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

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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.

1. 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 (Rockström et al., 2009; Steffen et al., 2015; IPCC, 2019). 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 (Willett et al., 2019; Springmann et al., 2018). 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 (Steffen et al., 2015; Willett et al., 2019, FAO).

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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 (IPCC, 2019; Macdiarmid et al., 2012; Aleksandrowicz et al., 2016).

The food system represents 20 to 30% of the global GHG emissions (Tilman and Clark, 2014; Chai et al., 2019). 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 (González-García et al., 2018) result in a reduction by about one-third of GHG emissions (van de Kamp et al., 2018), or that diet-related GHG emissions are twice lower for vegans than for meat eaters (Scarborough et al., 2014). 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 (Bengtsson et al., 2019, Dumont et al.), 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 (Aleksandrowicz et al., 2016). 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 (Hallström et al., 2015; Reganold and Wachter, 2016).

Although strong positive correlation between organic food consumption and vegetarianism have been observed (Lacour et al., 2018; Baudry et al., 2015) 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 (Perignon et al., 2017). 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 (Reganold and Wachter, 2016; Gomiero et al., 2011; Muller et al., 2017). Indeed, organic systems are characterized by higher energy efficiency (Reganold and Wachter, 2016; Clark and Tilman, 2017), better soil biophysics and biologic quality (Gomiero et al., 2011; Tuomisto et al., 2012) and contribute positively to plant and animal biodiversity (both in cropland and wild life) (Tilman and Clark, 2014; González-García et al., 2018; van de Kamp et al., 2018). Regarding GHG emissions, organic farming performs better than conventional, but only per area (Mondelaers et al., 2009; Meier et al., 2015). Indeed, organic farming has lower yield and, as a result, does not reduce significantly the GHG and increases the land use per product unit (Clark and Tilman, 2017; Tuomisto et al., 2012; Meier et al., 2015). 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 (Baudry et al., 2019). 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 (Hercberg et al., 2010) 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) (González-García et al., 2018) with photographs improving estimation of the portion size. The Org-FFQ was developed from a validated FFQ (Kesse-Guyot et al., 2010) 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 (Baudry et al., 2019).

Daily nutritional intakes were calculated using the NutriNet-Santé food composition table (Nutrinet-Santé, 2013).

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 (<1 g/day), but included dairy products, eggs, fish and seafood, (3) vegetarian: diet that did not include animal flesh (<1 g /day) but included dairy products and eggs and (4) vegan: diet that did not include any animal flesh (<1 g /day) or any animal products (no eggs or dairy products, <1 g/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 (de Gavelle et al., 2018).

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 (Seconda et al., 2018). Briefly, diet-related environmental impacts were assessed using a French database (DIALECTE (Pointereau et al., 2019)) of environmental measure for raw agricultural products and completed with other published data. Environmental data came from 2086 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 m²/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 (ADEME 2015). 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 (Seconda et al., 2018).

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 (Goedkoop et al., 2013). 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 (Kramer et al., 2017). 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 m²/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 (Touvier et al., 2011). The variables were gender, age, living area (rural, i.e. a population below 2000 inhabitants or urban, i.e. a population above 2000 inhabitants), education (<school diploma, high school diploma and post-secondary graduate) and monthly income per household unit (<1200 euros, between 1200 and 1800 euros, between 1800 and 2700 euros, and >2700 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 (Baudry et al., 2019).

2.3. Statistical analyses

Among the 37,685 NutriNet-Santé participants who completed de Org-FFQ, 8475 individuals were excluded. Exclusion criteria were: missing covariates ($n = 380$), under- or over-reporters ($n = 2109$), living overseas ($n = 743$) and no data regarding the place of purchase ($n = 5243$). 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 (Willett and Stampfer, 1986). 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.

Table 1
Participant characteristics according to the type of diet, $n = 29{,}210$, NutriNet-Santé[1].

	Total (*n = 29,210*)	Omnivorous (*n = 28,043*)	Pesco-vegetarian (*n = 464*)	Vegetarian (*n = 406*)	Vegan (*n = 297*)	*P*[2]
Sex (%)						<0 0.0001
Women	74.74	74.46	87.72	82.02	70.71	
Men	25.26	25.54	12.28	17.98	29.29	
Age (years)	54 (14)	54 (14)	49 (14)	42 (13)	39 (13)	<0.0001
Living Area (%)						0.0003
Rural	22.59	22.68	21.12	22.17	17.17	
Urban	77.42	77.33	78.88	77.84	82.83	
Education (%)						<0 0.0001
< High-School diploma	17.01	21.62	16.16	10.84	13.8	
High-School diploma	18.96	14.61	17.03	14.53	15.49	
Post-secondary graduate	64.04	63.77	66.81	74.63	70.71	
Monthly income (%)						<0.0001
900–1200 €	11.56	11.03	20.91	25.62	28.62	
1200 - 1800 €	23.11	23.08	24.14	24.14	22.56	
1800 - 2700 €	27.5	27.67	27.16	23.15	17.85	
> 2700 €	31.78	32.26	21.98	18.97	19.87	
Missing data	6.05	5.97	5.82	8.13	11.11	
Physical activity (%)						0.0002
Missing data	10.78	10.84	13.15	8.13	5.05	
Low (<30 min/day)	19.2	19.36	15.52	15.76	14.48	
Medium (30–60 min/day)	36.38	36.28	34.48	40.64	42.76	
High (> 60 min/day)	33.64	33.52	36.85	35.47	37.71	
Tobacco status (%)						0.68
Never smoker	48.78	48.79	44.83	49.51	53.54	
Former smoker	40.47	40.5	43.53	38.92	34.68	
Smoker	10.75	10.71	11.64	11.58	11.78	
Alcoholic consumption (g/day)	8.68 (12.35)	8.67 (12.36)	5.37 (9.52)	4.64 (8.29)	4.59 (26.40)	<0.0001
Diet monetary cost (€/day)	7.70 (2.99)	7.68 (2.90)	8.36 (4.33)	7.59 (4.10)	9.09 (5.63)	<0.0001

[1] Values are means (SD) or percent, as appropriate.
[2] *P*-values are based on chi-square test for categorical variables and variance analysis for continuous variables.

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 Fig. 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 (Aleksandrowicz et al., 2016; Chai et al., 2019; Perignon et al., 2017). Indeed, a reduction in meat consumption is a major leverage for reducing diet-related environmental impacts, and in particular GHG emissions (Willett et al., 2019; Springmann et al., 2018;

Table 3
pReCiPe and environmental impact indicators according to the type of diet, $n = 29{,}210$, NutriNet-Santé Study[1].

	Omnivorous (*n = 28,043*)	Pesco-vegetarians (*n = 464*)	Vegetarians (*n = 406*)	Vegans (*n = 297*)
pReCiPe	0.29 (0.29–0.30)	0.11 (0.10–0.13)	0.12 (0.11–0.14)	0.09 (0.08–0.11)
GHGe kgCO_2eq/day	4.16 (4.14–4.18)	1.74 (1.56–1.92)	1.59 (1.40–1.79)	1.02 (0.80–1.24)
CED MJ/day	17.92 (17.86–17.98)	12.33 (11.88–12.79)	10.20 (9.71–10.68)	8.84 (8.28–9.41)
LO m²/day	10.85 (10.79–10.92)	4.94 (4.45–5.44)	4.97 (4.44–5.50)	3.86 (3.24–4.48)
pReCiPe 100% organic	0.35 (0.34–0.35)	0.12 (0.10–0.14)	0.13 (0.11–0.15)	0.10 (0.08–0.12)
pReCiPe 100% conventional	0.28 (0.28–0.28)	0.11 (0.09–0.12)	0.11 (0.10–0.13)	0.09 (0.07–0.10)

Abbreviations: CED, Cumulative energy demand; GHGE, Greenhouse gas emissions; LO, Land occupation.
[1]Values are means adjusted for energy intake and 95% confidence interval.
[2]All *P*-values based on covariance analysis are <0.0001.

Table 2
Dietary characteristics according to the type of diet, $n = 29{,}210$, NutriNet-Santé[1],[2].

	Omnivorous ($n = 28{,}043$)	Pesco-vegetarians ($n = 464$)	Vegetarians ($n = 406$)	Vegans ($n = 297$)	P[3]
Energy intake (kcal/day)	2005.38 (628.29)	1862.10 (639.13)	1869.54 (607.17)	1963.98 (645.62)	<0.0001
Carbohydrates (% of EI)	39.36 (7.34)	43.76 (8.24)	45.74 (8.43)	49.20 (10.25)	<0.0001
Lipids (% of EI)	41.28 (7.02)	40.42 (8.72)	40.40 (8.50)	37.99 (10.40)	<0.0001
Monounsaturated fats (% of EI)	16.38 (4.01)	16.80 (5.41)	16.49 (5.14)	16.76 (6.48)	0.48
Polyunsaturated fats (%of EI)	6.74 (2.42)	8.57 (3.38)	8.98 (3.29)	10.92 (3.56)	<0.0001
Saturated fats (%of EI)	15.09 (3.51)	12.00 (3.91)	11.99 (4.38)	7.55 (2.40)	<0.0001
Omega 3 PUFA[4] (g/d)	2.10 (1.25)	3.00 (2.38)	2.31 (1.57)	2.86 (2.26)	<0.0001
Omega 6 PUFA[4] (g/d)	11.86 (4.98)	15.11 (6.13)	16.80 (6.50)	20.49 (7.65)	<0.0001
Proteins (%of EI)	18.97 (3.57)	15.39 (3.62)	13.44 (2.59)	12.31 (2.36)	<0.0001
Animal protein (%of EI)	13.18 (4.20)	6.79 (4.08)	3.94 (3.07)	0.64 (0.57)	<0.0001
Vegetable protein (% of EI)	5.79 (1.58)	8.61 (2.29)	9.50 (2.57)	11.67 (2.36)	<0.0001
Vegetable protein/total protein	0.32 (0.12)	0.58 (0.18)	0.72 (0.18)	0.95 (0.04)	<0.0001
Fiber[4] (g/d)	22.87 (8.13)	32.70 (11.34)	33.40 (11.58)	40.13 (13.59)	<0.0001
Food consumption (g/day)					
Ruminant meat	45.57 (43.58)	0.01 (0.05)	0.00 (0.03)	0.00 (0.00)	<0.0001
Other meat	72.17 (51.67)	0.05 (0.17)	0.01 (0.08)	0.00 (0.04)	<0.0001
Eggs	11.40 (11.59)	16.14 (19.08)	13.10 (19.12)	0.02 (0.11)	<0.0001
Fish and seafood	47.34 (43.36)	48.01 (54.69)	0.05 (0.19)	0.01 (0.07)	<0.0001
Dairy products	262.23 (213.33)	182.32 (206.78)	139.77 (198.90)	0.03 (0.14)	<0.0001
Fruits & vegetables	723.90 (410.28)	919.23 (542.60)	888.53 (630.94)	1114.17 (828.64)	<0.0001
Soy-based products	24.84 (81.57)	123.95 (219.13)	169.26 (190.87)	292.34 (216.84)	<0.0001
Starches[4]	171.30 (105.94)	180.53 (169.82)	211.82 (138.97)	269.35 (179.65)	<0.0001
Whole-grain products[5]	55.25 (69.64)	84.91 (86.29)	79.53 (80.18)	89.86 (86.97)	<0.0001
Oils	19.69 (15.62)	22.82 (18.01)	21.93 (17.48)	25.98 (20.12)	<0.0001
Butter	6.69 (6.90)	3.38 (5.14)	4.22 (6.64)	2.64 (4.78)	<0.0001
Other fats	3.43 (4.65)	3.56 (5.23)	4.45 (5.98)	5.31 (9.19)	0.01
Extra food[6]	16.62 (15.96)	20.15 (18.91)	23.17 (20.02)	31.54 (30.25)	<0.0001
Sweet and fatty products	70.78 (55.52)	54.53 (48.54)	57.88 (41.55)	39.36 (33.63)	<0.0001
Ready Meals[7]	33.52 (35.66)	21.43 (22.68)	27.53 (26.51)	22.37 (28.88)	<0.0001
Alcohol	102.73 (146.98)	65.40 (109.82)	61.25 (103.13)	62.12 (330.92)	<0.0001
Non Alcoholic Drinks	1751.69 (762.18)	1859.83 (933.16)	1687.36 (805.62)	1585.50 (763.92)	<0.0001
Organic food ratio[8]	0.28 (0.26)	0.57 (0.31)	0.58 (0.30)	0.67 (0.28)	<0.0001

Abbreviations: d, day; EI, energy intake; PUFA, polyunsaturated fatty acids.
1 Means and SDs are shown.
2 *P*-values are based on variance analysis.
3 Values are adjusted for energy intake.
4 Starch include bread, pasta, rice, potatoes, legumes and other cereals.
5 Whole grain products include whole bread, whole pasta and rice.
6 Extra food include sauces, dressing, ketchup and mustard.
7 Ready meal include sandwiches, pizza, hamburgers.
8 weight of organic food (in g) / weight of total food (in g), without water.

Table 4
pReCiPe and environmental indicators according to the type of diet for 100%organic and 100% conventional scenario, $n = 29{,}210$, NutriNet-Santé Study[1].

	Omnivorous ($n = 28{,}043$)	Pesco-vegetarians ($n = 464$)	Vegetarians ($n = 406$)	Vegans ($n = 297$)
100% organic				
pReCiPe	0.35 (0.34–0.35)	0.12 (0.10–0.14)	0.13 (0.11–0.15)	0.10 (0.08–0.12)
GHGe $kgCO_2eq$/day	4.20 (4.18–4.22)	1.63 (1.45–1.82)	1.49 (1.29–1.69)	0.96 (0.72–1.19)
CED MJ/day	16.92 (16.86–16.98)	11.22 (10.78–11.66)	9.17 (8.70–9.65)	8.00 (7.45–8.55)
LO m^2/day	13.69 (13.61–13.77)	5.65 (5.05–6.24)	5.70 (5.06–6.34)	4.26 (3.51–5.00)
100% conventional				
pReCiPe	0.28 (0.28–0.28)	0.11 (0.09–0.12)	0.11 (0.10–0.13)	0.09 (0.07–0.10)
GHGe $kgCO_2eq$/day	4.16 (4.14–4.18)	1.85 (1.67–2.03)	1.70 (1.51–1.89)	1.17 (0.95–1.39)
CED MJ/day	18.40 (18.34–18.46)	13.53 (13.08–13.98)	11.36 (10.88–11.85)	10.52 (9.95–11.09)
LO m^2/day	10.04 (9.98–10.10)	4.23 (3.75–4.71)	4.26 (3.75–4.77)	3.20 (2.60–3.80)

Abbreviations: CED, Cumulative energy demand; GHGE, Greenhouse gas emissions; LO, Land occupation.
1 Values are means adjusted for energy intake and 95% confidence interval.

Clark and Tilman, 2017; Jones et al., 2016; Tilman and Clark, 2014). 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 (Aleksandrowicz et al., 2016). 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 (Kim et al., 2019). 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 (Willett et al., 2019) 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 di-

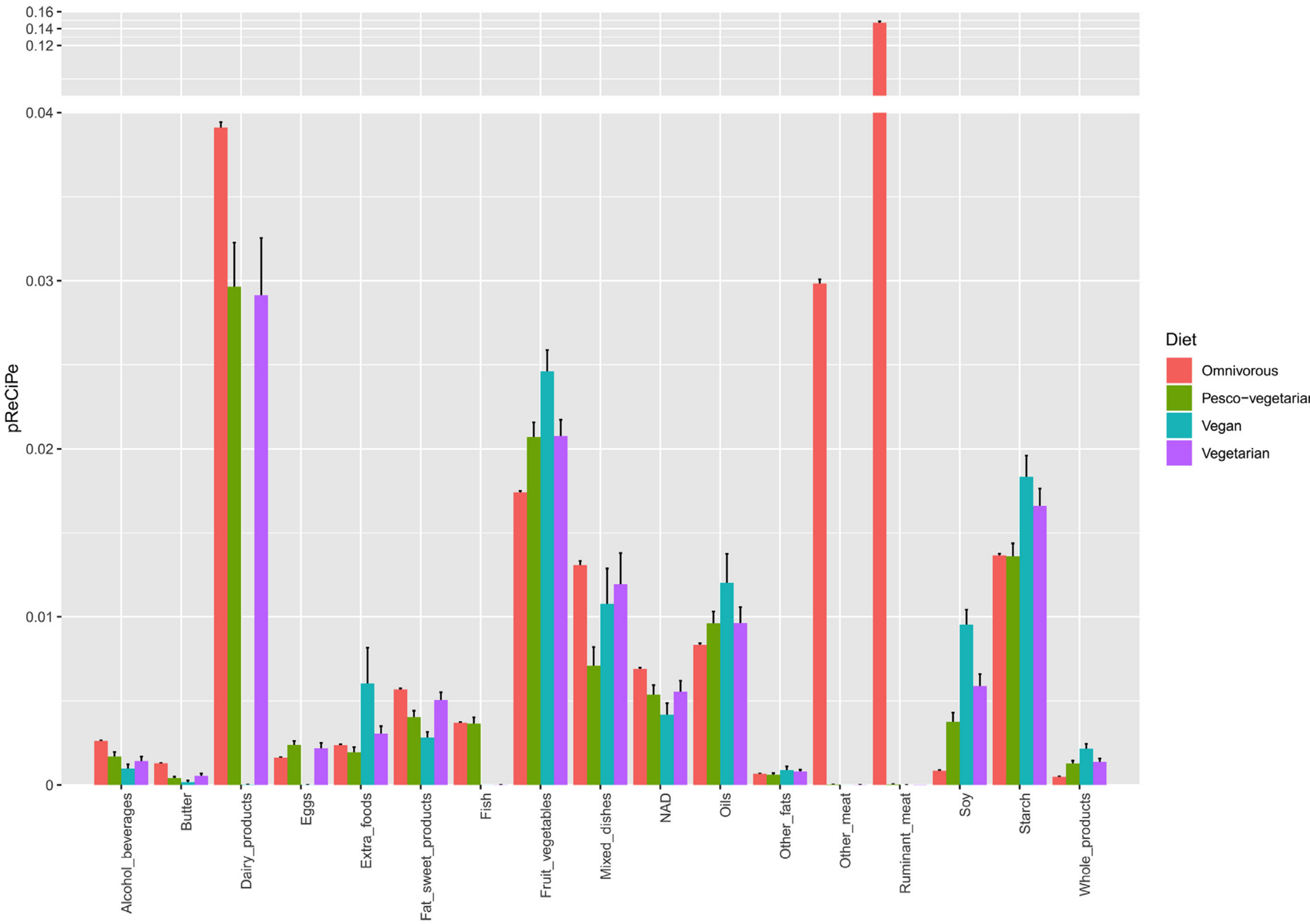

Fig. 1. pReCiPe of each food group according to the type of diet Abbreviation: NAD, nonalcoholic drinks.

etary 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" (Willett et al., 2019). 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 (Kim et al., 2019). 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 (Hallström et al., 2015; Hu et al., 2019). For instance, plant-based diet may exhibit various pressure. While legumes, presenting interesting nutritional profiles, exhibited 250 times lower GHGe ruminant meats (González-García et al., 2018), rice production emits five times more GHGe than wheat production when considering gram of protein as function unit (González-García et al., 2018).

However, most of these studiesdid not distinguish between farming practices, even though organic food consumption has been markedly and positively correlated with plant-based diet (Lacour et al., 2018; Baudry et al., 2019). 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) (Clark and Tilman, 2017; Tuomisto et al., 2012; Meier et al., 2015). 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 (Gomiero et al., 2011; Muller et al., 2017).

Herein, a reduction of GHGe of 76% was observed when comparing vegans to omnivorous. In comparison, in a work conducted by Scarborough et al. (2014) 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 (Clark and Tilman, 2017; Tuomisto et al., 2012; Meier et al., 2015), 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 (Tilman and Clark, 2014), pesco-vegetarian and vegetarian diets exhibited relatively similar GHGe (Tilman and Clark, 2014). Most of French studies did not focus on self-selected diets and used modeling approaches (Perignon et al., 2017; van Dooren, 2018; Gazan et al., 2018). 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 (Masset et al., 2014). 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 (Vieux et al., 2018). 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 (Aleksandrowicz et al., 2016). 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 (Clark and Tilman, 2017; Tuomisto et al., 2012; Meier et al., 2015). 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 modeling study evaluated environmental impact of omnivorous, vegetarian, vegan considering 100% organic or 100% conventional diet (Baroni et al., 2007). 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 (Baudry et al., 2019). 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 (Tilman and Clark, 2014) 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. (2007), pesco-vegetarians were not considered. It would be therefore of great importance to consider other environmental indicators such as water footprint or biodiversity (Scarborough et al., 2014). 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 (Tilman and Clark, 2014; Burlingame and Dernini, 2011; Dernini et al., 2017; Alessandra et al., 2014; Rosi et al., 2017).

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 (>120 g/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 (Vieux et al., 2020). 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 (Dumont et al.; Lebacq et al., 2013). In addition, there is also a great variability in livestock methods (Röös et al., 2016). Second, environmental impacts of the meat substitutes (Hallström et al., 2015) may be questionable. For instance, plant-based meat substitutes may exhibit important environment pressure but current data are scarce (Hallström et al., 2015; Hu et al., 2019). Third, besides cultural acceptability, a vegan diet may exhibit some disadvantages in terms of nutrition, raising health concerns in particular among young people (Tilman and Clark, 2014; Dinu et al., 2017; Springmann et al., 2016).

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 (Auestad and Fulgoni, 2015). 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.

5. 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2020.02.010.

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