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Original Research Article

Popular diets as selected by adults in the United States show wide variation in carbon footprints and diet quality

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A B S T R A C T

Background: Carbon footprints of vegetarian, pescatarian, and other popular diets have been studied previously, but mostly as idealized versions modeled to meet dietary recommendations. Less is known about the footprints of popular diets as they are consumed by US adults, and thus the potential trade-offs with diet quality for free-living individuals.

Objectives: This study estimated the carbon footprint and diet quality of popular diets as selected by a nationally representative sample of US consumers, including the recently trending keto- and paleo-style diets.

Methods: The 2005–2010 NHANES 24-h recall data were used to categorize individual adult diets (n = 16,412) into 6 types: vegan, vegetarian, pescatarian, paleo, keto, and all other diets, referred to here as omnivore diets. Average daily greenhouse gas emissions in kilograms of carbon dioxide equivalents per 1000 kcal (kg CO_2-eq/1000 kcal) were calculated for each diet by matching our previously developed database to NHANES individual diet data. Diet quality was determined using the Healthy Eating Index (HEI) and the Alternate Healthy Eating Index. Survey-weighted ordinary least-squares regression was used to assess mean differences in diets.

Results: The average carbon footprints of vegan (0.69 $\pm$ 0.05 kg CO_2-eq/1000 kcal) and vegetarian (1.16 $\pm$ 0.02) diets were lower ($P < 0.05$) than those of the pescatarian (1.66 $\pm$ 0.04), omnivore (2.23 $\pm$ 0.01), paleo (2.62 $\pm$ 0.33), or keto (2.91 $\pm$ 0.27) diets. Mean HEI scores were highest for pescatarian diets (58.76 $\pm$ 0.79) and higher ($P < 0.05$) for vegetarian (51.89 $\pm$ 0.74) than for omnivore (48.92 $\pm$ 0.33) or keto (43.69 $\pm$ 1.61) diets.

Conclusions: Our results highlight the nuances when evaluating the nutritional quality of diets and their carbon footprints. On average, pescatarian diets may be the healthiest, but plant-based diets have lower carbon footprints than other popular diets, including keto- and paleo-style diets.

Keywords: carbon footprint, Healthy Eating Index, NHANES, dataFIELD, dataFRIENDS, 24-h recall, keto diet, paleo diet

Introduction

Climate change continues to be a growing threat to the health and sustainability of the world's populations. The current food system contributes substantially to these environmental problems [1, 2]. Of particular interest is how changes in these food systems could contribute to both population health and environmental sustainability in the future, with dietary choices being a key determining factor [3–7]. Consumer demand, demonstrated by what individuals choose to purchase and eat, has the potential to shift production trends. Individual dietary patterns change over time [8], and previous research identified ~16% of a nationally representative sample from the US that might change their diets to align with recommendations for environmental sustainability [9]. Identifying types of diets that support individual health and environmental sustainability is the first step in developing educational and communication strategies to shift consumer behaviors to support this.

Previous research has shown that plant-based diets, such as vegetarian or vegan diets, are responsible for lower greenhouse gas emissions (GHGE) than meat-based diets. This finding has been shown using nationally-recommended diets [3, 10–14] as well as diets that were based on aggregate consumption from food availability data but modified to resemble recommended diets [4, 5, 7, 15–17]. Modeling the impacts of substitutions away from meat toward greater amounts of plant proteins has also shown potential reductions in GHGE [9, 16, 18]. For the most part, the literature has not emphasized studies based on individual diets, partly because of the complexity of linking thousands

Abbreviations used: AHEI, Alternate Healthy Eating Index; dataFIELD, database of food impacts on the environment for linking to diets; dataFRIENDS, database of Food Recall Impacts on the Environment for Nutrition and Dietary Studies; GHGE, greenhouse gas emissions; HEI, Healthy Eating Index; kg CO_2-eq/1000 kcal, kilograms of carbon dioxide equivalents per 1000 kilocalories.

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of food choices to environmental impacts. Scarborough et al. [6] examined vegans, vegetarians, fish-eaters, and meat-eaters in the UK using food frequency data and found GHGE to be the lowest in vegan and vegetarian diets. Carbon footprints of vegetarian and semi-vegetarian diets were also shown to be lower than nonvegetarian diets between Seventh-Day Adventists in the US [19]. Other research has examined the carbon footprints of diets consumed by individuals in Spain [15], the United Kingdom [20], or Lebanon [21] and found that GHGE was lower between those diets that accorded more with a Mediterranean-style diet than with other diets in those countries. The same was true for diets in accordance with the DASH diet in the United Kingdom [20, 22] but not in the Netherlands [23].

In addition to the diets mentioned above, paleo- and keto-style diets have gained popularity. A nationally-weighted online consumer survey estimated that ~10% of US adults reported following one of these diets in the previous year [24, 25]. As more consumers make choices about pursuing particular diets, information on both the nutritional quality and carbon footprints of these diets as commonly selected becomes more important. However, the GHGE of these popular diets, as selected and reported by US adults, has not been well studied. Nor have they been compared to the other diets discussed above using a common methodological framework that includes diet quality.

To fill this gap in the current literature, this study estimated the carbon footprint and diet quality of popular diets, as selected and reported by a nationally representative sample of US adults.

Methods

Study sample

This study analyzed individual 24-h dietary recall data from the 2005–2010 NHANES, a nationally representative, ongoing survey to measure the health and nutritional status of the US population [26]. The NHANES dietary recalls were collected by trained interviewers using the validated Automated Multiple-Pass Method since 2002 [27]. Once dietary recall data were collected, an extensive quality assurance review was conducted in which the acceptability of each recall was assessed, and reports of unusual foods or amounts were checked [28]. Data determined to be valid were then made accessible for analysis. For this study, a total of 16,800 adults (≥18 y of age) respondents had valid Day 1 dietary recall data and comprised the initial sample. However, there were 388 observations (2.3%) excluded from this sample because of having outlier values for one or more dependent variables (Statistical Methods Section) or a dietary intake that fit multiple diet definitions (Description of Diets Section and Supplementary Figure 1). This resulted in a final analytic sample of 16,412.

Sociodemographic variables

Demographic variables that were used to describe the sample overall and characteristics of those who consumed various diets included race and ethnicity, age, education, sex, and income-to-poverty ratio. Race and ethnicity were analyzed as 4 categories based on self-reported data from NHANES: Hispanic, Non-Hispanic White, Non-Hispanic Black, and other. The age variable also had 4 categories: 18–29, 30–49, 50–65, and ≥66. The highest level of education was examined using the following four categories: less than a high school diploma, high school graduate or equivalent, some college and college graduate. Five income-to-poverty ratio categories were analyzed: below the poverty guidelines <1, 1–2, 2–5, and >5 times the poverty guidelines, as well as a category for missing data on income. Income-to-poverty ratios were calculated specific to year, state, and family size [29]. Study protocols were reviewed by the Tulane University institutional review board and determined to meet federal criteria for exemption as study #802526.

Description of diets

Data from one 24-h recall were used to categorize individual adult intake into 1 of 6 mutually exclusive diets described in Table 1: omnivore, vegetarian, pescatarian, vegan, keto- or ketogenic-style, and paleo- or paleolithic-style. This approach was not intended to generalize individual patterns of food consumption over time but rather to categorize detailed 1-d diets into popular diet types and study the implications of their contents for carbon footprints and diet quality. These diets were defined using food groups in the United States Department of Agriculture Food Patterns Equivalents Database, a database used to translate NHANES as-eaten foods into measured equivalents of various food groups outlined in the Dietary Guidelines for Americans, such as cup equivalents of fruit, vegetables, and dairy. In defining the different diets, we allowed for minimal consumption of typically excluded foods to account for unintended consumption of a particular item, minor deviations from strict diet types, or default ingredients that were included in mixed dishes from the Food Patterns Equivalents Database but not known by the respondent. For example, vegetarian diets do not include meat, poultry, or seafood, but we characterized diets as vegetarian as long as they had <0.5 oz-equivalent (=14.17 g) of these foods combined. Pescatarian diets included those with seafood and <0.5 oz-equivalent of meat or poultry. The vegan diet included individuals who consumed <0.5 oz-equivalent total of meat, poultry, seafood, and eggs and <0.25 cup (=118.29 ml) equivalent total dairy. Diets with ≤50 g of net carbohydrates (total carbohydrates–total fiber) were categorized into the keto-style diet based on previous literature [30]. Those diets

TABLE 1
Diet definitions and frequencies[1]

Diet	Definition	Sample size (n = 16,412)	% ± SE	Population represented[2]
Omnivore	Anyone outside of the categories below	14,175	86.3 ± 0.4	192,203,100
Vegetarian	<0.5 oz-equivalent[3] of meat, poultry, and seafood	1179	7.5 ± 0.3	16,697,789
Pescatarian	<0.5 oz-equivalent[3] of meat and poultry; consumed seafood	778	4.7 ± 0.3	10,535,824
Vegan	<0.5 oz-equivalent[3] total of meat, poultry, seafood, eggs; <0.25 cup equivalent[4] of dairy	141	0.7 ± 0.1	1,617,799
Keto	≤50 g of net carbohydrates (total carbohydrates–total fiber)[5]	77	0.4 ± 0.1	792,171
Paleo	<0.5 oz-equivalent[3] total of grains and legumes; <0.25 cup-equivalent[4] of dairy[6]	62	0.3 ± 0.1	748,365

[1] Vegan, vegetarian, pescatarian, paleo, and keto diets are mutually exclusive. Individuals with intake matching >1 diet were excluded from the analysis. [2]Survey-weighted proportion multiplied by population totals from NHANES documentation [51]. [3]1 oz = 28.35 g. [4]1 cup = 236.59 mL. [5]See reference [30]. [6]See references [31–35].

with <0.5 oz-equivalent total of grains and legumes and <0.25 cup equivalent of dairy were categorized into the paleo-style diet. These 3 food groups represent the major defining criteria for the paleo-style diet based on previous studies [31–35]. Throughout the remainder of the manuscript, these will be referred to simply as keto and paleo diets. Individuals with dietary intake matching >1 of these 5 types of diet were excluded from the analysis. All other diets were classified as omnivore, which included diets that contained meat, dairy, and other animal-based foods along with plant-based sources of carbohydrates, including grains and legumes.

Additionally, to further characterize omnivore diets, scores were calculated to describe accordance with the DASH and Mediterranean diets, which have both been promoted by public health professionals for their beneficial effects on health. The DASH diet score was based on the score developed by Mellen [36], with a point total that ranged from 0–9. One point was allocated per each component when the target was achieved, so a higher score represented higher accordance with the DASH diet. The components included saturated fat, total fat, protein, cholesterol, fiber, magnesium, calcium, potassium, and sodium (Supplementary Table 1) [36]. The Mediterranean diet score was adapted from previously published methods and ranged from 0–10 points total [37–39]. One point was awarded for an intake above the sex-specific median consumption of each of 7 dietary components, including fruits, vegetables, legumes, nuts and seeds, whole grains, and the ratio of MUFA to SFA. For dairy and red and processed meats, points were assigned for intakes below the sex-specific median, and for alcohol, they were assigned for being within specific ranges (Supplementary Table 2). Higher scores indicated higher accordance to the Mediterranean diet.

Outcome variables

Daily GHGE in kilograms of carbon dioxide equivalents per 1000 kcal (kg CO_2-eq/1000 kcal) were calculated using our previously developed database of food impacts on the environment for linking to diets (dataFIELD) [40] and the database of Food Recall Impacts on the Environment for Nutrition and Dietary Studies (dataFRIENDS). DataFIELD was compiled from an extensive review of the food-based lifecycle assessment literature from 2005–2016. It includes GHGE (kg CO_2-eq) per kilogram of over 300 commodities. DataFRIENDS matched these commodity impacts to NHANES foods and calculated kg CO_2-eq/100 g of food. Foods and amounts reported by respondents were then summed to derive a carbon footprint for each individual's 1-d diet. Additional details on the development of dataFIELD, dataFRIENDS, and their application to dietary carbon footprints have been published previously [40, 41]. DataFIELD is available at http://css.umich.edu/page/datafield. DataFRIENDS is available at https://sph.tulane.edu/sbps/diet-environmental-impacts.

Diet quality was determined using the 2010 versions of the Healthy Eating Index (HEI) [41] and the Alternate Healthy Eating Index (AHEI) [42]. HEI included 12 components with a total maximum score of 100 points [43]. Components for which higher intake was associated with a higher score included whole fruits (5 points), total fruits (5 points), greens and beans (5 points), total vegetables (5 points), whole grains (10 points), dairy (10 points), total protein foods (5 points), seafood and plant proteins (5 points), and the ratio of PUFA plus MUFA to SFA (10 points). In addition, 3 components were scored so that higher intake corresponded with lower scores: refined grains (10 points), sodium (10 points), and empty calories (20 points). Each component was scored at the individual level based on methods established by the NCI [44].

We calculated an AHEI score using the criteria described by Wang et al. [42] for NHANES data, but with some minor adaptations. For this study, we calculated an AHEI score based on 10 components, each associated with a maximum of 10 points. This differed from that of Wang [42] by not including a component score for transfat because transfats are not included in NHANES data. Those AHEI components for which a higher score corresponds with higher consumption include vegetables, fruit, whole grains, nuts and legumes, long-chain fatty acids (eicosapentaenoic acid and docosahexaenoic acid), and PUFAs. Sugar-sweetened beverages and fruit juices, red and processed meat, and sodium were scored in a way so that higher consumption of each of these 3 components corresponded with lower scores. Similar to Wang [42], alcohol was scored as 0 for females consuming ≥2.5 drinks/d and males consuming ≥3.5 drinks/d. Respondents received a score of 10 if they consumed between 0.5–1.5 drinks/d (female) or 0.5–2 drinks/d (male). They received a linearly interpolated score between 2.5–10 when consuming between 0–0.5 drinks/d.

Statistical methods

Analyses were conducted in Stata version 17, accounting for the complex NHANES survey design and the use of sampling weights to produce statistical estimates that are representative of the noninstitutionalized civilian population of the US. GHGE, HEI, and AHEI were calculated per person, and the group average for each of the 6 diets was calculated. Outliers were identified as observations >3 SDs from the mean for each of these dependent variables (GHGE, HEI, and AHEI) and removed from the analytic sample. Survey-weighted proportions were calculated, and survey-weighted multinomial logistic regression was used to describe and identify differences in demographic characteristics of those consuming each of the 6 diets. Multinomial logistic regression is appropriate when there is a categorical dependent variable with ≥3 unordered levels. Diet type was included as the dependent variable, and each demographic variable (for example, race and ethnicity) was the independent variable in a separate model estimating the log odds of being in the vegetarian, pescatarian, vegan, keto, or paleo diet relative to the omnivore diet.

Three survey-weighted ordinary least-squares regression models were developed, each with GHGE, HEI, or AHEI entered as the dependent variable. For each model, the diet was a categorical independent variable with 6 levels corresponding to each of the 6 types of diet (vegan, vegetarian, pescatarian, keto, paleo, and omnivore). Post hoc pairwise comparisons with Bonferroni adjustments were used to test for differences in GHGE, HEI, and AHEI between all 6 diet types. A probability value of 0.05 was the threshold for significance for all statistical tests used here.

To better characterize omnivore diets, 3 models were developed to assess their accordance with the DASH diet. Each outcome of interest (GHGE, HEI, or AHEI) was the dependent variable of a separate linear regression model, with the independent variable being the continuous DASH diet score. Similar models were also developed to characterize the accordance of omnivore diets with the Mediterranean diet. Scatter plots verified a linear relationship between each of the 3 outcomes of interest and either the DASH or Mediterranean diet scores.

Our dependent variables (GHGE, HEI, and AHEI) were not normally distributed, a requirement for regression analysis. Therefore, we ran all analyses with log-transformed values of these variables. Because significance test results were the same using either the transformed or nontransformed outcome variables, analyses are presented here using the nontransformed variables, as they allow for interpreting results in common units.

Sensitivity analyses

As a check on our diet classification approach and exclusion of outlier values, we conducted 2 sensitivity analyses. The first, termed "outliers included," applied diet definitions identical to those described above but included individuals with outlier values that were excluded from the main analytic sample (n = 304). The second sensitivity analysis, termed "strict diets," applied strict diet definitions. That is, it did not allow for the inclusion of minimal amounts of typically excluded foods, as in a teaspoon of milk in a vegan diet, which was permitted in our diet definitions for the main analysis. However, as with the main analytic sample, we excluded individuals with outlier values or intakes that could be categorized into multiple diets. Definitions and sample sizes for these analyses are presented in Supplemental Table 3.

Results

The most frequently consumed 1-d diets (Table 1) were omnivore (n = 14,175, 86.3% ± 0.4), vegetarian (n = 1179, 7.5% ± 0.3), and pescatarian (n = 778, 4.7% ± 0.3) followed by vegan (n = 141, 0.7% ± 0.1), keto (n = 77, 0.4% ± 0.1), and paleo (n = 62, 0.3% ± 0.1). The descriptive statistics (kilocalories, GHGE, HEI, and AHEI) of these diets for the complete and omnivore analytic samples can be found in Supplemental Table 4.

Demographic characteristics of the overall sample, as well as those consuming each diet, are presented in Table 2. Results of survey-weighted multinomial logistic regressions identified sex, race and ethnicity, age, and education, but not income, to be significantly associated with the type of diet. All comparisons reported below are relative to the omnivore diet reference group. For example, compared to females, maleswere significantly ($P < 0.05$) less likely to consume a vegetarian or pescatarian diet than an omnivore diet. Those who identified as Hispanic and those who identified as Black were significantly more likely to consume a keto diet compared with an omnivore diet relative to White respondents, whereas Black respondents were also less likely to consume a vegetarian diet. Those who were 18–29 y were more likely to consume a vegan diet, and those 50–65 y and 66 y and older were more likely to consume a pescatarian diet compared with an omnivore diet compared to those who were 30–49 y old. Relative to those with a college degree, respondents without a college degree were less likely to consume a vegetarian diet than an omnivore diet, whereas those who had not completed high school were also less likely to consume a pescatarian diet.

As seen in Table 3, the lowest carbon footprint diets were vegan (mean = 0.69 ± 0.05 kg CO_2-eq/1000 kcal), vegetarian (1.16 ± 0.02), and pescatarian (1.66 ± 0.04), whereas the highest footprints were omnivore (2.23 ± 0.01), paleo (2.62 ± 0.33), and keto (2.91 ± 0.27). Significant differences ($P < 0.05$) in footprints between these groups using post hoc Bonferroni pairwise comparisons are indicated in this table. The Bonferroni-adjusted P values from these comparisons are presented in Supplemental Table 5. Of note, vegan diets had a significantly lower footprint than vegetarian diets, and these were significantly lower than all other diets, whereas omnivore, keto, and paleo diets were not significantly different in terms of carbon footprints.

TABLE 2
Characteristics of the study sample and of individuals consuming popular diets, adults ≥18 y, NHANES 2005–2010

Demographic variables	Overall (n = 16,412)	Omnivore[1] (n = 14,175)	Vegetarian (n = 1179)	Pescatarian (n = 778)	Vegan (n = 141)	Keto (n = 77)	Paleo (n = 62)
	% ± SE	% ± SE	% ± SE	% ± SE	% ± SE	% ± SE	% ± SE
Sex							
Female[1]	52.1 ± 0.4	50.1 ± 0.4	69.0 ± 1.5	59.5 ± 2.5	58.3 ± 4.5	63.9 ± 7.7	52.9 ± 9.3
Male	47.9 ± 0.4	49.9 ± 0.4	31.0 ± 1.5[2]	40.5 ± 2.5[2]	41.7 ± 4.5	36.1 ± 7.7	47.1 ± 9.3
Race and ethnicity							
Non-Hispanic White[1]	70.2 ± 1.9	70.0 ± 2.0	75.0 ± 2.3	70.6 ± 2.7	60.4 ± 5.1	53.8 ± 6.7	56.1 ± 8.8
Hispanic	12.6 ± 1.2	12.7 ± 1.2	12.5 ± 1.4	10.2 ± 2.1	15.7 ± 3.4	22.1 ± 6.1[2]	17.9 ± 5.8
Non-Hispanic Black	11.6 ± 1.0	12.1 ± 1.1	5.5 ± 0.9[2]	10.1 ± 1.2	11.2 ± 2.6	19.5 ± 5.3[2]	16 ± 5
Other	5.6 ± 0.5	5.3 ± 0.5	7.0 ± 1.2	9.0 ± 1.6[2]	12.7 ± 3.8[2]	4.6 ± 2.6	10 ± 7.9
Age							
18–29	22.1 ± 0.7	22.5 ± 0.7	22.5 ± 1.9	15.0 ± 2.4	27.0 ± 5.0[2]	11.8 ± 3.0	33.1 ± 9.6
30–49[1]	36.9 ± 0.9	37.4 ± 1.0	35.2 ± 2.2	31.2 ± 2.4	25.4 ± 5.5	35.1 ± 8.1	44.8 ± 10.1
50–65	25.5 ± 0.6	25.2 ± 0.7	24.6 ± 1.4	32.7 ± 2.1[2]	26.6 ± 4.9	27.7 ± 6.8	15.9 ± 5.7
66+	15.5 ± 0.6	14.9 ± 0.6	17.7 ± 1.4	21.0 ± 2.0[2]	21.0 ± 6.0	25.4 ± 5.5	6.2 ± 2.3[2]
Education[3]							
Less than high school	19.0 ± 0.7	19.1 ± 0.8	18.1 ± 1.8[2]	15.5 ± 1.5[2]	29.7 ± 4.1	33.3 ± 5.7	28.5 ± 7.6
High school graduate	25.0 ± 0.7	25.6 ± 0.7	20.3 ± 1.6[2]	24.1 ± 2.6	18.1 ± 3.4	16.9 ± 4.9	32.2 ± 8.9
Some college	30.6 ± 0.5	30.9 ± 0.6	28.3 ± 2.0[2]	31.4 ± 2.5	28.0 ± 4.5	23.4 ± 6.6	27.1 ± 9.0
College graduate[1]	25.3 ± 1.1	24.5 ± 1.1	33.3 ± 2.4	29.0 ± 2.2	24.3 ± 5.0	26.4 ± 7.2	12.1 ± 7.3
Income-to-poverty ratio							
<1	6.2 ± 0.4	6.2 ± 0.4	7.6 ± 1.2	5.6 ± 1.0	5.0 ± 1.7	3.1 ± 2.2	3.3 ± 1.8
1 to <2	13.1 ± 0.6	12.9 ± 0.6	13.3 ± 1.3	14.0 ± 1.7	18.9 ± 4.1	28.0 ± 6.0	16.1 ± 5.0
2 to <5	19.2 ± 0.6	19.2 ± 0.6	20.4 ± 1.9	17.1 ± 1.5	23.7 ± 5.1	14.3 ± 3.8	17.0 ± 5.7
5+[1]	37.0 ± 0.8	37.1 ± 0.9	35.4 ± 2.1	36.7 ± 2.1	39.6 ± 6.2	28.8 ± 6.8	53.8 ± 9.6
Missing	24.4 ± 1.0	24.5 ± 1.0	23.3 ± 1.9	26.6 ± 2.5	12.8 ± 5.1	25.8 ± 7.3	9.8 ± 5.1

[1] Reference group. [2]$P < 0.05$ for the difference from the reference diet (omnivore) using survey-weighted multinomial logistic regression. Multinomial logistic regression allows for a dependent variable with ≥3 unordered categories. In this case, with diet as the dependent variable, each demographic variable (for example, race and ethnicity) was the independent variable in a separate model estimating the log odds of consuming a vegetarian, pescatarian, vegan, keto, or paleo diet relative to the omnivore diet. For example, compared to 30–49 y-olds, 66+ y-olds had greater odds of consuming a pescatarian diet compared to an omnivore diet.
[3]Education variable included individuals ≥20 y of age (n = 16,391).

TABLE 3
Greenhouse gas emissions and quality of diets as reported by consumers, NHANES 2005–2010[1]

Diet	n	GHGE kg CO_2-eq/1000 kcal	Healthy Eating Index	Alternate Healthy Eating Index
		Mean ± SE	Mean ± SE	Mean ± SE
Omnivore	14,175	2.23 ± 0.01[d]	48.92 ± 0.33[c]	33.89 ± 0.29[d]
Vegetarian	1179	1.16 ± 0.02[b]	51.89 ± 0.74[b]	42.05 ± 0.64[b,c]
Pescatarian	778	1.66 ± 0.04[c]	58.76 ± 0.79[a]	51.61 ± 0.72[a]
Vegan	141	0.69 ± 0.05[a]	51.65 ± 2.58[a,b,c,d]	44.57 ± 1.89[b]
Keto	77	2.91 ± 0.27[d]	43.69 ± 1.61[d]	36.13 ± 1.91[c,d]
Paleo	62	2.62 ± 0.33[c,d]	45.03 ± 2.37[b,c,d]	33.86 ± 2.37[d]

n, sample size; GHGE, greenhouse gas emissions. [1]Analyses used survey-weighted ordinary least-squares regression. Each column represents a different regression for which the variable in the header was the dependent variable, and diet was a categorical independent variable with 6 levels corresponding to each of the 6 different diets reported. [a-d] Means sharing a superscript letter were not significantly different ($P < 0.05$) using posttest pairwise comparisons with a Bonferroni adjustment. Superscript letters are ordered by desirable outcome: that is, in ascending order beginning with "a" at the lowest GHGE value and descending order with "a" at the highest diet quality value.

Diet quality as measured by HEI was highest for pescatarian (58.76 ± 0.79), vegetarian (51.89 ± 0.74), and vegan (51.65 ± 2.58) diets, and lowest for omnivore (48.92 ± 0.33), paleo (45.03 ± 2.37), and keto (43.69 ± 1.61) diets (Table 3). When evaluated using the AHEI, the same diets were in the top 3 (pescatarian, vegan, and vegetarian) and bottom 3 (keto, omnivore, and paleo) of diet quality scores, but the specific rankings differed. As for pairwise comparisons, pescatarian diets scored significantly higher than all other diets on both measures of diet quality. Vegetarian diets also scored higher on both measures of diet quality relative to omnivore diets. The diet quality of omnivore diets, as measured by either HEI or AHEI, was no different than that of paleo diets and better than that of keto diets when assessed by HEI.

We conducted 2 additional analyses to see how sensitive our results were to either the exclusion of outliers or the decision not to use strict diet definitions. Supplemental Table 6 describes the demographic characteristics of each analytic sample. Results were largely consistent with our main results presented in Table 3 (Supplemental Table 7).

To better characterize omnivore diets, which made up the largest proportion of diets in our sample, we assessed them in accordance with DASH and Mediterranean diets. An inverse relationship was observed between average daily GHGE and both the DASH and Mediterranean scores, whereas a positive relationship was seen between diet quality (HEI or AHEI) and these scores (Figure 1). As presented in Table 4, GHGE decreased by 0.03 ± 0.01 kg CO_2-eq/1000 kcal for each point increase in DASH score and decreased by 0.17 ± 0.01 for each point increase in Mediterranean diet score. Additionally, the regression equations calculated to predict the mean HEI and AHEI by DASH and Mediterranean scores were also significant ($P < 0.001$). HEI scores increased by 4.16 ± 0.07 for each point increase in DASH diet score and increased by 5.33 ± 0.06 for each increased Mediterranean diet score. AHEI scores also showed positive increases for increased accordance with these diets, though somewhat smaller in magnitude.

Discussion

We found that popular diets, as consumed in the US, have a wide variation in carbon footprints and diet quality. Keto and paleo diets have not been well studied on both of these dimensions together. Our results show that keto diets have a higher mean carbon footprint and a lower mean diet quality than other diets, including vegetarian and pescatarian diets. On average, paleo diets also had a higher carbon footprint than vegetarian diets and a lower diet quality score than pescatarian diets. Both keto and paleo diets have been associated with negative effects on blood lipids, specifically increased low-density lipoprotein cholesterol [45–47], raising concern about the long-term health outcomes associated with these diets. These diets tend to be higher in animal foods and lower in plant foods than other popular

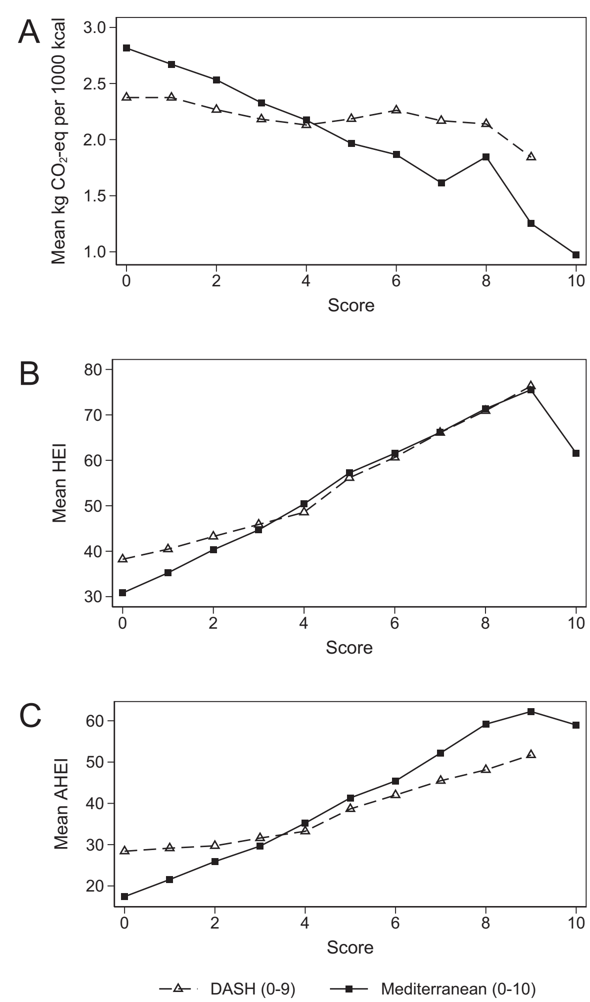

FIGURE 1. Average daily greenhouse gas emissions (GHGE), Healthy Eating Index (HEI), and Alternate Healthy Eating Index (AHEI) by DASH and Mediterranean diet score among omnivores.[1] (A) GHGE in kg CO_2-eq/1000 kcal. (B) HEI scores. (C) AHEI scores. [1]Omnivore diets ($n = 14{,}175$) were those that did not fall into the other 5 groups: vegetarian, pescatarian, vegan, keto, or paleo.

TABLE 4

Carbon footprints and quality of omnivore diets in relation to their accordance with the DASH and Mediterranean diet scores[1,2]

	GHGE kg CO_2-eq/1000 kcal		Healthy Eating Index		Alternate Healthy Eating Index	
	Coefficient (SE)	*P*	Coefficient (SE)	*P*	Coefficient (SE)	*P*
DASH[3]	−0.03 (0.01)	<0.001	4.16 (0.07)	<0.001	2.66 (0.09)	<0.001
Mediterranean[4]	−0.17 (0.01)	<0.001	5.33 (0.06)	<0.001	5.05 (0.08)	<0.001

GHGE, greenhouse gas emissions. [1]Omnivore diets ($n = 14{,}175$) were those that did not fall into the other 5 groups: vegetarian, pescatarian, vegan, keto, or paleo. [2]Values were generated using survey-weighted ordinary least-squares regression. Each cell represents results from different regressions in which variables in the column headers of the table were the dependent variable (GHGE, HEI, AHEI), and a continuous score developed for the DASH diet or Mediterranean diet was entered as independent variables. [3]Scores range from 0–9 with 1 point per component. See Mellen et al. [36] (**Supplementary** Table 1). [4]Scores range from 0–10 with 1 point per component. See Trichopoulou et al. [37–38] and Panagiotakos et al. [39] (**Supplementary** Table 2).

diets, which could, in part, explain the negative effects on blood lipids and our results on carbon footprints and diet quality.

Our analysis also adds new insights into more commonly studied diets. Although previous research has compared pescatarian and vegetarian diets to omnivore diets, they are rarely compared to each other on both health and environmental outcomes. Here we found that, on average, pescatarian diets scored better on diet quality but had higher carbon footprints than vegetarian diets, this latter finding being consistent with Scarborough's [6, 16] work in the UK. Either of these popular diets scored better on diet quality and had lower carbon footprints than omnivore diets in our analysis. There is variability in the specific foods and amounts that make up these diets, so that some individual omnivore diets may have a better diet quality score than some individual pescatarian diets, for example. However, our findings are similar to previous studies that have identified lower environmental impacts of vegetarian [5, 6, 10, 11, 16] and pescatarian diets [6, 16] and higher diet quality when compared to nonvegetarian diets [48] or omnivore diets [49].

Omnivore diets were the most commonly consumed. We used the DASH and Mediterranean diet scores to characterize them further and found that higher accordance with either of these diets was associated with lower dietary GHGE and higher diet quality. The Mediterranean diet promotes more seafood, plant protein foods, fruits and vegetables, and less red and processed meats, whereas the DASH diet recommends less saturated fat and total fat and more fiber. The lower dietary GHGE associated with these diets is consistent with most previous research [11, 15, 20–22]. Whereas other studies have used DASH and Mediterranean diet scores as standalone indicators for diet quality, here we show that they are also linearly associated with the HEI and the AHEI, corroborating their standalone use.

Vegan diets had the lowest carbon footprints, which is not surprising, given the substantial decrease in dietary GHGEs when meats are replaced with plant protein foods [9]. Diet quality was not significantly different from the other diets when assessed by the HEI, but it was better than keto, paleo, and omnivore diets when assessed by the AHEI. This latter finding is consistent with previous literature [42]. Unlike the HEI, the AHEI does not give points for dairy consumption and gives a lower score for higher intakes of red and processed meat, which could explain our results.

How meaningful is the lower carbon footprint of vegetarian diets? On average, we found a difference of 1.07 kg CO_2-eq/1000 kcal between vegetarian and omnivore diets. For any given day, if a third of the omnivores consumed a 2000 kcal vegetarian diet, and assuming accompanying shifts in domestic production, the savings would be equivalent to eliminating 340 million passenger vehicle miles [50]. If such a change were implemented year-round, this would amount to 4.9% of the reductions needed to meet the original US targets in the Paris accords [40, 50]. This reduction would come with an average 6% improvement in diet quality, as measured by the HEI, and an even larger improvement if measured by the AHEI. These improvements in scores would likely be because of lower saturated fats, higher mono- and poly-unsaturated fats, as well as increased plant protein foods.

This study has a number of strengths. The data analyzed included a nationally representative sample of self-selected diets rather than prescribed foods that fall within a specific diet type. To our knowledge, this describes the first analysis of the carbon footprints of keto and paleo diets based on how they are implemented in a nationally representative sample from the US. We were conservative in our characterization of diets, allowing for minimal consumption of typically excluded foods (for example, minor amounts of dairy in vegan diets) because this more realistically mirrors the behavior of free-living individuals who might not know the composition of mixed dishes or might choose to stray from strict rules. Interestingly, strict definitions of the diets did not appreciably change our main results, as we found in our second sensitivity analysis (Supplemental Table 7). We also triangulated our assessment of diet quality by using 2 indicators of this outcome, the HEI, and the AHEI.

As for the limitations of the article, a concern may be the use of 1 d of dietary data rather than the usual intake. Because our goal was to analyze the contents of different popular diets, we opted to preserve the largest sample size possible for each of the diets. Although some of the sample sizes appear to be low in percentage terms, when scaled to the population that these data are designed to represent, even the smallest groups (keto, $n = 77$; paleo, $n = 62$) represent significant numbers of people, about three-quarters of a million or more (Table 1). Diets were classified based on foods that were consumed on the day data were collected, although individuals may not necessarily identify as subscribing to such a diet. Although NHANES does include a variable to assess self-perception of vegetarian status, there is no such indicator for the other diets explored in this study. Although there are more recent NHANES data available, the use of dataFIELD to calculate the GHGE of foods consumed limited the analysis to the 2005–2010 NHANES survey waves. Finally, definitions for the various diets were set up to be mutually exclusive, even though one could construct examples in which there is overlap between different diets. This was a requirement of our approach to analyze all diets in 1 regression model; because individual diets can only be assigned to a single type. However, analysis of those cases ($n = 84$) of individual diets with multiple classifications reveals that our exclusion of them was justified. These are uncommon occurrences, just 0.5% of our analytic sample, with relatively low-calorie intakes, a mean of just 603 calories (Supplemental Table 8), compared to the mean of 2164 kcal for diets in our analytic sample.

In conclusion, our study provides evidence of the wide variation in diet quality and carbon footprints of popular diets as they are consumed by US adults. On average, diets that scored the highest on nutritional quality (for example, pescatarian) are not those with the lowest carbon footprints. Plant-based diets do have the lowest footprints, and vegetarian diets scored higher on diet quality than other popular diets, such as the keto and omnivore diets. Many individuals may not wish to give up specific foods. For those pursuing a mixed omnivore diet, our results suggest that improvements in both diet quality and carbon footprints can be attained in greater accordance with a DASH or Mediterranean diet. Clearly, the work of assessing diets for healthiness and environmental impacts is nuanced, as our results point out. This calls for additional research as well as public policy attention, given the urgency to address climate change.

Conflicts of interest

DR has received extramural funding from the Center for Biological Diversity, the NCI, and the Health Resources and Services Administration. AWS has received funding from CBD and NCI. KO has received funding from HRSA.

All other authors report no conflicts of interest.

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The authors' responsibilities were as follows—KO and DR designed the research and wrote the article. AWS helped develop the database underlying this work. AWS and KO analyzed data. KO had primary responsibility for final content. All authors read and approved the final manuscript.

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Data Availability

Data (and codebooks) described in the manuscript are freely available at the following locations. Analytic code is available from the authors on request.

NHANES data: https://wwwn.cdc.gov/nchs/nhanes/

GHGE of commodities (dataFIELD): http://css.umich.edu/page/datafield

GHGE of NHANES foods (dataFRIENDS): https://sph.tulane.edu/sbps/diet-environmental-impacts

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ajcnut.2023.01.009.

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