

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

Emmanuelle Kesse-Guyot, Florine Berthy, Justine Berlivet, Elie Perraud, Mathilde Touvier, Serge Hercberg, Benjamin Allès, Denis Lairon, François Mariotti, Christian Couturier, et al.

## ▶ To cite this version:

Emmanuelle Kesse-Guyot, Florine Berthy, Justine Berlivet, Elie Perraud, Mathilde Touvier, et al.. Alignment between greenhouse gas emissions reduction and adherence the EAT-Lancet diet: A modeling study based on the NutriNet-Santé cohort. Science of the Total Environment, 2024, 951 (10440), pp.175470. 10.1016/j.scitotenv.2024.175470. hal-04676885

## HAL Id: hal-04676885 https://hal.science/hal-04676885v1

Submitted on 24 Aug 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Contents lists available at ScienceDirect

### Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv



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

Emmanuelle Kesse-Guyot<sup>a,\*</sup>, Florine Berthy<sup>a</sup>, Justine Berlivet<sup>a</sup>, Elie Perraud<sup>a</sup>, Mathilde Touvier<sup>a</sup>, Serge Hercberg<sup>a,d</sup>, Benjamin Allès<sup>a</sup>, Denis Lairon<sup>e</sup>, François Mariotti<sup>b</sup>, Christian Couturier<sup>d</sup>, Hélène Fouillet<sup>b</sup>, Philippe Pointereau<sup>c</sup>, Julia Baudry<sup>a</sup>

<sup>a</sup> Sorbonne Paris Nord University, Inserm, INRAE, Cnam, Nutritional Epidemiology Research Team (EREN), Epidemiology and Statistics Research Center – University of Paris Cité (CRESS). 93017 Bobigny, France

<sup>b</sup> Université Paris-Saclay, AgroParisTech, INRAE, UMR PNCA, 91120, Palaiseau, France

<sup>c</sup> Solagro, 75, Voie TOEC, CS 27608, F-31076 Toulouse, Cedex 3, France

<sup>d</sup> Département de Santé Publique, Hôpital Avicenne, 93017 Bobigny, France

<sup>e</sup> Aix Marseille Université, Inserm, INRAE, C2VN, 13005 Marseille, France

#### HIGHLIGHTS

#### G R A P H I C A L A B S T R A C T

- 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.

#### ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords: Diet Optimization Mitigation Greenhouse gas emissions



#### 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.

\* Corresponding author at: Equipe de Recherche en Epidémiologie Nutritionnelle (EREN) SMBH Université Sorbonne Paris Nord, 74 rue Marcel Cachin, 93017 Bobigny, France.

E-mail address: emmanuelle.kesse-guyot@inrae.fr (E. Kesse-Guyot).

#### https://doi.org/10.1016/j.scitotenv.2024.175470

Received 26 April 2024; Received in revised form 9 August 2024; Accepted 10 August 2024

Available online 12 August 2024

0048-9697/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

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 dietrelated 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 (Hercberg 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 (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 neversmoker), 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):

$$ELD - I_{j} = \frac{100 \times \left\{ \sum_{component \ i=1}^{14} \frac{a_{i} \times \left( cut - off_{i} - \frac{consumption_{ij} \times 2500}{Energy init(k_{ij})} \right)}{cut - off_{i}} \right\}}{14}$$
(1)

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<sup>®</sup>. 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:

25 million tons of Milk (L)  $\Leftrightarrow$  1.52 million tons of beef  $\times$  41%  $\times$  68%<sub>carcass yield</sub>  $\times$  90%<sub>distribution yield</sub>  $\times$  68%<sub>preparation yield</sub>  $\times$  68%

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 sociodemographic 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 (GWP<sub>100</sub>) in kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>eq)), cumulative energy demand (MJ), and land occupation (m<sup>2</sup>) were

#### 1 L milk $\Leftrightarrow$ 100 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)):

$$Min \text{ GHGe} = \sum_{i}^{40} C_{organic \ i} \times GHGe_{organic \ i} + C_{conventional \ i} \times GHGe_{conventional \ i}$$
(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 <sup>a</sup> .

	Obs	Modeling diets						
	Obs	G1	G2	G3	G4	G5		
Constraints Nutritional references		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		
Acceptability cut- off Lower Upper Relaxing Fe and Zn			<p95<sup>th</p95<sup>	$\substack{>P5^{th}}{$	<p99<sup>th</p99<sup>	$^{<\mathrm{P99}^{\mathrm{th}}}$ $$		
Objective function Minimizing GHGe	_	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		
GHGe (kgCO <sub>2</sub> eq/ d)	4.34	0.46	2.99	3.18	1.45	0.72		
Eat-Lancet score Number of EAT- Lancet components achieved (/14)	20.93 10.09	38.22 7	47.28 9	46.19 9	40.82 8	41.46 8		
PNNS-GS2 Proportion of organic food in the diet	2.28 0.28	0.75 0.88	7.25 0.92	7.25 0.93	6.75 0.91	5.25 0.94		
% plant-based proteins	33.18	48.80	31.85	33.60	53.66	78.16		
Land occupation (m <sup>2</sup> /d)	11.36	3.83	9.20	9.80	6.13	4.24		
Dietary cost (€/d) Diet deviation	7.70 0	7.74 58.59	13.66 67.60	9.80 60.76	11.40 129.04	8.68 10,115.85		

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

<sup>a</sup> 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)):

$$\sum_{i}^{46} \left[ \frac{Opt_i - Obs_i}{SD_i} \right]^2 \tag{3}$$

where  $Opt_i$  and  $Obs_i$  denote the daily consumption of the food category (i) in the modeled and observed diets, respectively and SD<sub>i</sub> 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 "stan-dardized 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  $\pm$  14.07 year vs. 44.62  $\pm$  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 kgCO<sub>2</sub>eq/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.

<sup>1</sup>Food 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.

 $^{2}$ G1 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 emissions<sup>a</sup>.

	Obs	Modeling diets							
		M1	M2	M3	M4	M5	M6	M7	
Constraints									
Nutritional references		$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$			
Maximum acceptability cut-off (P99th)		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	
Relaxing Fe and Zn							$\checkmark$	$\checkmark$	
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	_	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$			
GHGe (kgCO <sub>2</sub> 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 <sup>b</sup>	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 <sup>2</sup> /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.

<sup>a</sup> 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.

<sup>b</sup> 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 dietaryrelated GHGe by up to a 4-factor (i.e. 1.09 kgeqCO<sub>2</sub>/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 m<sup>2</sup>/d) but the PNNS-GS2 reflecting compliance with food-based dietary recommendations, was maximum for the 1.5-factor reduction in GHGe (GHGe =  $2.9 \text{ kgeqCO}_2$ /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 emissions <sup>1</sup>. <sup>1</sup>M 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 an 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 GHG 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). Lowemitting diets are typically meat-free but can include certain unhealthy products such as sugared-sweetened beverages and energydense 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 (Chiriacò 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 Piorr, 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 (Chiriacò 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; Montejano Vallejo et al., 2022; Tepper et al., 2022). In addition, we previously observed that EAT-lancet score greatly varied for the diet less mitting, 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 kgCO<sub>2</sub>eq/d versus 3.62 kgCO<sub>2</sub>eq/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- $CO_2$  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 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 referces 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 "Agroforestery, Forestery and Other Land Use" in order to improve carbon stocks and reduce emissions.

#### **Transparency statement**

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.

#### Funding

The NutriNet-Santé study is funded by the French Ministry of Health and Social Affairs, Santé Publique France, Institut National de la Santé et de la Recherche Médicale, Institut de recherche pour l'agriculture, l'alimentation et l'environnement, Conservatoire National des Arts et Métiers, and Sorbonne Paris Nord University. The BioNutriNet project was supported by the French National Research Agency (Agence Nationale de la Recherche) in the context of the 2013 Programme de Recherche Systèmes Alimentaires Durables (ANR-13-ALID-0001). The funders had no role in the study design, data collection, analysis, interpretation of data, preparation of the manuscript, and the decision to submit the paper.

#### 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, 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.

#### Acknowledgements

We thank Cédric Agaesse, Alexandre De Sa, Rebecca Lutchia (dietitians); Thi Hong Van Duong, Selim Aloui (IT manager), Régis Gatibelza, Jagatjit Mohinder and Aladi Timera (computer scientists); Julien Allegre, Nathalie Arnault, Laurent Bourhis and Fabien Szabo de Edelenyi, PhD (supervisor) (data-manager/statisticians) for their technical contribution to the NutriNet-Santé study and Marine Ricau (operational coordination). We warmly thank all the volunteers of the NutriNet-Santé cohort.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175470.

#### References

- Alegria, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., 2022. Climate change 2022: impacts, adaptation and vulnerability. In: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, 2022: Summary for Policymakers [Internet]. Cambridge University Press, Cambridge, UK and New York NY, USA. https://doi.org/10.1017/ 9781009325844.001. Disponible sur.
- Aleksandrowicz, L., Green, R., EJM, Joy, Smith, P., Haines, A., 2016. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. Wiley AS, éditeur PLoS ONE 11 (11), 3 nov. e0165797
- Almaraz, M., Houlton, B.Z., Clark, M., Holzer, I., Zhou, Y., Rasmussen, L., et al., 2023. Model-based scenarios for achieving net negative emissions in the food system. PLOS Clim. 2 (9), 6 sept. e0000181.
- Armah, S.M., Carriquiry, A., Sullivan, D., Cook, J.D., Reddy, M.B., 2013. A complete dietbased algorithm for predicting nonheme iron absorption in adults. J. Nutr. 143 (7), 1136–1140 juill.
- Baudry, J., Méjean, C., Allès, B., Péneau, S., Touvier, M., Hercberg, S., et al., 2015. Contribution of organic food to the diet in a large sample of French adults (the NutriNet-Santé cohort study). Nutrients 7 (10), 8615–8632.
- Baudry, J., Pointereau, P., Seconda, L., Vidal, R., Taupier-Letage, B., Langevin, B., et al., 2019. Improvement of diet sustainability with increased level of organic food in the diet: findings from the BioNutriNet cohort. Am. J. Clin. Nutr. 109 (4), 1173–1188, 1 avr.
- Bazaraa, M., Shrali, H., Shetty, C., Wiley.com, 2021. cité 23 juin Nonlinear Programming: Theory and Algorithms, 3rd Edition. Wiley. Disponible sur. https ://www.wiley.com/en-al/Nonlinear+Programming%3A+Theory+and+Algorithms %2C+3rd+Edition-p-9780471486008.
- Berthy, F., Brunin, J., Allès, B., Reuzé, A., Touvier, M., Hercberg, S., et al., 2023. Higher adherence to the EAT-lancet reference diet is associated with higher nutrient adequacy in the NutriNet-Sante cohort: a cross-sectional study. Am. J. Clin. Nutr. 117 (6), 1174–1185 juin.
- Cacau, L.T., 2021. Adherence to the planetary health diet index and obesity indicators in the Brazilian longitudinal study of adult health (ELSA-Brasil). Nutrients 13 (11), 3691.
- Cambeses-Franco, C., Feijoo, G., Moreira, M.T., González-García, S., 2022. Co-benefits of the EAT-lancet diet for environmental protection in the framework of the Spanish dietary pattern. Sci. Total Environ. 836, 25 août. 155683.
- Chaltiel, D., Adjibade, M., Deschamps, V., Touvier, M., Hercberg, S., Julia, C., et al., 2019. Programme National Nutrition Santé guidelines score 2 (PNNS-GS2): development and validation of a diet quality score reflecting the 2017 French dietary guidelines. Br. J. Nutr. 122 (3), 331–342 août.
- Chiriacò, M.V., Castaldi, S., Valentini, R., 2022. Determining organic versus conventional food emissions to foster the transition to sustainable food systems and diets: insights from a systematic review. J. Clean. Prod. 380, 20 déc. 134937.
- Clark, M., Hill, J., Tilman, D., 2018. The diet, health, and environment trilemma. Annu. Rev. Environ. Resour. 43 (1), 109–134.
- Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., et al., 2020. Global food system emissions could preclude achieving the  $1.5^{\circ}$  and  $2^{\circ}C$  climate change targets. Science 370 (6517), 705–708, 6 nov.
- Colizzi, C., Harbers, M.C., Vellinga, R.E., Verschuren, W.M.M., Boer, J.M.A., Biesbroek, S., et al., 2023. Adherence to the EAT-lancet healthy reference diet in relation to risk of cardiovascular events and environmental impact: results from the EPIC-NL cohort. JAHA 12 (8), 18 avr. e026318.
- Couturier, C., Charru, M., Doublet, S., Pointereau, P., 2016. The Afterres 2050 le scénario [Internet] [cité 8 juin 2020]. Disponible sur. https://afterres2050.solagro.or g/wp-content/uploads/2020/02/Afterres2050-eng.pdf.
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat. Food 2 (3), 198–209 mars.
- Dussiot, A., Fouillet, H., Perraud, E., Salomé, M., Huneau, J., Mariotti, F., et al., 2023. How to best reshape diets to be healthier with lower or no ruminant meat, and implications for environmental pressures. J. Clean. Prod. 414, 15 août.
- Dussiot A, Fouillet H, Wang J, Salomé M, Huneau JF, Kesse-Guyot E, et al. Modeled healthy eating patterns are largely constrained by currently estimated requirements for bioavailable iron and zinc. Am. J. Clin. Nutr.
- EFSA, 2021. Dietary reference values | DRV finder. Disponible sur: https://www.efsa. europa.eu/en/interactive-pages/drvs [Internet]. [cité 22 janv].
- European Commission. Climate Action European Commission. 2016 [cité 5 févr 2021]. Paris Agreement. Disponible sur: https://ec.europa.eu/clima/policies/internation al/negotiations/paris\_en.
- European Public Health Association EUPHA, 2017. Healthy and Sustainable Diets for European Countries [Internet]. Disponible sur: https://eupha.org/repository/ad vocacy/EUPHA\_report\_on\_healthy\_and\_sustainable\_diets\_20-05-2017.pdf.
- France Agrimer, 2012. Filière bovine, quotas laitiers [cité 22 sept 2020];12. Disponible sur: https://www.franceagrimer.fr/fam/content/download/14506/document/f ilière. bovine, quotas laitiers février 2012 A4.pdf.
- French Agency for Food, Environmental and Occupational Health Safety (Anses), 2016. Actualisation des repères du PNNS: élaboration des références nutritionnelles [Internet]. ANSES, Maison Alfort déc. Disponible sur: Available from: https://www. anses.fr/fr/system/files/NUT2012SA0103Ra-2.pdf.
- Frumkin, H., Haines, A., 2019. Global environmental change and noncommunicable disease risks. Annu. Rev. Public Health 40 (1), 261–282, 1 avr.
- Gao, J., Hou, H., Zhai, Y., Woodward, A., Vardoulakis, S., Kovats, S., et al., 2018. Greenhouse gas emissions reduction in different economic sectors: mitigation

measures, health co-benefits, knowledge gaps, and policy implications. Environ. Pollut. 240, 683–698, 1 sept.

- Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32 janv.
- Gazan, R., Brouzes, C.M.C., Vieux, F., Maillot, M., Lluch, A., Darmon, N., 2018. Mathematical optimization to explore tomorrow's sustainable diets: a narrative review. Adv. Nutr. 9 (5), 602–616, 1 sept.
- GBD 2019 Risk Factors Collaborators, 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10258), 1223–1249, 17 oct.
- Giampieri, F., Mazzoni, L., Cianciosi, D., Alvarez-Suarez, J.M., Regolo, L., Sánchez-González, C., et al., 2022. Organic vs conventional plant-based foods: a review. Food Chem. 383, 30 juill. 132352.
- Hagströmer, M., Oja, P., Sjöström, M., 2006. The International Physical Activity Questionnaire (IPAQ): a study of concurrent and construct validity. In: Public Health Nutrition [Internet], 9(06) sept. [cité 28 avr 2016]. Disponible sur. http://www.jo urnals.cambridge.org/abstract\_S1368980006001261.
- Hallström, E., Carlsson-Kanyama, A., Börjesson, P., 2016. Environmental impact of dietary change: a systematic review. J. Clean. Prod. 91, 1–11.
- Hamilton, I., Kennard, H., McGushin, A., Höglund-Isaksson, L., Kiesewetter, G., Lott, M., et al., 2021. The public health implications of the Paris agreement: a modelling study. Lancet Planet. Health 5 (2), e74–e83, 1 févr.
- Hercberg, S., Castetbon, K., Czernichow, S., Malon, A., Mejean, C., Kesse, E., et al., 2010. The Nutrinet-Sante Study: a web-based prospective study on the relationship between nutrition and health and determinants of dietary patterns and nutritional status. BMC Public Health 10 (1471–2458), 242.
- HLPE, 2014. Food losses and waste in the context of sustainable food systems. In: A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, Italy, p. 117.
- HLPE, 2017. Nutrition and food systems. In: A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security,. Rome, Italy, p. 152 (Report No.: 12).
- Idèle, 2016. Chiffres clés Bovins, p. 2016.
- Intergovernmental Panel on Climate Change, 1992. Climate Change: The IPCC 1990 and 1992 Assessments IPCC [Internet] [cité 13 juill 2023]. Disponible sur. https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/.
- IPCC, 2018. Global Warming of 1.5 °C. In: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty [Internet] [cité 4 juin 2020]. Disponible sur. https://www.ipcc. ch/sr15/download/.
- Jarmul, S., Dangour, A.D., Green, R., Liew, Z., Haines, A., Scheelbeek, P.F., 2020. Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of "sustainable diets". Environ. Res. Lett. 15, 22 déc. 123014.
- Kesse-Guyot, E., Assmann, K., Andreeva, V., Castetbon, K., Méjean, C., Touvier, M., Salanave, B., Deschamps, V., Péneau, S., Fezeu, L., Julia, C., Allès, B., Galan, P., Hercberg, S., 2016. Lessons learned from methodological validation research in eepidemiology. JMIR Public Health Surveill. 2 (2), e160 https://doi.org/10.2196/ publichealth.5880. Jul-Dec.
- Kesse-Guyot, E., Chaltiel, D., Wang, J., Pointereau, P., Langevin, B., Allès, B., et al., 2020. Sustainability analysis of French dietary guidelines using multiple criteria. Nat. Sustain. 1–9, 23 mars.
- Kesse-Guyot, E., Rebouillat, P., Brunin, J., Langevin, B., Allès, B., Touvier, M., et al., 2021a. Environmental and nutritional analysis of the EAT-Lancet diet at the individual level: insights from the NutriNet-Santé study. J. Clean. Prod. 296, 10 mai. 126555.
- Kesse-Guyot, E., Fouillet, H., Baudry, J., Dussot, A., Langevin, B., Allès, B., et al., 2021b. Halving food-related greenhouse gas emissions can be achieved by redistributing meat consumption: progressive optimization results of the NutriNet-Santé cohort. Sci. Total Environ. 789, 24 mai. 147901.
- Kesse-Guyot, E., Pointereau, P., Brunin, J., Perraud, E., Toujgani, H., Berthy, F., et al., 2023. Trade-offs between blue water use and greenhouse gas emissions related to food systems: an optimization study for French adults. Sustain. Prod. Consum. 42, 33-43 nov.
- Kramer, G.F., Tyszler, M., Veer, P.V., Blonk, H., 2017. Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. Public Health Nutr. 20 (9), 1699–1709 juin.
- Laine, J.E., Huybrechts, I., Gunter, M.J., Ferrari, P., Weiderpass, E., Tsilidis, K., et al., 2021. Co-benefits from sustainable dietary shifts for population and environmental health: an assessment from a large European cohort study. Lancet Planet. Health 5 (11), e786–e796 nov.
- Leonard, U.M., Leydon, C.L., Arranz, E., Kiely, M.E., 2024. Impact of consuming an environmentally protective diet on micronutrients: a systematic literature review. Am. J. Clin. Nutr. [Internet], 11 mars. [cité 14 mars 2024]; Disponible sur: https:// www.sciencedirect.com/science/article/pii/S0002916524000479.
- Lonnie, M., Johnstone, A.M., 2020. The public health rationale for promoting plant protein as an important part of a sustainable and healthy diet. Nutr. Bull. 45 (3), 281–293.
- Mazac, R., Meinilä, J., Korkalo, L., Järviö, N., Jalava, M., Tuomisto, H.L., 2022. Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80%. Nat. Food 3 (4), 286–293 avr.

#### E. Kesse-Guyot et al.

- Miller, L.V., Krebs, N.F., Hambidge, K.M., 2007. A mathematical model of zinc absorption in humans as a function of dietary zinc and phytate. J. Nutr. 137 (1), 135–141 janv.
- Ministère de la Transition Écologique et de la Cohésion des Territoires, 2024. Stratégie Nationale Bas-Carbone (SNBC). Disponible sur. https://www.ecologie.gouv.fr/stra tegie-nationale-bas-carbone-snbc [Internet]. [cité 30 janv].
- Montejano Vallejo, R., Schulz, C.A., van de Locht, K., Oluwagbemigun, K., Alexy, U., Nöthlings, U., 2022. Associations of adherence to a dietary index based on the EAT–lancet reference diet with nutritional, anthropometric, and ecological sustainability parameters: results from the German DONALD Cohort Study. J. Nutr. 152 (7), 1763–1772 juil.
- Myers, S.S., Smith, M.R., Guth, S., Golden, C.D., Vaitla, B., Mueller, N.D., et al., 2017. Climate change and global food systems: potential impacts on food security and undernutrition. Annu. Rev. Public Health 38 (1), 259–277, 20 mars.
- Nelson, M.E., 2016. Alignment of healthy dietary patterns and environmental sustainability: a systematic review. Adv. Nutr. 7 (6), 1005–1025.
- Neufingerl, N., Eilander, A., 2022. Nutrient intake and status in adults consuming plantbased diets compared to meat-eaters: a systematic review. Nutrients 14 (1), 29 janv.
- Nordman, M., Lassen, A.D., Stockmarr, A., van 't Veer, P., Biesbroek, S., Trolle, E., 2023. Exploring healthy and climate-friendly diets for Danish adults: an optimization study using quadratic programming. Front. Nutr. 10, 1158257.
- Etude Nutrinet-Santé, 2013. Table de composition des aliments de l'étude Nutrinet-Santé (Nutrinet-Santé Study Food Composition Database). Economica, Paris.
- Perignon, M., Masset, G., Ferrari, G., Barre, T., Vieux, F., Maillot, M., et al., 2016. How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. Public Health Nutr. 19 (1475-2727 (Electronic)), 2662–2674 oct.
- Pointereau, P., Langevin, B., Gimaret, M., 2012. DIALECTE, a comprehensive and quick tool to assess the agro-environmental performance of farms. Disponible sur: http ://ifsa.boku.ac.at/cms/index.php?id=ifsa2012.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992, 1 juin.
- Seconda, L., Baudry, J., Alles, B., Boizot-Szantai, C., Soler, L.G., Galan, P., et al., 2018. Comparing nutritional, economic, and environmental performances of diets

according to their levels of greenhouse gas emissions. Clim. Chang. 148 (1–2), 155–172 mai.

- Steenson, S., Buttriss, J.L., 2021. Healthier and more sustainable diets: what changes are needed in high-income countries? Nutr. Bull. 46 (3), 279–309.
- Tepper, S., Kissinger, M., Avital, K., Shahar, D.R., 2022. The environmental footprint associated with the Mediterranean diet, EAT-lancet diet, and the sustainable healthy diet index: a population-based study. Front. Nutr. 9, 870883.
- Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515 (1476-4687 (Electronic)), 518–522, 27 nov.
- Touvier, M., Mejean, C., Kesse-Guyot, E., Pollet, C., Malon, A., Castetbon, K., et al., 2010. Comparison between web-based and paper versions of a self-administered anthropometric questionnaire. Eur. J. Epidemiol. 25, 287–296 mai.
- Tulloch, A.I.T., Borthwick, F., Bogueva, D., Eltholth, M., Grech, A., Edgar, D., et al., 2023. How the EAT-lancet commission on food in the Anthropocene influenced discourse and research on food systems: a systematic review covering the first 2 years post-publication. Lancet Glob. Health 11 (7), e1125–e1136 juill.
- van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3 (6), 419–425 juin.
- van Dooren, C., 2018. A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally. Front. Nutr. 5, 48.
- Vergnaud, A.C., Touvier, M., Méjean, C., Kesse-Guyot, E., Pollet, C., Malon, A., et al., 2011. Agreement between web-based and paper versions of a socio-demographic questionnaire in the NutriNet-Santé study. Int. J. Public Health 56 (4), 407–417, 1 août.
- Vicente-Vicente, J.L., Piorr, A., 2021. Can a shift to regional and organic diets reduce greenhouse gas emissions from the food system? A case study from Qatar. Carbon Balance Manag. 16 (1), 2, 9 janv.
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492, 02.
- Wilson, N., Cleghorn, C.L., Cobiac, L.J., Mizdrak, A., Nghiem, N., 2019. Achieving healthy and sustainable diets: a review of the results of recent mathematical optimization studies. Adv. Nutr. 10 (Suppl 4), S389–S403, 01.