Trade-offs between blue water use and greenhouse gas emissions related to food systems : An optimization study for French adults

Emmanuelle Kesse-Guyot, Philippe Pointereau, Joséphine Brunin, Elie Perraud, Hafsa Toujgani, Florine Berthy, Benjamin Allès, Mathilde Touvier, Denis Lairon, François Mariotti, et al.

To cite this version:

Emmanuelle Kesse-Guyot, Philippe Pointereau, Joséphine Brunin, Elie Perraud, Hafsa Toujgani, et al.. Trade-offs between blue water use and greenhouse gas emissions related to food systems : An optimization study for French adults. Sustainable Production and Consumption, 2023, 42, pp.33-43. 10.1016/j.spc.2023.09.008 . hal-04238352

HAL Id: hal-04238352
https://hal.inrae.fr/hal-04238352v1

Submitted on 23 Aug 2024

Abstract

Food systems face challenges from both their water and carbon footprints. Data suggest that it is possible to improve these both footprints simultaneously, but their potential conflicts and trade-offs have not been systematically explored. To this end, we here used a compromise programming approach to identify the dietary changes required to improve one and/or the other of these footprints, while ensuring nutritional adequacy and adherence to dietary guidelines, using French data on food consumption (1,456 adults aged 18-64 years from the INCA 3 study) and food environmental impact (Agribalyse® database). A full range of scenarios was identified by prioritizing the two objectives differently, giving weight from 0% to 100%, by 5-% steps, to the improvement in greenhouse gas emissions (GHGe) over the improvement in blue water use (BWU).

Overall, we have shown that it is possible to significantly reduce both BWU and GHGe compared to observed levels. The BWU reduction ranged from 14% to 36% with increasing prioritization, while the simultaneous GHGe reduction varied less, from 52% to 44% with decreasing prioritization. The consumption of some foods varied according to the priority given to BWU over GHGe reduction (namely, vegetables, fruit juice, dairy products, eggs, refined cereal, substitutes, offal and potatoes). In contrast, meat consumption (beef, pork, poultry and processed meat) was systematically removed, while the consumptions of offal and dairy products remained moderate in order to meet nutrient reference values. Fish, whole grains, and fruit also remained relatively constant across scenarios due to the constraints based on dietary guidelines. Whatever the scenario, the modeled diets were more plant-based than the observed diet from which they differed significantly (only 23-31% of common food consumptions), and were therefore healthier (63-76% reduction in the distance to theoretical minimum risk of chronic diseases).

To conclude, while focusing solely on BWU reduction induces a joint GHGe reduction that is near-maximal, the reverse is not true, showing that there is good alignment but also some divergence between these objectives.

Keywords: GHGe, Water use, compromise modelling, diet optimization, nutrient adequacy, healthy diet

Symbols

i : denotes the 45 food groups

λ: increment from 0% to 100%

Abbreviations

BWU: blue water use (m^3 world eq/d)

DALYs: Disability-Adjusted Life Years

DD: diet departure

DSI: diet similarity index

GBD: Global Burden of diseases HRS: health risk score

GHGe: greenhouse gas emissions (CO_2 eq/d)

HRS: Health Risk Score

INSEE: Institut Nationale des Statistiques et des Etudes Economiques

Opt: optimized value

Obs: observed

TMREL: theoretical minimum-risk exposure levels

1 Introduction

Urbanization and modernization have significantly impacted dietary patterns, especially in developed countries. These patterns have shifted towards animal-based diets high in salt, fat, and sugar, leading to increased prevalence of various chronic diseases such as cardiovascular disease, diabetes, and cancer, particularly colorectal cancer (GBD 2017 Diet Collaborators, 2019; GBD 2019 Risk Factors Collaborators, 2020), with ~190 million disability-adjusted life years (DALYs) attributed to dietary risk factors worldwide in 2019 (GBD 2019 Risk Factors Collaborators, 2020). Besides harming health, the current food system damages the environment by depleting natural resources, such as water and forests, and contribute climate instability through increased GHGe (Clark et al., 2019; HLPE, 2017). Planetary boundaries are exceeded for six critical indicators (Campbell et al., 2017; Rockström et al., 2009; Steffen et al., 2015), including climate change and one component of total water use, namely green water use (mainly from rainwater and water stored in the soil), the other component being BWU (groundwater or surface water). Recently, some authors have highlighted the need for integrated environmental assessments and policy decisions to better understand the trade-offs between different environmental footprints, which should be studied simultaneously (Vanham et al., 2019).

Today, GHGe from animal-based food production are twice higher than those from plant-based food (Xu et al., 2021). Specifically, red and processed meat production are the most impactful globally, regardless of climate change or water use (Clark et al., 2019; Poore and Nemecek, 2018). However, other productions have a substantial role in GHGe, such as dairy products and some fish, depending on the production method (captured or farmed). In addition, some of the lower emitting foods (e.g. fresh fruit, vegetables, and some refined and whole grains) have quite strong water demands (Clark et al., 2019; Poore and Nemecek, 2018). With regard to diet, there is a large body of scientific literature documenting its link to environmental pressures, and studies have reported that diets rich in plant-based foods have lower pressures than animal-based diets, particularly for GHGe (Aleksandrowicz et al., 2016; Auestad and Fulgoni, 2015; Carey et al., 2023; Perignon et al., 2016; van Dooren, 2018; Wilson et al., 2019). While studies on diet-related environmental pressures have largely focused on climate change and the associated GHGe criterion (Jones et al., 2016; Ridoutt et al., 2017), it is not the only environmental indicator threatened by the food systems, which also significantly impact natural resource depletion and biodiversity loss (Campbell et al., 2017; Eyhorn et al., 2019; Poore and Nemecek, 2018).

Regarding studies on the water footprint of food systems, the available results are not always consistent and are subject to debate depending on the type of indicator (water footprint, BWU and/or green water use). In reviews, healthier diets have been associated with higher (Steenson and Buttriss, 2021), similar (Harris et al., 2020) or lower (Aleksandrowicz et al., 2016) BWU. This may be because some plant-based foods, such as fruits, oils, and nuts, which are essential components of a healthy diet, are also important contributors to BWU (Clark et al., 2022; Harris et al., 2020; Willett et al., 2019).

Most of the diet modeling studies to identify the dietary changes needed to reduce environmental impact have focused on GHGe, even if some have also considered BWU (Wilson et al., 2019). Only one diet modeling study has alternately optimized different footprints (Gephart et al., 2016): in this American study, all optimized diets were rich in plant-based products and low in animal-based products, regardless of the considered environmental criteria (such as BWU and green water use or GHGe), and the authors concluded to similarities between diets limiting carbon and water footprints. However, to date, no study has comprehensively analyzed the similarities or differences between diets that minimize carbon or water footprints, and little is still known about the alignments and/or conflicts (with potential trade-offs) between these two objectives.

To address this question adequately and systematically, we have used a compromise programming approach to explore all possible trade-off scenarios between the two extremes of optimizing only one of the carbon and water footprints. Compromise modelling is a key tool to explore such multi-criteria optimization problem, which has not yet been applied to this research question. This was done here by sequentially balancing GHGe and BWU minimization under a set of constraints to ensure nutrient security, not worsen long-term health risk, and consider cultural acceptability in the French context, using the average observed diet from the most recent representative dietary survey combined with the diet-related environmental footprints data from the Agribalyse ® database.

2 Methods

2.1 Population

This study was conducted using data from the INCA 3 study, a nationally representative French survey conducted in 2014-2015 by the French Agency for Food, Environmental and Occupational Health Safety (ANSES). This study initially included 2,121 adult participants who provided food consumption data using a validated method (Dubuisson et al., 2019). Details of the study design, recruitment and survey plan (definition of individual weight), and methods used have been described in detail elsewhere (Dubuisson et al., 2019).

Overall, participants were selected according to a three-stage random sampling design (geographic units, dwellings, and then individuals) drawn by the National Institute of Statistics and Economic Studies (INSEE). One individual per dwelling was then drawn at random from the eligible individuals at the time of the household contact. The weight of individuals was calculated according to the INSEE method to improve representativeness by region, size of the urban area, occupation and socio-professional category of the household's reference person, household size, education level, gender, and age (Sautory, 1993).

The INCA 3 study protocol was authorized by the National Commission on Informatics and Liberty, after a favorable opinion from the Advisory Committee on Information Processing in Health Research. The study also received a favorable opinion from the Conseil National de l'Information Statistique on 15 June 2011 (n°121/D030) and was awarded the label of “general interest” and statistical quality by the INSEE Label Committee (n°47/Label/D120).

The data collected in the INCA 3 survey encompass food and drink consumption and socio-demographic and lifestyle characteristics. In the present study, we selected adults <65y old (N=1,665) who were not under-reporter (N=1,456) for energy intake (the procedure for identification of under-reporters is described in **Method S1**).

2.2 Dietary data

Food and beverage consumption data were collected over 3 non-consecutive days (2 weekdays and 1 weekend day) distributed over approximately three weeks, using the 24-hour recall method by phone conducted by trained interviewers using a standardized validated software for data entry (GloboDiet)(Aglago et al., 2017). Estimation of portion sizes consumed was performed using a picture booklet of food portions and household measurements, previously sent by post. Mixed dishes were decomposed in ingredients using the standardized recipes validated by dieticians.

Nutrient intakes were calculated using the 2016 food composition database published by the French Information Centre on Food Quality (Agence nationale de sécurité sanitaire de l’alimentation de l’environnement et du travail (ANSES), 2012). In the modeling procedure, food items consumptions were collapsed into 45 broader food groups (the list is provided in **Table S1**). Nutrient composition and environmental pressure of each food group were calculated as mean over all items of the group weighted by the contribution of the food item consumption to the food group consumption.

2.3 Health risk and diet similarity scores

Health risk associated with each observed and modeled diet was assessed using the Health Risk Score (HRS) (Fouillet et al., 2023), representing the global normalized distance to the theoretical minimum-risk exposure levels (TMREL) for three unhealthy (red meat, processed meat and sweetened beverages) and six healthy (whole grains, fruit, vegetables, legumes, nuts and seeds, and milk) food groups established by the 2019 Global Burden of diseases (GBD) study (GBD 2019 Risk Factors Collaborators, 2020). The HRS measures the distance to each consumption target (TMREL) weighted by its relative importance using DALYs attributable to each food group in the French population. By construct, HRS varies between 0% and 100%, depending on whether the diet meets all the food group targets (i.e., minimum risk) or deviate from them at most (i.e., maximum risk), respectively. The HRS calculation is presented and detailed in **Method S2**.

For each modeled diet, we also computed DSI (diet similarity index) reflecting the proportion of food group consumptions that remained similar to those of the observed diet (Mertens et al., 2020) using the following formula:

$$\mathrm{DSI} = 100 \times \frac{\sum_{\mathrm{i}=1}^{44} \min(\mathrm{Opt}_\mathrm{i},\mathrm{Obs}_\mathrm{i})}{\sum_{\mathrm{i}=1}^{44} \mathrm{Obs}_\mathrm{i}}$$

where i denotes the 45 food groups except water used in the optimization model. Opt refered to the optimized value and Obs to the observed value.

2.4 Environmental indicators

Environmental indicators for pressure along with the food chain were estimated using data from the French database Agribalyse ® 3.1 developed by the French Agency for the Environment and Energy Management (ADEME). Agribalyse ® 3.1 contains environmental indicators for 2,517 foods consumed in France. The list was based on the consumption declared in the INCA 3 survey using common coding (Colomb et al., 2015). The methodology has been extensively explained in *ad hoc* published reports (*ADEME*, 2020; Koch and Salou, 2020) and is summarized in **Method S3**. In the Agribalyse ® database, water footprint has been estimated using the guidelines of The Water Footprint Network (Hoekstra, 2011) and refers to blue water. The other available indicators are defined in Method S3. GHGe and BWU for each food group are shown in **Table S1**.

2.5 Multicriteria optimization by compromise programming for analyzing GHGe and BWU trade-offs

Diet optimization was performed using the procedure SAS/OR ® *optmodel* (version 9.4; SAS Institute, Inc.) using a non-linear optimization algorithm with multi-start option to minimize the risk of obtaining only a local minimum. The methodologic approach and used data are summarized in **Figure 1**.

Starting from the observed food consumptions, we modeled fully nutrient-adequate diets by including the following constraints in diet optimization:

- Nutritional constraints on daily energy intake and a set of nutrient intakes were based on the recently revised ANSES Reference Values (French Agency for Food, Environmental and Occupational Health Safety (Anses), 2016) according to the 2021 EFSA opinion ("Dietary Reference Values | DRV Finder," n.d.). For bioavailable iron and zinc, lower bounds were not based on current reference values but on lower threshold values ensuring ≤5% deficiency prevalence, as in our previous study (Fouillet et al., 2023), because we have shown that such flexibility enables the identification of healthier diets with a better balance in DALYs due to less cardiometabolic disease, despite a higher prevalence of iron-deficiency anemia (Dussiot et al., 2021). Nutritional constraints are presented in **Table A.2**. For zinc and iron, bioavailability was considered using reference equations (Armah et al., 2013; Miller et al., 2013). Details of computation and formula are presented in **Method S4.**

- Acceptability constraints were defined by upper bounds set at the weighted 99th percentiles values of each food group based on the distribution in the INCA3 study (**Table S1).** In the lack of specific data on acceptability, these constraints rather represent the overall feasibility given current consumption levels, and only an upper threshold was used to limit aberrant/unattainable consumption levels while leaving room for change.
- Epidemiological constraints have been also defined to avoid increasing the health risk (as considered by the GBD) beyond its observed level, as follows:
    - at least equal of the observed average (among consumers) consumption for healthy food groups (fruits, vegetables, legumes, nuts, whole grains and milk)
    - less than or equal to the observed average intake (among consumers) for the unhealthy food groups (red meat, processed meat and sweetened beverages), outweighing the corresponding acceptability constraints.

Diet optimization was conducted on the mean dietary data for each sex and for both sexes, by considering an average individual constituted of 50% male and 25% non-menopaused and 25% menopaused female. In the average individual, nutritional references were defined as the weighted values of sex specific nutritional references (**Table S1)**, and the 99th and 95th percentiles (see below) of food group consumptions were calculated using the same weighting scheme.

In a preliminary step (**Figure 1**), we applied the nutritional, epidemiological and acceptability constraints to identify the modifications needed to comply with the nutritional and epidemiologic references only. For this model, the objective function was the minimization of the diet departure (DD) from to the initial (observed) situation using a formula accounting for dietary inertia (Kramer et al., 2018) as:

$$\mathrm{DD} = \sum_{i=1}^{45}\left[\frac{\mathrm{Opt_i}-\mathrm{Obs_i}}{\mathrm{SD_i}}\right]^2 \qquad [1]$$

Where $\mathrm{Opt_i}$ and $\mathrm{Obs_i}$ denoted the optimized and observed daily consumption of food group (i) and $\mathrm{SD_i}$ was the standard deviation of the observed daily consumption of food group (i).

Then, in a first step (**Figure 1**) we performed a multi-criteria optimization of GHGe and BWU by compromise programming.

First, we determined the best (minimal) and worst (maximal) values achievable for GHGe and BWU, respectively, while satisfying all the model constraints defined above, by mono-criteria optimization as following:

$$\text{Min GHGe} = \sum_{i=1}^{45}[\mathrm{Opt_i} \times \mathrm{GHGe_i}], \text{ giving } \mathrm{GHGe_{best}} \text{ and } \mathrm{BWU_{worst}} \quad [2]$$

and

$$\text{Min BWU} = \sum_{i=1}^{45}[\mathrm{Opt_i} \times \mathrm{BWU_i}], \text{ giving } \mathrm{BWU_{best}} \text{ and } \mathrm{GHGe_{worst}} \quad [3]$$

where i is the food group, $\mathrm{Opt_i}$ denotes the daily consumption of the food group i (g/d) in the optimized model, $\mathrm{GHGe_i}$ is the greenhouse gas emission for 1 g of the food group i and $\mathrm{BWU_i}$ is the blue water use for 1 g of the food group i, $\mathrm{GHGe_{best}}$ and $\mathrm{BWU_{best}}$ are the best values and $\mathrm{GHGe_{worst}}$ and $\mathrm{BWU_{worst}}$ the worst values of the corresponding criteria (i.e., the parameters of the pay-off matrix in compromise programming) extracted from equations [2] and [3] (Rohmer et al., 2019; Van Mierlo et al., 2017).

For purpose of fairness between the GHGe and BWU criteria with different units, the multi-criteria optimization was then conducted on the normalized distances to their ideal best values, i.e., on the degree of closeness to ideal points $\mathrm{d_{GHGe}}$ and $\mathrm{d_{BWU}}$ defined by:

$$\mathrm{d_{GHGe}} = \frac{\mathrm{GHGe} - \mathrm{GHGe_{best}}}{\mathrm{GHGe_{worst}} - \mathrm{GHGe_{best}}} \quad [4]$$

$$\mathrm{d_{BWU}} = \frac{\mathrm{BWU} - \mathrm{BWU_{best}}}{\mathrm{BWU_{worst}} - \mathrm{BWU_{best}}} \quad [5]$$

The compromise programming weighted by λ and (100% - λ) the $\mathrm{d_{GHGe}}$ and $\mathrm{d_{BWU}}$ terms, respectively, using a multi-objective function defined as (Garcia-Launay et al., 2018; Oliveira and Saramago, 2010):

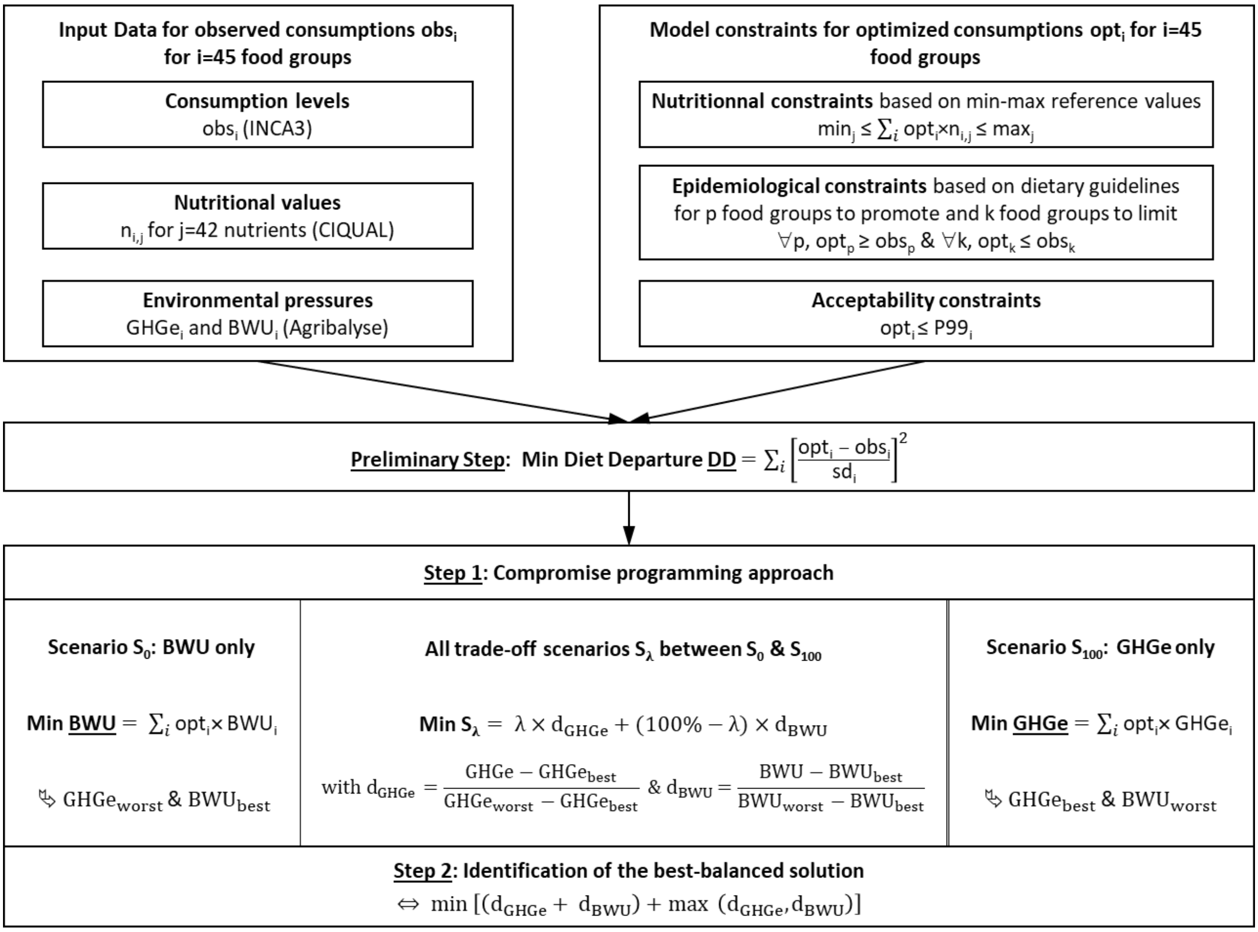
$$\text{Min multi-objective function} = \lambda \times \mathrm{d_{GHGe}} + (100\% - \lambda) \times \mathrm{d_{BWU}} \quad [6]$$

with λ ranging from 0% to 100% by increment of 5%, to explore all the compromise solutions between minimizing only BWU (λ =0%) or GHGe (λ =100%).

Finally, in a last second step, we identified the *best-balanced* solution between the *minsum* (i.e., sum of $\mathrm{d_{GHGe}}$ and $\mathrm{d_{BWU}}$, efficiency metric) and *minmax* (i.e., maximum of $\mathrm{d_{GHGe}}$ and $\mathrm{d_{BWU}}$, equity metric) objectives (Oliveira and Saramago, 2010; Rohmer et al., 2019; Van Mierlo et al., 2017), as:

$$best - balanced \Leftrightarrow \min\left[(\mathrm{d_{GHGe}} + \mathrm{d_{BWU}}) + \max\,(\mathrm{d_{GHGe}}, \mathrm{d_{BWU}})\right] \qquad [7]$$

Figure 1: Schematic diagram of the optimization phases, models, and parameters[1]



Abbreviations: BWU, blue water use; GHGe, greenhouse gas emissions; Obs: observed consumption; Opt; optimized consumption

$\mathrm{Nut_j}$ denotes intake of nutrient j and nutritional constraints are based on revised ANSES Reference Values (2016), $\mathrm{c_i}$ denotes consumption of a food item i. The k and p food categories referred to those defined by the GBD (red meat, processed meat, sweetened beverages, fruits, vegetables, legumes, nuts, whole grains and milk) ; these epidemiologic constraints impose consumption lower/higher than the observed mean for unhealthy/healthy food categories. Sx denotes the scenario λ=x% in the compromise programming approach, where λ is the relative weight given to Greenhouse gas emissions over blue water use in the multi-criteria optimization (i.e. S0 and S100 correspond to the minimization of water use only and GHGe only, respectively). The preliminary step allows to identify the modifications needed to comply with the nutritional and epidemiologic references only.

2.6 Sensitivity analysis

First, we analyzed the influence of the acceptability constraints: we used stricter acceptability constraints by lowering the food group consumption limits to their observed 95th percentile, rather than their 99th percentile as in our main analysis.

Second, we analyzed the influence of some nutrient constraints: we used stricter requirements for bioavailable iron and zinc by raising their lower bounds to current reference values (1.92 g/d and 3.62 g/d, respectively), rather than lower threshold values (1.11 g/d and 1.83 g/d, respectively) ensuring ≤5% deficiency prevalence as in our main analysis.

For each modeled diet, we conducted a dual value analysis to identify, among the different constraints we used, those that were the most active (compared to the inactive ones that had no effect on the results) and that most limited the objective gain (i.e., GHGe and/or WU reduction). In particular, this allowed the identification of nutrients requirements that proved to be limiting for GHGe and WU reductions. This analysis was conducted as in our previous work (Dussiot et al., 2021), by calculating the standardized dual values corresponding to the potential gain in objective (i.e., GHGe and/or WU) in the case of a 100% relaxation of the limiting bound of the constraint.

2.7 Statistical analysis

The sociodemographic and lifestyle characteristics of the men and women were presented as mean (SD) or percentage. The observed and modeled diets were described in terms of food group consumptions, environmental pressures, HRS and DSI.

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.

3 Results

3.1 Description of the sample

The characteristics of the total study population are presented in **Table 1**. The studied population included 1,456 participants (57% women), with a mean age of 42.2 years (SD= 13.5). About 96% of the sample completed three 24-hour recalls.

Table 1: Characteristics of study participants, (INCA 3 study, n=1,456)[1]

	Men	Women

N	621	835
Age (y)	42.05 (13.86)	42.42 (12.45)
Education		
Primary + College	42.82	40.03
High school	17.62	21.59
Undergraduate level	19.39	20.13
Postgraduate level	20.03	16.54
No information	0.14	1.72
Physical activity[2] (%)		
Low	24.4	45.56
Moderate	53.69	46.36
High	21.91	8.08
Living area (%)		
Rural	27.48	23.9
2,000-19,999 inhabitants	13.91	20.04
20,000-99,999 inhabitants	10.39	10.27
≥100,000 inhabitants	35.88	30.97
Paris area	12.35	14.81
Health risk score[3] **(%)**	92 (29)	83 (26)
Body mass index (kg.m^{-2})	25.08 (3.82)	24.95 (4.94)
Number of 24h recall	2.96 (0.19)	2.95 (0.21)
Energy intake (kcal/d)	2682.64 (747.70)	1963.31 (521.05)
Greenhouse gas emissions (kg CO_2 eq /d)	6.23 (2.68)	4.42 (1.50)
Blue water use (m^3 water eq deprivation /d)	7.07 (3.76)	5.82 (3.26)

[1] Values are n, means (SD) or % as appropriate, all data are weighted on the survey design

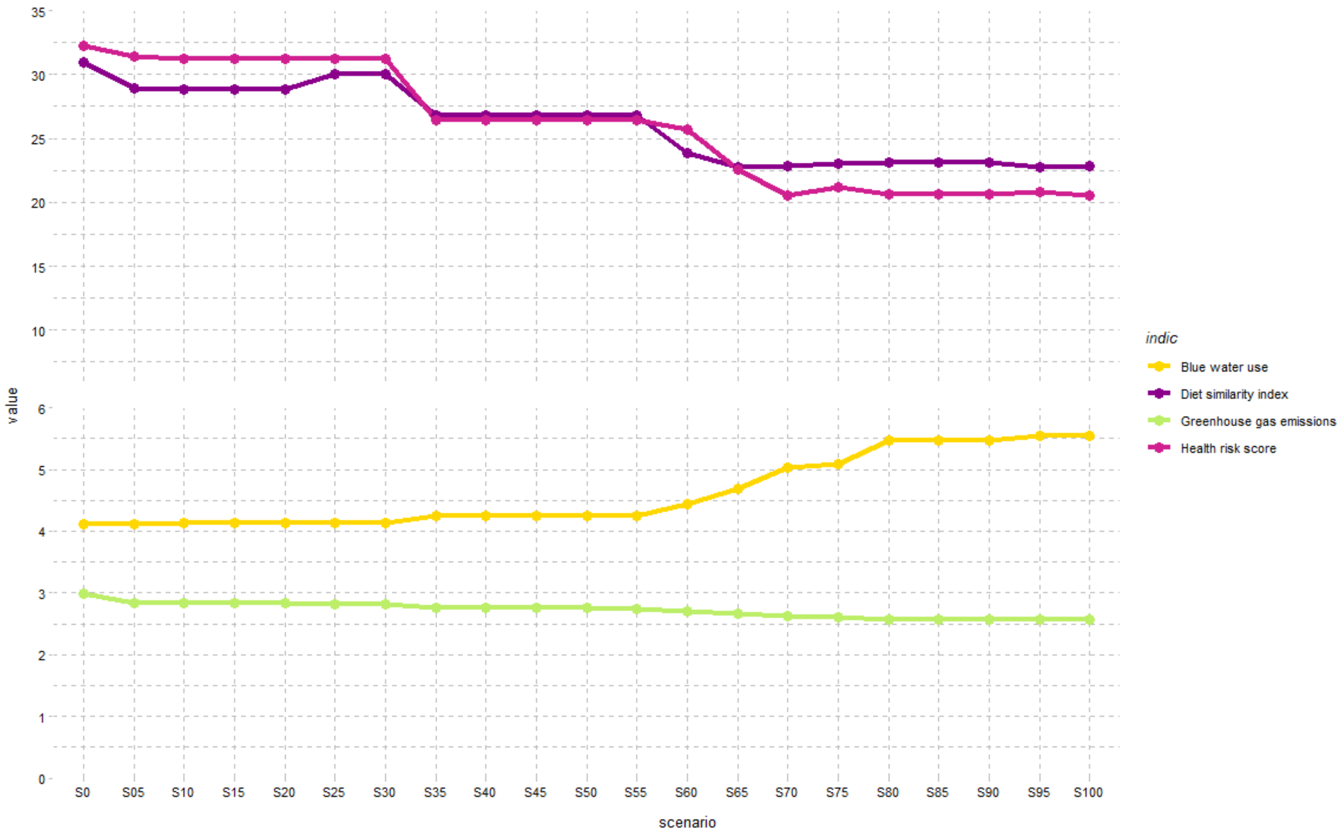
[2] Estimated using the RPAQ questionnaire

[3] HRS is the normalized distance to the theoretical minimum-risk exposure levels (TMREL) from the Global Burden of Diseases (i.e. HRS= 0% when the diet is at minimal risk by meeting all the TMREL and HRS=100% when the diet is at maximal risk by deviating from them at most).

3.2 Environmental and other key indicators of modeled diets across trade-off scenarios

Compared to the mean observed diet, the modeled diet issued from the first step, i.e., the one closest to the observed diet meeting the nutritional and epidemiological constraints, had a Diet Similarity Index (DSI, percentage of common food group consumption) of 68%, and 13% higher GHGe (6.05 vs 5.34 kg CO_2 eq/d), 33% higher BWU (8.56 vs 6.46 m^3 water eq deprivation/d), but 26% lower Health Risk Score (HRS, 64 vs 87 %) (**Table S.3**).

Figure 2: Objective functions and diet descriptors in scenarios differentially prioritizing blue water use over greenhouse gas emissions minimization



Greenhouse gas emissions in kg CO2 eq/d and blue water use inm^{3} world eq /d).

Abbreviations: DSI, diet similarity index (%); HRS, health risk score (%);

Sx denotes the scenario λ=x% in the compromise programming approach, where λ is the relative weight given to Greenhouse gas emissions over blue water use in the multi-criteria optimization (i.e. S0 and S100 correspond to the minimization of water use only and GHGe only, respectively). HRS (%) is the normalized distance to the theoretical minimum-risk exposure levels (TMREL) from the Global Burden of Diseases, expressed in % (i.e., HRS = 0% when the diet is at minimal risk by meeting all the TMREL and HRS=100% when the diet is at maximal risk by deviating from them at most). DSI (%) is the proportion of food group consumptions remaining similar to those observed.

Figure 2 depict the environmental and other key indicators (HRS and DSI) for each modeled diet issued from the second step, i.e., from compromise programming by tuning λ from 0% (minimizing BWU only) to 100% (minimizing GHGe only) by steps of 5%, always under the nutritional, epidemiological and acceptability constraints. As regards environmental indicators, whatever the trade-off scenario (λ value), GHGe and BWU were lower in the modeled than observed diets. From λ = 0% (BWU minimization) to 100% (GHGe minimization), GHGe lowered gradually by -14%, from 2.98 to 2.57 kg CO_2 eq/d (i.e., from -44% to -52% of the observed situation, respectively), while BWU increased by 35%, from 4.12 to 5.54 m^{3} world eq/d (i.e., from -36% to -14% of the observed situation, respectively). Gradually prioritizing GHGe reduction (from λ=0% to 100%) resulted in diets with a progressive but slight GHGe decrease, while BWU showed an initially slight and progressive increase that became more marked from λ≈60%.

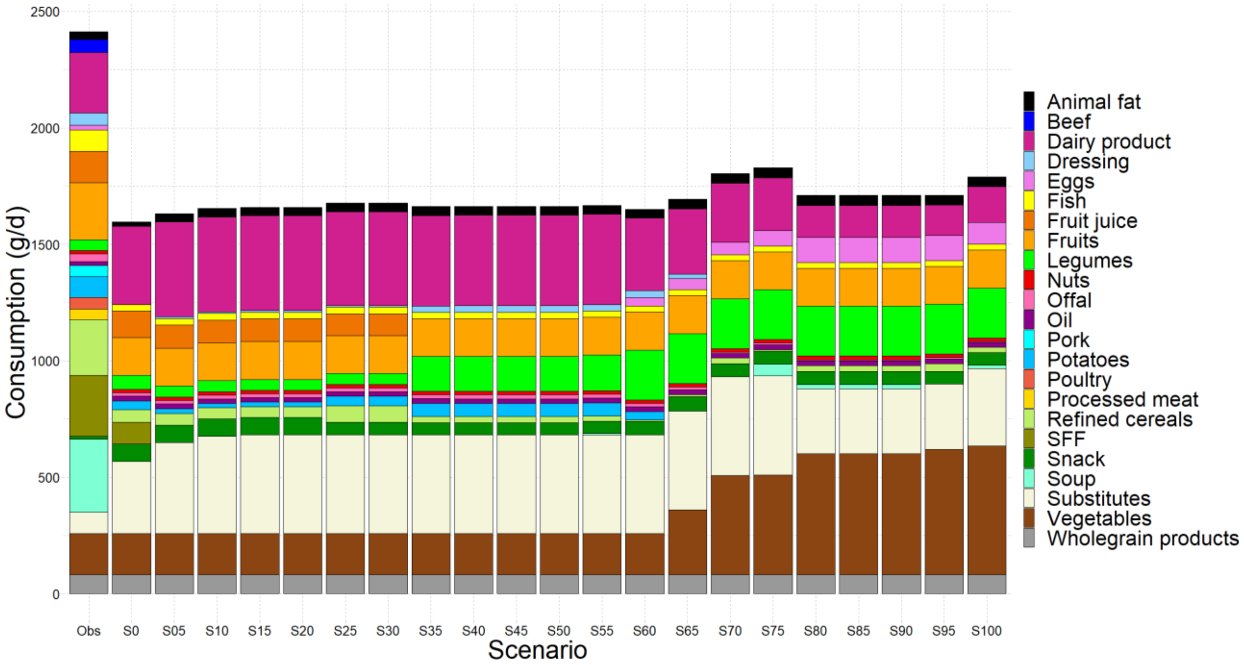
Other environmental indicators calculated using the Agribalyse ® database are presented in the **Table S.4**. Many indicators (notably land use and energy demand) as well as the single aggregated environmental footprint score varied little across the λ range, with similar values at both extreme λ values, but slightly lower values in the middle range (≈-15% for land use, ≈-5% for energy demand and ≈-7% single environmental footprint score for λ=35-60% vs λ=0%).

As regards other key indicators (DSI and HRS, **Figure 2**), all modeled diets were actually greatly distant from the observed diet but also greatly healthier. From λ = 0% to 100%, the modeled diets had no more than 32% to 23% common food group consumptions with the observed diet (DSI) and the estimated health risk (HRS) was decreased to 32% to 21%, respectively (i.e., -63% to -76% decrease compared to the observed situation). DSI and HSR both reached their minimal values for the scenarios with λ ≥ 65% (prioritization of GHGe reduction), but globally they varied only moderately over the λ range.

3.3 Food group consumptions in modeled diets across trade-off scenarios

Compared to the observed diet, some food groups were totally removed from modeled diets, namely beef, processed meat, poultry, and pork, alcoholic beverages, sodas, and other beverages (hot drinks) (**Figure 3** and **Table S.5**). Across the scenarios gradually prioritizing GHGe reduction (from λ=0% to 100%), there was an increase in eggs, animal fat, legumes, vegetables, and soup, and inversely a decrease in dairy products, offal and snack. Fruit juices were present in the modeled diets up to λ=30% then disappeared. Potatoes, refined cereals, substitutes and dressing showed bell-shaped curves and the other food groups (fish, oil, fruits, nuts and whole grains) were present in nearly constant quantities in most of the modeled diets.

Figure 3: Food group consumptions (g/d) in modeled diets differentially prioritizing blue water use over greenhouse gas emissions minimization



Abbreviations: Obs, observed situation; SFF: sweet and fat foods. For clarity purpose, the 45 food groups are pooled into 26 broader food categories and beverages are not shown. Sx denotes the scenario λ=x% in the compromise programming approach, where λ is the relative weight given to greenhouse gas emissions over blue water use in the multi-criteria optimization (i.e., S0 and S100 correspond to the minimization of blue water use only and greenhouse gas emissions only, respectively).

The contributions of food groups to GHGe and BWU for each modeled diet are presented in **Figure S.1 (Tables S.6 and S.7)**. Overall, as meat (beef, pork and poultry) was removed from all modeled diets over the λ range, the main contributors to GHGe were dairy products, offal, eggs, and vegetables and substitutes. The main contributors to BWU were vegetables and fruits.

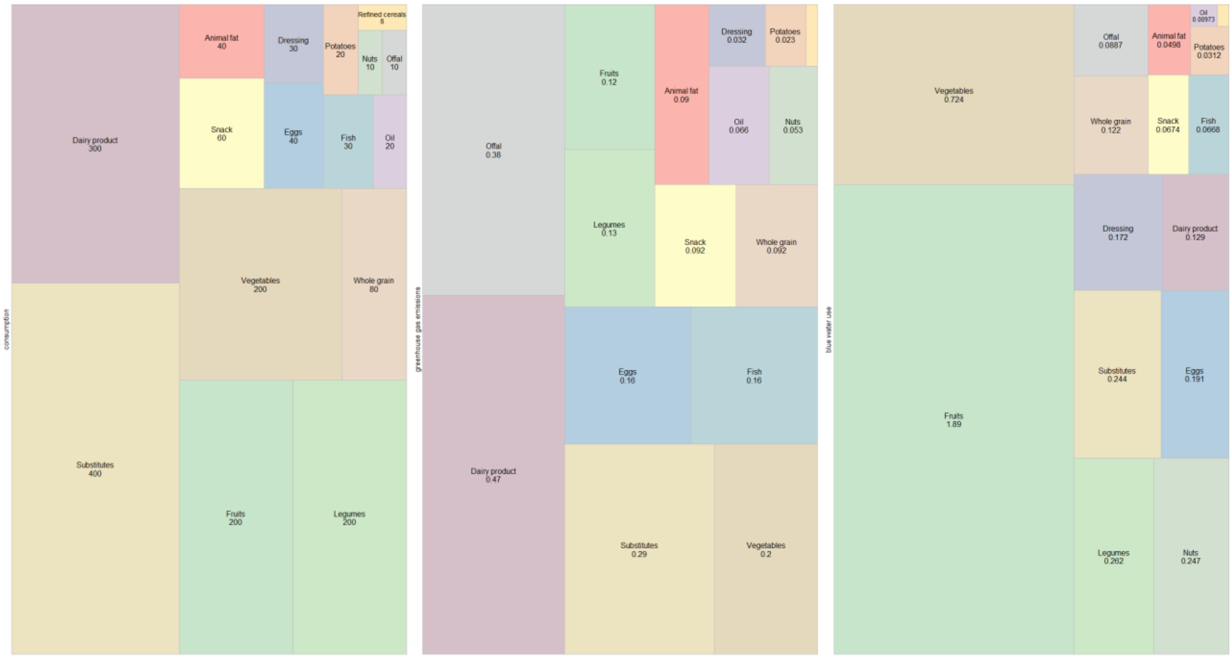
The consumption changes explaining the HRS improvement in the modeled compared to the observed diets were the lower consumptions of sugar-sweetened beverages, red and processed meat and higher consumption of vegetables (**Figure S.2**). Across the scenarios gradually prioritizing GHGe reduction (from λ=0% to 100%), there was a slight progressive improvement in HRS with the vegetables and legumes increases and red meat reduction.

3.4 Best trade-off and best-balanced diet

The main characteristics and environmental impacts of this diet are presented in **Figure 4** and **Table S3**. The best compromise between efficiency and equity in GHGe and BWU improvements (i.e., best-balanced solution issued from the last third step) was identified for GHGe of 2.69 kg CO_2 eq/d and

BWU of 4.52 m^3 world eq/d (i.e., -50% and -30% of the observed values, respectively). This best-balanced diet, corresponding to $\lambda \approx 65\%$, had a HRS value of 25% (-71% of the observed value) and a DSI of 23%. This diet was composed mainly of dairy products, vegetables, legumes, and substitutes and did not contain any animal flesh, except for a little offal.

Figure 4: Food group consumptions, greenhouse gas emissions and blue water use for the best-balanced modeled diet



Abbreviation: SFF: sweet and fat foods. For clarity purpose, the 45 food groups are pooled into 28 broader food categories.

Food group consumptions in g/d, and contributions of food groups to greenhouse gas emissions (GHGe) in kg CO_2 eq/d and blue water use (BWU) in m^3 world eq/d for the best-balanced modeled diet regarding efficiency and equity, identified by minimizing $(d_{GHGe} + d_{BWU}) + \max\ (d_{GHGe},\ d_{bBWU})$, where d_{GHGe} and d_{BWU} are the normalized distances to the best GHGe and BWU values, respectively.

Some discrepancies were noted between men and women as shown in **Figure S3.** Main differences in terms of food group consumptions concerned higher consumption of legumes, offal, nuts, fruits and substitutes in men and higher consumption of vegetables in women.

3.5 Sensitivity analysis

The most limiting nutrients in the modeled diets were quite systematically iodine, sodium, vitamin A, EPA+DHA, and vitamin B2, vitamin C and the linolenic acid / alpha-linoleic acid ratio (data not shown).

We tested the influence of being stricter regarding cultural acceptability, by limiting the food group consumptions to their observed 95th rather than 99th centile as in our main analysis. The best-balanced diet identified using these stricter acceptability constraints (**Figure S4**) had quite similar BWU and GHGe values (4.49 world eq/d and 2.73 kg CO_2 eq/d, respectively, Supplemental Table 1), but was characterized by lower consumption of legumes, dairy products and substitutes and higher consumption of refined cereals, potatoes and eggs.

We also tested the influence of being stricter regarding nutritional requirements for bioavailable iron and zinc, by using current reference values rather than lower threshold values ensuring ≤5% deficiency prevalence. The best-balanced diet identified using these stricter nutritional constraints was characterized by higher BWU and GHGe values (7.50 m^3 world eq /d and 4.39 kg CO_2 eq/d, respectively, **Table S3**), less dairy product and snack, more fruit juice, eggs, potatoes, sweet and fat foods, and, importantly, the reintroduction of processed meat and poultry that had previously been removed in our main analysis (data not shown).

4 Discussion

In the present study we have shown that under a set of nutritional and epidemiological constraints limiting the extent of their potential improvement, it is still possible to reduce BWU up to 36% and GHGe up to 52%, and also to reduce them jointly by 30% and 50%, respectively. The modeled diets prioritizing one or the other of these impact reductions share some common main characteristics, such as the absence of some food groups being important contributors to both GHGe and BWU (beef, poultry, pork, fatty and sugary products), while they differ in their content in other food groups having more divergent effects on GHGe and BWU, such as fruit and vegetables which exhibit low GHGe but elevated BWU.

Nutrition/Health

Regarding the nutritional constraints, based on our previous results (Dussiot et al., 2021), we here considered lowered threshold values than nutritional references for iron and zinc, allowing for a small increase in anemia to a 5% prevalence. This should not be considered a limitation, insofar as we have documented that the current nutritional references for iron and zinc are impediments to identifying healthy and sustainable diets: lowering these thresholds can greatly limit the overall burden of disease as we have previously shown (Dussiot et al., 2021), and it also allows greater decreases in environmental pressures as shown here. Besides, as expected, and in line with available data in the literature, we found that some nutrients typically provided by animal products were limiting in the modeled diets designed to reduce environmental pressure, usually characterized by reduced consumption of animal products (Dussiot et al., 2021; Van Mierlo et al., 2017). Furthermore, although the health risk was greatly improved compared to the observed situation, it was still burdened by low overall consumption of whole grains.

Regarding the nutritional and health dimensions, the modeled diet proposed here as the "best" compromise, which allowed a substantial reduction in both GHGs (-50%) and BWU (-30%) compared to the observed situation, also had a reduced human health risk (as estimated by HRS) due to the suppression of red meat combined with the increase of plant-based foods (except for whole grains, remained at its lower limit, corresponding to its initial observed value, well below its TMREL value). The lack of increase in consumption of whole grains seems to be due to their lack of competitive advantage (or added value) over other food groups: their environmental costs (in terms of GHGe and BWU) outweigh their nutritional benefits (in terms of nutrients provided).

Also, the consumption of substitutes was greatly increased in all the diets modeled, regardless of the prioritization of BWU over GHGe reduction. Therefore, substitutes could be a good lever for water use, climate, and food sustainability. However, when we tested stricter dietary requirements for iron and zinc, substitutes were less introduced and failed to improve GHGe and BWU, arguing for their fortification as previously reported by us (Salomé et al., 2023). In addition, while substitutes have lower overall environmental impacts than animal products (Bryant, 2022; Mertens et al., 2017), their quality may be compromised because they are often ultra-processed (Kraak, 2022). In addition, some adverse health effects of soy foods have been suspected (Ahsan et al., 2018).

GHGe

The modeled diets prioritizing GHGe reduction ($\lambda \geq 0.70$) were slightly healthier than others, due to lower consumption of red meat and higher consumption of legumes.

Numerous observational studies have documented that Mediterranean, vegetarian diets with a high contribution of plant-based foods are more favorable to the preservation of natural resources (Aleksandrowicz et al., 2016; Perignon et al., 2017; Ridoutt et al., 2017; Willett et al., 2019; Wilson et al., 2019). Diet optimization studies have also confirmed that reducing the share of animal products in favor of plant-based foods minimizes GHGe (Fouillet et al., 2023; Kesse-Guyot et al., 2021; Wilson et al., 2019).

BWU

Although the literature has been growing recently on that topic (Harris et al., 2020), a lower number of studies have focused on water use in food systems compared to those on GHGs (Hatjiathanassiadou et al., 2023) and the footprint indicators used were not consistent (blue, green, or blue and green). Results can vary greatly depending on the indicator, especially for fruit and rice requiring more blue water than green water. This is illustrated by the findings reported by Mirzaie-Nodoushan et al. in a Iranian study aiming at minimizing water use (blue+green and blue) (Mirzaie-Nodoushan et al., 2020). The dietary changes identified were consistent with our results, regarding the reduced consumptions of food groups with low “nutritional water productivity” (water demand relative to their nutritional value) such as red meat and poultry, and the increased consumptions (by up to 80% in the Iranian study) of food groups with high “nutritional water productivity”, such as milk, fish, vegetables and legumes, which allowed to comply with certain nutritional references of which animal products are the principal supports. The intensity of the changes in food group consumptions depended on the type of water use to be minimized.

The findings strongly depend on how the acceptability constraints are defined. A diet modeling study that aimed at minimizing water use (in the first step of a hierarchical optimization approach) in food systems was conducted using Hungarian data (Tompa et al., 2022). This study found smaller reductions in diet-related water footprint (blue and green water use) for women and men compared to our study, possibly due to the different acceptability constraints used as the Hungarian study more drastically limited food changes by forcing modeled consumptions to stay between their observed 10th and 90th percentiles, which limited the reduction in the animal products being large contributors to green water use (Harris et al., 2020).

Compromise between GHGe and BWU

In diet modeling studies about environmental footprint reductions, environmental indicators were generally included as constraints and not as objectives/targets to be minimized (Wilson et al., 2019), which makes not possible to assess the extent of their maximal improvements and their potential conflicts or alignments as in our study.

In the available scientific literature, the study with the closest design to our study, offering easier comparison of results, is the study conducted in 2016 by Gephart et al. (Gephart et al., 2016). This study was conducted on US data to identify diets minimizing several environmental footprints (with blue+green water use), one by one, under nutritional constraints. The authors concluded that the modeled diets were relatively similar regardless of the optimized indicator (high in plant foods and fish and low in other animal products), and interpreted these results as demonstrating synergies rather than conflicts between environmental indicators.

This is partially consistent with our findings. Indeed, we found that the GHGe and BWU values in all modeled diets, regardless of the relative weight given to their reduction in our compromise programming approach, were always markedly lower than their initial values in the observed diets. This argues for a kind of synergy between BWU and GHGe in their responses to dietary changes, due to the fact that their strongest contributors are often the same food groups (e.g. beef, pork, poultry, offal). However, BWU varied much more widely than GHGe over their differential prioritization range. Our results show that a reduction in BWU leads to and is accompanied by a reduction in GHGe, but not necessarily vice versa. This is helpful in explaining why some studies have found a moderate decrease or even an increase in BWU with low GHGe diets (Fouillet et al., 2023). Indeed, our findings illustrate that among low emitting foods (e.g. fresh fruit, vegetables, and some refined and whole grains), some have quite strong water demands.

Best model

In line with the best-balanced solution identified here, a study in India (Milner et al., 2017) that aimed at reducing BWU and GHGe through dietary changes showed that by reducing wheat, dairy products, poultry, and nuts, and increasing plants and legumes could achieve BWU reductions of 18% and 30%

by 2025 and 2050, respectively, and that there BWU reductions were accompanied by GHGe reductions of up to 13%.

These results seem to concur with ours to indicate that a decrease in water footprint leads to a concomitant GHGe decrease, while the reverse is not systematic according to our results.

This best-balanced diet is also globally coherent with the EAT-Lancet diet (Willett et al., 2019) proposed to preserve both human and planetary health. It should be noted that dairy products and offal (in small quantity) are present in this diet to meet the nutrient reference values, including vitamin A, zinc, iron and calcium.

Transferability, application, and perspectives

Our research was based on data from a French context, covering food supply, eating habits, nutritional content, and environmental pressures. However, it is uncertain how applicable these findings are to other geographic locations. Furthermore, our emphasis on BWU, which pertains to reservoirs that can be used for irrigation, restricts the relevance of our outcomes to areas with differing top resources, water constraints, and climate conditions. It would be beneficial to examine alterations in environmental indicators caused by reallocating agricultural land via consequential LCA. Unfortunately, the Agribalyse database does not permit such analysis. Further, climate change may lead to fluctuations in nutrient content, thereby influencing the nutritional worth of foods (Frumkin and Haines, 2019) like proteins, iron, zinc, and calcium, which must be kept in mind while designing prospective diets. These findings provide scientific evidence to inform sustainable food policies and highlight the importance of taking water usage into greater consideration.

Strengths/limitations

Firstly, the main limitation is that the water footprint only considered the use of blue water.. The results are necessarily affected by this limitation because the food groups contributing to blue or green water differ (Harris et al., 2020). For example, animal products strongly contribute to green water while fruits and cereals strongly contribute to blue water. Second, LCA used herein did not consider the type of farming system (organic or conventional), limiting the consideration of the variety of practices and regionality along the food chain. Data on waste were not available, not allowing to focus on potentially avoidable environmental pressures while some authors have argued that limiting waste throughout the food systems may be an important lever for reducing water use (Jalava et al., 2016). Furthermore, the models use parameters (nutritional contents, nutritional references, TMREL, environmental indicators) which are subject to uncertainties. Finally, optimization applied to the diet has inherent limitations in the methodology, which depends on the options selected in terms of definitions of constraints (e.g., no lower bound for food group consumption in our study), food grouping process and objectives (Mariotti et al., 2021). Concerning strengths, the data were based on LCA according to the standardized guidelines and methodologies environmental data were validated by several expert entities (*ADEME*, 2020). We used a food grouping with an appropriately high level of detail (45 distinct food groups), which provides an averaged picture of the nutrient density and environmental impact of detailed food categories, in order to identify the rebalancing of food groups required to achieve each studied objective (BWU and/or GHGe reduction) without the possible selection and over-representation in the modeled diets of particular food items that are not nutritionally and/or environmentally representative of their categories. Of note, an innovative compromise programming approach was used to thoroughly describe and understand the potential conflicts between environmental indicators which are multiple and not necessarily in alignment.

5 Conclusions

This study is the first to consider the reduction of GHGe and BWU in the same optimization model using compromise modelling. While focusing solely on BWU reduction induces a joint GHGe reduction that is near-maximal, the reverse is not true, showing that there is good alignment but also some divergence between the two objectives of lowering the carbon and water footprints. Meat is a major contributor to both indicators and the diets limiting both GHGe and water use are much more plant-based than actual diets, but if such more plant-based and healthy diets have low GHGe they may have more or less pronounced water use. Thus, this study suggests that water use in food systems should be better considered to define healthy and sustainable diets, and that otherwise prioritizing a lower-emitting diet per se may be counterproductive in terms of water use.

The authors' contributions

EKG conducted the research, implemented the databases, conducted the analyses and wrote the manuscript; HF provided tools and methodological support; All authors critically helped in the interpretation of results, revised the manuscript and provided relevant intellectual input. They all read and approved the final manuscript; EKG had primary responsibility for the final content, she is the guarantor.

6 Conflict of Interest

The other authors declared no conflict of interest.

Data availability

The data collected in the INCA 3 study are available on the website https://www.data.gouv.fr/fr/datasets/donnees-de-consommations-et-habitudes-alimentaires-de-letude-inca-3/

The data from Agribalyse ® are available on the ADEME website: https://agribalyse.ademe.fr/

7 References

Agence nationale de sécurité sanitaire de l'alimentation de l'environnement et du travail (ANSES), 2012. French food composition table (CIQUAL) [WWW Document]. ANSES. URL http://www.afssa.fr/TableCIQUAL (accessed 29 september 2012)

Aglago, E.K., Landais, E., Nicolas, G., Margetts, B., Leclercq, C., Allemand, P., Aderibigbe, O., Agueh, V.D., Amuna, P., Annor, G.A., El Ati, J., Coates, J., Colaiezzi, B., Compaore, E., Delisle, H., Faber, M., Fungo, R., Gouado, I., El Hamdouchi, A., Hounkpatin, W.A., Konan, A.G., Labzizi, S., Ledo, J., Mahachi, C., Maruapula, S.D., Mathe, N., Mbabazi, M., Mirembe, M.W., Mizéhoun-Adissoda, C., Nzi, C.D., Pisa, P.T., El Rhazi, K., Zotor, F., Slimani, N., 2017. Evaluation of the international standardized 24-h dietary recall methodology (GloboDiet) for potential application in research and surveillance within African settings. Globalization and Health 13, 35. https://doi.org/10.1186/s12992-017-0260-6

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

Ahsan, F., Imran, M., Gilani, S.A., Bashir, S., Khan, A.A., Khalil, A.A., Shah, F.H., Mughal, M.H., 2018. Effects of Dietary Soy and Its Constituents on Human Health: A Review. BJSTR 12, 001–006. https://doi.org/10.26717/BJSTR.2018.12.002239

Aleksandrowicz, L., Green, R., Joy, E.J., Smith, P., Haines, A., 2016. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. PLoS.One. 11, e0165797. https://doi.org/10.1371/journal.pone.0165797

Armah, S.M., Carriquiry, A., Sullivan, D., Cook, J.D., Reddy, M.B., 2013. A complete diet-based algorithm for predicting nonheme iron absorption in adults. J. Nutr. 143, 1136–1140. https://doi.org/10.3945/jn.112.169904

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

Bryant, C.J., 2022. Plant-based animal product alternatives are healthier and more environmentally sustainable than animal products. Future Foods 6, 100174. https://doi.org/10.1016/j.fufo.2022.100174

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

Carey, C.N., Paquette, M., Sahye-Pudaruth, S., Dadvar, A., Dinh, D., Khodabandehlou, K., Liang, F., Mishra, E., Sidhu, M., Brown, R., Tandon, S., Wanyan, J., Bazinet, R.P., Hanley, A.J., Malik, V., Sievenpiper, J.L., Jenkins, D.JA., 2023. The Environmental Sustainability of Plant-Based Dietary Patterns: A Scoping Review. The Journal of Nutrition. https://doi.org/10.1016/j.tjnut.2023.02.001

Clark, M., Springmann, M., Rayner, M., Scarborough, P., Hill, J., Tilman, D., Macdiarmid, J.I., Fanzo, J., Bandy, L., Harrington, R.A., 2022. Estimating the environmental impacts of 57,000 food products. Proceedings of the National Academy of Sciences 119, e2120584119. https://doi.org/10.1073/pnas.2120584119

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

Colomb, V., A. Colsaet, S. Ait-Amar, C. Basset-Mens, G. Mevel, V. To, A. Gac, P. Koch, J. Mousset, T. Salou, A. Tailleur, H. Van Der Werf, 2015. AGRIBALYSE: the French public LCI database for agricultural products.

Dietary Reference Values | DRV Finder [WWW Document], n.d. . EFSA. URL https://www.efsa.europa.eu/en/interactive-pages/drvs (accessed 1.22.21).

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

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

Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttikholt, L., Mueller, A., Sanders, J., Scialabba, N.E.-H., Seufert, V., Smith, P., 2019. Sustainability in global agriculture driven by organic farming. Nature Sustainability 2, 253–255. https://doi.org/10.1038/s41893-019-0266-6

Fouillet, H., Dussiot, A., Perraud, E., Wang, J., Huneau, J.-F., Kesse-Guyot, E., Mariotti, F., 2023. Plant to animal protein ratio in the diet: nutrient adequacy, long-term health and environmental pressure. Front Nutr 10, 1178121. https://doi.org/10.3389/fnut.2023.1178121

French Agency for Food, Environmental and Occupational Health Safety (Anses), 2016. Actualisation des repères du PNNS : élaboration des références nutritionnelles. ANSES, Maison Alfort.

Frumkin, H., Haines, A., 2019. Global Environmental Change and Noncommunicable Disease Risks. Annu. Rev. Public Health 40, 261–282. https://doi.org/10.1146/annurev-publhealth-040218-043706

Garcia-Launay, F., Dusart, L., Espagnol, S., Laisse-Redoux, S., Gaudré, D., Méda, B., Wilfart, A., 2018. Multiobjective formulation is an effective method to reduce environmental impacts of livestock feeds. Br J Nutr 120, 1298–1309. https://doi.org/10.1017/S0007114518002672

GBD 2017 Diet Collaborators, 2019. Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393, 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

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, 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2

Gephart, J.A., Davis, K.F., Emery, K.A., Leach, A.M., Galloway, J.N., Pace, M.L., 2016. The environmental cost of subsistence: Optimizing diets to minimize footprints. Sci. Total Environ. 553, 120–127. https://doi.org/10.1016/j.scitotenv.2016.02.050

Harris, F., Moss, C., Joy, E.J.M., Quinn, R., Scheelbeek, P.F.D., Dangour, A.D., Green, R., 2020. The Water Footprint of Diets: A Global Systematic Review and Meta-analysis. Adv Nutr 11, 375–386. https://doi.org/10.1093/advances/nmz091

Hatjiathanassiadou, M., Rolim, P.M., Seabra, L.M.J., 2023. Nutrition and its footprints: Using environmental indicators to assess the nexus between sustainability and food. Frontiers in Sustainable Food Systems 6.

HLPE, 2017. Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, (No. 12). Rome, Italy.

Hoekstra, A.Y. (Ed.), 2011. The water footprint assessment manual: setting the global standard. Earthscan, London ; Washington, DC.

Jalava, M., Guillaume, J.H.A., Kummu, M., Porkka, M., Siebert, S., Varis, O., 2016. Diet change and food loss reduction: What is their combined impact on global water use and scarcity? Earth’s Future 4, 62–78. https://doi.org/10.1002/2015EF000327

Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., Shapiro, L.F., 2016. A Systematic Review of the Measurement of Sustainable Diets. Advances in Nutrition: An International Review Journal 7, 641–664. https://doi.org/10.3945/an.115.011015

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

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

Kraak, V.I., 2022. Perspective: Unpacking the Wicked Challenges for Alternative Proteins in the United States: Can Highly Processed Plant-Based and Cell-Cultured Food and Beverage Products Support Healthy and Sustainable Diets and Food Systems? Adv Nutr 13, 38–47. https://doi.org/10.1093/advances/nmab113

Kramer, G.F.H., Martinez, E.V., Espinoza-Orias, N.D., Cooper, K.A., Tyszler, M., Blonk, H., 2018. Comparing the Performance of Bread and Breakfast Cereals, Dairy, and Meat in Nutritionally Balanced and Sustainable Diets. Front Nutr 5, 51. https://doi.org/10.3389/fnut.2018.00051

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

Mertens, E., Biesbroek, S., Dofková, M., Mistura, L., D’Addezio, L., Turrini, A., Dubuisson, C., Havard, S., Trolle, E., Geleijnse, J.M., van ’t Veer, P., 2020. Potential Impact of Meat Replacers on Nutrient Quality and Greenhouse Gas Emissions of Diets in Four European Countries. Sustainability 12, 6838. https://doi.org/10.3390/su12176838

Mertens, E., Van’t Veer, P., Hiddink, G.J., Steijns, J.M., Kuijsten, A., 2017. Operationalising the health aspects of sustainable diets: a review. Public Health Nutr 20, 739–757. https://doi.org/10.1017/S1368980016002664

Miller, L.V., Krebs, N.F., Hambidge, K.M., 2013. Mathematical model of zinc absorption: effects of dietary calcium, protein and iron on zinc absorption. Br J Nutr 109, 695–700. https://doi.org/10.1017/S000711451200195X

Milner, J., Joy, E.J.M., Green, R., Harris, F., Aleksandrowicz, L., Agrawal, S., Smith, P., Haines, A., Dangour, A.D., 2017. Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. Lancet Planet Health 1, e26–e32. https://doi.org/10.1016/S2542-5196(17)30001-3

Mirzaie-Nodoushan, F., Morid, S., Dehghanisanij, H., 2020. Reducing water footprints through healthy and reasonable changes in diet and imported products. Sustainable Production and Consumption.

Oliveira, L.S. de, Saramago, S.F.P., 2010. Multiobjective optimization techniques applied to engineering problems. J. Braz. Soc. Mech. Sci. & Eng. 32, 94–105. https://doi.org/10.1590/S1678-58782010000100012

Perignon, M., Masset, G., Ferrari, G., Barre, T., Vieux, F., Maillot, M., Amiot, M.J., Darmon, N., 2016. How low can dietary greenhouse gas emissions be reduced without impairing nutritional adequacy, affordability and acceptability of the diet? A modelling study to guide sustainable food choices. Public Health Nutr. 19, 2662–2674. https://doi.org/10.1017/S1368980016000653

Perignon, M., Vieux, F., Soler, L.-G., Masset, G., Darmon, N., 2017. Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. Nutrition Reviews 75, 2–17. https://doi.org/10.1093/nutrit/nuw043

Poore, J., Nemecek, T., 2018. Reducing food’s environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216

Ridoutt, B.G., Hendrie, G.A., Noakes, M., 2017. Dietary Strategies to Reduce Environmental Impact: A Critical Review of the Evidence Base. Adv Nutr 8, 933–946. https://doi.org/10.3945/an.117.016691

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a

Rohmer, S.U.K., Gerdessen, J.C., Claassen, G.D.H., 2019. Sustainable supply chain design in the food system with dietary considerations: A multi-objective analysis. European Journal of Operational Research 273, 1149–1164. https://doi.org/10.1016/j.ejor.2018.09.006

Salomé, M., Mariotti, F., Dussiot, A., Kesse-Guyot, E., Huneau, J.-F., Fouillet, H., 2023. Plant-based meat substitutes are useful for healthier dietary patterns when adequately formulated – an optimization study in French adults (INCA3). Eur J Nutr 62, 1891–1901. https://doi.org/10.1007/s00394-023-03117-9

Sautory, O., 1993. INSEE: La macro CALMAR-Redressement d’un échantillon par calage sur marges. http://www.insee.fr/fr/methodes/outils/calmar/doccalmar.pdf.

Steenson, S., Buttriss, J.L., 2021. Healthier and more sustainable diets: What changes are needed in high-income countries? Nutrition Bulletin 46, 279–309. https://doi.org/10.1111/nbu.12518

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855

Tompa, O., Kiss, A., Maillot, M., Sarkadi Nagy, E., Temesi, Á., Lakner, Z., 2022. Sustainable Diet Optimization Targeting Dietary Water Footprint Reduction—A Country-Specific Study. Sustainability 14, 2309. https://doi.org/10.3390/su14042309

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

Van Mierlo, K., Rohmer, S., Gerdessen, J.C., 2017. A model for composing meat replacers: Reducing the environmental impact of our food consumption pattern while retaining its nutritional value. Journal of Cleaner Production 165, 930–950. https://doi.org/10.1016/j.jclepro.2017.07.098

Vanham, D., Leip, A., Galli, A., Kastner, T., Bruckner, M., Uwizeye, A., van Dijk, K., Ercin, E., Dalin, C., Brandão, M., Bastianoni, S., Fang, K., Leach, A., Chapagain, A., Van der Velde, M., Sala, S., Pant, R., Mancini, L., Monforti-Ferrario, F., Carmona-Garcia, G., Marques, A., Weiss, F., Hoekstra, A.Y., 2019. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Science of The Total Environment 693, 133642. https://doi.org/10.1016/j.scitotenv.2019.133642

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

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, S389–S403. https://doi.org/10.1093/advances/nmz037

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F.N., Smith, P., Campbell, N., Jain, A.K., 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat Food 2, 724–732. https://doi.org/10.1038/s43016-021-00358-x