Greenhouse gas emissions, energy demand and land use associated with omnivorous, pesco-vegetarian, vegetarian, and vegan diets accounting for farming practices

Anaëlle Rabès, Louise Seconda, Brigitte Langevin, Benjamin Allès, Mathilde Touvier, Serge Hercberg, Denis Lairon, Julia Baudry, Philippe Pointereau, Emmanuelle Kesse-Guyot

Greenhouse gas emissions, energy demand and land use associated with omnivorous, pesco-vegetarian, vegetarian, and vegan diets accounting for farming practices

Anaëlle Rabès[1], Louise Seconda[1, 2], Brigitte Langevin[3], Benjamin Allès[1], Mathilde Touvier[1], Serge Hercberg[1, 4], Denis Lairon[5], Julia Baudry[1], Philippe Pointereau[3] and Emmanuelle Kesse-Guyot[1*]

Authors' affiliations:

[1] Sorbonne Paris Nord (Paris 13) University, Inserm, Inrae, Cnam, Nutritional Epidemiology Research Team (EREN), Epidemiology and Statistics Research Center – University of Paris (CRESS), 93017 Bobigny, France

[2]ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie), 20 avenue du Grésillé BP 90406, 49004 Angers, France

[3] Solagro, 75 Voie Toec, 31000 Toulouse, France

[4] Département de Santé Publique, Hôpital Avicenne, 125 rue de Stalingrad, 93000 Bobigny, France

[5] Aix Marseille Université, INSERM (U1062), INRA (U1260), C2VN, Faculté de Médecine de la Timone, 27 boulevard Jean Moulin, 13005 Marseille, France

***Corresponding author:**

Emmanuelle Kesse, PhD

Equipe de Recherche en Epidémiologie Nutritionnelle (EREN)-Université Paris 13, SMBH - 74 rue Marcel Cachin-93017 Bobigny France

Phone number: + 33 1 48 38 89 79

e.kesse@eren.smbh.univ-paris13.fr

ABSTRACT

In the present context of environmental damages, food systems constitute one of the key burdens on the environment and resources. Dietary patterns emerge as a main leverage to preserve a healthy environment.

The aim is to compare the environmental impacts of different diets with different levels of animal product consumption, while accounting for the type of farming systems (organic or conventional) of the food consumed.

Dietary environmental impacts of the diet of 29,210 NutriNet-Santé participants were estimated using databases developed within the BioNutriNet project. Four diets, differing from their animal-based food proportion, were studied: omnivorous, pesco-vegetarian, vegetarian, and vegan. Three individual environmental indicators were assessed (greenhouse gas emissions, cumulative energy demand and land occupation) and combined in one aggregated partial score (pReCiPe, partial ReCiPe). Means of these indicators adjusted for energy intake were estimated across diet groups using covariance analysis.

About 95% of the study sample was omnivorous. Organic consumption was much higher among non–omnivorous than other groups. The pReCiPe were 64%, 61%, and 69% lower for diet of pesco-vegetarians, vegetarians and vegans respectively, in comparison to the omnivorous diet. Regarding the three individual environmental indicators included in the pReCiPe index, the same trend was observed but trade-offs exist in organic with cumulative energy lowered and land occupation augmented.

A positive link between animal-sourced food consumption and total environmental impact was observed in this large sample of French adults. By far, omnivorous had the highest-level of greenhouse gas emissions, cumulative energy demand and land occupation while vegan diets had the lowest. Further research on environmental indicators distinguishing farming practices is needed to allow a more comprehensive evaluation of the impact.

Keywords: diet-related environmental impacts, animal-based food, farming system, greenhouse gas emissions, cumulative energy demand, land occupation.

INTRODUCTION

Over the past decades, environmental damage, such as climate disruption, the sixth mass extinction of biodiversity, deforestation, water use and human interference with the nitrogen and phosphorus cycles, has intensified (1–3). This damage is the consequence of the current society's dominant model, specifically that of agriculture and food consumption, causing major pressures on the environment (4,5). If there is no change in the food system by 2050, the increase in greenhouse gas (GHG) emissions, cropland use, freshwater use, and nitrogen and phosphorus application would drive biophysical processes beyond planetary boundaries (2,4,6).

There is a growing body of scientific literature dealing with environmental impacts of food production and consumption, with data mainly focusing on agriculture-related greenhouse gas emissions (3,7,8).

The food system represents 20 to 30% of the global GHG emissions (9,10). Therefore, at both collective and individual level, food behaviors and food choices represent major levers of action against the ongoing environmental disaster. These emissions could be attenuated by reduction of meat consumption, illustrated by many studies showing that removing entirely meat from a healthy diet will (11) result in a reduction by about one-third of GHG emissions (12), or that diet-related GHG emissions are twice lower for vegans than for meat eaters (13). Livestock, in particular, exhibits significant pressures on the environment including extensive land use and energy demand, biodiversity loss, N surplus and water use. Beyond the ecosystem services of livestock including grasslands for the biodiversity and carbon storage (14,15), Aleksandrowicz et al. showed that diets reducing the amount of animal-based foods had the largest environmental benefits (first vegans, then vegetarians, and pesco-vegetarians), not only in terms of GHG emissions, but also in terms of land use and energy demand (8). Land cropping, especially when intensively cultivated, contributes to greenhouse gases, deforestation, biodiversity loss, water use and pollution through fertilizers and synthetic pesticides as well as soil pollution and erosion (16,17).

Although strong positive correlation between organic food consumption and vegetarianism have been observed (18,19) driving by some similar motives, namely ethic and environment preservation, few studies have considered the type of farming practices when studying the environmental impacts of diets (20). These farming models may play an important positive role in terms of environmental impacts. Thus, there is a lack of information regarding organic farming in previous studies that usually consider only the prevailing conventional agriculture. Organic farming is, with respect to many indicators, more environment-friendly than conventional farming (17,21,22). Indeed, organic systems are characterized by higher energy efficiency (17,23), better soil biophysics and biologic quality (21,24) and contribute positively to plant and animal biodiversity (both in cropland and wild life) (9,11,12). Regarding GHG emissions, organic farming performs better than conventional, but only per area (26,27). Indeed, organic farming has lower yield and, as a result, does not reduce significantly the GHG and increases the land use per product unit (23,24,27). At the individual diet level, we previously reported that regular organic food consumers exhibited environmental benefits. Disentangling the role of food patterns (plant-based diet) and farming system (organic or conventional) revealed that organic farming system led to a slight reduction in cumulative energy demand but to a rise of land occupation (28). Thus, the studies investigating environmental impacts related to different diets, in particular vegetarian and vegans, without consider farming practices, may have underestimated some impacts as these consumers are more prone to choose organic food.

In that context, the aim of this study is to compare the environmental pressure and impact of diets of participants of the large cohort NutriNet-Santé study across different diets (omnivorous, pesco-vegetarians, vegetarians, and vegan), while distinguishing farming practice (organic or conventional) in the assessment of impacts.

2.METHODS AND DATA

2.1 NutriNet-Santé Study

The NutriNet-Santé Study (29) is a prospective cohort conducted in French volunteers' adults. Since 2009, data are collected by questionnaires through a secured on-line platform. On a yearly basis, the participants are required to provide information as regards sociodemographic and socioeconomic status, weight, height, smoking status, alcohol consumption, health events, medication use and food consumption. They are also regularly requested to fill-in additional questionnaires focusing on diet-related topics.

This study is piloted in line with the Declaration of Helsinki, and all processes were officially accepted by the Institutional Review Board of the French Institute for Health and Medical Research (IRB Inserm 0000388FWA00005831) and the Commission Nationale de l'Informatique et des Libertés (CNIL908). The volunteers completed and signed electronically an informed consent. The NutriNet-Santé Study is registered in ClinicalTrials.gov (NCT03335644).

2.2 Data Collection

2.2.1 Dietary intake assessment and diet group classification

In 2014, food consumption over the last year was estimated through the Org-FFQ, a self-administered organic food-frequency questionnaire (Org-FFQ) (11) with photographs improving estimation of the portion size. The Org-FFQ was developed from a validated FFQ (30) with additional questions inquiring organic food consumption. Thus, volunteers reported their consumption frequency and the portion consumed for 264 food items grouped in 17 groups. Participants also specified the frequency of consumption as organic for 257 food and beverage items (existing with organic label). Then to the question "How often was the product of organic origin?", the respondents could answer by: never, rarely, half-of-the-time, often or always. Then, each modality was assigned a percentage, respectively 0%, 25%, 50%, 75% and 100% to estimate the organic food consumption (in g) for each food item (28).

Daily nutritional intakes were calculated using the NutriNet-Santé food composition table (31).

For this study, NutriNet-Santé participants were classified into one of the following diet groups: 1) omnivorous: diet that included meat or fish intake almost every day, 2) pesco-vegetarian: diet that did not include meat (<1g/day), but included dairy products, eggs, fish and seafood, 3) vegetarian: diet that did not include animal flesh (<1g /day) but included dairy products and eggs and 4) vegan: diet that did not include any animal flesh (<1g /day) or any animal products (no eggs or dairy products, <1g/day)).

We also calculated the PANDiet (probability of adequate nutrient intake score), a 100-point index reflecting the nutritional quality of the whole diet. PANDiet is the average of a moderation and an adequation subscores which are based on the Probability of Adequate Nutrient intake (32).

2.2.2 Environmental impact assessment

Details of the assessment of the environmental impact, LCA and sources by product and production method have been extensively detailed elsewhere (33). Briefly, diet-related environmental impacts were assessed using a French database (DIALECTE (34)) of environmental measure for raw agricultural products and completed with other published data. Environmental data came from 2,086 farms with different farming practices (46% were organic farms). The Life Cycle Assessment (LCA) methodology was applied to the data pertaining to resources consumption and environmental impacts for about 60 agricultural commodities. Due to a lack of data for organic food system, LCA were calculated at the farm gate only.

Three environmental indicators were evaluated: greenhouse gas emissions (GHGe) ($kgCO_2$ eq/kg), cumulative energy demand (CED) (in MJ/kg) and land occupation (LO) (in m^2/kg). GHG emissions covered the sum of three GHGs (carbon dioxide CO_2, methane CH_4 and nitrous oxide N_2O). The CED encompassed renewable and unrenewable energy consumption as (35). The Dia'terre® method was used for GHGe and CED (36). The land occupation (LO) corresponded to the area required to produce agricultural commodities within one year. Economic and transformation weights were applied to translate commodities to consumption (33).

The environmental impacts of individual diet were estimated by multiplying the environmental impacts by the food quantity consumed (g/day), while accounting for the method of food production. The three above-mentioned indicators were combined in a single indicator to get a more synthetic measure of the overall environmental impacts. To account for existing trade-offs between environmental pressures, the ReCiPe aggregating several pressure indicators has been proposed. This approach considers the matching of midpoint-oriented and endpoint-oriented indicators (37). As GHGe, CED and land occupation represent about 90% of the total environmental dimension of the ReCiPe, the partial ReCiPe (pReCiPe) for environmental impact assessment of food product and diet has been defined (38). This score was computed, as follows:

$$\text{pReCiPe} = [0.0459 * \text{GHGe} + 0.0025 * \text{CED} + 0.0439 * \text{LO}]$$

Where GHGe is greenhouse gas emissions, in $kgCO_2$ eq/kg, CED is cumulative energy demand, in MJ/kg and LO is land occupation, in m^2/kg. The highest the pReCiPe index is high the environmental impact. We also computed the pRecipe index and the three individual indicators for 100% organic and 100% conventional diet by attributing organic or conventional environmental value to all the foods consumed.

2.2.3 Covariates

The covariates used were those closest to the filling date of the Org-FFQ (39). The variables were gender, age, living area (rural, i.e. a population below 2,000 inhabitants or urban, i.e. a population above 2,000 inhabitants), education (< school diploma, high school diploma and post-secondary graduate) 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), physical activity, (< 30 min/day, 30 to 60 min/day, and > 60 min/day), tobacco status (former smoker, non-smoker, and current smoker). The daily diet monetary cost (€/day) was estimated for each participant by multiplying the quantities consumed (g/day) by the corresponding item prices (€/g), while accounting for farming practice and place of purchase as previously extensively described (28).

2.3 Statistical analyses

Among the 37,685 NutriNet-Santé participants who completed de Org-FFQ, 8,475 individuals were excluded. Exclusion criteria were: missing covariates (n=380), under- or over-reporters (n=2,109), living overseas (n=743) and no data regarding the place of purchase (n=5,243). Therefore, the final sample included 29,210 participants (**Supplemental Figure 1**). Participants' characteristics were reported as means (SD) or percentages. P-values referred to chi-square test for categorical variables or variance analysis (ANOVA) for continuous variables. ANCOVA (analysis of covariance) models were performed (for other characteristics) to estimate the nutritional and environmental characteristics according to the diets, providing means (95% CI) adjusted for energy intake**.** For the nutrients, energy adjustment was performed using the residual method (40). P-values were estimated via covariance analysis. For statistical tests, the type I error was set at 5%. Data management and statistical analyses were conducted using SAS 9.4 software (SAS Institute Inc.).

3. RESULTS

3.1 Socio-demographic characteristics of participants across diets

The sociodemographic characteristics of the study sample are presented in **Table 1**. A total of 74.7 % were women and the mean age (SD) was 53.5 (13.99). About 95% of the participants were omnivorous. Pesco-vegetarians (1.59%), vegetarians (1.39%) and vegans (1.02%) were younger, more likely to live in urban area, more often graduated and had more often lower income than omnivorous. They were also more often less physically active and drank on average less alcohol than omnivorous. However, there was no significant difference for tobacco status. Finally, vegetarians had the lowest diet monetary cost and vegans the highest.

3.2 Nutritional characteristics

Nutrient and food group intakes (in g/day) according to each diet group were presented in **Table 2**. The energy intake was higher in the omnivorous than in the 3 other diet groups. Pesco-vegetarians, vegetarians and vegans had higher intake of carbohydrates, polyunsaturated fats, fibers and lower intake of saturated fats than omnivorous. As expected, the ratio of vegetable to total proteins was far higher for vegans (0.95), vegetarians (0.72) and pesco-vegetarians (0.58) than for omnivorous (0.32). Organic food consumption was positively associated with the reduction of animal-based products in the diet, with the highest organic food ratio in the diet observed among vegans (0.67 vs 0.28 among omnivorous). Micronutrient intakes are shown in **Supplemental Table 1**. The PANDiet score was higher among vegans than among omnivorous.

3.3 Environmental impacts

Table 3 presents the values of the aggregated environmental impact (as expressed by the pReCiPe) as well as the values of three individual indicators reflecting environmental pressures, for each type of diet. The pReCiPe index was the highest for omnivorous, and decreased when shifting toward more plant-based diet. However, the pReCiPe of pesco-vegetarians and vegetarians were not statistically different. Regarding the individual environmental impacts, omnivorous had by far the highest GHG emissions, CED and LO values, whereas vegans showed the lowest ones. Moreover, pesco-vegetarian, vegetarian diets' indicators values were similar and higher than those of vegans. Scenarios referring to a 100% conventional diet or 100% organic diet are presented in **Table 4**. While 100% conventional diets exhibited a lower pReCiPe value compared to 100% organic diets, particularly for omnivorous, environmental pressures were differentially affected by farming practices. Thus, GHGe were quite similar for both scenarios. CED was higher for 100% conventional diets while land occupation was higher for 100% organic diets.

In addition, differences across the type of diets were less pronounced in 100% conventional diets. However, omnivorous were always those who exhibited the highest environmental pressures. pReCiPe by food groups for each diet type is presented in **Figures 1**. After animal foods, the highest environmental impacts were attributable to the fruit and vegetables, starchy foods, oil and ready meals.

4. DISCUSSION

The present study assessed the environmental impacts of four types of diets (differing by the proportion of animal-based food) in a large sample of French adults, participants from the NutriNet-Santé cohort.

We observed significant differences between various types of diets, with respect to each indicator of environmental pressure and with respect to the aggregated index (as assessed by the pReCiPe). The more animal food in the diet, the higher the value of pReCiPe index. However, pesco-vegetarians exhibited a similar pReCiPe value compared to vegetarians although pesco-vegetarians had higher intakes of animal-based food than vegetarians. It is noteworthy that land occupation related to fish and seafood consumption may have been underestimated in the present study. Consequently, diet-related environmental impacts were ranked (in ascending order) as follows: omnivorous, vegetarian, pesco-vegetarian and then vegan. Notably, the omnivorous' diet had by far the highest environmental impacts. Extents of reduction of the aggregated indicator, i.e. the pReCiPe, of environmental impact were 64%, 61%, and 69% for pesco-vegetarians, vegetarians and vegans respectively, compared with the omnivorous. Although the two first reductions were not statistically significantly different. Also, using LCA differentiating farming practices (organic or conventional), we showed that vegans' diet emitted 78% less GHG, required 53% less energy and 67% less land occupation than omnivorous' diet. These results are in line with several recent works documenting associations between dietary patterns and a set of environmental impacts (GHG emissions, land occupation, and water use) in modelled and observed data (8,10,20). Indeed, a reduction in meat consumption is a major leverage for reducing diet-related environmental impacts, and in particular GHG emissions (4,5,23,41,9). Aleksandrowicz et al., in a systematic review focusing on GHG emissions, land occupation, and water use, concluded that the least impacting diets on the environment, compared to omnivorous diets, were in descending sequence the vegan diet, followed by the vegetarian, and then the pesco-vegetarian (8). In a recent study, in line with our results, based on simulation and covering 140 countries, vegan diets exhibited a reduced per capita GHG footprint by 70% compared to current diets (42). As extensively documented, these results are largely due to higher environmental impacts of animal-based products, especially ruminant meat, compared to plant-based products.

Recently, the EAT-Lancet commission on healthy diets from sustainable food systems (4) was fashioned to assess which diets and food production systems would ensure the achievement of the UN Sustainable Development Goals (SDGs) and Paris Agreement. They concluded in their commission, "that a dietary change towards increased adoption of plant-based diets has high mitigation potential, which is probably needed to limit global warming to a less than 2°C increase" (4). Similarly, a recent modeling study conducted for 140 different countries underlined that vegan diets exhibited a 70% reduction GHG footprint per capita compared to current diets (42). However, GHG emissions' reduction certainly depends on the amount and type of meat included in the diet, but also on the environmental impact of the meat substitute (16,43). For instance, plant-based diet may exhibit various pressure. While legumes, presenting interesting nutritional profiles, exhibited 250 times lower GHGe ruminant meats (11), rice production emits five times more GHGe than wheat production when considering gram of protein as function unit (11).

However, most of these studies did not distinguish between farming practices, even though organic food consumption has been markedly and positively correlated with plant-based diet (18,28). While organic production usually reduces CED compared to conventional production, it often increases land use and has comparable on GHG emissions (when considered by amount of food) (23,24,27). We found that a 100% organic omnivorous diet exhibited higher environmental pressures, suggesting that following an organic diet without changing towards a more plant-based diet is of little help, at least as regards the studied indicators. It should be however noted that organic farming may contribute to maintain biodiversity and limit water and soil pollution (21,22).

Herein, a reduction of GHGe of 76% was observed when comparing vegans to omnivorous. In comparison, in a work conducted by Scarborough et al (44) in the EPIC-Oxford cohort study, aimed at comparing GHGe four different groups, namely meat-eaters, fish-eaters, vegetarians and vegans (defined using self-reporting), GHGe (kgCO_2eq/day) were 7.19 for high meat eaters, 5.63 for medium meat-eaters and 2.89 for vegans (corresponding to a reduction of 60% compared to high meat-eaters). Since it has been documented that organic farming has no substantial effect on GHGe (23,24,27), with some variations according to the food product considered, these can be explained by the stages accounting in the LCA in the present study which focus on the cradle-to-farm perimeter. Of note, in the present study as well as in a modeling study (9), pesco-vegetarian and vegetarian diets exhibited relatively similar GHGe (9). Most of French studies did not focus on self-selected diets and used modeling approaches (20,45,46). A French work based on INCA2 data has compared pre-defined diets (i.e. “Lower-Carbon,” “Higher-Quality,” and “More Sustainable” diets) and concluded that food choices could lead to a 20% reduction in GHGe (47). As expected, this is far lower than the differences observed between the groups in the present study and hardly comparable as in the INCA2 study, participants were mostly omnivorous. Another recent study has optimized several European diets to identify the dietary changes to operate by applying stepwise 10% decrease in GHGe (48). In all these models, a reduction in the consumption of animal products was necessary, with some variations between countries. In this study, it was also observed that reductions in GHGe higher than 60% could be achieved only with drastic diet changes, which is the case for vegetarian diet. Furthermore, in line with our results, this study showed that, for large reductions in overall GHGe, animal food consumption decreased leading to higher contributions of fruits, vegetables and starchy foods to GHGe.

There are fewer studies that have investigated land occupation associated with different types of diets and those available are mostly not based on observational data (8). The present results are consistent with the available literature in terms of differences in land occupation according to diet, with significantly lower land use, despite smaller differences than for GHGs, for diets avoiding animal products and in particular for vegan diets.

However, farming practices were not considered in the previous observational studies while it has been documented that organic farming requires higher land use but lower energy demand than conventional one (23,24,27). In this study, organic farming for food production led to higher pReCiPe for omnivorous’ diet only. For other diets, excluding meat, compensation between indicators (higher land use, lower energy demand) results in few differences in pReCiPes for 100% organic and 100% conventional scenarios. An interesting modelling study evaluated environmental impact of omnivorous, vegetarian, vegan considering 100% organic or 100% conventional diet (49). In this study, consistently with the present findings, for a type of diet, land use was higher in organic than in conventional for a given diet. As regards GHGe, we have previously shown that organic farming has overall no effect (28). Finally, logically, vegetarian diets have always environmental impacts between those of meat consumers and those of vegans.

Based on actual data, as vegans and all types of vegetarians consumed a higher proportion of organic food than meat eaters, some differences observed in the previous studies may have been overestimated for some indicators. Similarly to the present findings, a modeling study (9) reported slight differences in environmental pressures between pesco-vegetarian and other vegetarian diets. However, land use of fishing is often considered as null. In the study of Baroni et al. (49), pesco-vegetarians were not considered. It would be therefore of great importance to consider other environmental indicators such as water footprint or biodiversity (50). A recent small study conducted in Italy documented higher environmental pressures (GHGe, water and ecological footprints) for omnivorous diets than for ovo-lacto-vegetarians and vegans diets and interestingly highlighted that vegetarians and vegans were more adherent to the Mediterranean diet, whose sustainability s has been consistently documented (9,51–54).

Overall, to the best of our knowledge, this study is the first, to introduce farming practices in the LCA assessment of the diets. Despite accounting higher land occupation in organic farming, the vegan diet, whatever the indicator considered, remained less resource-intensive and environmentally damaging than other diets. It is noteworthy that omnivorous in the present study exhibited relatively high consumption of meat (>120g/d on average with a wide variability in intake). It is therefore essential to identify possible food substitutions, as they may induce counterproductive effects. First, with regard to environmental pressures of meat, interestingly, a recent modeling study, based on baseline data from 5 European countries, identified sustainable diets who did not entirely exclude meat (55). It should be born in mind that the present study considers three indicators but other environmental pressures not accounted herein are also of great interest when considering pressure of livestock (15,56). In addition, there is also a great variability in livestock methods (57). Second, environmental impacts of the meat substitutes (16) may be questionable. For instance, plant-based meat substitutes may exhibit important environment pressure but current data are scarce (16,43). Third, besides cultural acceptability, a vegan diet may exhibit some disadvantages in terms of nutrition, raising health concerns in particular among young people (9,58,59).

Some limitations should be considered. First, as the NutriNet-Santé cohort is composed of volunteers, participants are certainly more concerned about food issues. Therefore, the consumption data are not representative of the French population consumption, which may limit the generalization of the results. Regarding the environmental impact assessment, herein, the stages of food transportation and processing, as well as the environmental cost of food waste and losses were not accounted for. The use of a FFQ, which is prone to an overestimation of intakes, has probably led to some imprecisions in the estimations. Moreover, due to the lack of data regarding pressure of sea farming (land occupation and other reliable indicators) the present results minimize seafood and fish environmental impacts, and consequently impacts of pesco-vegetarian diets. Finally, other indicators related to water use, biodiversity, excess nitrogen or soil quality were not available, which limited a more comprehensive assessment of the environmental footprint.

However, this study has also major strengths. To our knowledge, this is the first study considering different farming practices, hereby organic and conventional, in the evaluation of diet-related environmental impacts. Furthermore, environmental impacts were computed for three indicators: GHG emissions, LO and CED while most of previous studies generally only assess carbon footprint (60). Furthermore, in order to consider environmental impacts more globally, the pReCiPe index was used. Regarding the data collection, the large size of the sample allowed to provide a large range of eating habits, food consumption choices, and validated dietary data were available.

CONCLUSION

The present observational study conducted in French adults highlighted that omnivorous, with respect to GHGe, cumulative energy demand and land occupation, have by far the diets with the most serious consequences on resources and environment when compared to diets with restricted animal food. These findings also emphasize the positive link between organic consumption and plant-based diets underlying the significance of accounting for farming practices in environmental pressure assessment, as organic production may offer potential environmental benefits/disadvantages depending on the indicator considered. In future research, other environmental indicators should be considered, including, for instance, biodiversity and ecotoxicity impacts, nitrate and pesticide leaching, soil quality or water use. A systemic and holistic assessment only will make it possible to consider diets' consequences on the environment in a broader scale. However, environmental indicators distinguishing several farming practices are scarce underlining the need for more research in this field to conduct a broadly evaluation.

Acknowledgements

We especially thank Younes Esseddik, and Thi Hong Van Duong, computer scientists; Fabien Szabo, Nathalie Arnault and Laurent Bourhis, statisticians; and Cédric Agaësse, dieticians. We warmly thank all of the dedicated and conscientious volunteers involved in the NutriNet-Santé cohort. We also thank Bioconsom'acteurs' members for price collection. The NutriNet-Santé cohort study is funded by the following public institutions: the French Ministry of Health, Santé Publique France, the National Institute for Health and Medical Research, the National Institute for Agricultural Research, the National Conservatory of Arts and Crafts and the University of Paris 13. The BioNutriNet project was supported by the French National Research Agency (Agence Nationale de la Recherche) in the context of the 2013 Programme de Recherche Systèmes Alimentaires Durables (ANR-13-ALID-0001). The funders had no role in the study design, data collection, analysis, interpretation of data, preparation of the manuscript, and decision to submit it for publication.

REFERENCES

1. Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, et al. A safe operating space for humanity. Nature. 2009 Sep 24;461(7263):472–5.

2. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. Planetary boundaries: Guiding human development on a changing planet. Science [Internet]. 2015 Feb 13 [cited 2020 Feb 5];347(6223). Available from: https://science.sciencemag.org/content/347/6223/1259855

3. IPCC. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. [Internet]. 2019 [cited 2020 Feb 5]. Available from: https://www.ipcc.ch/srccl/chapter/technical-summary/

4. Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet. 2019 02;393(10170):447–92.

5. Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L, et al. Options for keeping the food system within environmental limits. Nature. 2018 Oct;562(7728):519–25.

6. How to feed nine billion within the planet's boundaries | FAO [Internet]. [cited 2020 Feb 5]. Available from: http://www.fao.org/agroecology/database/detail/fr/c/463434/

7. Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, et al. Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? AmJClinNutr. 2012 Sep;96(1938-3207 (Electronic)):632–9.

8. Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A. The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. PLoS ONE. 2016;11(11):e0165797.

9. Tilman D, Clark M. Global diets link environmental sustainability and human health. Nature. 2014 Nov 27;515(7528):518–22.

10. Chai BC, van der Voort JR, Grofelnik K, Eliasdottir HG, Klöss I, Perez-Cueto FJA. Which Diet Has the Least Environmental Impact on Our Planet? A Systematic Review of Vegan, Vegetarian and Omnivorous Diets. Sustainability. 2019 Jan;11(15):4110.

11. González-García S, Esteve-Llorens X, Moreira MT, Feijoo G. Carbon footprint and nutritional quality of different human dietary choices. Sci Total Environ. 2018 Dec 10;644:77–94.

12. van de Kamp ME, van Dooren C, Hollander A, Geurts M, Brink EJ, van Rossum C, et al. Healthy diets with reduced environmental impact? - The greenhouse gas emissions of various diets adhering to the Dutch food based dietary guidelines. Food Res Int. 2018;104:14–24.

13. Scarborough P, Appleby PN, Mizdrak A, Briggs ADM, Travis RC, Bradbury KE, et al. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Clim Change. 2014;125(2):179–92.

14. Bengtsson J, Bullock JM, Egoh B, Everson C, Everson T, O'Connor T, et al. Grasslands—more important for ecosystem services than you might think. Ecosphere. 2019;10(2):e02582.

15. Dumont B, Ryschawy J, Duru M, Benoit M, Chatellier V, Delaby L, et al. Review: Associations among goods, impacts and ecosystem services provided by livestock farming. animal. undefined/ed;1–12.

16. Hallström E, Carlsson-Kanyama A, Börjesson P. Environmental impact of dietary change: a systematic review. Journal of Cleaner Production. 2015 Mar 15;91:1–11.

17. Reganold JP, Wachter JM. Organic agriculture in the twenty-first century. Nature Plants. 2016 Feb 3;2(2):15221.

18. Lacour C, Seconda L, Allès B, Hercberg S, Langevin B, Pointereau P, et al. Environmental Impacts of Plant-Based Diets: How Does Organic Food Consumption Contribute to Environmental Sustainability? Front Nutr. 2018;5:8.

19. Baudry J, Méjean C, Allès B, Péneau S, Touvier M, Hercberg S, et al. Contribution of Organic Food to the Diet in a Large Sample of French Adults (the NutriNet-Santé Cohort Study). Nutrients. 2015;7(10):8615–32.

20. Perignon M, Vieux F, Soler L-G, Masset G, Darmon N. Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. Nutr Rev. 2017 Jan;75(1):2–17.

21. Gomiero T, Pimentel D, Paoletti MG. Environmental Impact of Different Agricultural Management Practices: Conventional vs. Organic Agriculture. Critical Reviews in Plant Sciences. 2011 Jan;30(1–2):95–124.

22. Muller A, Schader C, Scialabba NE-H, Brüggemann J, Isensee A, Erb K-H, et al. Strategies for feeding the world more sustainably with organic agriculture. Nature Communications. 2017 Nov 14;8(1):1290.

23. Clark M, Tilman D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters. 2017 Jun 1;12(6):064016.

24. Tuomisto HL, Hodge ID, Riordan P, Macdonald DW. Does organic farming reduce environmental impacts? – A meta-analysis of European research. Journal of Environmental Management. 2012 Dec;112:309–20.

25. Reganold JP, Wachter JM. Organic agriculture in the twenty-first century. Nat Plants. 2016 03;2:15221.

26. Mondelaers K, Aertsens J, Van Huylenbroeck G. A meta-analysis of the differences in environmental impacts between organic and conventional farming. British Food Journal. 2009 Sep 26;111:1098–119.

27. Meier MS, Stoessel F, Jungbluth N, Juraske R, Schader C, Stolze M. Environmental impacts of organic and conventional agricultural products--are the differences captured by life cycle assessment? J Environ Manage. 2015 Feb 1;149:193–208.

28. Baudry J, Pointereau P, Seconda L, Vidal R, Taupier-Letage B, Langevin B, et al. Improvement of diet sustainability with increased level of organic food in the diet: findings from the BioNutriNet cohort. Am J Clin Nutr. 2019 Apr 1;109(4):1173–88.

29. Hercberg S, Castetbon K, Czernichow S, Malon A, Mejean C, Kesse E, et al. The Nutrinet-Santé Study: a web-based prospective study on the relationship between nutrition and health and determinants of dietary patterns and nutritional status. BMC Public Health. 2010 May 11;10:242.

30. Kesse-Guyot E, Castetbon K, Touvier M, Hercberg S, Galan P. Relative validity and reproducibility of a food frequency questionnaire designed for French adults. Ann Nutr Metab. 2010;57(3–4):153–62.

31. Etude Nutrinet-Santé. Table de composition des aliments. Paris: Economica; 2013. 296 p.

32. Gavelle E de, Huneau J-F, Mariotti F. Patterns of Protein Food Intake Are Associated with Nutrient Adequacy in the General French Adult Population. Nutrients. 2018 Feb 17;10(2).

33. Seconda L, Baudry J, Allès B, Boizot-Szantai C, Soler L-G, Galan P, et al. Comparing nutritional, economic, and environmental performances of diets according to their levels of greenhouse gas emissions. Climatic Change. 2018 May 1;148(1):155–72.

34. Pointereau P, Langevin B, Gimaret M. DIALECTE, a comprehensive and quick tool to assess the agro-environmental performance of farms. 2019 Apr 25; Available from: https://www.researchgate.net/publication/265288497_DIALECTE_a_comprehensive_and_quick_tool_to_assess_the_agro-environmental_performance_of_farms

35. Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, et al. Implementation of Life Cycle Impact Assessment Methods Report 3.

36. ADEME. Dia'terre®. Synthèse du guide de la méthode et guide des valeurs. 2015.

37. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. 2013;132.

38. Kramer GF, Tyszler M, Veer PV, Blonk H. Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. Public Health Nutr. 2017 Jun;20(9):1699–709.

39. Touvier M, Méjean C, Kesse-Guyot E, Vergnaud A-C, Hercberg S, Castetbon K. Sociodemographic and economic characteristics associated with dairy intake vary across genders. J Hum Nutr Diet. 2011 Feb;24(1):74–85.

40. Willett W, Stampfer MJ. Total energy intake: implications for epidemiologic analyses. Am J Epidemiol. 1986 Jul;124(1):17–27.

41. Jones AD, Hoey L, Blesh J, Miller L, Green A, Shapiro LF. A Systematic Review of the Measurement of Sustainable Diets. Advances in Nutrition: An International Review Journal. 2016 Jul 1;7(4):641–64.

42. Kim BF, Santo RE, Scatterday AP, Fry JP, Synk CM, Cebron SR, et al. Country-specific dietary shifts to mitigate climate and water crises. Global Environmental Change. 2019 Aug 7;101926.

43. Hu FB, Otis BO, McCarthy G. Can Plant-Based Meat Alternatives Be Part of a Healthy and Sustainable Diet? JAMA. 2019 Aug 26;1–3.

44. Rose D, Heller MC, Willits-Smith AM, Meyer RJ. Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates. Am J Clin Nutr. 2019 Mar 1;109(3):526–34.

45. van Dooren C. A Review of the Use of Linear Programming to Optimize Diets, Nutritiously, Economically and Environmentally. Front Nutr. 2018;5:48.

46. Gazan R, Brouzes CMC, Vieux F, Maillot M, Lluch A, Darmon N. Mathematical Optimization to Explore Tomorrow's Sustainable Diets: A Narrative Review. Adv Nutr. 2018 Sep 1;9(5):602–16.

47. Masset G, Vieux F, Verger EO, Soler L-G, Touazi D, Darmon N. Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults. Am J Clin Nutr. 2014 Apr 2;

48. Vieux F, Perignon M, Gazan R, Darmon N. Dietary changes needed to improve diet sustainability: are they similar across Europe? Eur J Clin Nutr. 2018;72(7):951–60.

49. Baroni L, Cenci L, Tettamanti M, Berati M. Evaluating the environmental impact of various dietary patterns combined with different food production systems. EurJ ClinNutr. 2007 Feb;61(2):279–86.

50. Scarborough P, Appleby PN, Mizdrak A, Briggs AD, Travis RC, Bradbury KE, et al. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. ClimChange. 2014;125(0165-0009 (Print)):179–92.

51. Burlingame B, Dernini S. Sustainable diets: the Mediterranean diet as an example. Public Health Nutr. 2011 Dec;14(1475-2727 (Electronic)):2285–7.

52. Dernini S, Berry EM, Serra-Majem L, La Vecchia C, Capone R, Medina FX, et al. Med Diet 4.0: the Mediterranean diet with four sustainable benefits. Public Health Nutr. 2017 May;20(7):1322–30.

53. Alessandra DM, Maria V, Cecilia C, Augusto S, Marcello V. The Adherence of the Diet to Mediterranean Principle and Its Impacts on Human and Environmental Health. International Journal of Environmental Protection and Policy. 2014 Jan 1;2(2):64.

54. Rosi A, Mena P, Pellegrini N, Turroni S, Neviani E, Ferrocino I, et al. Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. Sci Rep. 2017 21;7(1):6105.

55. Vieux F, Privet L, Soler LG, Irz X, Ferrari M, Sette S, et al. More sustainable European diets based on self-selection do not require exclusion of entire categories of food. Journal of Cleaner Production. 2020 Mar 1;248:119298.

56. Lebacq T, Baret PV, Stilmant D. Sustainability indicators for livestock farming. A review. Agron Sustain Dev. 2013 Apr 1;33(2):311–27.

57. Röös E, Patel M, Spångberg J, Carlsson G, Rydhmer L. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy. 2016 Jan 1;58:1–13.

58. Dinu M, Abbate R, Gensini GF, Casini A, Sofi F. Vegetarian, vegan diets and multiple health outcomes: A systematic review with meta-analysis of observational studies. Crit Rev Food Sci Nutr. 2017 Nov 22;57(17):3640–9.

59. Springmann M, Godfray HCJ, Rayner M, Scarborough P. Analysis and valuation of the health and climate change cobenefits of dietary change. PNAS. 2016 Apr 12;113(15):4146–51.

60. Auestad N, Fulgoni VL. What current literature tells us about sustainable diets: emerging research linking dietary patterns, environmental sustainability, and economics. Adv Nutr. 2015 Jan;6(1):19–36.

Figure 1: pReCiPe of each food group according to the type of diet

Abbreviation: NAD, nonalcoholic drinks