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REVIEW

Key Findings of the French BioNutriNet Project on Organic Food–Based Diets: Description, Determinants, and Relationships to Health and the Environment

Emmanuelle Kesse-Guyot,[1] Denis Lairon,[2] Benjamin Allès,[1] Louise Seconda,[1,3] Pauline Rebouillat,[1] Joséphine Brunin,[1,3] Rodolphe Vidal,[4] Bruno Taupier-Letage,[4] Pilar Galan,[1] Marie-Josèphe Amiot,[5] Sandrine Péneau,[1] Mathilde Touvier,[1] Christine Boizot-Santai,[6] Véronique Ducros,[7] Louis-Georges Soler,[6] Jean-Pierre Cravedi,[8] Laurent Debrauwer,[8] Serge Hercberg,[1] Brigitte Langevin,[9] Philippe Pointereau,[9] and Julia Baudry[1]

[1]Sorbonne Paris Nord University, National Institute of Health and Medical Research (INSERM), National Research Institute for Agriculture, Food, and the Environment (INRAE), National Conservatory of Arts and Crafts (CNAM), Nutritional Epidemiology Research Team (EREN), Epidemiology and Statistics Research Center–University of Paris (CRESS), Bobigny, France; [2]Aix Marseille University, INSERM, INRAE, Centre for Cardiovascular Research and Nutrition (C2VN), Marseille, France; [3]Agency for the Environment and Energy Management (ADEME), Angers, France; [4]Organic Food and Farming Institute, Paris, France; [5]MOISA, INRAE, International Cooperation in Agricultural Research for Development (CIRAD), International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM), Institut Agro-SupAgro (SUPAGRO), Montpellier University, Montpellier, France; [6]Paris-Saclay, INRAE, UR ALISS, Ivry-sur-Seine, France; [7]Biochemistry Department, Grenoble-Alpes Hospital, Grenoble, France; [8]Toxalim, Toulouse University, INRAE, National Veterinary School (ENVT), National Polytechnic Institute of Toulouse-Purpan, Paul Sabatier University, Toulouse, France; and [9]Solagro, Toulouse Cedex, France

ABSTRACT

Few studies have investigated the relationships between organic food consumption, dietary patterns, monetary diet cost, health, and the environment. To address these issues, a consortium of French epidemiologists, nutritionists, economists, and toxicologists launched the BioNutriNet project in 2013. In 2014, an FFQ documented the usual organic and nonorganic (conventional) food consumption of approximately 35,000 NutriNet-Santé participants. Then, individual organic and conventional food intakes were merged with price, environmental, and pesticide residue data sets, which distinguished between conventional and organic farming methods. Many studies were conducted to characterize organic consumers and their environmental impacts (i.e., greenhouse gas emissions, energy demand, and land use) and organic food consumption impacts on health. We observed that organic consumers had diets that were healthier and richer in plant-based food than nonorganic consumers. Their diets were associated with higher monetary costs, lower environmental impacts, and reduced exposure to certain pesticide residues. Regular consumption of organic food was associated with reduced risks of obesity, type 2 diabetes, postmenopausal breast cancer, and lymphoma. Although several observations have been confirmed by several studies conducted in other countries, our results should be replicated in other cultural settings and coupled with experimental studies to be able to draw causal conclusions. Finally, the main finding of the BioNutriNet project is that while organic food consumption could be associated with positive externalities on human health and the environment, organic-based diets should be accompanied by dietary shifts toward plant-based diets to allow for better planetary and human health. *Adv Nutr* 2022;13:208–224.

Statement of Significance:

- Compared with nonorganic food consumers, organic food consumers have a healthier diet that is richer in plant-based food, translating into lower environmental pressures related to production (i.e., greenhouse gas emissions, cumulative energy demand, and land use), and exhibit specific characteristics.
- After accounting for multiple confounding factors, organic food consumers have lower risks of obesity, diabetes, and cancer than nonorganic food consumers, which could be partly explained by lower exposure to synthetic pesticide residues.

Keywords: organic food consumption, sustainability indicators, dietary scores, dietary greenhouse gas emissions, cumulative energy demand, monetary diet cost, dietary pesticide exposure, observational data, chronic diseases

 Adv Nutr 2022;13:208–224; doi: https://doi.org/10.1093/advances/nmab105.

Introduction

The global food system is currently facing considerable challenges with the double or even triple burden of malnutrition (i.e., the various forms of malnutrition coexisting, including undernutrition along with overnutrition and micronutrient deficiencies) gaining ground worldwide (1) and unhealthy diets being the second greatest risk factor for mortality (2).

Additionally, agricultural intensification, which began decades ago, highly jeopardizes natural resources and ecosystems. Because of this intensification, the food system accounts for 20%–30% of the total annual greenhouse gas emissions (GHGE) globally, significantly contributing to climate change (3). The energy supply for the agri-food chain makes up for an additional 10% of global GHGE (4). The global food system is also responsible for biodiversity loss and deforestation, while requiring high levels of fossil fuel (3, 5). Numerous scenarios state that alternative strategies are the most suitable way to ensure sustainable food systems in the future (3, 5–7). The principles of organic farming encompass social, environmental, and economic sustainability dimensions (8), and the expansion of organic farming is at the core of the Farm to Fork Strategy of the European Green Deal. In parallel, the growing demand from consumers for pesticide-free food has increased the production of organically farmed food. A recent literature review has assessed the environmental benefits and performances of organic farming (9). Organic farming appears to present clear benefits: that is, enhanced biodiversity and improved agricultural soil health (10–13). The lower yield per area under organic conditions, however, remains a major challenge in scaling up organic farming (14–16). Other significant challenges include accessibility and affordability for deprived populations.

In that context, in 2010, the FAO defined sustainable diets as those "with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. They are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy, while optimizing natural and human resources" (17). Moreover, in 2015, the United Nations adopted a new sustainable development program defining 17 overall objectives to be achieved by 2030, and most relate to food issues (18). Research so far has focused on food production, processing, and consumption behaviors separately. Despite the growing consumer demand for organic food, the diversity of production methods is rarely considered in the scientific literature or national guidelines evaluating the environmental and sanitary impacts of food (5). Studies on dietary patterns, their changes over time, and their impacts on health and the environment have mostly considered only the current intensive industrial farming system. This is mainly due to fragmented (impacts related to production) or nonexistent (consumption data from different production systems) data.

Therefore, new, innovative, and ambitious studies using multicriteria approaches are needed. This will allow an accurate quantitative analysis of the interrelations between agriculture, health, and the environment, while accounting for differing farming practices and consumer diets. The BioNutriNet project was launched in 2014 and uses the organic farming system as a model of alternative production to assess the effects of organic farming on both the environment and human health in a single multicriteria analysis. Although the environmental impacts of organic farming are relatively well documented (10, 19), data on the purported health benefits of organic food consumption are limited (20, 21). A comprehensive analysis, examining both the environmental and health impacts of the organic farming system, has never been conducted.

This study was designed to provide a synthesis of the findings of the French BioNutriNet project, embedded in the NutriNet-Santé study, regarding the profiles of organic consumers, their diets, and the relationships between organic food consumption, the environment, and health.

Methods

Population

This study is based on data derived from the NutriNet-Santé study, an ongoing, web-based, prospective, observational cohort study launched in France in May 2009 and targeting Internet-using, adult volunteers from the general population. The study was designed to investigate the relationships between nutrition and health and the determinants of dietary behaviors and nutritional status. The rationale, design, and methodology of the study have been fully described elsewhere (22).

The included participants completed a baseline set of self-administered, web-based questionnaires assessing dietary intake, physical activity, anthropometric and socioeconomic characteristics, lifestyle, and health status. As part of the follow-up, the participants were requested to complete the same set of questionnaires each year. Moreover, the participants were invited by e-mail to fill in optional questionnaires related to dietary behaviors and their nutritional and health status monthly.

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).

Author disclosures: The authors report no conflicts of interest.

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.

Supplementary Methods are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/advances/.

Address correspondence to EK-G (e-mail: e.kesse@eren.smbh.univ-paris13.fr).

Abbreviations used: AMAP, associations supporting small farming; cDQI, comprehensive Diet Quality Index; CNIL, Commission Nationale de l'Informatique et des Libertés; CVUA, Chemisches und Veterinäruntersuchungsam; FBDG, food-based dietary guidelines; GHGE, greenhouse gas emissions; LCA, Life Cycle Assessment; MetS, metabolic syndrome; Org-FFQ, organic FFQ; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; Q, quintile.

The BioNutriNet project was launched in 2014 to assess the effects of organic farming (reflecting an alternative production model) on both the environment and human health in a single multicriteria analysis. As part of the project, a specific tool was developed to collect information on organic and conventional food consumption, and served as an anchor for matching with other collected data.

Individuals who completed a specific questionnaire (see below) were included in the BioNutriNet project. The NutriNet-Santé study was conducted according to the guidelines stated in the Declaration of Helsinki, and all procedures were approved by the Institutional Review Board of the French Institute for Health and Medical Research (IRB INSERM number 0000388FWA00005831) and the Commission Nationale de l'Informatique et des Libertés (CNIL; numbers 908450 and 909216). All participants provided informed consent with an electronic signature. This study is registered in EudraCT (number 2013–000929–31) and ClinicalTrials.gov (NCT03335644). Several methodological studies have been conducted to characterize the NutriNet-Santé participants and validate the questionnaires and tools (23).

Sociodemographic, economic, lifestyle, food-choice-motive, and place-of-purchase data

As part of the follow-up, data on individual characteristics, including sex, birth date, BMI, educational level, occupational category, employment status, income, household composition, living area, smoking status, and physical activity, were collected yearly. Specific questionnaires were also used to assess the usual consumption of alcohol.

Food choice motives, including sustainability concerns during purchasing, were collected using a questionnaire specifically developed and validated in the NutriNet-Santé study (24). Details on the questionnaire validation have been given elsewhere (24). Briefly, the questionnaire was reduced, through the validation procedure, to 63 items, leading to 9 food choice dimensions: *1*) the absence of contaminants; *2*) environmental limitations; *3*) ethics and environment; *4*) taste; *5*) innovation; *6*) local and traditional production; *7*) price; *8*) health; and *9*) convenience. In a complementary questionnaire designed to assess attitudes toward organic food, the participants were also instructed to report their primary and secondary places of purchase for different organic and conventional food groups. The places of purchase included supermarkets, discount stores, markets, associations supporting small producers, box schemes [i.e., associations supporting small farming (AMAP)], retail stores (e.g., bakeries and butcheries), grocery stores, farms, self-production, and specialized organic food stores.

Health data

The NutriNet-Santé participants self-reported health events via the yearly health status questionnaire, through a specific checkup questionnaire for health events (every 3 mo), or at any time through a specific interface on the study website. For cancer and cardiovascular diseases, following the declaration, the participants were invited to provide their medical records (e.g., report, diagnosis, and hospitalization); if necessary, the study's medical doctors contacted the participants' physicians or their hospitals to collect additional information. All collected data were reviewed by an expert physician committee to validate major health events. The vital status and causes of death were thoroughly monitored and obtained according to the procedure described in Decree 98–37, authorizing access to the CépiDc database of INSERM (national mortality registry). Moreover, declared health data was linked to the medico-administrative registers of the national health insurance system databases [Système national d'information inter-régimes de l'assurance maladie (SNIIRAM)].

Moreover, in 2011–2014, the NutriNet-Santé participants were invited to undergo biological sampling (i.e., blood and urine) and a clinical examination in 1 of the local centers throughout France. This checkup was proposed on a voluntary basis, and approximately 20,000 volunteer participants were examined. Electronic and paper written informed consents were obtained from all volunteer participants. All procedures were approved by the Consultation Committee for the Protection of Participants in Biomedical Research (C09-42 on 5 May 2010) and the CNIL (number 1460707). During the clinical examination, blood pressure and anthropometric characteristics were measured by trained personnel using standardized procedures.

Dietary data

Different information sources were used to retrieve the total and organic food consumption data in the NutriNet-Santé study.

Before launching the BioNutriNet project, a questionnaire inquiring about organic consumption and reasons for not consuming organic food was sent to the NutriNet-Santé participants at 2 mo of follow-up in 2009 (**Figure 1**) (25). The participants reported their consumption frequency (i.e., never, occasionally, or most of the time) of 16 labeled organic food categories (i.e., fruits, vegetables, soybeans, dairy products, meat and fish, eggs, grains and legumes, bread and cereals, flour, vegetable oils and condiments, ready-to-eat meals, coffee/tea/herbal tea, wine, sweet products, dietary supplements, and other foods) and reasons in case of nonconsumption. The reasons given for nonconsumption included prices, availability, being uninterested in organic products, avoiding organic products, and having no specific reason. An organic food score was obtained by allocating, for each of the 16 food groups, 2 points to the "most of the time" modality, 1 point to the "occasionally" modality, and 0 otherwise (maximum range, 32 points). As part of their follow-up, at inclusion and yearly after, daily food consumption data were collected using repeated 24-h records randomly allocated over a 2-wk period, including 2 weekdays and 1 weekend day. The participants reported all foods and beverages consumed on each eating occasion using an online tool objectively validated against biomarkers (26, 27).

FIGURE 1 Questionnaire administration timeline.

Portion sizes were estimated using photographs, derived from a validated picture booklet (28). In 2014, as part of the BioNutriNet project, food consumption was assessed using a previously validated, self-administered, semiquantitative FFQ (29), supplemented by additional questions regarding the frequencies of organic food consumption. The Organic-FFQ (Org-FFQ) has been described in detail elsewhere (30). In brief, it includes 264 food and beverage items. For each food item, the participants were instructed to provide their consumption frequency over the past year (in yearly, monthly, weekly, or daily units) and the quantities consumed. The consumed portion sizes were determined using specified serving sizes or photographs for specific categories. Additionally, the organic food consumption frequency was assessed using the following question: "how often was the product of organic origin?" Answer modalities were assessed using a frequency-category scale with 5 modalities ranging from never to always (i.e., never, rarely, half of the time, often, and always).

The frequency modalities of organic food consumption were translated into quantitative data by attributing weights of 0, 0.25, 0.5, 0.75, and 1 to the categories of never, rarely, half of the time, often, and always, respectively. The proportion of organic food, both in the whole diet and by food group, was calculated by dividing the organic food consumption (g/day) by the total consumption without water (g/day). Approximately 35,000 participants have completed the Org-FFQ (30). Nutrient intakes were assessed using a generic food composition database (possible nutrient differences between organic and conventional products were not considered due to lack of data) specifically developed for the Org-FFQ, which was based on the NutriNet-Santé original food composition data set that includes more than 3000 items (31). Within the frame of the BioNutriNet project, information on anteriority of organic food consumption was also collected using another questionnaire regarding attitudes toward organic food, administered in July 2014.

Various nutritional indexes and dietary-related indicators were developed that reflect adherence to nutrient- or food-based guidelines or the amount of plant food consumed (**Figure 2**) (32–36).

Cost data

A cost database was built by compiling a list of prices for the 264 items of the Org-FFQ, accounting for the place of purchase and farming practices (organic compared with conventional). To do so, the 2012 Kantar Worldpanel database, including prices from supermarkets and other stores, was used (37). Additional data for short supply chains (e.g., local markets or AMAP) were collected by the members of the BioConsom'acteurs Association. From 9 French metropolitan departments, 1100 prices in autumn 2014 and 862 prices in spring 2015 were collected (38). The cost of an individual diet (total and derived from conventional or organic food consumption) was calculated by combining food consumption, the place of purchase, farming practices, and individual prices (average of the available data points).

Environmental data

Resources and environmental data were obtained from the diagnostic tool DIALECTE (39), a comprehensive tool developed by SOLAGRO. This tool assesses the environmental performance of organic and conventional farms using a global approach. In 2017, DIALECTE included information on 2086 French farms (of which 46% were organic farms) with various agricultural production systems, allowing the provision of the environmental impacts of organic and conventional products for most agricultural products. Information collected by DIALECTE using the

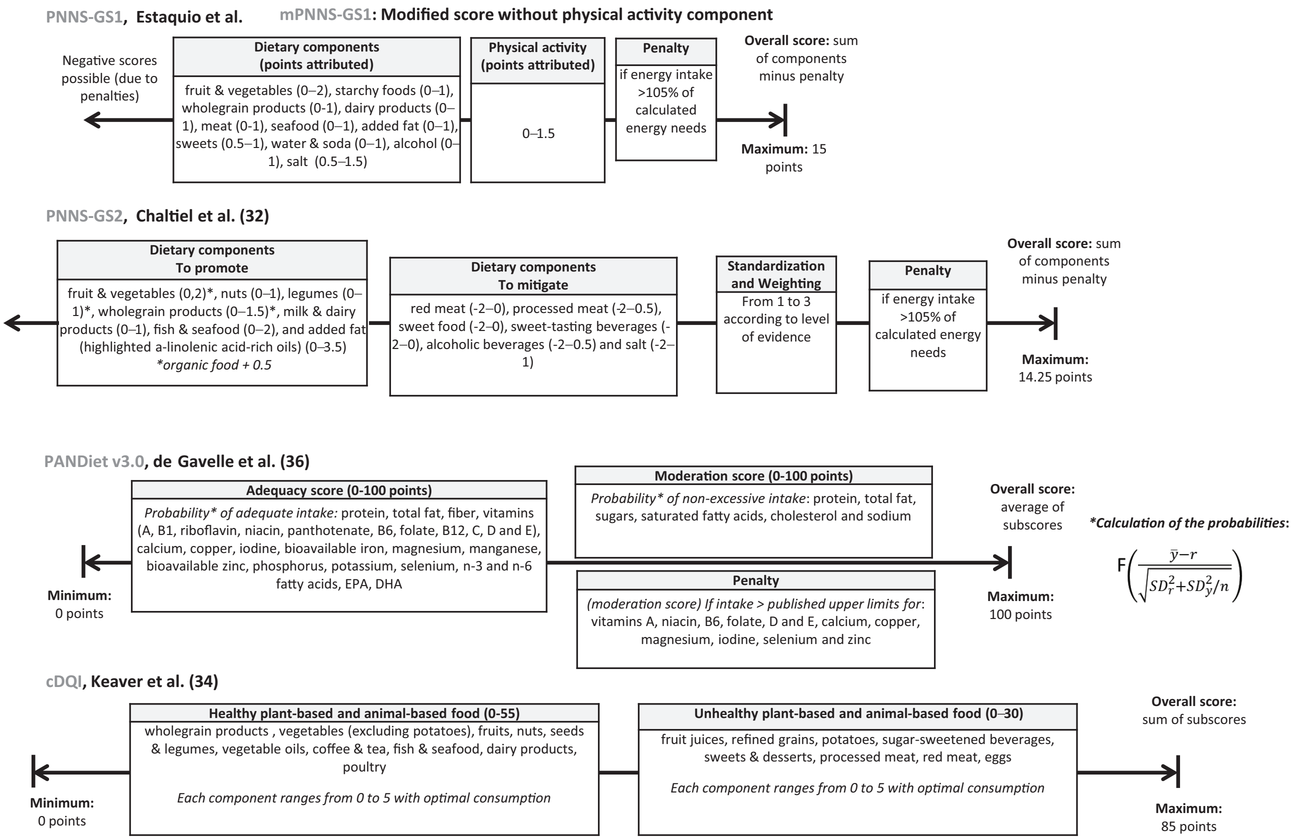

FIGURE 2 Computation of the dietary scores used in the BioNutriNet project. Dietary scores refer to the mPNNS-GS1, the PNNS-GS2, the PANDiet, and the cDQI (32–36). *Probabilistic calculation to estimate the adequacy of the usual intake of a nutrient, where *F* is the *probnorm* function in SAS, *y* is the mean intake, *r* is the nutrient reference value, *SDr* is the interindividual variability, *SDy* is the intraindividual variability across the *n* dietary assessment. In that case *SDy* = 0 and case *n* = 1 as a FFQ was used. The mPNNS-GS1 is based on the 2001 dietary guidelines; the PNNS-GS1 is based on the 2001 dietary guidelines; and the PNNS-GS2 is based on the 2017 dietary guidelines. Abbreviations: cDQI, comprehensive Diet Quality Index; mPNNS-GS1, modified Programme National Nutrition Santé–guideline score 1; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; PNNS-GS1, Programme National Nutrition Santé-guideline score 1; PNNS-GS2, Programme National Nutrition Santé-guideline score 2.

Life Cycle Assessment (LCA) method allowed for estimates of the environmental impacts at the farm level of 92 raw agricultural products, constituting ingredients of the 264 food items of the Org-FFQ, while distinguishing the method of food production (organic or conventional food production). For the other 30 raw products, the published values were used. All data and procedures have been extensively described elsewhere (38). The LCA perimeter was limited to the farm, but production for food represents most impacts (40). Thus, conditioning, transport, processing, storage, and recycling were excluded from the analysis. Economic allocations accounting for coproducts and edible coefficients were used to estimate the environmental impact of each food item. The diet-related GHGE (CO_2 eq/day), land use (m^2/day), and energy consumption (MJ/day) were obtained by multiplying the quantity of food consumed by its corresponding environmental impact and were summed up to estimate the environmental impact of each diet.

Estimated pesticide residue data

A pesticide residue data set was also compiled using the database built by the Chemisches und Veterinäruntersuchungsamt (CVUA) Stuttgart (European reference laboratory for the analysis of residues in plant products). For each of the 442 ingredients constituting at least 5% of the 264 items of the Org-FFQ, the mean contamination of a list of compounds was calculated from more than 6 billion data points collected between 2012 and 2015 by the CVUA. The CVUA database contained pesticide residue data for both organic and conventional products. Approximately 180 plant foods from 88 countries were considered. Different scenarios (lower- and upper-bound) were used to estimate the pesticide residue exposure, as recommended by the WHO (41).

For each active substance (>40), the estimated daily intake [in μg/(kg · day)] was calculated under a lower-bound scenario, using the reference method described by Nougadère et al. (42), combining food consumption, contamination, farming practices, and individual body weight after applying edible coefficients for cooking and peeling. Pesticide residues included different active substances, such as organophosphates, pyrethroids, natural pyrethrins, and spinosad (43).

Clinical studies

In a subsample of the NutriNet-Santé participants who attended the clinical visit (with available blood and urine samples) and completed the Org-FFQ, 300 participants were selected using propensity score matching (44) to identify pairs with similar profiles regarding sociodemographic characteristics, dietary patterns, and health history but differing in organic food consumption (with organic food consumption making up either >50% or <10% of the diet). The procedure and quality of the matching have been described in detail elsewhere (45).

Various biomarkers, including pesticide and nutritional biomarkers, were examined (45, 46).

Statistical analysis

This section provides a general overview of the methods used in the BioNutriNet project. A detailed description of the statistical techniques used can be found in the corresponding articles.

Overall, descriptive comparisons were performed using either Student's *t*-tests or nonparametric tests for continuous variables and the Chi-square test for categorical variables.

Analysis of covariance models were used to assess the associations between organic food consumption (modeled as quantiles or continuous variables) and the different outcomes of interest (e.g., dietary characteristics, pesticide residue exposure, monetary cost, and environmental indicators). The cross-sectional associations between organic food consumption and health- and diet-related traits (e.g., following a specific diet, dietary supplement use, or reporting allergies) were examined using logistic regressions. The risks of overweight and obesity in relation to the organic food consumption frequency were examined using logistic regressions, while the cross-sectional association between organic food consumption and metabolic syndrome (MetS) was assessed using Poisson regressions. Cox proportional hazards models were performed using age as a timescale to model the prospective associations between various exposures and health outcomes. The HR or OR and 95% CI were estimated. Several adjustment factors were used to account for residual confounding. A typology of organic food consumers was constructed using a principal component analysis and cluster analysis. In certain works, analyses across quintiles of organic food consumption were weighted to improve the representativeness of the sample using the iterative proportional fitting procedure (47). Weighting was based on the 2009 national census reports, using age, category of occupation, level of education, area of residence, the presence of children (<18 y), and marital status as variables.

Additionally, in a subsequent analysis, we attempted to disentangle the effects of dietary patterns and organic food consumption (independent variables) on environmental pressures and monetary cost (dependent variable) using breakdown methods (**Supplemental Methods**).

Significance tests were 2-tailed, and a type I error probability (*P* value) less than 0.05 was regarded as statistically significant.

Further details on the statistics used are given in the study's respective section.

An overview of the assessed sustainability indicators is presented in **Table 1**.

Results

Approximately 34,000 participants completed the Org-FFQ. The mean age of the participants was 53 y, and 75% were women. Of note, depending on the research question, the sample size varied (**Table 2**).

Profiles of French organic food consumers

We conducted several analyses on organic food consumption and its correlates (30, 43, 48, 49). Overall, compared with nonconsumers, high organic food consumers were more often women, had higher levels of education, lived in rural areas, and had high physical activity levels (50). High organic food consumers also consumed less alcohol and were less likely to smoke (50).

Besides, high organic food consumers were more often vegetarians [ORs, 9.93 (95% CI, 7.42–13.29) in women and 13.07 (95% CI, 7.00–24.41) in men] and dietary supplement users [ORs, 2.87 (95% CI, 2.65–3.04) in women and 2.94 (95% CI, 2.58–3.34) in men]. They were less likely to be on a weight loss diet and reported allergies more often [ORs, 1.99 (95% CI, 1.69–2.33) in women and 1.82 (95% CI, 1.15–2.87) in men] (48).

Using principal component analysis based on conventional and organic food intakes, we also established a typology of consumers according to their dietary habits among 28,245 NutriNet-Santé participants (49). Five clusters were identified, differing in their eating habits: standard conventional food small eaters, unhealthy conventional food big eaters, standard organic food small eaters, green organic food eaters, and hedonist moderate organic food eaters (**Figure 3**). A detailed description of the clusters is given in the next sections.

Food choice motives of French organic food consumers

The motives were described in the 5 consumer clusters identified above (51).

Green organic food eaters had the highest mean score for the health dimension, whereas unhealthy conventional food big eaters obtained the lowest mean score for the absence-of-contaminants dimension. Standard organic food small eaters, green organic food eaters, and hedonist moderate organic food eaters had comparable scores for the taste dimension. Unhealthy conventional food big eaters had the highest mean score for the price dimension, whereas green organic food eaters had the lowest mean scores for the innovation and convenience dimensions.

TABLE 1 List of main indicators used in the NutriNet-Santé cohort study and in the BioNutriNet project

Indicator	Dimension measured by the indicator	Data sources	Aim/Definition	Indicator level
Sociodemographic data (N)[1]	Sociocultural dimension	Validated questionnaire (self-report)	Characterization of socioeconomic profiles (gender, age, education, employment, etc.)	Individual level
Lifestyle data (N)	Cultural dimension	Questionnaire (self-report)	Characterization of tobacco status, physical activity, alcohol consumption	Individual level
Health data (N)	Health dimension	Questionnaire (self-report and further validation by a medical committee)	Characterization of health status (major health events)	Individual level
Purchase motives (N)	Cultural dimension	Validated questionnaire (self-report)	Assessment of food choice motives during purchase based on 9 dimensions: *1*) absence of contaminants; *2*) environmental limitations; *3*) ethics and environment; *4*) taste; *5*) innovation; *6*) local and traditional production; *7*) price; *8*) health; and *9*) convenience	Individual level
Place of food purchase (B)[2]	Cultural dimension	Questionnaire (self-report)	Assessment of food practices, perception, attitudes towards organic food, and place of purchase of main (organic and conventional) food categories	Individual level
Dietary intakes (B)	Nutritional dimension	Org-FFQ[3]/composition database	Measure of the absolute and relative intakes of main foods and nutrients	Individual level. Derivation of the intakes using a specially Org-FFQ adapted food composition database
Dietary scores (B)	Nutritional dimension	Org-FFQ/composition database	Measure of the consumption of the overall dietary quality (including adequacy to French food-based nutritional guidelines and nutrient-based reference values)	Individual level
BMI (N)	Anthropometry dimension	Validated questionnaire (self-report) + clinical data	Measure of underweight and different levels of overweight	Individual level
Greenhouse gas emissions (B)	Environmental dimension	Mostly DIALECTE database, partially completed by data available in the literature	Measure of climate change	Farm level considering the food production systems (organic vs. conventional) and further allocations of economic, mass, cooking, and edibility factors to obtain impacts at the consumer level
Primary energy consumption (B)	Environmental dimension	Mostly DIALECTE database partially completed by data available in the literature for 442 ingredients	Measure of use of energy resource	Farm level considering the food production systems (organic vs. conventional) and further allocations of economic, mass, cooking, and edibility factors to obtain impacts at the consumer level
Land use (B)	Environmental dimension	Mostly DIALECTE database, partially completed by data available in the literature for 442 ingredients	Partial measure of the reflection of natural resource depletion	Farm level considering the food production systems (organic vs. conventional) and further allocations of economic, mass, cooking, and edibility factors to obtain impacts at the consumer level

(*Continued*)

TABLE 1 (*Continued*)

Indicator	Dimension measured by the indicator	Data sources	Aim/Definition	Indicator level
Diet costs (B)	Economic dimension	Kantar-World panel purchase database (2012), completed by ~2000 prices collected from short supply chains by Bioconsom'acteurs' members (Autumn 2014 and Spring 2015)	Assessment of the budget devoted to diet	Individual level. Computation of the indicators considering the place of purchase of main food categories, as well as the food production systems (organic vs. conventional) and further allocations of edibility and cooking factors to obtain impacts at the consumer level
Dietary pesticide residue exposure (B)	Food safety dimension	CVUA Stuttgart database (2012–2015) European reference laboratory for the development of methods for the analysis of residues on plant products	Measure of the exposure from plant-derived products to >40 pesticides through 2 scenarios (lower- and upper- bounds)	Individual level. Assessment of the pesticide exposure from 180 plant ingredients, considering the food production systems (organic vs. conventional) and further allocations of edibility and cooking factors to obtain impacts at the consumer level

Abbreviations: CVUA, Chemisches und Veterinäruntersuchungsamt; Org-FFQ, organic FFQ.
[1](N) refers to data collected in the NutriNet-Santé cohort study.
[2](B) refers to data collected specifically in the BioNutriNet project.
[3]The Org-FFQ was built on a previously validated FFQ with additions for each food and beverage item existing in an organic version on a 5-point ordinal scale so as to estimate the organic food consumption frequency.

Dietary patterns of French organic food consumers

The Org-FFQ enabled us to evaluate the share of organic food consumption in the diets of 28,245 participants (30) and identify the associated determinants. Overall, less than 12% of the respondents reported never consuming organic food in the past year. On average, women consumed organic food as 20% of their whole diet per day, whereas men consumed 18%. The proportions of vegetables consumed that came from organic sources were 31% among women and 28% among men. Overall, the estimate of the contribution of organic food from products of plant origin was higher than that from products of animal origin.

When dividing the study population into 5 equivalent groups [quintiles (Q); Q1–Q5] according to their organic food consumption level, we observed that the intakes of foods of plant origin increased along with the contribution of organic foods to the diet, whereas a reverse trend was identified for meats and processed meats, dairy products, cookies, fast foods, and soda. The dietary patterns of consumers across the weighted organic food consumption quintiles are presented in **Figure 4**.

Overall, high organic food consumers exhibited better diet quality (**Table 3**). Several indicators of the nutritional quality of the diet have been estimated across the weighted quintiles of organic food consumption (as a percentage of the total weight in the diet). While high organic food consumers exhibited 13% more adherence to the 2001 French food-based dietary guidelines (FBDG) compared with nonconsumers, they showed 69% more adherence to the 2017 French FBDG. They also had higher Diet Quality Index Based on the Probability of Adequate Nutrient Intake (PANDiet) scores, reflecting the probability of adequacy to nutritional references (Q5 compared with Q1 + 11%), and higher comprehensive Diet Quality Index (cDQI) scores, reflecting the quality of the diet (Q5 compared with Q1 + 20%).

The nutritional characteristics of the typology's groups were as follows: *1*) standard conventional food small eaters were characterized by low energy intake, low organic food consumption, and a high prevalence of inadequate nutrient intakes; *2*) unhealthy conventional food big eaters had high intakes of saturated fatty acids and cholesterol; *3*) standard organic food small eaters were characterized by high organic food consumption and relatively adequate nutritional diet quality; *4*) green organic food eaters included a high percentage of organic food consumers, 14% of whom were either vegetarians or vegans, and exhibited a high nutritional diet quality and a low prevalence of inadequate intakes of most vitamins, except for vitamin B-12; and *5*) standard organic food small eaters had particularly high intakes of proteins and alcohol and a poor overall nutritional diet quality (**Figure 5**).

Clinical studies

Based on a sample of 1:1 matched NutriNet-Santé participants who had available biological samples (150 high organic food consumers compared with 150 low organic

TABLE 2 Tools used to collect organic food consumption in the NutriNet-Santé cohort study and in the BioNutriNet project

Publication	Study aim	Sample size, *n*	Dietary tool	Organic assessment tool	Date of administration	Additional data treatment analysis	Other
Kesse-Guyot et al., 2017 (52)	Obesity	$n = 62,224$	24-h dietary records (2 first years of follow-up)	Organic food choice questionnaire (16 food groups)	2 mo after inclusion	—	—
Baudry et al., 2018 (55)	Cancer	$n = 68,946$	24-h dietary records (2 first years of follow-up)	Organic food choice questionnaire (16 food groups)	2 mo after inclusion	—	—
Baudry et al., 2015 (48)	Health- and diet-related traits	$n = 54,283$	24-h dietary records (2 first years of follow-up)	Organic food choice questionnaire (16 food groups)	2 mo after inclusion	—	—
Baudry et al,. 2015 (30)	Level of organic consumption in the diet, Org-FFQ[1] development description	$n = 28,245$	264-item Org-FFQ[1]	264-item Org-FFQ	June 2014	Weighted data	—
Baudry et al., 2016 (49)	Dietary patterns	$n = 28,245$	264-item Org-FFQ	264-item Org-FFQ	June 2014	—	—
Baudry et al., 2017 (50)	Dietary patterns	$n = 28,245$	264-item Org-FFQ	264-item Org-FFQ	June 2014	Weighted data	—
Baudry et al., 2017 (51)	Food choice motives	$n = 22,366$	264-item Org-FFQ	264-item Org-FFQ	June 2014	—	Use of a questionnaire related to food choice motives
Baudry et al., 2018 (53)	Metabolic syndrome	$n = 8,174$	264-item Org-FFQ	264-item Org- FFQ	June 2014	—	—
Baudry et al., 2019 (43)	Sustainable values	$n = 29,210$	264-item Org-FFQ	264-item Org-FFQ	June 2014	Weighted data	—
Kesse-Guyot et al., 2020 (54)	Type 2 diabetes	$n = 33,256$	264-item Org-FFQ	264-item Org-FFQ	June 2014	—	—
Baudry et al., 2018 (45)	Biomarkers	$n = 300$	264-item Org-FFQ	264-item Org-FFQ	June 2014	—	—
Baudry et al., 2019 (46)	Biomarkers	$n = 300$	264-item Org-FFQ	264-item Org-FFQ	June 2014	—	—

Abbreviation: Org-FFQ, organic FFQ.
[1]The Org-FFQ was built on a previously validated FFQ with additions for each food and beverage item existing in an organic version on a 5-point ordinal scale so as to estimate the organic food consumption frequency.

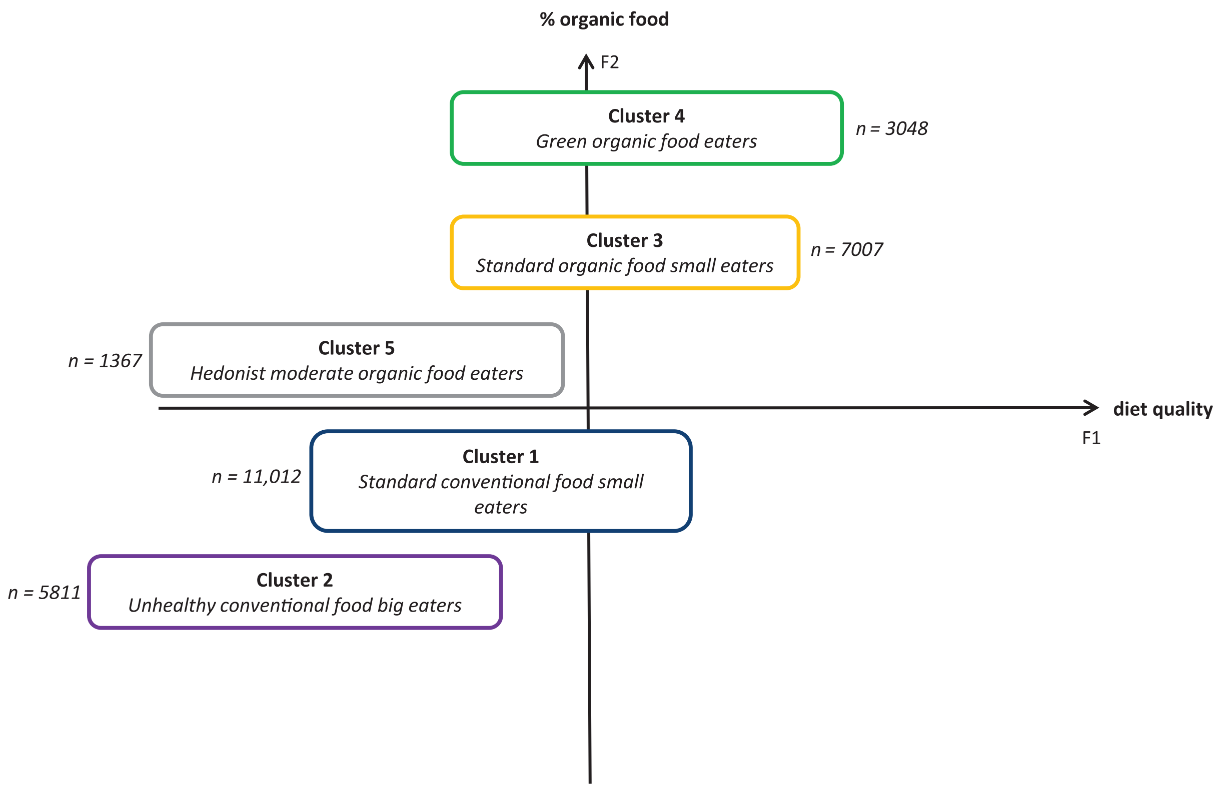

FIGURE 3 Typology of conventional and organic consumers ($N = 28{,}245$). The 5 clusters are derived from a principal component analysis based on the consumption of 16 organic and 16 conventional food groups, followed by a hierarchical clustering. The clusters are placed on the 2 first-factors (F) of the principal component analysis, with F1 reflecting healthy food consumption and F2 organic food consumption.

food consumers) for all traits, including dietary patterns (45), significant reductions in the median urinary concentrations, ranging from −17% to −55%, were observed for diethylthiophosphate, dimethylthiophosphate, dialkylphosphates, and free 3-phenoxybenzoic acid in most frequent organic consumers (>50% organic foods) compared with low organic consumers (<5% or 10%).

In another nested clinical investigation using the same subsample (46) from the NutriNet-Santé study, we also compared the nutritional statuses of organic and nonorganic food consumers. Fasting plasma samples were analyzed using acknowledged laboratory methods to assess nutritional statuses. We found significant differences in the plasma levels of magnesium, fat-soluble micronutrients (i.e., α-carotene, β-carotene, lutein, and zeaxanthin), fatty acids (i.e., linoleic, palmitoleic, γ-linolenic, and docosapentaenoic acids), and some fatty acid desaturase indexes between low and high organic food consumers with comparable dietary patterns. No differences in the plasma levels of iron, copper, cadmium, lycopene, β-cryptoxanthin, and vitamins A and E were detected between the 2 groups. Our data suggest that a high consumption of organic foods, compared with low consumption, improved some features of the nutritional status beyond dietary patterns (46).

Associations between organic food consumption and health outcomes

Various health outcomes were investigated in relation to organic food consumption in the NutriNet-Santé study and as part of the BioNutriNet project.

Data from 62,224 NutriNet-Santé participants (78% women; mean age, 45 y) with information on the organic food score, dietary intake, and repeated anthropometric measurements were analyzed regarding weight outcomes (52). After an average follow-up of 3.1 y, a lower BMI increase was observed when increasing the organic score. Moreover, an increase in the organic score was associated with lower risks of overweight and obesity among nonoverweight and nonobese participants, respectively, at inclusion [ORs for Q4 compared with Q1, 0.77 (95% CI, 0.68–0.86) and 0.69 (95% CI, 0.58–0.82), respectively]. This study supports a strong protective role of the consumption frequency of organic foods regarding the risks of overweight and obesity.

MetS, a multicomponent condition, is a cardiovascular disease predictor. We investigated the cross-sectional association between organic food consumption and MetS in 8174 French adults who completed the Org-FFQ and had available measurements during clinical visits from the NutriNet-Santé study (53).

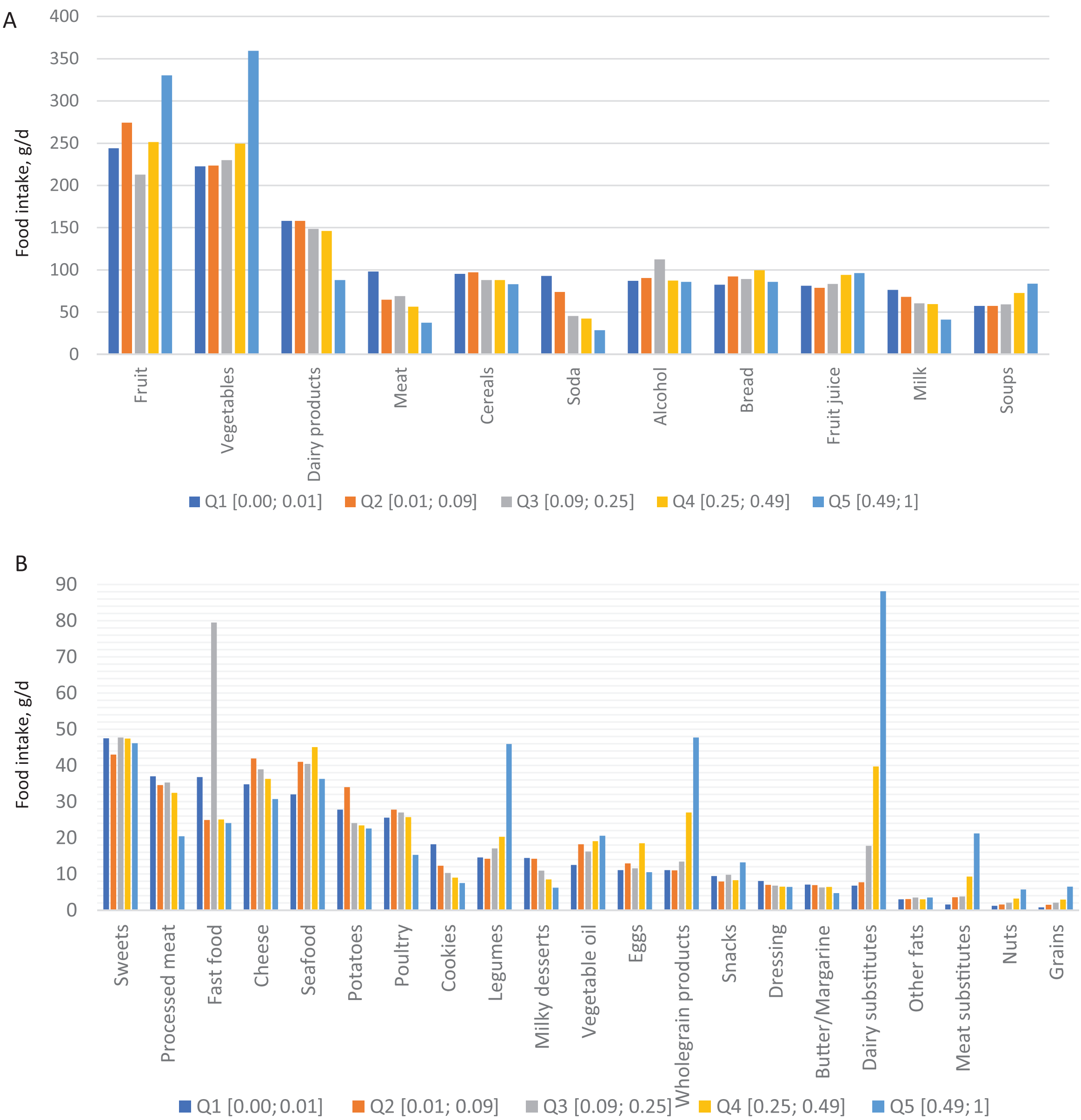

FIGURE 4 Food consumption (g/d) according to the level of organic food consumption (weighted data; $N = 28,245$). Values are means of consumption (g/d) across quintiles of the share of organic food in the diet (defined as the total weight without water). For clarity, food groups are split into panels A and B. Abbreviation: Q, quintile.

Higher organic food consumption was negatively associated with the prevalence of MetS (while adjusting for potential confounders). A higher consumption of organic, plant-based foods was also related to a lower probability of having MetS and most of its components. When considering lifestyle factors (i.e., nutritional quality of the diet, smoking status, and physical activity), a significant negative association was detected in each subgroup, except among smokers.

The association between organic food consumption and the risk of type 2 diabetes was investigated in 33,256 participants (mean age, 53 y) who completed the Org-FFQ (54). Many confounding factors were also collected. During the follow-up (mean, 4.01 y), 293 new cases of diabetes were recorded. After adjusting for the main confounding factors, organic food consumption (Q5 compared with Q1) was associated with a reduction in the risk of type 2 diabetes (HR, 0.65; 95% CI, 0.43–0.97), and the HR for a 5% incremental increase of the organic food proportion in the diet was 0.97 (95% CI, 0.95–0.99). The association was observed in women but not in men. Concerning the share of organic food for plant-based products, the HR of Q5 compared with Q1 was 0.77 (95% CI, 0.53–1.12). The organic share of animal-based products was not associated with the risk of type 2 diabetes.

TABLE 3 Dietary scores across quintiles of organic food consumption (weighted data)[1]

	Q1	Q2	Q3	Q4	Q5
Unweighted, *n* (%)	3723 (13)	5112 (17)	6519 (22)	6649 (23)	7207 (25)
Weighted, *n* (%)	5838 (20)	5840 (20)	5731 (20)	5954 (20)	5847 (20)
Proportion of organic food in the diet	0.00–0.01	0.01–0.09	0.09–0.25	0.25–0.50	0.50–1.00
PNNS-GS1	7.80 (7.76–7.85)	8.25 (8.20–8.29)	8.30 (8.26–8.34)	8.60 (8.56–8.64)	8.83 (8.79–8.87)
PNNS-GS2	0.05 (-0.02–0.12)	0.81 (0.74–0.88)	1.35 (1.28–1.42)	2.71 (2.64–2.77)	4.72 (4.65–4.79)
PANDiet	61.5 (61.3–61.6)	63.2 (63.0–63.4)	63.5 (63.3–63.7)	65.2 (65.0–65.4)	68.4 (68.2–68.6)
cDQI	44.4 (44.2–44.6)	47.2 (47.0–47.4)	48.2 (48.0–48.4)	50.9 (50.7–51.1)	53.46 (53.2–53.7)
aDQI	13.9 (13.8–14.0)	15.2 (15.1–15.3)	14.9 (14.8–15.0)	15.7 (15.6–15.8)	14.9 (14.8–15.0)
pDQI	30.5 (30.3–30.6)	32.0 (31.8–32.2)	33.3(33.1–33. 5)	35.15 (35.0–35.3)	38.6 (38.4–38.8)

N = 29,210. The PNNS-GS1 was based on the 2001 dietary guidelines and the PNNS-GS2 was based on the 2017 dietary guidelines. Abbreviations: aDQI, animal Diet Quality Index; cDQI, comprehensive Diet Quality Index; PANDiet, Diet Quality Index Based on the Probability of Adequate Nutrient Intake; pDQI, plant Diet Quality Index; PNNS-GS1, Programme National Nutrition Santé-guideline score 1; PNNS-GS2, Programme National Nutrition Santé-guideline score 2; Q, quintiles.

[1]Values are means (95% CI) assessed using an analysis of covariance. Models are adjusted for age, sex, and energy intake. All *P* values for linear contrast are <0.001.

The association between the level of organic food score and the risk of developing cancers was investigated in approximately 69,000 participants of the NutriNet-Santé cohort (55). The level of organic food consumption was computed as an organic score. After a mean follow-up of 4.6 y, 1340 first incident cancer cases were identified. The risk of cancer was lower for consumers with a diet rich in organic foods (HR, 0.75; 95% CI, 0.63–0.88). This association was observed for postmenopausal breast cancer (HR, 0.66; 95% CI, 0.45–0.96; $n = 232$ cases) and total lymphomas (HR, 0.24; 95% CI, 0.09–0.66; $n = 62$ cases); the latter is a type of cancer consistently observed among farmers and is associated with occupational pesticide exposure (55). This was observed after adjusting for potential confounders. One possible major explanation for the negative association between the organic food frequency and the cancer risk is the prohibition of synthetic chemical pesticides in organic farming. This leads to a lower frequency or the absence of pesticide residues in organic foods compared with conventional foods and, consequently, lower pesticide metabolite levels in urine (45).

Sustainable values of organic diets

Within the frame of the BioNutriNet project, the inter-relationships between the organic agricultural system and

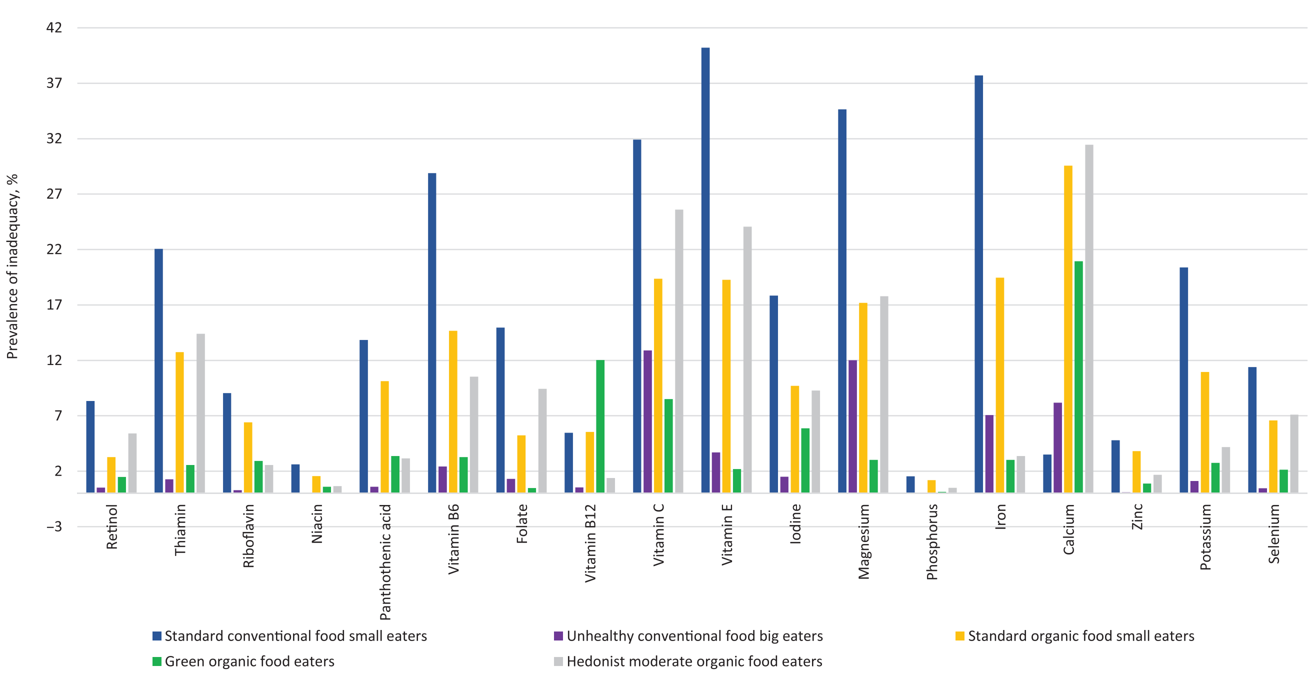

FIGURE 5 Prevalence of nutritional inadequacy among the 5 clusters ($N = 28,245$). Values are the prevalence (%) of nutritional inadequacy for micronutrients across clusters, estimated by the proportion of participants with intake below the estimated average requirement for the French population. The 5 clusters are derived from a principal component analysis based on the consumption of 16 organic and 16 conventional food groups, followed by a hierarchical clustering.

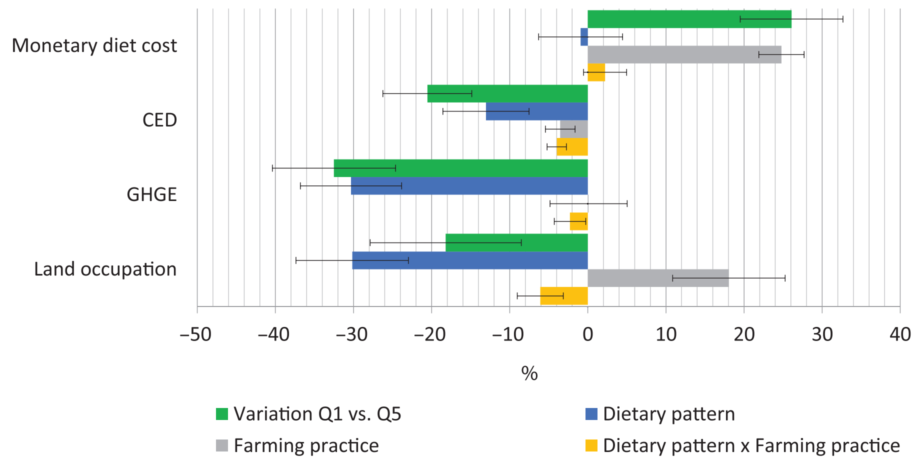

FIGURE 6 Breakdown of the variation between Q1 and Q5 for the environmental and economic indicators (weighted data; $N = 29{,}210$). Q1 and Q5 refer to the first and fifth quintiles of organic food consumption, respectively. Values are means and 95% CIs. CIs were obtained with bootstrapping using 1000 replications. Abbreviations: CED, cumulative energy demand; GHGE, greenhouse gas emissions; Q, quintile.

various environmental pressures have been evaluated in several analyses. We also assessed the overall sustainability of food patterns while differentiating the production systems.

In a first study, the conventional and organic food intakes of 29,210 French adults included in the NutriNet-Santé cohort were assessed. Organic food consumers exhibited high consumption of plant-based food and a healthier diet quality (43). The cost of their diet was, however, higher (+26%). A decrease in GHGE (−35%) was observed with an increase in organic food in the diet, and comparable findings were observed for primary energy consumption (−23%) and land use (−21%).

Original scenarios were used to disentangle the roles and impacts of dietary pattern from those of the production systems and are presented in **Figure 6**. They revealed that the structure of the diet was mostly responsible for the observed associations (i.e., decreased GHGE and land use among organic food consumers compared with their counterparts), whereas for primary energy consumption for food production, the organic farming practices were, to a lesser extent, a lever used to reduce the cumulative energy demand. Conversely, the production system (the organic farming system) was responsible for the moderate increase in the diet cost.

Finally, dietary exposure to synthetic active substances (estimated using a contamination data set differentiating the method of food production) was drastically reduced among high organic food consumers (average: −40%, except for some active substances allowed in organic food production).

Additionally, the participants with diets rich in plant-based foods were characterized by an overall healthier lifestyle, including a healthier diet, no tobacco smoking, and more physical activity. Moreover, a higher provegetarian score was associated with lower environmental impacts to produce foods: namely, in the highest compared with the lowest group there were decreases in the GHGE (−49.6%), energy demand (−26.9%), and land use (−41.5%). Organic food consumption was also an important modulator of the relationship between provegetarian dietary patterns and environmental impacts (56).

Discussion

The BioNutriNet project has provided insight into the interrelations between organic food consumers, organic food consumption, diet, health, and the environment. Overall, in this large sample of French adults, we observed that organic consumers exhibited specific characteristics (e.g., they were more likely to be women and holders of a graduate degree), specific dietary profiles (e.g., they had healthier plant-based dietary patterns), and particular food choice motives (e.g., they were more prone to purchase foods for sanitary and environmental reasons) compared with their conventional counterparts. Regarding the environment, organic food consumers exhibited decreases in their GHGE, land use, and cumulative energy demand.

Those particular dietary and sociodemographic profiles of organic food consumers were accounted for in etiological studies that formed part of the NutriNet-Santé study.

Considering the risk of chronic diseases in relation to organic food consumption, prospective cohort studies, particularly studies considering several confounders, were lacking, except for a few studies from the Norwegian Mother, Father, and Child Cohort Study that documented a decrease in preeclampsia in pregnant women consuming organic vegetables (57) and a lower incidence of hypospadias in male newborns whose mothers consumed organic food during pregnancy (58). Based on the NutriNet-Santé data, we observed reduced risks of cancer (especially lymphomas and postmenopausal breast cancer), diabetes, and overweight/obesity and a reduced probability of MetS among high consumers of organic food. To the best of our knowledge, no other study has investigated the association of organic food consumption with MetS, and the studies documenting the associations between organic food consumption and obesity and overweight were not prospective (59, 60). Regarding type 2 diabetes, an American study based on purchase data has reported lower odds of diabetes among regular buyers of organic foods (61).

A study involving British women has also reported a lower risk of non-Hodgkin lymphoma among regular organic food consumers, which agrees with our findings (62). However, no association was observed between the overall cancer risk and regular organic food consumption, whereas a marginally higher breast cancer risk was detected among regular consumers (a possible explanation proposed by the authors was the potential elevated frequency of breast screening among organic food consumers) (62).

The volume of scientific literature documenting the differences between organic and nonorganic foods in terms of pesticide and nutritional content is growing. According to a meta-analysis by Baranski et al. (63), organic foods contain greater amounts of certain antioxidant compounds, such as carotenoids in plant-based foods and n-3 fatty acids in animal-based foods (20, 64, 65). Additionally, pesticide residues are found more frequently and in higher concentrations (66) in nonorganic foods than in organic foods. The lower quantity of pesticide residues in organic foods could partly explain the negative association between organic food consumption and chronic diseases. In line with other authors (67–69), we showed that organic food consumers exhibited lower concentrations of urinary pesticide metabolites compared with nonconsumers (45). The role of pesticides in several molecular pathways is well documented in experimental studies deciphering mechanisms inducing obesity and diabetes. Organochlorine pesticides, whose role in the etiology of type 2 diabetes is well documented (70), are now widely prohibited. Currently authorized pesticides, such as organophosphorus, pyrethroids, and neonicotinoids, may also be involved in developing chronic diseases (71) through various mechanisms of action, including inflammatory pathways, oxidative homeostasis disturbances, mitochondrial dysfunction, endocrine disruption, and epigenetic modifications (71–74). As recently shown in mice (75), chronic intake of mixtures of low doses of various common pesticides induces metabolic disturbances and traits of diabetes with sexual dysmorphism. The carcinogenic properties of pesticides encompass apoptosis dysregulation and DNA damage (71, 74).

One barrier for consumers for purchasing organic food is price; organic foods are more expensive and thus unaffordable to some segments of the population, especially low-income individuals. We observed that organic food consumers had higher monetary diet costs due to their choice of organic foods, whereas the more plant-based dietary patterns of organic food consumers did not play a role. The higher price of organic food is due to the higher labor intensity of organic farming, lower yields, and the request of producers for a fair income, among other factors. Additionally, none of the costly negative externalities of the present food system are considered in monetary diet cost (e.g., water and air pollution, biodiversity loss, and health impacts).

Regarding environmental aspects, organic farming systems are often considered more sustainable than conventional ones and are an alternative to the dominant industrial model. These beliefs are corroborated by the fact that organic food production methods are associated with greater levels of biodiversity preservation, the nonuse of synthetic fertilizers and pesticides, the diversification of crops and livestock, and the improvement of the soil composition via compost and manures (10, 19). The BioNutriNet project was the first project considering 2 farming practices in its assessment of environmental pressures related to dietary patterns. The fact that dietary patterns rich in plant-based foods are better for some environmental indicators, such as GHGE and land use, is well known (76, 77). We observed in the BioNutriNet project that dietary patterns were the main driver for the decreased GHGE and land use. The organic farming system itself had no substantial effect on GHGE and led to a lower cumulative energy demand, but resulted in increased land use. From the available data, it appears that the diet of organic food consumers, as studied in the project, exhibits several traits of the FAO definition of sustainable diets (17), such as a plant-based diet; better adherence to the FBDG; improved nutrition; reduced exposure to food pesticides; better health status; and reduced impacts on land use, energy demand, and GHGE to produce foods. The fact that organic food, with its associated potential health and environmental benefits, remains unaffordable for the lower-income segments of the population contributes to health inequalities within society and will need appropriate political interventions.

It is noteworthy that the updated FBDG released in 2019 for France (78) recommends a more plant-based diet and the selection of organic plant-based foods when possible to reduce pesticide exposure, with an objective of having 20% of plant-based foods be organic before 2023 for each French consumer. We recently evaluated the potential sustainability impacts of increasing adherence to these new guidelines and found that it would result in reduced environmental impacts and lower exposure to synthetic active substances (79).

Some limitations should be mentioned in our studies. First, the LCA was conducted at the production step only. It is also now well documented that LCA approaches, which can be applied to dietary consumption, are probably inappropriate when evaluating some amenities related to organic farming (80). Second, certain environmental indicators were unavailable, particularly water use and biodiversity, and should be investigated in the future since a main benefit of organic farming is the preservation of biodiversity (10, 81), which has been recently undergoing massive extinction (82). Third, limitations related to the observational design of the NutriNet-Santé study should be highlighted. The NutriNet-Santé cohort study is based on self-reported dietary data, which are prone to measurement errors, and desirability bias may have also occurred. Nonetheless, we used several validated tools. Additionally, we observed that organic and nonorganic food consumers exhibited expected differences in the urinary concentrations of some pesticide residue markers (45). Next, the associations between organic food consumption and health outcomes were estimated using observational data; causal inference is limited, and we cannot entirely rule out existing potential residual confounding despite the set of sensitivity analyses conducted. Furthermore, generalizability to other populations is limited, as the NutriNet-Santé population consists of volunteers with specific profiles. These volunteers are more often women, are younger, have higher levels of formal education, and have healthier dietary patterns than the French population (83, 84). These characteristics have enabled us to estimate the associations between organic food consumption and health outcomes at higher levels than those usually observed. Furthermore, regarding health events, classification bias cannot be excluded. However, the ascertainment of cases was based on validated data using several sources, such as the medico-administrative databases of the French national health insurance.

In conclusion, overall, the BioNutriNet project has shed some light on organic food consumption and its correlates and on its associations with chronic disease risks. Particularly, it has enabled us to broaden our understanding of the characteristics; determinants; and nutritional, environmental, and health-related impacts of organic food consumption. However, it should be noted that general conclusions on the topic cannot be drawn solely from the BioNutriNet project. Our data should be replicated in other cultural settings and coupled with experimental studies to understand the possible mechanistic pathways underlying the associations. Replication of our studies in different settings will allow us to gain knowledge and perform meta-analyses to increase the level of evidence. Finally, the main lesson of the BioNutriNet project could be that while organic food consumption may have some potential health and environmental benefits, it should be accompanied by dietary shifts toward more plant-based dietary patterns. In the near future, repeated data collected every 4 y from 2014 onwards will allow us to develop extensive research on dietary transitions toward sustainability, linking production, consumption, environmental, and health factors to gain a more complete overview.

Acknowledgments

We thank Cédric Agaesse (dietitian); Thi Hong Van Duong and Younes Esseddik (IT managers); Régis Gatibelza, Djamal Lamri, Jagatjit Mohinder, and Aladi Timera (computer scientists); Julien Allegre, Nathalie Arnault, Laurent Bourhis, and Fabien Szabo de Edelenyi, PhD (supervisor; data-manager/statisticians) for their technical contributions to the NutriNet-Santé study. We thank Nathalie Druesne-Pecollo, PhD (operational coordination) and all the volunteers of the NutriNet-Santé cohort. We also thank BioConsom'acteurs' members for price collection, Oualid Hamza for price collection and data management, the Chemisches und Veterinäruntersuchungsam (CVUA) for the pesticide residue database, and Noémie Soton for her contribution to the data management of the CVUA database.

The authors' responsibilities were as follows – PG, SH, DL, and EK-G: conducted the study; EK-G and J Baudry: drafted the manuscript, had primary responsibility for the final content, and are the guarantors; and all authors: conducted the research, implemented databases, critically helped in revising the manuscript, provided relevant intellectual input, and read and approved the final manuscript.

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