherence level to the EAT-Lancet diet.

The literature suggests that a more plant-based diet can drastically reduce emissions, but that certain nutrients provided by animal sources are major nutritional (Lonnie and Johnstone, 2020; Neufingerl and Eilander, 2022). However, by making the bioavailability of iron, and zinc more flexible, as previously performed in other studies (Nordman et al., 2023; Dussiot et al., 2023; Kesse-Guyot et al., 2021b; Kesse-Guyot et al., 2023) it is possible to reduce diet-related GHGs by a factor of four while still meeting other nutritional requirements.

4.3. Reducing greenhouse gas emissions and optimal health, the role of changing dietary habits in mitigating climate change

Eliminating fossil fuel combustion is needed to achieve the Paris agreement goals but the food systems are also an important lever to reach net zero (Alegria et al., 2022). The potential reduction will involve a reduction in food waste and loss, but also changes in both low-CO₂ emit agricultural production methods (which emit less) and changes in food demand through changes in individual eating habits (HLPE, 2017; European Public Health Association - EUPHA, 2017). The breakdown of carbon budgets between these different sectors remains poorly documented, and the carbon budget for food must not compromise human health. We have shown here that a reduction in emissions from the diet alone can mathematically reach 75 % with high agreement with the EAT-Lancet diet, but all the low emitting diets are not necessarily healthy as showed by the models minimizing GHGe without constraints

on healthy diet. Furthermore, climate change is expected to impact the nutritional values of our food, specifically resulting in decreased levels of protein, iron, and zinc. As a result, it is important to take this into account when planning for a healthy diet in the future (Frumkin and Haines, 2019).

4.4. Limitations and strengths

It is important to note that our study has some limitations. Firstly, the LCA only covered the production stage as organic systems did not have data available for the entire system (from farm to fork). Additionally, it has been well-documented that LCA may misjudge some ecosystem services, particularly for agroecological practices (van der Werf et al., 2020). It would be also valuable to consider other environmental indicators such as biodiversity loss or water use, and consequential LCA. Indeed, these findings should be reevaluated while accounting evolution of the food systems and in particular future available food and modification in GHGe while considering consequential LCA. Here, the consequences in terms of reshaping agricultural practices and mitigation associated with lower production of animal products are not considered.

It should be noted that the participants in the study were all volunteers who were likely more interested in nutritional issues. Thus, they are not representative of the general French adult population as the cohort includes volunteers, resulting in a sample with more women, older people, and more graduates as well as healthier diets. These profiles are also linked to a greater sensitivity to environmental and health issues as illustrated by the higher consumption of organic food (Kesse-Guyot et al., 2016). As a result, the baseline diet being before optimization was already quite rich in plant-based foods compared to this observed in the general population. Besides, our results depend on the measures used to quantify adherence to the EAT-Lancet diet. However, a comparative analysis of these measures revealed that they could differed between various levels of GHG. Finally, we used a food grouping with an appropriately high level of detail (46 distinct food groups), which provides an averaged representation of the nutrient density and environmental pressure of detailed food categories, in order to identify the rebalancing of food groups required to achieve the controlled objective without the potential selection and over-representation in the modeled diets of some particular food items that are not nutritionally and/or environmentally representative of their categories.

Our study has many strengths. We took into consideration a high number of nutritional references values, bioavailability for iron and zinc, cultural acceptability, and co-production links (sensitivity analysis) when modeling diets. We also used a proxy for diet-related health impact using recent and reliable data from the GBD. Additionally, we differentiated between organic farming systems and standard/conventional farming systems for LCAs, which has not been done previously.

5. Conclusion

By making changes to current diets and farming methods, GHGe can be drastically reduced while complying with nutritional requirements but involves important changes compared to current diets which are not necessarily the healthiest in the long-term. Our study suggests that, while dietary changes can help reduce emissions concomitantly to increase in health value, all low emitting diets are not necessarily healthy. This suggests the need to consider the health of humans and the planet together in order to limit side-effects. These results also illustrate that 80 % reduction in GHGe and even more net zero emissions require modification of dietary habits coupled with strong changes in the sector of “*Agroforestry, Forestry and Other Land Use*” in order to improve carbon stocks and reduce emissions.

Transparency statement

Dr. Kesse-Guyot (the guarantor) affirms that the manuscript is an

honest, accurate, and transparent account of the study being reported, that no important aspects of the study have been omitted, and that any discrepancies from the study as planned have been explained.

Code availability statement

Code and programs can be retrieved from the corresponding author upon reasonable request.

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CRediT authorship contribution statement

Emmanuelle Kesse-Guyot: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Florine Berthy:** Writing – review & editing. **Justine Berlivet:** Writing – review & editing. **Elie Perraud:** Writing – review & editing. **Mathilde Touvier:** Writing – review & editing, Data curation. **Serge Hercberg:** Writing – review & editing, Funding acquisition, Data curation. **Benjamin Allès:** Writing – review & editing. **Denis Lairon:** Writing – review & editing, Conceptualization. **François Mariotti:** Writing – review & editing, Conceptualization. **Christian Couturier:** Writing – review & editing. **Hélène Fouillet:** Writing – review & editing, Methodology. **Philippe Pointereau:** Writing – review & editing, Conceptualization. **Julia Baudry:** Writing – review & editing, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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