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Title

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Author Names

Louise Seconda[1,2*], Julia Baudry[1], Benjamin Allès[1], Christine Boizot-Szantai[3], Louis-Georges Soler[3], Pilar Galan[1], Serge Hercberg[1,4], Brigitte Langevin[5], Denis Lairon[6], Philippe Pointereau[5], and Emmanuelle Kesse-Guyot[1]

Author Affiliations

[1] Equipe de Recherche en Epidémiologie Nutritionnelle (EREN), Université Paris 13, Inserm (U1153), Inra (U1125), Centre d'Epidémiologie et Statistiques Paris Cité, Cnam, COMUE Sorbonne-Paris-Cité, 93017 Bobigny, France; l.seconda@eren.smbh.univ-paris13.fr (L.S. ORCID : 0000-0003-3460-5457), j.baudry@eren.smbh.univ-paris13.fr (J.B.); b.alles@eren.smbh.univ-paris13.fr (B.A. ORCID : 0000-0002-7970-171X (B.A.); p.galan@uren.smbh.univ-paris13.fr (P.G.); s.hercberg@uren.smbh.univ-paris13.fr (S. H. ORCID : 0000-0002-3168-1350); e.kesse@eren.smbh.univ-paris13.fr (E.K.-G. ORCID : 0000-0002-9715-3534)

[2] Agence de l'Environnement et de la maîtrise de l'Energie, 20, avenue du Grésillé- BP 90406 49004 Angers Cedex 01, France

[3] INRA Aliss UR 1303, 94200 Ivry sur Seine, France; Christine.Boizot@ivry.inra.fr (C.B.-S.); lgsoler@ivry.inra.fr (L.-G.S.)

[4] Département de Santé Publique, Hôpital Avicenne, 93017 Bobigny, France; s.hercberg@uren.smbh.univ-paris13.fr (S.H.)

[5] Solagro, 75, Voie TOEC, 31000 Toulouse, France ; b.langevin@laposte.net (B. L.); philippe.pointereau@solagro.asso.fr (P.P.)

[6] Nutrition, Obésité et Risque Thrombotique (NORT), Aix Marseille Université, INSERM, UMR S 1062, INRA 1260, 13005 Marseille, France; denis.lairon@orange.fr ORCID : 0000-0001-9941-3742 (D.L.)

***Corresponding author**

Louise Seconda

Equipe de Recherche en Epidémiologie Nutritionnelle (EREN)

SMBH Université Paris 13

74 rue Marcel Cachin, 93017 Bobigny, France

Phone number: + 33 1 48 38 89 79

Fax number: + 33 1 48 38 89 31

l.seconda@eren.smbh.univ-paris13.fr

Abstract

In response to climate change, reduction of GHGEs (greenhouse gas emissions) from food systems is required. Shifts of agricultural practices and dietary patterns could reduce GHGEs. We aimed to characterize observed diets with different levels of GHGEs, and compare their nutritional, economic and environmental performances.

Food consumptions of 34,193 French adults participating in the NutriNet-Santé cohort were assessed using a food frequency questionnaire. Nutritional, environmental and economic indicators were computed for each individual diet. Adjusted means of food group intakes, contribution of food groups to dietary GHGEs, nutritional, environmental and economic indicators were compared between weighted quintiles of GHGEs.

Diets with high GHGEs (ranging from 2,318 to 4,099 $kgCO_{2eq}$/y) contained more animal-based food, and provided more calories. Few differences were found for unhealthy food (alcohol or sweet/fatty food) consumption across the categories of dietary GHGEs. Diets with low GHGEs were characterized by a high nutritional quality. Primary energy consumption and land occupation increased with GHGEs (from Q1: 3,978 MJ/y (95%CI=3,958-3,997) to Q5: 8,980 MJ/y (95%CI=8,924-9,036)) and (from Q1: 1,693m^2/y (95%CI=1,683-1,702) to Q5: 7,188m^2/y (95%CI=7,139-7,238)) respectively. Finally, participants with lower GHGEs related-diets were the highest organic food consumers. After adjustment for sex, age and energy intake, monetary diet cost increased with GHGEs (from Q1: 6.89€/y (95%CI=6.84-6.93) to Q5: 7.68€/y (95%CI=7.62-7.74)).

Based on large observational cohort, this study provides new insights concerning the potential of current healthy and emergent diets with low monetary cost and good nutritional quality to promote climate mitigation. However, the question of a large acceptability remains.

Keywords

Climate change, Dietary pattern, GreenHouse Gas Emissions, Organic food

Abbreviations

AMAPs: Associations Supporting Small Farming

ANCOVA: Analysis of Covariance

BMI: Body Mass Index

CI: Confidence Intervals

CU: Consumption Unit

CH_4: Methane

CO_2: Carbon dioxyde

GHG: GreenHouse Gas

GHGEs: GreenHouse Gas Emissions

INSEE: National Institute of Statistical and Economic Studies

IPAQ: International Physical Activity Questionnaires

IPCC: Intergovernmental Panel on Climate Change

LCA : Life Cycle Assessment

mPNNS-GS: modified Programme National Nutrition Santé Guidelines Score

N_2O: Nitrous oxide

Org-FFQ: Organic Food Frequency Questionnaire

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

Q: Quintile

UK: United Kingdom

WHO: World Health Organisation

Introduction:

The last IPCC (Intergovernmental Panel on Climate Change) report concluded with 95% certainty that human activities have been the primary cause of global warming since the middle of the 20th century (1). In response to the temperature rise and its harmful consequences, deep reduction of greenhouse gas emissions (GHGEs) is required, notably in food systems which account for 19-29% of global anthropogenic GHGEs (2). Three gases contribute for almost 91.5% to the agricultural total emissions, nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). CH_4 and N_2O emissions are generally limited to the agricultural phase, while CO_2 emissions are spread out among the whole food chain (3). At the agricultural stage, some measures and innovative processes (e.g. enhancing carbon removals, optimising nutrient use, etc.) have emerged to reduce the GHGEs (4). However, several studies concluded that agricultural technical options are not sufficient and important shifts in dietary patterns by a large proportion of the world population will be required to achieve the necessary climate mitigation (4–6).

In particular, the modelled French scenario Afterres2050 plans a mandatory 50% cut in agricultural GHGEs by 2050, by changing the French diet, implementing agro ecological practices, and reducing energy consumption (7). This scenario applies the road map of the European Commission for a low carbon economy with the objective of -42% to -49% GHGEs (without CO_2) in 2050 compared to 1990 (8).

Low GHGEs diets have already been estimated using modelling approaches or depicted using observational data (8–10).

However, due to the small size of the samples restraining the variety of dietary patterns, or the constraints included in the models when performing optimization or simulation studies, issues as regards the reality and the acceptability of such diets in large populations remain

(9). Moreover, the consistency between eco-friendly dietary practices and nutritional requirements were scarcely evaluated. A high-nutritional quality diet has previously been associated with greater environmental impact in some studies (9,12–14). Conversely, a recent meta-analysis concluded that a shift from Western to sustainable dietary patterns generally provided benefits for the environment and health (10). Finally, published findings about the associations between monetary costs and low GHGEs diets are contradictory (9,15).

As primary production is responsible for a large proportion of carbon footprints (16), and given the high diversity of the current farming systems, the model of food production (conventional or organic) seems an important factor to take into account, for the assessment and comparison of the environmental performances of various diets (17–19). Also, most existing studies considered a single environmental indicator (11) while the assessment of several environmental indicators can contribute to consolidate the validity of results for different environmental dimensions (11).

In that context, we aimed to depict the diets observed in a large sample of adults with different levels of GHGEs in terms of food composition while accounting for the mode of food production. We also compared their nutritional, environmental and economic characteristics.

Materials and methods:

Study design and participants

The NutriNet-Santé Study is an ongoing web-based prospective observational cohort of French adult volunteers, launched in May 2009 with a scheduled follow-up of 10 years. The design has been comprehensively described elsewhere (20). The inclusion in the cohort is based on a set of self-administered web-based questionnaires on dietary intake, health and anthropometric, socio-demographic and lifestyle characteristics. Included volunteers are regularly invited to update their data and to fill in optional complementary questionnaires.

Standard protocol approvals, registrations and participant consents

The study was conducted observing the guidelines from the Declaration of Helsinki, and all protocols were approved by the Institutional Review Board of the French Institute for Health and Medical Research (IRB INSERM no. 0000388FWA00005831) and the Commission Nationale de l'Informatique et des Libertés (CNIL no. 908450 and no. 909216). Participant informed consents were signed by all volunteers with an electronic signature. The NutriNet-Santé study is registered in ClinicalTrials.gov (NCT03335644).

Data collection

Assessment and treatment of dietary data

Usual dietary food intake was assessed using an organic semi-quantitative food frequency questionnaire (Org-FFQ)(21), based on a previously validated questionnaire (22). Participants had to report their frequency (yearly, monthly, weekly or daily units) of consumption over the past year for 264 items (food and beverage). Standard portion sizes were described as typical household measurements or using colour standardized and validated photographs. Food intakes in grams per day were obtained by multiplying the portion size and frequency. Food items were grouped into 15 food groups for descriptive purpose. Nutrient intakes were estimated using nutritional values from the published NutriNet-Santé food composition table (23).

Moreover, to assess the level of organic food consumption, participants were asked for each item except those that do not exist in organic form how often they came from organic source (identified through label certification) through a 5-point ordinal scale ranging from “never” to “always”. A weight of 0, 0.25, 0.5, 0.75 and 1 was applied to the five respective frequencies to obtain the share of organic food in the diet for each item and overall (without water). The over-reporters and under-reporters were identified by a ratio of energy intake to energy requirement (estimated with the Schofield equations (24) according to sex, age, weight and height) below or above the cut-offs (0.35 and 1.93).

Finally, three dietary indicators were also computed to assess the overall nutritional quality of the diet: 1) the energy density of the diet, 2) the nutrient-based PANDiet score (25) measures the probability of adequate nutrient intake based on current nutrient reference values and 3) the food-based mPNNS-GS (26) (modified Programme National Nutrition Santé Guideline-Score) assesses adherence to the French official nutrition guidelines. A detailed description of these scores is proposed in the **Supplemental Material 1**.

Assessment of the environmental impacts of the diet

A database gathering the environmental indicators associated with the Org-FFQ items accounting for the method of production (conventional or organic) was developed. To do that, we used DIALECTE, a comprehensive tool developed by Solagro (Toulouse, France) (27) which aims to describe French farming systems and to assess the environmental performance of farms, which contained environmental impacts related to 60 raw products. The selected indicators were the GHGEs (in kg CO_{2eq}/kg), the primary energy consumption (in MJ/kg) and land occupation (in m^2/kg). As detailed in the first part of the Supplemental Material 2, the perimeter of DIALECTE environmental impact assessment included the upstream processes such as the production of inputs or energy provision, while conditioning, transport, processing, storage and recycling were excluded due to missing information for the organic sector. The database was completed with published literature data, to obtain the environmental impact in organic and conventional of 92 raw agricultural products. As our objective was to assess the environmental impacts of diets, it was necessary to conduct a set of conversions (described in the Supplemental Material 2) from the environmental impacts assessed for raw agricultural products in order to estimate environmental impacts for food items of the food frequency questionnaire. Briefly, the items were decomposed into ingredients. The environmental impacts of ingredients (organic and conventional) were assessed from raw products by applying an economic allocation (accounting for co-products) and cooking and edibility coefficients (28,29). The individual environmental impacts of diet were estimated by multiplying the environmental impacts by food quantity consumed (g/d) accounting for the method of food production.

Assessment of the monetary cost of diet

Volunteers were also invited to fill in a complementary questionnaire focusing on attitudes and motivations as regards food choices inquiring the place of purchase.

A database gathering the prices of the 264 items of the Org-FFQ accounting for the place of purchase and the food production mode (organic vs. conventional) was developed (30). The 2012 KANTAR database was used to collect the prices from supermarkets and specialized stores (31). Additionally, members of the Bioconsom'acteurs association collected 1,100 additional prices in autumn 2014 and 862 prices in spring 2015 over nine French metropolitan regions, in short supply chains (local markets or associations supporting small farming (AMAPs)). The individual monetary cost of diet was calculated by multiplying price

(€/g) by food quantity consumed (g/d) accounting for the place of purchase and the method of food production.

Covariates

Sociodemographic and lifestyle data were collected using the inclusion set and yearly update questionnaires. Data used was the closest to the date of the completion of the Org-FFQ.

Sociodemographic data included sex, age (over 18), education (< high school diploma, high school diploma and post-secondary graduate), place and area of residence (rural community, urban units with a population smaller than 20,000 inhabitants, between 20,000 and 200,000 inhabitants and higher than 200,000 inhabitants) and monthly income per household unit (<1,200 euros, between 1,200 and 1,800 euros, between 1,800 and 2,700 euros and >2,700 euros per household unit) obtained using the income by month in the household and the composition of the household.

Lifestyle variables were smoking status (former, occasional, current, or non-smoker), level of physical activity (as measured by the IPAQ (International Physical Activity questionnaires (32–34)), weight and height assessed by a health operator, medical doctor, or from self-measurement guided by standardized procedures. Body mass index (BMI) (kg/m^2) was computed.

Statistical analysis

A total of 37,685 adult participants completed the Org-FFQ. We excluded participants who were under/over-reporters (n=2,109), as well as those with missing covariates (n=391), living abroad (n=716) or in overseas territories (n=249), leading to a sample of 34,193 volunteers.

Data concerning monetary cost of diet were collected from a subsample of volunteers (N=29,210) who completed the questionnaire on place of purchase.

The sample was weighted, in order to improve representativeness of the population identified, using the SAS Calmar macro, developed by the National Statistics and Economic Studies Institute (INSEE) (35). The weighting was made by gender, taking into account the age, educational level, area of residence and whether or not the household included any children. We used the 2009 national Census data as reference. . Then, participants were divided into weighted quintiles according to diet-related GHGEs. Sociodemographic and lifestyle characteristics were compared across quintiles: means with standard deviation or percentages were presented and overall differences were tested using Mantel-Haenzel trend $\chi 2$ or linear contrast tests.

The adjusted means for sex, age and energy intake with the residual method (36) and 95%CI of food group consumption by diet according to GHGEs were calculated. The contribution of each food group to the total dietary GHGEs were also assessed across quintiles.

Finally, analyses of covariance (ANCOVA) models according to the observed margins (this option changes the coefficients to be proportional to those observed in the input data set) were performed to identify the associations between GHGEs and dietary, health, other environmental and economic indicators. When appropriate, a log-transformation was applied to improve the normality of continuous variables (namely for expenditure, primary energy consumption and land occupation). Post-hoc differences across categories were evaluated after adjustment for multiple testing using the Dunnett's correction. P values for linear trend across quintiles were estimated using linear contrast tests. The type I error was set at 5% for all statistical tests.

SAS 9.4 software (SAS Institute Inc., Cary, NC, USA) was used to perform all analyses.

Results

Participant characteristics

The sample was composed of 34,193 volunteers with a mean age of 53.3 (SD=14.0), and 75.5% women (before weighting).

Table 1 shows the sociodemographic and lifestyle characteristics of participants across quintiles of diet-related GHGEs. Participants in Q1 were more often women, younger, as well as more often large town inhabitants, physically active, never smokers, and post-secondary graduate. The level of income per household unit did not seem associated with GHGEs. Lower dietary GHGEs were associated with a greater part of organic food in the diet.

Food intakes according to quintiles of dietary GHGEs

Concerning the dietary characteristics, the prominent gap across quintiles of diet-related GHGEs concerned the intake of red meat (**Table 2**). Red meat intake was positively associated with GHGEs. A similar trend was observed to a lesser extent for white meat, mixed dishes and dairy products. The average consumption of sweet and fatty products was not significantly different across quintiles of GHGEs. Participants exhibiting the lower GHGEs consumed more starches, whole grains, fruits, vegetables, and soya products.

The relative contributions of food groups to total GHGEs showed strong disparities across quintiles (**Figure 1**). The contribution of red meat to dietary GHGEs increased across quintiles, while opposite trends were observed for fruit and vegetables and starchy foods.

Nutritional characteristic of participants

Table 3 shows the nutritional characteristics of participants according to the diet-related GHGEs. First, caloric intake linearly increased with the GHGEs of the diet as well as the energy density. Participants in Q4 and Q5 showed the lowest dietary quality (mPNNS-GS and PANDiet). However, for the first three quintiles, the differences in the nutritional quality of diet are less obvious. Indeed, the participants in Q3 exhibited the better compliance with the French nutritional guidelines, while Q1 participants presented the highest PANDiet score, reflecting a good adequacy match to nutrients guidelines. However, the highest PANDiet score in Q1 was mostly explained by higher moderation sub-score than high adequacy sub-score which was higher in Q3.

Finally, the mean BMI of participants increased along with the level of diet GHGEs (Q1 to Q5).

Environmental and economic characteristics of diet

Table 4 shows the data for environmental and economic indicators according to the level of GHGEs. Two adjusted models are presented with and without adjustment for energy intake. Land occupation, primary energy consumption to produce foods and diet purchase increased with the level of GHGEs from the diet.

All these associations remained significant after adjustment for energy intake although the magnitudes of the differences were reduced.

Discussion

The present study showed, from a large adult cohort, that diet-related with low GHGEs are characterized by a low intake of food from animal origin and provided fewer calories. They were also characterized by a high nutritional quality and a higher proportion of organic food.

No or few differences in consumption of unhealthy food (alcohol or sweet and fatty products) across categories of dietary GHGEs were observed. Concerning environmental indicators, a diet with low GHGEs was produced with a minimum primary energy consumption and land occupation.

Recent studies, based on modelled or observed diets, have reported the major contribution of animal products to diet-related GHGEs. (37–40). At the individual level, a decrease in animal product consumption, especially from ruminants, remains a necessary key challenge to maintain global temperature increase below 2°C(5). Moreover, a lower level of animal production does not reduce only GHGEs, but it is also of land occupation and energy saving (9,41,42).

In our study, the average dietary energy intake increased across quintiles of diet-related GHGEs. This finding is consistent with previous studies reporting a linear relationship between energy intake and dietary GHGEs (40,43). Based on these observational data, it appears that the lowest levels of energy intake are observed among some subgroups of the population (Q1 & Q2) while others have higher energy intakes and animal food based-dietary patterns (Q4 & Q5).

Moreover, we observed that participants with low-GHGEs diet consumed more plant-based products, in line with findings from other observational studies (39,40). However, for consumption of sweet or fatty products, no difference was detected across quintiles. In contrast to the study of Temme et al. (40), participants with lower GHGEs diets had slightly higher intakes of alcoholic beverages. Of note, participants of our cohort presented low consumption of unhealthy food (alcohol and sweet or fatty products) (44). This may be explained by a potential desirability bias often observed in self-reported dietary records or by specific profiles of volunteers in the cohort. Even though alcohol and sweet or fatty food have low impacts on the environment compared to animal products, their intakes provide low nutritionally benefits and their consumption is thus limited in nutritional recommendations (45).

It is now well documented that the overall quality of the diet (as assessed herein with two dietary scores) decreases with increasing GHGEs (13,43,46). In our study, the highest PANDiet score observed in low GHG 'emitters' was mostly explained by the highest sub-score related to moderation (for fat, sugar, salt).Besides, the Q3 exhibited the highest sub-score related to nutrient adequacy, meaning participants generally presented the lowest probability of having nutrient deficiency. The mPNNS-GS score of Q1 and Q2 were lower than Q3. This result may be explained by the low consumption of animal-based products in these groups. Indeed, the 2001 French nutrition guidelines by promoting a moderate consumption of animal products (one or two servings of meat, fish or egg per day and three servings of dairy products) although vegetarians and low-meat consumers can still meet nutritional needs through appropriate alternative dietary choices (47). Concerning nutrition-health status, low GHGs 'emitters' exhibited the lowest BMI (Q1 & Q2). A number of hypotheses may be proposed to explain such observation including healthier dietary patterns as lower overall caloric intake and higher ratio of plant-based to animal-based foods(48). Other studies have identified individual health benefits of low GHGEs or meat diets (37,49,50).

Interestingly, participants in the lowest GHG 'emitters' quintiles, showed the highest consumption of organic food, while the available data of GHGEs in current organic food production showed limited or doubtful benefits (19) depending of the indicators considered.

In particular, the organic animal-based products these products presented sometimes a greater carbon footprint (mainly due to the longer cycle of production and to lower growth rate (52–54)). However, our results seem to show that heavy organic consumers have a less GHG emitting diet. That can be explained by the overall higher intake of low-GHG foods such as plant-based foods, which is a main characteristic of the organic diet, and may more than compensate for the potential additional GHGEs from some organic production. For others environmental indicators as energy efficiency biodiversity organic farming may present environmental benefits (18,19). Muller et al. concluded that organic agriculture can contribute to decrease environmental impacts only if adequately high proportions of legumes are produced concomitantly with significant reductions of food-competing feed use, livestock product quantities and food wastage (55).

Some limitations should be mentioned. Firstly, participants in the study exhibited specific profiles, as they are volunteers in a long-term cohort focusing on nutrition and health. Participants are likely to display healthier behaviors than in general population. This may have led to an underestimation of unhealthy dietary patterns. However, this specific sample provided an interesting large diversity of pro-environmental dietary behaviors profiles. Secondly, the assessment of food consumption was based on a food frequency questionnaire, which is, as other self-administered methods, prone to measurement error and desirability bias. It is as illustrated, at least partly, by elevated consumption of fruits or vegetables and low levels of unhealthy foods such as sweet or fatty foods and alcohol. Thirdly, environmental database was based on farms registered in DIALECTE on a volunteer basis leading to a potential under representation of farms which are not sensitive to environmental issues and whom the pressures on the environment could be greater. This may have led to an underestimation of environmental impact. However, the high number of farms and the use of the median value may have partly overcome this limitation. Only the agricultural production was included in the Life Cycle Assessment, thus transformation, packaging and transport were not taken into account. This limitation should be considered as relative since the major part of environmental impacts generally occur from the agricultural phase (56–58). Some exceptions should be noted such as the alcoholic beverages. However, these foods generally contribute poorly to the total food consumption. Finally, the three environmental indicators assessed do not sufficient reflect all environmental pressures. Other indicators such as eutrophication or biodiversity are important. However, the used of three indicators is an advance because previous studies generally used a single environmental indicator (11). Besides, the study exhibited important contributions. Indeed, scientific literature about the environmental impacts of the diet is growing (9,10), but our study is the first that distinguished modes of production.

In conclusion, based on observed individual data in a large cohort of adults, a low GHG-emitting diet appeared to be healthier in terms of nutrition, presents environmental benefits, and is less expensive. Other environmental indicators as the biodiversity footprints or water use are also major indicators which should be accounted in future research including farming practices.

Acknowledgments

We especially thank Younes Esseddik, Paul Flanzy,Thi Hong Van Duong, Veronique Gourlet, Fabien Szabo, Nathalie Arnault, Laurent Bourhis and Stephen Besseau, Cédric Agaësse, Claudia Chahine and the Bioconsom'acteurs' members. We warmly thank all of the dedicated and conscientious volunteers involved in the Nutrinet-Santé cohort.

Support

The NutriNet-Santé study is supported by the French Ministry of Health (DGS), the national public health agency (Santé Publique France), the National Institute for Health and Medical Research (INSERM), the National Institute for Agricultural Research (INRA), the National Conservatory of Arts and Crafts (CNAM) and the University of Paris 13. This study is supported by the BioNutriNet project which is a research project 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). Louise Seconda is supported by a doctoral fellowship from the French Environment and Energy Management Agency (ADEME) and the National Institute for Agricultural Research (INRA).

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