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Original Research Article

Greenhouse gas emissions, cost, and diet quality of specific diet patterns in the United States

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A B S T R A C T

Background: Major policy agendas are calling for accelerated investment in research that addresses the impact of diet patterns on multiple domains of sustainability.

Objectives: To evaluate the comparative greenhouse gas emissions, diet cost, and diet quality of plant-based, low-grain, restricted carbohydrate, low-fat, and time-restricted diet patterns on a daily per capita basis.

Methods: Dietary data from the National Health and Nutrition Examination Survey (2013–2016, $n = 4025$) were merged with data on greenhouse gas emissions (GHGEs) and food prices from multiple databases. The Healthy Eating Index-2015 was used to measure diet quality.

Results: The plant-based diet pattern had the lowest GHGEs [3.5 kg carbon dioxide equivalent (CO_2eq); 95% confidence interval (CI): 3.3, 3.8 kg CO_2eq] and among the lowest diet cost ($11.51; 95% CI: $10.67, $12.41), but diet quality (45.8; 95% CI: 43.3, 48.5) was similar ($P > 0.005$) to most other diet patterns. All of the sustainability impacts of the low-grain diet pattern were intermediate. The restricted carbohydrate diet pattern had the highest diet cost ($18.46; 95% CI: $17.80, $19.13) but intermediate diet quality (46.8; 95% CI: 45.7, 47.9) and moderate-to-high GHGEs (5.7 kg CO_2eq; 95% CI: 5.4, 5.9 kg CO_2eq). The low-fat diet pattern had the highest diet quality (52.0; 95% CI: 50.8, 53.1) and intermediate GHGEs (4.4 kg CO_2eq; 95% CI: 4.1, 4.6 kg CO_2eq) and diet cost ($14.53; 95% CI: $13.73, $15.38). The time-restricted diet pattern had among the lowest diet quality score (42.6; 95% CI: 40.8, 44.6), had GHGEs similar to most other diet patterns (4.6 kg CO_2eq; 95% CI: 4.2, 5.0 kg CO_2eq), and low-to-moderate diet cost ($12.34; 95% CI: $11.38, $13.40).

Conclusions: Most diet patterns are associated with sustainability trade-offs. The nature of these trade-offs can help inform discussions on food and nutrition policy in the United States, including the National Strategy on Hunger, Nutrition, and Health, and future Dietary Guidelines for Americans.

Keywords: sustainability, plant-based, low carbohydrate, greenhouse gas emissions, diet cost, diet quality, Healthy Eating Index-2015

Introduction

The 4 domains of sustainability are nutrition and health, environment, economics, and society [1]. Globally, food systems account for 25%–35% of greenhouse gas emissions (GHGEs) [2], and suboptimal diets are the leading modifiable risk factor for mortality [3], accounting for 9–11 million deaths annually [3,4]. Although the affordability of nutritious diets has improved, these are still financially out of reach for much of the global population, and threats to equity and inclusion are worsening [5]. Transforming food systems for greater sustainability is needed to meet the United Nations Sustainable Development Goals for 2030, which include safe and nutritious food (target 2.1), improved health (target 3.4), better management of agricultural systems and natural resources (targets 2.4 and 12.2), safe working environments (target 8.8), and others [6].

To achieve more sustainable food systems, measuring the impact of diet patterns on sustainability outcomes is critical, which is known as

Abbreviations: CO_2eq, carbon dioxide equivalent; dataFIELD, database of Food Impacts on the Environment for Linking to Diets; DGA, Dietary Guidelines for Americans; ERS, Economic Research Service; FAFH, food away from home; FAH, food at home; FCID, Food Commodity Intake Database; FoodAPS, National Household Food Acquisition and Purchase Survey; GHGE, greenhouse gas emission; HEI, Healthy Eating Index; LAFA, Loss-adjusted Food Availability; PPPT, Purchase-to-Plate Price Tool; TFD, Total Food Demand.

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diet sustainability analysis [7,8]. In the United States, the recent National Strategy on Hunger, Nutrition, and Health has called for greater investment in research to evaluate the intersection of nutrition, environment, affordability, and equity [9]. Additionally, the USDA and the Department of Health and Human Services have committed to supporting a number of new initiatives that examine the relationships between nutrition and other domains of sustainability [10]. These include the convening of a Federal Workgroup to evaluate integration of sustainability into future Dietary Guidelines for Americans (DGAs), as well as the new National Institutes of Health initiative titled Agriculture and Diet: Value Added for Nutrition, Translation, and Adaptation in a Global Ecology (ADVANTAGE), which will support federal efforts to evaluate the evidence base for nutrition-sustainability interactions [10].

Although diet sustainability analyses have become more common [7], systemic barriers continue to prevent a more rapid acceleration of this field [11,12]. Data from different sustainability domains are distributed across federal agencies and other repositories without standardized methods to link them, and incorporating these diverse data into a common analytic framework often requires crosswalk databases (that is, databases that provide coding linkages between multiple other databases) that are not always updated [8]. As a result, many diet sustainability studies do not include economic and social domains [7], and many food security studies do not include the environment domain [13]. Fortunately, recent methodological advancements have led to the development of new databases [14–16] and data linkage procedures [8,17–19] that reduce these barriers, allow for multiple sustainability domains to be evaluated simultaneously, and present opportunities to address emergent and multifaceted research questions. These opportunities are particularly relevant to major policy and programming initiatives at the global [6] and national [10] levels.

Because chronic disease prevalence continues to rise in the United States [20], more people have adopted specific diet patterns for weight control and general health improvement [21,22]. These diet patterns typically restrict food groups (for example, plant-based), macronutrients (for example, low carbohydrate or fat), or eating time (for example, intermittent fasting). Over 17% of the United States adult population reported following a specific diet pattern on a given day in 2017–2018 [21], and a 2022 survey found that 52% of people reported following a specific diet pattern at some point over the past year, representing an increase of 13 percentage points since the 2021 survey [22]. Common reasons for adopting a new diet pattern included general health improvement (35% of people), environmental sustainability (21%), and wanting to follow the DGAs (16%) [22]. In recognition of this trend, the proposed questions for consideration by the 2025 Dietary Guidelines Advisory Committee include evaluating the relationship between time-restricted eating and adherence to the DGAs, as well as a more general focus on diet pattern analyses [23]. Prior studies have evaluated specific theoretical diet patterns that reflect varying amounts of animal protein [24–30] and the Mediterranean diet pattern [24], as well as self-perceived vegetarians [31,32], but few have evaluated specific diet patterns using individual-level data from dietary surveys [33], especially low-grain, restricted carbohydrate, low-fat, and time-restricted diet patterns. To inform contemporary policy discussions, this study deployed recent analytical advancements to evaluate the comparative environmental impacts, cost, and diet quality of specific diet patterns in the United States.

Methods

Dietary data

Individual-level data on dietary intake and sociodemographic characteristics were acquired from the NHANES, 2013–2016 [34]. Data were collected from ~5000 noninstitutionalized participants per year by trained staff using in-person surveys, physical examinations, and laboratory tests. Some population groups were oversampled to increase reliability and precision. Dietary data were collected using a 24-h recall and the computer-assisted Automated Multiple Pass Method was used to increase reliability and validity and minimize respondent burden. Data were collected continuously and released in 2-y cycles [34]. The present study is a secondary analysis of publicly available and deidentified data and was deemed exempt from human studies ethical review by the Institutional Review Board at William & Mary.

Diet pattern categorization

Participants were categorized into food group-restricted (plant based, low grain), macronutrient-restricted (restricted carbohydrate, low fat), and time-restricted diet patterns using data on daily food and nutrient intake. These diet patterns were operationalized according to Conrad et al. [35] and informed by published literature [36,37], as described in Table 1 and Supplemental Table 1. The Food Patterns Equivalents Database [38] was used to convert data on food intake from NHANES into food groups, which was used to categorize food group-restricted diet patterns. Data on daily nutrient intake from NHANES were used to categorize macronutrient-restricted diet patterns. NHANES files also provide the time between each eating occasion for each participant, and these data were used to categorize the time-restricted diet pattern. Some participants consumed more than one diet pattern, which may introduce bias when performing analyses at the diet pattern level and can obscure interpretation of the results. For example, some participants who consumed plant-based diet patterns also consumed restricted carbohydrate diet patterns, which presents challenges for making clear distinctions in outcomes between diet patterns. To ensure that diet patterns were mutually exclusive, participants who were categorized into more than one diet pattern were not included in the final analytic sample, as described below.

Diet quality measurement

Diet quality is a multidimensional construct that represents the healthfulness of diet patterns. Multiple indexes have been developed

TABLE 1
Criteria for diet pattern categorization

Diet pattern	*n*	Inclusion criteria[1]
Food group restricted		
Plant based	487	<1 ounce-equivalent of meat, poultry, and seafood
Low grain	331	≤25th percentile of total grain intake
Macronutrient restricted		
Restricted carbohydrate	1714	<45% kcal from carbohydrate
Low fat	1183	<30% kcal from fat
Time restricted	310	≥11 h fast of food and beverages >0 kcal

[1] Data on daily nutrient intake were acquired from the nutrient intake files in the NHANES, and data on daily intake of food groups were acquired from the Food Pattern Equivalents Database.

and validated to measure diet quality [39], and the present study used the Healthy Eating Index-2015 (HEI-2015) because it assesses adherence to the DGAs [40] and is therefore relevant to emergent policy discussions in the United States [9,23]. HEI-2015 includes 9 components to encourage (total fruit, whole fruit, total vegetables, greens and beans, whole grains, dairy, total protein foods, seafood and plant proteins, and the ratio of unsaturated to saturated fats) and 4 components to limit (refined grains, sodium, added sugars, and saturated fats). The intake of most components is energy-adjusted to 1000 kcal and is scored using a standard that specifies the minimum and maximum number of points, and intermediate intakes are scored proportionally. Components are scored from 0 to 5 or 0 to 10, with higher scores being more favorable. Scores for all components are summed to estimate a total score for each participant out of a maximum score of 100 [40]. The simple scoring algorithm with regression modeling was appropriately used to calculate HEI-2015 scores [41].

Diet cost

Data on national mean food prices (2013–2016) for each NHANES food were acquired from the Purchase-to-Plate Price Tool (PPPT), developed by the USDA's Economic Research Service (USDA ERS) [16]. These data were derived from InfoScan, which is owned by Information Resources, Inc., and provided to USDA ERS under contract [42]. InfoScan collects price data from retail checkout scanners across the United States, and USDA ERS adjusts these prices for losses and waste to reflect the cost associated with the consumed portion only, and matches these data with foods reported consumed by NHANES participants using machine learning. PPPT uses price data from 350,000 products to derive national mean prices, representing ~50% of all retail food sales in the United States [42].

PPPT data represent prices paid by consumers at retail outlets for foods purchased for consumption at home [food at home (FAH)], and USDA ERS applies these prices to all foods reported consumed by NHANES participants whether they indicated it was consumed at home or away from home [food away from home (FAFH)]. Therefore, PPPT data do not account for the higher prices that consumers typically face when purchasing FAFH compared with FAH. There is no publicly available data on national mean FAFH prices matched to foods reported consumed by NHANES participants, so these data were derived using a methodology demonstrated by others [19,43]. Data on FAH and FAFH prices from the National Household Food Acquisition and Purchase Survey (FoodAPS) [44] were used to derive a coefficient that converted FAH prices (from PPPT) to FAFH prices for each of the foods consumed away from home by NHANES participants.

FoodAPS is a cross-sectional, multistage survey of United States households that collected data on the price of foods from receipts and scanned barcodes from April 2012 through January 2013 [44]. FoodAPS represents the only publicly available data on nationally representative household-level expenditures for FAH and FAFH. These data were used to estimate survey-weighted mean prices for each major food group (meat, poultry, seafood, eggs, dairy, fats and oils, fruits and vegetables, sweets, grains, nonalcoholic beverages, and other foods), which were used to derive a coefficient that represents the ratio of FAFH-to-FAH prices for each food group. These coefficients were multiplied by the price of each FAFH in PPPT to estimate its FAFH price. For example, if the price of a given vegetable was \$1.47 (from PPPT), and if the mean price of FAFH vegetables was 1.53 times greater than the mean price of FAH vegetables (from FoodAPS), the adjusted price of that given vegetable would be estimated as \$2.25 (\$1.47 × 1.53). This methodology has been described in detail elsewhere [19,43].

Greenhouse gas emissions

Data on GHGEs for each food reported consumed by NHANES participants were obtained from the database of Food Impacts on the Environment for Linking to Diets (dataFIELD) [45]. dataFIELD was developed through a systematic review of food environmental life cycle assessments published between 2005 and 2016 that evaluated the GHGEs associated with the production of agricultural commodities and minimally processed ingredients [14]. This literature review resulted in 1645 combinations of food types and production scenarios from 321 unique sources. Nearly all entries accounted for impacts from agricultural production, 51% accounted for impacts from food processing, 19% accounted for impacts from retail and regional food hubs, and 6% accounted for consumer-level impacts [14]. Estimates were averaged across studies and connected to commodities in the Food Commodity Intake Database (FCID), maintained by the United States Environmental Protection Agency, which provides information on the amount of ~500 ingredients in each food reported consumed by NHANES participants [46]. dataFIELD provides data on GHGEs for 332 of the most commonly consumed ingredients in FCID [14] and the present study did not evaluate the GHGEs of these remaining ingredients that are consumed in smaller amounts. To our knowledge, dataFIELD is the only publicly available database on food-related GHGEs that links to NHANES (via FCID). The United States Environmental Protection Agency has not updated FCID since 2010 but others have developed methods for updating these data to align with more recent NHANES surveys [17], which were used in the present study.

Retail loss, consumer waste, and inedible portions

The environmental impacts of consumer food demand include the impacts associated with food loss and waste at both retail and consumer levels, but dataFIELD only provides these impacts associated with the consumed portion [14]. Similarly, the prices that consumers pay for food reflect the prices they paid upon transaction, which includes the portion of food that will eventually be wasted as well as the inedible portion, but PPPT only provides the prices associated with the consumed portion [15]. To comprehensively evaluate the sustainability impacts of consumer food choices, the present study used methods developed by others to estimate the environmental impacts of Total Food Demand (TFD), which represents the sum of environmental impacts from retail loss, consumer food waste, inedible portions, and consumed food [18,47], as well as the cost of purchased food, which represents the sum of costs associated with consumer food waste, inedible portions, and consumed food [19,43]. Briefly, each food reported consumed by NHANES participants was disaggregated into its component ingredients using FCID [17,46]. Each FCID ingredient was then linked with a distinct food commodity in the USDA Loss-adjusted Food Availability data series (LAFA) [48], which provides information on the amount of retail loss, consumer waste, and inedible portions associated with each ingredient. For each loss and waste category (retail loss, consume waste, and inedible portions) for each food reported consumed by NHANES participants, the values were summed to estimate the total amount (in g) of retail loss, consumer waste, and inedible portions associated with each NHANES food. These gram amounts were multiplied by data from PPPT (prices per gram of food) and dataFIELD (GHGE per gram of food) to estimate the GHGE and cost associated with food loss and waste for each food reported consumed by NHANES participants. For each NHANES food, the environmental impacts associated with retail loss, consumer waste, inedible portions, and consumed food were summed to estimate the impacts attributable to TFD, and the costs associated with consumer waste, inedible portions, and consumed food were summed to estimate the cost attributable to purchased food. Additional details of the NHANES-FCID-LAFA linkage procedure, including sources of uncertainty and embedded assumptions, are described in detail elsewhere [18,43].

Statistical analyses

A nonnormal distribution of residuals of each dependent variable (diet quality, GHGE, and diet cost) was assessed and confirmed using the Shapiro-Francia test at $P < 0.05$, and was log-transformed for analysis. All results were back-transformed to their original units for reporting purposes. Mean daily diet quality (consumed), GHGE (TFD), and diet cost (purchased) for each diet pattern were assessed using linear regression models adjusted for kcal (continuous) and survey cycle (continuous), which can be expressed as follows:

$$ln(impact) = \alpha + \beta_1 diet\ pattern + \beta_2 kcal + \beta_3 survey\ cycle$$

where *impact* is a given sustainability outcome (GHGE, cost, or diet quality), α is the intercept, β is the beta-coefficient for a given variable (diet pattern, kcal, or survey cycle), *diet pattern* is a given diet pattern (plant-based, low-grain, restricted carbohydrate, low-fat, or time-restricted), *kcal* is the daily intake of kilocalories (continuous), and *survey cycle* is the NHANES data release (2013–2014 or 2015–2016).

Statistical significance was set at $P < 0.005$ with an integrated Bonferroni correction for multiple comparisons ($P < 0.05/10$ comparisons $= 0.005$). Sensitivity analyses evaluated the sustainability impacts of each popular diet pattern without adjustment for losses, waste, and FAFH prices. All analyses accounted for the multistage probability sampling design of NHANES using standardized procedures and variables provided by the National Center for Health Statistics. Stata16.1 (StataCorp) was used for data management and analysis.

Results

A total of 17,166 participants provided dietary data from 2013 to 2016 (Supplemental Figure 1). Exclusion criteria were <20 y (n = 7102), pregnant or breastfeeding (n = 203), did not consume one of the diet patterns of interest (n = 1971), consumed >1 diet patterns of interest (3732), and had ≥1 sustainability impact (diet quality, GHGE, or diet cost) that was >3SD from the mean. The final analytic sample included 4025 participants.

In the plant-based diet group (n = 487), the greatest proportion of participants were 51–70 y (38%), female (63%), college graduates (39%), had an income-to-poverty ratio ≥4.00 (34%), and were non-Hispanic white (71%; Table 2). In the low-grain group (n = 331), the greatest proportion of participants were 51–70 y (36%), female (58%), completed some college (42%), had an income-to-poverty ratio of 2.00–3.99 (37%), and were non-Hispanic white (66%). Most participants in the restricted carbohydrate group (n = 1714) were 51–70 y (39%), male (54%), graduated college (41%), had an income-to-poverty ratio ≥4.00 (47%), and were non-Hispanic white (73%). In the low-fat group (n = 1183), most participants were 31–50 y (35%) or 51–70 y (35%), completed some college (32%) or graduated college (32%), had an income-to-poverty ratio ≥4.00 (35%), were non-Hispanic white (61%), and approximately half were male (50%). Most participants in the time-restricted group were 31–50 y (38%), completed some college (37%), had an income-to-poverty ratio ≤1.30, and just over one-half were male (51%) and non-Hispanic white (53%).

Table 3 presents the mean daily per capita diet quality, GHGE, and diet cost for each diet pattern. The low-fat diet pattern had the highest diet quality score (52.0; 95% CI: 50.8, 53.1). The time-restricted diet pattern had a lower diet quality score (42.6; 95% CI: 40.8, 44.6) than all other diet patterns, but was similar to the plant-based diet pattern (45.8; 95% CI: 43.3, 48.5). The diet quality score of the plant-based diet pattern was also similar to the low-grain (46.9; 95% CI: 45.1, 48.7) and restricted carbohydrate (46.8; 95% CI: 45.7, 47.9) diet patterns.

The plant-based diet pattern had the lowest daily per capita GHGE [3.5 kg carbon dioxide equivalent (CO_2eq); 95% CI: 3.3, 3.8 kg CO_2eq; Table 3]. The GHGEs for the low-grain diet pattern (5.2 kg CO_2eq; 95% CI: 4.8, 5.6 kg CO_2eq) were higher than the plant-based and low-fat diet patterns (4.4 kg CO_2eq; 95% CI: 4.1, 4.6 kg CO_2eq), but were similar to the restricted carbohydrate (5.7 kg CO_2eq; 95% CI: 5.4, 5.9 kg CO_2eq) and time-restricted (4.6 kg CO_2eq; 95% CI: 4.2, 5.0 kg CO_2eq) diet patterns.

The plant-based diet pattern had among the lowest daily per capita diet cost ($11.51; 95% CI: $10.67, $12.41) and was similar to the time-restricted ($12.34; 95% CI: $11.38, $13.40) diet pattern (Table 3). The restricted carbohydrate diet pattern had the highest diet cost ($18.46; 95% CI: $17.80, $19.13). The diet cost for the time-restricted diet pattern was lower than the low fat ($14.53; 95% CI: $13.73, $15.38) and restricted carbohydrate diet patterns, but was similar to the plant-based and low-grain ($13.70; 95% CI: $12.39, $15.14) diet patterns.

For all diet patterns, sensitivity analyses demonstrated that removing the adjustment for losses and waste decreased daily per capita GHGE by 35%–37% (Supplemental Table 2) and decreased daily per capita diet cost by 31%–34% (Supplemental Table 3), but did not alter the rank order of most diet patterns. Additional sensitivity analyses demonstrated that removing the adjustment for FAFH prices further decreased diet cost by 15% for the plant-based diet pattern and by 28%–33% for all other diet patterns. After removal of the adjustment for losses, waste, and FAFH, the diet cost of the plant-based diet pattern ($6.44; 95% CI: $6.10, $6.80) remained similar to the time restricted diet pattern ($6.10; 95% CI: $5.87, $6.34) but also became similar to the low-grain diet pattern ($6.44; $6.10, $6.80), and the diet cost of the restricted carbohydrate diet pattern ($8.50; 95% CI: $8.33, 8.68) remained among the highest, followed by the low-fat diet pattern ($7.37; 95% CI: $7.13, $7.61).

Discussion

In this nationally representative study of over 4000 United States adults, most diet patterns were associated with sustainability trade-offs. These findings are timely, given the rising popularity of these diet patterns and the urgent need to inform major policy discussions at the nexus of nutrition, environment, and affordability.

In the present study, the diet quality of the plant-based diet pattern was similar to all other diet patterns except the time-restricted diet pattern. This finding is consistent with another recent study using NHANES data that demonstrated that some plant-based diet patterns have similar diet quality compared with keto and paleo diet patterns [49]. However, this finding is not consistent with prior research using NHANES data [35,50] and is also not consistent with data from other higher-income countries and those that used modeled diet patterns [51, 52], which generally demonstrate higher diet quality of plant-based diet patterns. This difference may be due to several factors in the present study. Similar to others [49], the plant-based diet pattern allowed for

TABLE 2
Characteristics of study participants, 2013–2016 (n = 4025)

Characteristic	Food group restricted				Macronutrient restricted				Time restricted[5] (n = 310)	
	Plant based[1] (n = 487)		Low grain[2] (n = 331)		Restricted carbohydrate[3] (n = 1714)		Low fat[4] (n = 1183)			
	% (95% CI)									
Age, y										
20–30	17.7	(13.1, 23.4)	21.1	(15.3, 28.4)	15.7	(13.2, 18.6)	17.4	(14.2, 21.1)	29.1	(22.9, 36.2)
31–50	28.6	(22.6, 35.5)	32.4	(24.9, 41.0)	32.6	(27.7, 37.9)	34.5	(31.0, 38.1)	38.0	(31.1, 45.4)
51–70	37.5	(31.4, 44.1)	35.8	(28.1, 44.2)	38.9	(34.7, 43.3)	35.1	(29.8, 40.9)	21.1	(14.3, 30.0)
>70	16.2	(11.7, 22.2)	10.7	(7.0, 15.9)	12.8	(10.7, 15.2)	13.1	(10.3, 16.4)	11.8	(7.5, 18.3)
Sex										
Male	37.0	(29.3, 45.5)	41.8	(35.5, 48.4)	54.4	(50.9, 57.8)	49.8	(45.3, 54.3)	51.4	(42.5, 60.2)
Female	63.0	(54.5, 70.7)	58.2	(51.6, 64.5)	45.6	(42.2, 49.1)	50.2	(45.7, 54.7)	48.6	(39.8, 57.5)
Education										
<High school	12.8	(9.1, 17.6)	16.4	(12.9, 20.6)	10.3	(8.1, 13.0)	15.7	(12.8, 19.2)	16.8	(11.3, 24.2)
High school or equivalent	16.8	(12.6, 22.0)	24.3	(17.4, 32.8)	19.1	(16.6, 22.0)	20.9	(17.0, 25.5)	29.5	(22.7, 37.4)
Some college	31.0	(25.4, 37.2)	41.7	(35.9, 47.8)	29.8	(26.1, 33.8)	31.9	(27.6, 36.5)	36.6	(27.1, 47.3)
College graduate	39.4	(32.5, 46.8)	17.6	(11.7, 25.6)	40.7	(35.6, 46.0)	31.5	(26.7, 36.7)	17.0	(10.8, 25.8)
Income-to-poverty ratio										
≤1.30	23.2	(18.0, 29.5)	23.9	(18.1, 30.8)	14.9	(12.5, 17.6)	24.7	(19.7, 30.4)	33.7	(26.8, 41.4)
1.31–1.99	18.1	(13.9, 23.1)	16.5	(11.4, 23.3)	9.6	(7.6, 12.1)	13.2	(10.6, 16.4)	11.3	(6.7, 18.5)
2.00–3.99	24.9	(18.8, 32.2)	36.5	(28.2, 45.7)	28.8	(25.5, 32.4)	27.5	(22.6, 33.0)	28.3	(20.9, 37.0)
≥4.00	33.7	(25.7, 42.8)	23.1	(15.4, 33.2)	46.6	(41.5, 51.9)	34.6	(28.5, 41.3)	26.7	(18.7, 36.6)
Race and Hispanic origin[6]										
Non-Hispanic white	70.5	(63.5, 76.7)	66.2	(56.0, 75.1)	72.6	(67.7, 76.9)	61.0	(54.0, 67.5)	52.5	(41.8, 63.0)
Non-Hispanic black	4.9	(3.0, 8.1)	13.7	(9.2, 20.0)	8.7	(6.3, 11.8)	10.8	(8.0, 14.4)	20.3	(14.5, 27.8)
Hispanic[7]	13.9	(9.5, 20.0)	12.9	(9.0, 18.2)	12.2	(9.0, 16.3)	18.3	(14.7, 22.5)	21.3	(13.8, 31.4)
Other[8]	10.6	(7.4, 15.1)	7.2	(4.7, 10.9)	6.6	(5.1, 8.6)	9.9	(7.1, 13.8)	5.9	(2.6, 12.8)

Sample sizes are unweighted.
[1] <1 ounce-equivalent of meat, poultry, and seafood.
[2] ≤25th percentile of total grain intake.
[3] <45% kcal from carbohydrate.
[4] <30% kcal from fat.
[5] ≥11 h food and beverage fast.
[6] Self-identified based on the interview prompts "Do you consider yourself to be Hispanic, Latino, or of Spanish origin?," "Please give me the number of the group that represents your Hispanic/Latino or Spanish origin or ancestry," and "What race do you consider yourself to be [check all that apply]?"
[7] Includes Mexican American.
[8] Includes multiracial.

discretionary intake of meat, seafood, and poultry (<1 ounce-equivalent) to reflect real world conditions in which many self-perceived vegetarians and pescatarians may not be eliminating meat, poultry, and seafood entirely [51], and excluded participants who were categorized into >1 diet pattern to ensure independent samples, both of which decreased the diet quality score of the plant-based diet pattern in post hoc analyses by 6–10 points, whereas the diet quality scores of the other diet patterns decreased by ≤2.9 points. The present study also evaluated the diet quality of actual low-grain, restricted carbohydrate, low-fat, and time-restricted diet patterns in a nationally representative United States sample, which directly addresses proposed scientific questions for the 2025 Dietary Guidelines Advisory Committee ("What is the relationship between time-restricted eating and a diet pattern that is more aligned with the Dietary Guidelines for Americans?") [23]. This research also directly addresses Pillar 5 in the National Strategy on Hunger, Nutrition, and Health, which includes supporting the 2025 DGAs Committee because they explore whether additional examples of healthy diet patterns should be developed and

TABLE 3
Mean diet quality, greenhouse gas emissions, and cost of popular diet patterns, 2013–2016

Diet pattern	Diet quality (HEI-2015)		Greenhouse gas emissions (kg CO_2eq)		Cost (United States $)	
	Mean (95% CI)					
Plant-based	45.8	(43.3, 48.5)[a,b]	3.5	(3.3, 3.8)	11.51	(10.67, 12.41)[a]
Low-grain	46.9	(45.1, 48.7)[b]	5.2	(4.8, 5.6)[bc]	13.70	(12.39, 15.14)[a,b]
Restricted carbohydrate	46.8	(45.7, 47.9)[b]	5.7	(5.4, 5.9)[c]	18.46	(17.80, 19.13)
Low-fat	52.0	(50.8, 53.1)	4.4	(4.1, 4.6)[a]	14.53	(13.73, 15.38)[b]
Time-restricted	42.6	(40.8, 44.6)[a]	4.6	(4.2, 5.0)[a,b]	12.34	(11.38, 13.40)[a]

Within each column, diet patterns sharing a letter are not statistically different at $P < 0.005$ using Wald tests (Bonferroni correction: 0.05 ÷ 10 pairwise tests = 0.005).
All results were adjusted for kcal and survey cycle using linear regression models.
CO_2eq, carbon dioxide equivalent; HEI-2015, Healthy Eating Index-2015.

proposed [9]. All of the diet patterns evaluated in the present study had low diet quality, which raises questions about whether dietary restriction of food groups, macronutrients, or eating time is a useful strategy for consumers.

Using modeled diet patterns, Willits-Smith et al. [32] demonstrated that shifts toward more plant-based diets can lower diet costs in the United States, although they did not evaluate seafood substitutions. Modeling studies for other higher-income countries demonstrated lower costs for vegetarian diet patterns and similar or greater diet costs for pescatarian diet patterns when compared with an average diet pattern [29], which raises questions about the comparative costs of vegetarian and pescatarian diet patterns in the United States. The present study demonstrated that the plant-based diet pattern had among the lowest diet cost but limited sample sizes prevented disaggregation of plant-based diets by seafood intake (that is, vegetarian vs. pescatarian), which presents an area for further research. The authors are not aware of any United States studies that evaluated the cost of actual low-grain, restricted carbohydrate, low-fat, or time-restricted diet patterns in the United States, and the present study shows that these can range from $12.34 (time restricted) to $18.46 (restricted carbohydrate) per day. These findings directly address key policy priorities in the National Strategy on Hunger, Nutrition, and Health to identify healthy and affordable diet patterns, which may be incorporated into public health campaigns such as the DGAs and resources for general nutrition counseling (Pillar 2A) and specifically for participants in the Supplemental Nutrition Assistance Program (Pillar 3C), as well as educational training for nutrition professionals (Pillar 2C) [9].

The National Strategy on Hunger, Nutrition, and Health also calls for more research at the intersection of climate change, food security, and nutrition (Pillar 5) [9]. The present study demonstrated that a plant-based diet pattern was associated with 19%–38% lower GHGE compared with other diet patterns, which is consistent with a recent study using NHANES data that showed that plant-based diet patterns had 26%–76% lower GHGE compared with others) [49]. These findings are also consistent with prior United States studies that compared theoretical [24,26,30] or self-categorized [31] plant-based diet patterns with the average United States diet pattern (10%–50% lower GHGE), and are consistent with data from other higher-income countries that demonstrated 27%–120% lower GHGE from plant-based diet patterns compared with the average diet [53–55]. Differences in GHGE between the low-grain, restricted carbohydrate, low-fat, and time-restricted diet patterns were less dramatic (low-grain was similar to restricted carbohydrate and time-restricted, low-fat was similar to time-restricted, and time-restricted was similar to all but plant-based). Further research is needed to understand how specific food choices within each of these diet patterns may affect the relationship between their environmental impact, diet quality, and cost.

To comprehensively inform active policy discussions [9], research designs that integrate multiple sustainability domains are needed to evaluate potential trade-offs so that unintended consequences can be minimized [56]. This represents a critical pillar of the National Strategy on Hunger, Nutrition and Health (Pillar 5), which emphasizes the need to "improve nutrition metrics, data collection, and research to inform nutrition and food security policy, particularly on issues of equity, access, and disparities." Fortunately, this body of research is emerging. Globally, Ambikapathi et al. [5] showed that food affordability has increased over time but still prevents much of the world from accessing a healthy diet, and that markers of diet quality, environmental sustainability, and equity and inclusion have worsened. In the United States, He et al. [57] demonstrated that diet patterns that are high quality and associated with low GHGE could theoretically be achieved without additional cost for the majority of the United States population, although may still be unaffordable for lower-income minority groups. Others have shown that fruits and vegetables, which are pillars of all healthy diet patterns, are associated with forced labor risk [58]. And recently, Musicus et al. [33] showed that higher diet quality was associated with lower GHGE for healthy United States vegetarian diets but not for unhealthy United States vegetarian diets. Similar trade-offs between sustainability domains in the United States have been demonstrated by others [5,47,59]. This line of research shows that it can be challenging to optimize all sustainability domains at the same time, which raises questions about how to construct policies and programs that promote healthy eating while not compromising other societal goals.

Despite recent research advancements, persistent barriers continue to slow the type of accelerated advancements in sustainability research that are needed to address the most urgent societal needs [8,11,12,60]. Data from different sustainability domains are maintained independently by different federal agencies and most do not provide standardized methods to link them [8,60]. And not all federal databases are maintained regularly [46,61], thus preventing analyses of contemporary data that are needed to respond to emerging societal issues. In some cases, researchers have developed novel methods for linking these data [14,18,19] and updating these databases [17], which include linking data on rates of food loss and waste from the USDA LAFA data series to FCID [18], which in turn links to NHANES; conducting life cycle assessments for most foods in FCID to estimate their associated GHGE [14]; estimating FAFH prices for all NHANES foods by linking to data from FoodAPS [19]; and updating FCID so it aligns with contemporary NHANES data [17]. The present work utilizes all of these advancements.

However, more systematic and standardized maintenance and integration should fall under the purview of government agencies rather than individual scientists. Greater efforts are needed to quantify the social domains of sustainability as they relate to food, such as accessibility of healthy food establishments, food advertising, psychosocial well-being, labor practices, personal safety, and many others. The present study was not able to address these important indicators because of limited data availability, which can be overcome by greater federal efforts to coordinate data collection. Greater efforts are specifically needed to measure the cost of FAFH at the individual or household level, given that it represents ~50% of consumer food spending in the United States [62]; here, too, others have developed methods for measuring these data at the individual level [19], whereas government agencies may be in a better position to reliably perform this task on an ongoing basis. Fortunately, the National Strategy on Hunger, Nutrition, and Health proposes widespread support for increased coordination between federal agencies to promote data collection and sharing (Pillar 5), and specifically calls for another deployment of FoodAPS (last released in 2013), which represents the only publicly available data on FAFH spending at the individual level in the United States [44].

Greater efforts are needed to collect and share data on the environmental impacts of supply chains, which include processing, manufacturing, storage, transportation, wholesale, retail, and food service, which are inconsistently available and thus are often not incorporated into sustainability studies [60], with some exceptions [25,26]. Again, the National Strategy on Hunger, Nutrition, and Health can provide the critical impetus needed to overcome these barriers. This whole-of-society approach calls for greater investment in research that evaluates the intersection of food, nutrition, environment, affordability, and equity [9], which is needed to inform a broad range of policy and program efforts, including the development of future DGAs.

This study is not without limitations. Diet patterns were established using data from 1 d of dietary recall; therefore, these do not represent usual intake. Establishing mutually exclusive diet patterns may have introduced bias because it required excluding many participants who consumed more than one diet pattern of interest and obscured variability in adherence to these diet patterns (that is, people follow the same diet pattern in different ways), which may have biased the interpretation of results. The HEI-2015 was used to evaluate diet quality because it measures adherence to the DGAs and therefore provides relevance to ongoing and future policy efforts, but other diet quality indices may produce different results [47]. Although higher HEI-2015 scores are a good predictor of future health outcomes [63], further research is needed to evaluate the association between specific diet patterns with health and disease outcomes. Self-reported dietary data are subject to social desirability bias in which participants may alter their reported intake of foods so their diets appear healthier than they really are. Despite the potential for this bias to occur, the diet quality of all diet patterns in this study was far below optimal, and there remains no objective method to measure the intake of all foods consumed by individuals in large nationally representative studies. Despite the limitations of self-reported dietary data, these remain useful for comparing diet patterns between groups. Because of limited data availability, most (63%) data on GHGE from dataFIELD are based on European production systems and do not include environmental impacts beyond the farmgate or processing stage, which represents a critical need for further research efforts.

This study also has several strengths. This study evaluated multiple sustainability impacts of popular diet patterns in the United States and utilized data on national mean food prices from USDA ERS that represent scanner data from 50% of all retail food sales in the United States. To comprehensively measure the sustainability impacts of diet patterns, this study incorporated losses and waste that occur throughout the food system to represent the environmental impacts of TFD and the cost of purchased food, rather than just evaluating the impacts associated with consumed food. To further account for the true cost of food, FAFH prices were adjusted to reflect the added value of foods purchased at food service outlets.

In conclusion, this study merges data on environmental impacts, cost, and diet quality from diverse datasets, which was made possible by recent methodological advancements in diet sustainability science. Most diet patterns were associated with sustainability trade-offs in this nationally representative study. These findings are timely, given that many United States adults are experimenting with specific diet patterns that had, until now, limited evidence to support their impacts on environment, affordability, and health. These results can help inform future policy discussions, such as the implementation of the National Strategy on Hunger, Nutrition, and Health, and the development of the DGA 2025–2030.

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Author contributions

The authors' responsibilities were as follows – ZC: designed the research, conducted the research, provided essential materials, analyzed the data, wrote the paper, and had primary responsibility for the final content; and all authors: revised the paper for critical content and approved the final version.

Conflict of Interest statement

ZC has research awards from The Thomas F. and Kate Miller Jeffress Memorial Trust for a project unrelated to the present study; and received honoraria from the USDA, Routledge, MKYoung Food & Nutrition Strategies, National Geographic Society, The Ohio State University, and *Nutrition Today* for professional activities unrelated to the present research. AD is the original developer of the Naturally Nutrient Rich and the Nutrient Rich Food indices. That work was supported at the time by the Nutrient Rich Coalition whose members were The Beef Checkoff Program through the National Cattlemen's Beef Association, California Avocado Commission, California Kiwifruit, California Strawberry Commission, Egg Nutrition Center, Florida Department of Citrus, Grain Foods Foundation, National Dairy Council, National Pork Board, United States Potato Board, Wheat Foods Council, and Wild Blueberry Association of North America. AD is a member of the Nestlé Scientific Advisory Board and an invited member of the Quality Carbohydrate Coalition supported by APRE and Potatoes USA. He has received multiple grants, contracts, and honoraria from entities both public and private with an interest in nutrient density metrics and nutrient profiling of foods. MAB has a research award from the United Soybean Board that has no relevance to the present project, serves as a scientific advisor for Bath and Body Works, and serves on the Board of Directors for the American Society for Nutrition in roles that are unrelated to this project.

Data availability

The data described in the manuscript, code book, and analytic code will be made available upon request. Data on food prices will not be made available because their use is currently restricted by USDA.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ajcnut.2023.04.018.

References

[1] United Nations, High Level Panel of Experts on Food Security and Nutrition. Nutrition and food systems: a report by the High Level Panel of Experts on food security and nutrition [Internet], United Nations, Rome, 2017 [cited 1 January 2022]. Available from: http://www.fao.org/cfs/cfs-hlpe/hlpe-reports/report-12-elaboration-process/en/.

[2] M.A. Clark, M. Springmann, J. Hill, D. Tilman, Multiple health and environmental impacts of foods, Proc. Natl Acad. Sci. USA 116 (46) (2019) 23357–23362, https://doi.org/10.1073/pnas.1906908116.

[3] J.D. Stanaway, A. Afshin, E. Gakidou, S.S. Lim, D. Abate, K.H. Abate, et al., Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195

countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017, Lancet 392 (10159) (2018) 1923–1994, https://doi.org/10.1016/S0140-6736(18)32225-6.
[4] D.D. Wang, Y. Li, A. Afshin, M. Springmann, D. Mozaffarian, M.J. Stampfer, et al., Global improvement in dietary quality could lead to substantial reduction in premature death, J. Nutr. 149 (6) (2019) 1065–1074, https://doi.org/10.1093/jn/nxz010.
[5] R. Ambikapathi, K.R. Schneider, B. Davis, M. Herrero, P. Winters, J.C. Fanzo, Global food systems transitions have enabled affordable diets but had less favourable outcomes for nutrition, environmental health, inclusion and equity, Nat. Food. 3 (9) (2022) 764–779, https://doi.org/10.1038/s43016-022-00588-7.
[6] United Nations, Sustainable Development Goals [Internet], 2021 [cited 31 May 2021]. Available from: https://sustainabledevelopment.un.org/?menu=1300.
[7] S.L. Reinhardt, R. Boehm, N.T. Blackstone, N.H. El-Abbadi, J.S. McNally Brandow, S.F. Taylor, et al., Systematic review of dietary patterns and sustainability in the United States, Adv. Nutr. 11 (2020) 1016–1031, https://doi.org/10.1093/advances/nmaa026.
[8] Z. Conrad, A. Stern, D.C. Love, M. Salesses, A. Cyril, A. McDowell, et al., Data integration for diet sustainability analyses, Sustainability 13 (14) (2021) 8082.
[9] The White House, Biden-Harris Administration National Strategy on Hunger, Nutrition, and Health [Internet], 2022 [cited 3 October 2022]. Available from: https://health.gov/our-work/nutrition-physical-activity/white-house-conference-hunger-nutrition-and-health.
[10] US Departments of Agriculture and Health and Human Services, Projects related to the Dietary Guidelines [Internet], 2023 [cited 30 January 2023]. Available from: https://www.dietaryguidelines.gov/about-dietary-guidelines/related-projects.
[11] J. Finley, L.M. Jaacks, C.J. Peters, D.R. Ort, A.M. Aimone, Z. Conrad, et al., Perspective: understanding the intersection of climate/environmental change, health, agriculture, and improved nutrition – a case study: type 2 diabetes, Adv. Nutr. 10 (5) (2019) 731–738, https://doi.org/10.1093/advances/nmz035.
[12] G.N. Sixt, M. Hauser, N.T. Blackstone, A. Engler, J. Hatfield, S.L. Hendriks, et al., A new convergent science framework for food system sustainability in an uncertain climate, Food Energy Secur 11 (2022) e423, https://doi.org/10.1002/fes3.423.
[13] A.K. Farmery, T.D. Brewer, P. Farrell, H. Kottage, E. Reeve, A.M. Thow, et al., Conceptualising value chain research to integrate multiple food system elements, Glob. Food Sec. 28 (2021), 100500, https://doi.org/10.1016/j.gfs.2021.100500.
[14] M.C. Heller, A. Willits-Smith, R. Meyer, G.A. Keoleian, D. Rose, Greenhouse gas emissions and energy use associated with production of individual self–selected US diets, Environ. Res. Lett. 13 (4) (2018), 044004, https://doi.org/10.1088/1748-9326/aab0ac.
[15] A.C. Carlson, C.E. Tornow, E.T. Page, A. Brown McFadden, T. Palmer Zimmerman, Development of the purchase to plate crosswalk and price tool: estimating prices for the National Health and Nutrition Examination Survey (NHANES) foods and measuring the healthfulness of retail food purchases, J. Food Compos. Anal. 106 (2022), 104344, https://doi.org/10.1016/j.jfca.2021.104344.
[16] A. Carlson, K. Kuczynski, T. Pannucci, K. Koegel, E.T. Page, C.E. Tornow, et al., Estimating prices for foods in the National Health and Nutrition Examination Survey: the Purchase to Plate Price Tool [Internet], US Department of Agriculture, Economic Research Service, Washington, DC, 2020 [cited 31 May 2021]. Available from: https://www.ers.usda.gov/publications/pub-details/?pubid=99294.
[17] Z. Conrad, A. Cyril, C. Kowalski, E. Jackson, B. Hendrickx, J.J. Lan, et al., Diet sustainability analyses can be improved with updates to the Food Commodity Intake Database, Front. Nutr. 9 (2022), 868485, https://doi.org/10.3389/fnut.2022.868485.
[18] Z. Conrad, M.T. Niles, D.A. Neher, E.D. Roy, N.E. Tichenor, L. Jahns, Relationship between food waste, diet quality, and environmental sustainability, PLOS ONE 13 (4) (2018), e0195405, https://doi.org/10.1371/journal.pone.0195405.
[19] Z. Conrad, Daily cost of consumer food wasted, inedible, and consumed in the United States, 2001–2016, Nutr. J. 19 (1) (2020) 35, https://doi.org/10.1186/s12937-020-00552-w.
[20] M. O'Hearn, B.N. Lauren, J.B. Wong, D.D. Kim, D. Mozaffarian, Trends and disparities in cardiometabolic health among U.S. adults, 1999-2018, J. Am. Coll. Cardiol. 80 (2) (2022) 138–151, https://doi.org/10.1016/j.jacc.2022.04.046.
[21] B. Stierman, N. Ansai, S. Mishra, C. Hales, Special diets among adults: United States, 2015-2018 [Internet], National Center for Health Statistics, 2020 [cited 5 November 2020]. Available from: https://www.cdc.gov/nchs/products/databriefs/db389.htm#Data.
[22] International Food Information Council, Food and Health Survey [Internet], 2022 [cited 10 October 2022]. Available from: foodinsight.org.
[23] US Departments of Agriculture and Health and Human Services, Proposed scientific questions for the 2025 Dietary Guidelines Advisory Committee [Internet], 2023 [cited 30 January 2023]. Available from: https://www.dietaryguidelines.gov/sites/default/files/2022-07/Proposed%20Scientific%20Questions_508c_Final.pdf.
[24] N.T. Blackstone, N.H. El-Abbadi, M.S. McCabe, T.S. Griffin, M.E. Nelson, Linking sustainability to the healthy eating patterns of the Dietary Guidelines for Americans: a modelling study, Lancet Planet. Health. 2 (8) (2018) e344–e352, https://doi.org/10.1016/S2542-5196(18)30167-0.
[25] S. Rehkamp, P. Canning, Measuring embodied blue water in American diets: an EIO supply chain approach, Ecol. Econ. 147 (2018) 179–188, https://doi.org/10.1016/j.ecolecon.2017.12.028.
[26] C. Hitaj, S. Rehkamp, P. Canning, C.J. Peters, Greenhouse gas emissions in the United States food system: current and healthy diet scenarios, Environ. Sci. Technol. 53 (9) (2019) 5493–5503, https://doi.org/10.1021/acs.est.8b06828.
[27] B.F. Kim, R.E. Santo, A.P. Scatterday, J.P. Fry, C.M. Synk, S.R. Cebron, et al., Country-specific dietary shifts to mitigate climate and water crises, Glob. Environ. Change 62 (2020), 101926, https://doi.org/10.1016/j.gloenvcha.2019.05.010.
[28] M.M. Mekonnen, J. Fulton, The effect of diet changes and food loss reduction in reducing the water footprint of an average American, Water Int 43 (6) (2018) 860–870, https://doi.org/10.1080/02508060.2018.1515571.
[29] M. Springmann, M.A. Clark, M. Rayner, P. Scarborough, P. Webb, The global and regional costs of healthy and sustainable dietary patterns: a modelling study, Lancet Planet. Health 5 (11) (2021) e797–e807, https://doi.org/10.1016/s2542-5196(21)00251-5.
[30] D. Kim, R. Parajuli, G.J. Thoma, Life cycle assessment of dietary patterns in the United States: a full food supply chain perspective, Sustainability 12 (4) (2020) 1586, https://doi.org/10.3390/su12041586.
[31] D. Rose, M.C. Heller, A.M. Willits-Smith, R.J. Meyer, Carbon footprint of self-selected US diets: nutritional, demographic, and behavioral correlates, Am. J. Clin. Nutr 109 (3) (2019) 526–534, https://doi.org/10.1093/ajcn/nqy327.
[32] A. Willits-Smith, R. Aranda, M.C. Heller, D. Rose, Addressing the carbon footprint, healthfulness, and costs of self-selected diets in the USA: a population-based cross-sectional study, Lancet Planet. Health 4 (3) (2020) e98–e106, https://doi.org/10.1016/s2542-5196(20)30055-3.
[33] A.A. Musicus, D.D. Wang, M. Janiszewski, G. Eshel, S.A. Blondin, W. Willett, et al., Health and environmental impacts of plant-rich dietary patterns: a US prospective cohort study, Lancet Planet. Health 6 (11) (2022) e892–e900, https://doi.org/10.1016/S2542-5196(22)00243-1.
[34] US Department of Health and Human Services, Centers for Disease Control and Prevention, About the National Health and Nutrition Examination Survey [Internet], 2017 [cited 23 November 2022]. Available from: https://www.cdc.gov/nchs/nhanes/about_nhanes.htm.
[35] Z. Conrad, C. Kowalski, D. Dustin, L.K. Johnson, A. McDowell, M. Salesses, et al., Quality of popular diet patterns in the United States: evaluating the effect of substitutions for foods high in added sugar, sodium, saturated fat, and refined grains, Curr. Dev. Nutr. 12 (2022), nzac119.
[36] R. Freire, Scientific evidence of diets for weight loss: different macronutrient composition, intermittent fasting, and popular diets, Nutrition 69 (2020), 110549, https://doi.org/10.1016/j.nut.2019.07.001.
[37] C.F. Kirkpatrick, J.P. Bolick, P.M. Kris-Etherton, G. Sikand, K.E. Aspry, D.E. Soffer, et al., Review of current evidence and clinical recommendations on the effects of low-carbohydrate and very-low-carbohydrate (including ketogenic) diets for the management of body weight and other cardiometabolic risk factors: a scientific statement from the National Lipid Association Nutrition and Lifestyle Task Force, J. Clin. Lipid. 13 (5) (2019) 689–711.e1, https://doi.org/10.1016/j.jacl.2019.08.003.
[38] US Department of Agriculture, Agricultural Research Service, Food Patterns Equivalents Database (FPED) [Internet], 2021 [cited 31 May 2021]. Available from: www.ars.usda.gov/Services/docs.htm?docid=23871.
[39] J. Reedy, A.F. Subar, 90th anniversary commentary: diet quality indexes in nutritional epidemiology inform dietary guidance and public health, J. Nutr. 148 (10) (2018) 1695–1697, https://doi.org/10.1093/jn/nxy184.
[40] National Cancer Institute, National Institutes for Health, Overview and background of the Healthy Eating Index [Internet], 2020 [cited 31 May 2021]. Available from: https://epi.grants.cancer.gov/hei/.
[41] National Institutes of Health, National Cancer Institute, How to choose an analysis method dependent on purpose [Internet], 2022 [cited 4 October 2022]. Available from: https://epi.grants.cancer.gov/hei/tools.html.
[42] D. Levin, D. Noriega, C. Dicken, A.M. Okrent, M. Harding, M. Lovenheim, Examining food store scanner data: a comparison of the IRI InfoScan data with other data sets, 2008-2012 [Internet], US Department of Agriculture, Economic Research Service, 2018 [cited 31 May 2021]. Available from: https://www.ers.usda.gov/publications/pub-details/?pubid=90354.

[43] Z. Conrad, S. Reinhardt, R. Boehm, A. McDowell, Higher diet quality is associated with higher diet costs when eating at home and away from home: National Health and Nutrition Examination Survey, 2005-2016, Public Health Nutr 24 (2021) 5047–5057, https://doi.org/10.1017/s1368980021002810.
[44] US Department of Agriculture, Economic Research Service, National Household Food Acquisition and Purchase Survey [Internet]. 2012, 2013 [cited 31 May 2021]. Available from: https://www.ers.usda.gov/data-products/foodaps-national-household-food-acquisition-and-purchase-survey/.
[45] Center for Sustainable Systems, University of Michigan, Database of Food Impacts on the Environment for Linking to Diets [Internet], 2017 [cited 31 May 2021]. Available from: http://css.umich.edu/page/datafield.
[46] US Environmental Protection Agency, Food Commodity Intake Database (FCID) [Internet]. 2001, 2010 [cited 31 May 2021]. Available from: http://fcid.foodrisk.org/#.
[47] Z. Conrad, N.T. Blackstone, E.D. Roy, Healthy diets can create environmental trade-offs, depending on how diet quality is measured, Nutr. J. 19 (1) (2020) 117, https://doi.org/10.1186/s12937-020-00629-6.
[48] US Department of Agriculture, Economic Research Service, Loss-Adjusted Food Availability (LAFA) data series documentation [Internet], 2020 [cited 31 May 2021]. Available from: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/.
[49] K. O'Malley, A. Willits-Smith, D. Rose, Popular diets as selected by adults in the United States show wide variation in carbon footprints and diet quality, Am. J. Clin. Nutr. 117 (4) (2023) 701–708, https://doi.org/10.1016/j.ajcnut.2023.01.009.
[50] Z. Conrad, M. Karlsen, K. Chui, L. Jahns, Diet quality on meatless days: National Health and Nutrition Examination Survey (NHANES), 2007-2012, Public Health Nutr 20 (9) (2017) 1564–1573, https://doi.org/10.1017/s136898001700026x.
[51] H.W. Parker, M.K. Vadiveloo, Diet quality of vegetarian diets compared with nonvegetarian diets: a systematic review, Nutr. Rev. 77 (3) (2019) 144–160, https://doi.org/10.1093/nutrit/nuy067.
[52] G. Turner-McGrievy, M.D. Wirth, K.L. Hill, E.R. Dear, J.R. Hébert, Examining commonalities and differences in food groups, nutrients, and diet quality among popular diets, Clin. Nutr. ESPEN 41 (2021) 377–385, https://doi.org/10.1016/j.clnesp.2020.10.017.
[53] D. Tilman, M. Clark, Global diets link environmental sustainability and human health, Nature 515 (7528) (2014) 518–522, https://doi.org/10.1038/nature13959.
[54] M. Springmann, H.C. Godfray, M. Rayner, P. Scarborough, Analysis and valuation of the health and climate change cobenefits of dietary change, Proc. Natl Acad. Sci. USA 113 (15) (2016) 4146–4151, https://doi.org/10.1073/pnas.1523119113.
[55] M. Springmann, K. Wiebe, D. Mason-D'Croz, T.B. Sulser, M. Rayner, P. Scarborough, Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail, Lancet Planet. Health 2 (10) (2018) e451–e461, https://doi.org/10.1016/S2542-5196(18)30206-7.
[56] J.W. Finley, N.K. Fukagawa, Integrated data across multiple and diverse disciplines are essential for developing a sustainable food system, J. Soil Water Conserv. 74 (6) (2019) 632, https://doi.org/10.2489/jswc.74.6.632.
[57] P. He, K. Feng, G. Baiocchi, L. Sun, K. Hubacek, Shifts towards healthy diets in the US can reduce environmental impacts but would be unaffordable for poorer minorities, Nat. Food 2 (9) (2021) 664–672, https://doi.org/10.1038/s43016-021-00350-5.
[58] N.T. Blackstone, C.B. Norris, T. Robbins, B. Jackson, J.L. Decker Sparks, Risk of forced labour embedded in the US fruit and vegetable supply, Nat. Food 2 (9) (2021) 692–699, https://doi.org/10.1038/s43016-021-00339-0.
[59] A. Chaudhary, D. Gustafson, A. Mathys, Multi-indicator sustainability assessment of global food systems, Nat. Commun. 9 (1) (2018) 848, https://doi.org/10.1038/s41467-018-03308-7.
[60] Q. Marshall, A.L. Bellows, R. McLaren, A.D. Jones, J. Fanzo, You say you want a data revolution? Taking on food systems accountability, Agriculture 11 (5) (2021) 422.
[61] US Department of Agriculture, Agricultural Research Service, Food Intakes Converted to Retail Commodities Database [Internet], 2021 [cited 30 May 2021]. Available from: https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/ficrcd-overview/.
[62] A. Okrent, H. Elitzak, T. Park, S. Rehkamp, Measuring the value of the U.S. food system: revisions to the Food Expenditure Series [Internet], US Department of Agriculture, Economic Research Service, Washington, DC, 2018 [cited 24 October 2019]. Available from: https://www.ers.usda.gov/publications/pub-details/?pubid=90154.
[63] A.D. Liese, E. Wambogo, J.L. Lerman, C.J. Boushey, M.L. Neuhouser, S. Wang, et al., Variations in dietary patterns defined by the Healthy Eating Index 2015 and associations with mortality: findings from the dietary patterns methods project, J. Nutr. 152 (3) (2022) 796–804, https://doi.org/10.1093/jn/nxab383.