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Plant- and animal-protein diets in relation to sociodemographic drivers, quality, and cost: findings from the Seattle Obesity Study

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ABSTRACT

Background: Promoting plant-based proteins is at the forefront of many initiatives in public health nutrition.

Objectives: The aim of this study was to characterize the socio demographic drivers of plant-based protein diet consumption, and to study these in relation to diet quality and cost.

Methods: The Seattle Obesity Study series (SOS I and II) yielded the study sample ($n = 1636$). Sociodemographic data were obtained by survey self-report. Diet quality and cost came from the Fred Hutchinson Cancer Research Center Food-Frequency Questionnaire linked to retail food prices. The Healthy Eating Index 2010 (HEI-2010) and mean adequacy ratio (MAR) served as measures of diet quality. Linear regressions with robust standard errors examined associations.

Results: Total proteins contributed 16.8% of daily dietary energy. The breakdown by animal and plant proteins was 10.9% and 5.9%, respectively. The sociodemographic factors associated with plant-protein consumption were a positive attitude towards healthy eating and higher education but not income. Plant-protein diets were characterized by severalfold increases in nuts and seeds, soy and legumes, but much less meat, poultry, dairy, solid fats, and added sugars. Higher quartiles of plant-based diets were associated with significantly higher HEI-2010 (β: 13.0 from quartile 1 to quartile 4; 95% CI: 11.8, 14.3) and higher MAR (β: 6.0; 95% CI: 3.5, 8.5) with minimal impact on diet costs (β: 0.35; 95% CI: 0.04, 0.67). In contrast, higher quartiles of animal-protein diets were associated with higher diet costs (β: 1.07; 95% CI: 0.77, 1.36) but lower HEI-2010 (β: −3.2; 95% CI: −4.5, −1.9). Each additional 3% of energy from plant proteins was associated with an 8.4-unit increase in HEI-2010 (95% CI: 7.6, 9.1) and with a 4.1-unit increase in MAR (95% CI: 2.7, 5.5) with a minimal increase in diet cost (β: 0.28; 95% CI: 0.06, 0.50).

Conclusion: Plant-based protein diets may be a cost-effective way to improve diet quality at all levels of income. Future research needs to evaluate the quality of plant-based protein in relation to amino acids and health. *Am J Clin Nutr* 2019;0:1–10.

Keywords: plant-protein diets, animal-protein diets, diet cost, diet quality, protein consumption, attitudes, sociodemographic drivers

Introduction

The protein content of the US diet has been estimated at 14–16% of energy based on nationally representative NHANES (1–3) and large prospective cohort studies (4). Animal-based proteins from meat, poultry, seafood, and dairy continue to account for some 10% of daily energy intake. Plant-based proteins account for only 4–6% of daily energy intakes. Promoting plant-based proteins from whole grains, legumes, nuts, and seeds has recently received much attention as a sustainable approach to both diets and health (5).

The risk and benefits of different sources of proteins have been widely demonstrated in numerous studies, meta-analyses, and systematic reviews (6–11). Higher consumption of animal-based proteins has been linked to increased risk of type 2 diabetes, cardiovascular disease, and mortality (4, 12–16). Among different sources of animal-based proteins, red meats (beef, pork, and lamb) were more strongly linked with poor health outcomes and mortality as compared to white meats (poultry). In contrast, higher consumption of plant-based proteins has been linked with lower blood pressure, lower LDL, improved insulin sensitivity, lower obesity rates and lower risk of all-causes mortality (17–25). The consumption of nuts and seeds has been particularly associated with reduced blood lipid concentrations, oxidative stress, inflammation, hyperglycemia, and lower risk of cardiovascular and all-cause mortality (26–28). The Dietary Guidelines for Americans 2015–2020 pointed out that beef, chicken, pork, processed meats, and eggs are the most commonly consumed sources of proteins in the US diet (29). The recent EAT-Lancet report strongly advocates a shift towards plant-based dietary patterns (11).

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Abbreviations used: AHEI, Alternate Healthy Eating Index; FFQ, food-frequency questionnaire; FHCRC, Fred Hutchinson Cancer Research Center; HEI-2010, Healthy Eating Index 2010; MAR, mean adequacy ratio; MPED, My Pyramid Equivalents Database; SOS, Seattle Obesity Study.

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Although the health benefits of plant-protein diets have been widely studied, less is known about the sociodemographic and attitudinal drivers of plant-based protein consumption (30–32). Data on who selects plant-based protein and why remain limited (31). One popular view is that health-conscious consumers are driven to plant-based proteins for various health-related reasons (33–35). Another view is that plant-protein consumption is strongly age dependent and driven by millennials (36). Cost is another potential barrier linked to healthy eating (37–39). However, the impact of plant-based protein diets on diet cost remains unclear. Addressing some of these questions will help position plant-based proteins as a viable dietary option for population health.

The present study utilized a representative sample of Seattle-King County adults with rich data on sociodemographics, attitudes and preferences, and dietary and health variables to address these questions. The specific aims were the following: *1*) to identify socioeconomic, demographic, and attitudinal drivers of plant-protein compared with animal-protein diets; *2*) to examine the gradient in plant-protein compared with animal-protein diets consumption by diet cost and diet quality; and *3*) to characterize key foods or food groups that constitute plant-based compared with animal-based diets in this sample.

Methods

Participant sample

The ongoing population-based Seattle Obesity Study (SOS) has been conducted since 2008. The present analyses were based on 1636 male and female residents of Washington state who participated in SOS I and SOS II. Sampling and data collection procedures have been published previously (39, 40). Briefly, SOS I was a cross-sectional study of 2001 male and female adult (aged >21 y) residents of King County conducted over a period of 3 y (2008–2011). Participant recruitment and data collection were conducted over the telephone, following procedures used in the US Behavioral Risk Factor Surveillance System for Washington state. A stratified sampling scheme was used to ensure adequate representation by income and race/ethnicity. Each SOS I participant completed a telephone-based behavior survey that addressed sociodemographics, attitudes toward food and health, diet quality, and health outcomes. The Fred Hutchinson Cancer Research Center (FHCRC) food-frequency questionnaire (FFQ) was used to assess dietary intakes, a standard dietary assessment tool widely used in large-scale studies on population health and disease risk (41, 42). SOS I yielded 1314 participants with complete demographic, attitudinal, health, and dietary data.

SOS II, conducted during 2011–2015, was a longitudinal study of 516 King County adults, identified through a random stratified sampling scheme. Eligible adults were in the >21–55 y age range, household gatekeepers, and without any mobility issues. Study details have been published previously (43–45). Each SOS II participant completed a computer-based behavior survey that addressed sociodemographics, attitudes toward food and health, diet quality, and health outcomes. The FHCRC FFQ was used to assess dietary intakes. SOS II yielded 490 participants with complete demographic, attitudinal, health, and dietary data. All the study procedures for both SOS I and II were approved by the University of Washington Institutional Review Board. For the present analyses, data from SOS I and II were pooled to yield a total sample of 1804 adults. After taking missing data on key variables of interest such as age, race, income, and education into account, the final analytic sample consisted of 1636 adults.

Sociodemographic and attitudinal variables

Data on age, gender, race/ethnicity, annual household income, highest education completed, and marital status were obtained by survey self-report. Attitudes were captured from standard questions analogous to the one used in national-level surveys (NHANES) and in other health studies (46). Each respondent was presented with the statement: "It is important to me that foods I usually eat are healthy." The responses were elicited on a 5-point Likert scale from "strongly agree" to "strongly disagree." For analytic purposes, the variable was coded into 3 main categories that best suited the data distribution obtained: highly positive (strongly agree), somewhat positive (somewhat agree), and the rest (neutral and disagrees).

Plant and animal proteins

The FHCRC FFQ is a widely used dietary data collection instrument. Each respondent is asked to provide self-reported data on frequency and amount of consumption for a list of 150 commonly consumed foods and beverages visible to them. Each of these 150 food items are constituted by ≥1–4 specific foods in the forms commonly consumed in the US population, yielding a more expansive database of 384 items that is not visible to the respondent. For example: FFQ line item "pizza" that is visible to the respondent is constituted by 4 types of meat and vegetarian pizzas in the database that builds the FFQ. The nutrient-level information for each of these pizzas is linked with the Minnesota Nutrition Database to calculate energy, and macro- and micronutrient content, including the amount of total protein, animal proteins, and plant proteins. This procedure is repeated for each FFQ line item and summed across all the line items to compute average daily nutrient intakes for each respondent. This is a standard procedure well-established by the FHCRC and widely used in epidemiologic studies. For analytic purposes in the present study, the percentages of total daily energy from both plant and animal proteins were computed for each respondent. This is a standard approach in the literature.

Energy-adjusted daily diet cost

Estimates of individual-level daily diet cost were obtained by joining retail prices to each of the 384 FFQ foods that build the expansive FFQ database. This procedure treated the food price vector as a "nutrient," following the same procedures as established to assess the energy and nutrient composition of the diets. The detailed procedures of estimating diet costs from the FFQ have been described in detail previously (39, 47), and this approach has been widely used in the epidemiologic literature to study diet costs, diet quality, and health. For the present study, a daily diet cost variable was obtained for each participant from the SOS I and II FFQ data. For analytic purposes, the daily diet cost variable for each respondent was adjusted to 1800 kcal/d to compute a daily diet cost estimate for isocaloric diets. This is a standard practice in the epidemiologic literature, and accounts for differences in diet costs due to differences in calorie intakes. Energy-adjusted diet cost ($/1800 kcal) served as the analytic variable in the present study.

Diet quality measures

The Healthy Eating Index 2010 (HEI-2010) was used an indicator of diet quality. HEI-2010 is a federal measure of diet quality used to assess compliance with US 2010 dietary guidelines (48, 49). The HEI-2010 score reflects an overall diet quality computed from 12 components: 9 adequacy components where higher score reflects higher intake (total fruit, whole fruit, total vegetables, greens and beans, whole grains, dairy, total protein foods, seafood and plant proteins, and fatty acids), and 3 moderate components to limit where higher score reflects lower intake (refined grains, sodium, and empty calories). The development of HEI-2010 for the SOS series has been published previously (36). HEI-2010 provides a continuous score on the scale of 0–100, where a higher score reflects a higher diet quality. The mean adequacy ratio (MAR) was used as a measure of nutrient density of the diet. MAR, widely used in previous studies (39, 50, 51), is a truncated index of the percentage of daily recommended intakes for key nutrients. Ten key nutrients were used to compute this indicator, namely vitamins A, C, D, B-12, calcium, iron, magnesium, potassium, folate, and fiber. Most of these nutrients continue to be expressed as the nutrients of concern in Dietary Guidelines for Americans (29, 52).

The My Pyramid Equivalents Database (MPED) was used as another measure of diet quality. MPED reflects the number of serving equivalents for each food group consumed. It is a standard measure created by the USDA (53). In the present study, MPEDs for each of the key food groups and foods were examined, namely total grains, total fruits, total vegetables, legumes, nuts and seeds, soy products, total milk, eggs, red meat, poultry, fish, added sugars, and solid fats. Distinction was made among red meats, poultry, and fish.

Statistical Data Analyses

First, descriptive statistics, i.e., means and SDs, examined the consumption of plant compared with animal proteins by key sociodemographic and attitudinal indicators in this sample. Pairwise comparisons tested for specific groups that were statistically different for each sociodemographic and attitudinal indicator.

Second, linear regression analyses examined sociodemographic and attitudinal drivers of plant- compared with animal-protein consumption. The energy percentages from plant proteins compared with animal proteins were the primary dependent variables, with gender, race/ethnicity, income, education, and importance of nutrition as the independent variables of interest. Model 1 examined the bivariate association of each independent variable with the outcome, whereas Model 2 was a multivariate model that took all the variables and covariates into account.

Third, a series of linear regression models examined the associations of plant compared with animal protein based on diet cost and diet quality indicators. The percentage energy from plant-protein and animal-protein variables were each converted into quartiles as primary independent variables for analytic purposes. Energy-adjusted diet cost, HEI-2010, and MAR score each served as the primary dependent variables of interest. Bivariate and multivariate linear regressions with robust standard errors examined quartiles of plant-protein intake in relation to energy-adjusted diet cost, HEI-2010 scores, and MAR score separately. In adjusted models, the covariates included age, gender, race/ethnicity, income, and education. Additional regression analyses examined the change in energy-adjusted diet cost, HEI, and MAR scores with every 3% increment in percentage energy from plant-proteins. Trend tests were conducted to estimate the *P* value. The same set of analyses were replicated to examine these associations with animal-protein intake.

Fourth, to characterize diets higher in plant proteins compared with animal proteins, the mean $\pm$ SD MPED values were computed for key foods and food groups by quartiles of plant-protein and animal-protein consumption through the use of descriptive statistics. *P* values were computed to test for trends.

All the analyses were conducted with STATA version 14.0. A P value of <0.05 was used to indicate statistical significance.

Results

Sample distribution

The study sample was predominantly female (65%), white (85%), college educated (57%), and married (53%). The sample was evenly distributed by age from <40 to ≥60 y, and by household income from <US$50,000 to ≥US$100,000.

Proteins accounted for a mean $\pm$ SD of 16.8% $\pm$ 3.1% of total daily energy with a median of 16.7% (5th–95th percentile: 11.9, 22.1). Plant-based protein accounted for a mean of 5.9% $\pm$ 1.7% of total daily energy with a median of 5.6% (5th–95th percentile: 3.4, 9.3), whereas animal-based protein accounted for a mean of 10.9% $\pm$ 3.6% with the median of 10.7% (5th–95th percentile: 5.2, 17.1).

Table 1 shows that the percentage energy from total protein did not vary by age, education, or race/ethnicity. However, females, those with annual household income ≥US$100,000 and those who were married had slightly higher total protein intake ($P < 0.05$ for each). In terms of percentage energy from plant proteins, there were no significant differences by age, race/ethnicity, income, and marital status. Females, respondents with higher education, and those with a highly positive attitude towards healthy eating were more likely to consume plant-based proteins in the diet. In contrast, higher-income, lower-educated groups and those who did not prioritize eating healthy foods consumed more animal-based proteins in the diet.

Sociodemographic and attitudinal correlates of plant-based protein consumption

In bivariate linear regressions (unadjusted models), placing importance on healthy eating was associated with significantly higher percentage energy from plant proteins (β: 1.40 among

TABLE 1 Sociodemographic and attitudinal factors by total-protein, plant-protein and animal-protein consumption[1]

	n	% energy from total protein	% energy from plant protein	% energy from animal protein
Overall	1804			
Mean ± SD		16.8 ± 3.1	5.9 ± 1.7	10.9 ± 3.6
Median (5th–95th percentile)		16.7 (11.9, 22.1)	5.6 (3.4, 9.3)	10.7 (5.2, 17.1)
Age, y				
<40	240	16.8 ± 2.8	6.1 ± 1.8	10.7 ± 3.7
40–<50	454	16.7 ± 3.0	6.0 ± 1.8	10.7 ± 3.6
50–<60	541	17.0 ± 3.2	5.8 ± 1.7	11.2 ± 3.6
≥60	544	16.6 ± 3.3	5.7 ± 1.6	10.9 ± 3.6
Gender				
Male	631	16.5 ± 3.1	5.6 ± 1.8	10.8 ± 3.7
Female	1173	16.9 ± 3.1**	6.0 ± 1.7***	10.9 ± 3.6
Race/ethnicity				
Whites	1545	16.8 ± 3.1	5.8 ± 1.7	10.9 ± 3.6
Nonwhites	246	16.9 ± 3.4	6.1 ± 1.9	10.7 ± 3.7
Income, US$				
<50,000	591	16.5 ± 3.1	5.8 ± 1.8	10.6 ± 3.6
50,000–<100,000	579	16.7 ± 3.0	5.9 ± 1.7	10.7 ± 3.6
≥100,000	466	17.3 ± 3.1***	5.8 ± 1.7	11.4 ± 3.7***
Education, y				
≤12	285	16.6 ± 3.3	5.4 ± 1.6	11.1 ± 3.6
12–<16	477	17.0 ± 3.2	5.6 ± 1.7***	11.3 ± 3.7
≥16	1036	16.7 ± 3.0	6.1 ± 1.7*	10.6 ± 3.6*
Marital status				
Married	968	17.0 ± 3.0	5.8 ± 1.7	11.1 ± 3.6
Others	827	16.6 ± 3.2**	5.8 ± 1.8	10.7 ± 3.6*
Important to me that foods I eat are healthy				
Disagree/neutral	93	16.5 ± 3.3	4.8 ± 1.4	11.6 ± 3.6
Somewhat agree	597	16.7 ± 3.2	5.4 ± 1.4***	11.3 ± 3.5
Strongly agree	1113	16.8 ± 3.0	6.2 ± 1.8***	10.6 ± 3.7**

[1]Values are means ± SDs or medians (5th–95th percentiles). Significance of pairwise comparisons are indicated by asterisks as follows: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$. The first category was the reference for each sociodemographic and attitudinal measure. *indicates those groups that were statistically significantly different from the reference category.

the "strongly agree" group). Relatively weaker but significant effects were observed for gender (β: −0.35 for males, $P < 0.001$), race (β: −0.28 for whites), and education (β: 0.26 among 12–<16 y, and 0.69 among ≥16 y of education) (**Model 1**). The observed associations slightly attenuated but remained strong and significant in the adjusted model (**Model 2**). Among all the indicators, a positive attitude towards healthy eating was most strongly associated with higher plant-protein consumption (β: 1.25 among the "strongly agree" group) followed by education (β: 0.56 among college graduates). No significant associations were observed between income and plant-protein intake in both unadjusted and adjusted models.

In contrast, higher-income groups were associated with significantly higher percentage energy from animal proteins even after adjusting for covariates (β: 1.21 among those with income ≥US$100,000, $P < 0.001$) (**Table 2**, Model 2). Higher education and those with a positive attitude towards healthy eating, on the other hand, were associated with significantly lower intake of animal proteins (Table 2, Model 2: β: −0.63 among college graduates, $P < 0.05$; β: −1.18 among "strongly agree" group, $P < 0.05$). Among all the socioeconomic and attitude indicators, income and attitude towards healthy eating were strongly associated with animal-protein consumption, followed by education.

Plant-based protein consumption in relation to diet cost and diet quality

Table 3 presents bivariate and multivariate associations of protein consumption with dietary and health indicators. Higher quartiles of percentage energy from plant proteins were associated with higher energy-adjusted diet cost in unadjusted models (β: 0.37 in quartile 3 and 0.64 in quartile 4 with quartile 1 as the reference category, $P < 0.05$). However, the associations attenuated significantly in the adjusted model. Only the highest quartile of plant-protein consumption remained associated with higher energy-adjusted diet cost (β: 0.35 in quartile 4 with quartile 1 as the reference), after taking sociodemographic and other covariates into account.

In contrast, a much stronger association was observed for both of the diet quality indicators, i.e., HEI-2010 and MAR. A dose-response relation was observed such that every quartile of percentage energy from plant protein was associated with significantly higher HEI-2010 scores (β: 5.93, 9.44, and 13.08 for quartile 2, quartile 3, and quartile 4, respectively, with quartile 1 as the reference category), and MAR (β: 2.19, 3.92, and 6.05, respectively). Additional analyses showed that every 3% increment in total energy from plant proteins was associated with significantly higher HEI-2010 scores (β: 8.4; 95% CI: 7.6, 9.1), higher MAR scores (β: 4.1; 95% CI: 2.7, 5.5), and only a minimal

TABLE 2 Linear regression analyses examining associations of sociodemographic and psychosocial indicators with consumption of plant and animal proteins[1]

	Model 1			Model 2		
	Coefficient	*P* value	95% CI	Coefficient	*P* value	95% CI
Percentage of energy from plant proteins						
Gender						
Female	Ref.	—	—	Ref.	—	—
Male	−0.35	<0.001	−0.52, −0.18	−0.22	0.012	−0.39, −0.04
Race/ethnicity						
Nonwhites	Ref.	—	—	Ref.	—	—
Whites	−0.28	0.017	−0.52, −0.05	−0.34	0.005	−0.59, −0.10
Income, US$						
<50,000	Ref.	—	—	Ref.	—	—
50,000–<100,000	0.05	0.621	−0.15, 0.25	−0.11	0.262	−0.31, 0.08
≥100,000	0.00	0.999	−0.21, 0.21	−0.27	0.016	−0.49, −0.04
Education, y						
≤12	Ref.	—	—	Ref.	—	—
12–<16	0.26	0.040	0.12, 0.52	0.11	0.400	−0.15, 0.38
≥16	0.69	<0.001	0.46, 0.92	0.56	<0.001	0.31, 0.82
Marital status						
Married	Ref.	—	—	Ref.	—	—
Others	0	0.964	−0.16, 0.16	−0.03	0.688	−0.22, 0.14
Important to me that foods I eat are healthy						
Disagree/neutral	Ref.	—	—	Ref.	—	—
Somewhat agree	0.57	0.002	0.20, 0.95	0.50	0.013	0.10, 0.89
Strongly agree	1.40	<0.001	1.03, 1.76	1.25	<0.001	0.87, 1.64
Percentage of energy from animal proteins						
Gender						
Female	Ref.	—	—	Ref.	—	—
Male	−0.11	0.529	−0.46, 0.24	−0.21	0.257	−0.58, 0.15
Race/ethnicity						
Nonwhites	Ref.	—	—	Ref.	—	—
Whites	0.17	0.491	−0.31, 0.66	0.09	0.732	−0.42, 0.60
Income, US$						
<50,000	Ref.	—	—	Ref.	—	—
50,000–<100,000	0.11	0.582	−0.30, 0.53	0.33	0.132	−0.09, 0.76
≥100,000	0.83	<0.001	0.39, 1.27	1.21	<0.001	0.74, 1.69
Education, y						
≤12	Ref.	—	—	Ref.	—	—
12–<16	0.20	0.461	−0.33, 0.73	0.29	0.317	−0.28, 0.86
≥16	−0.52	0.031	−1.00, −0.04	−0.63	0.021	−1.17, −0.09
Marital status						
Married	Ref.	—	—	Ref.	—	—
Others	−0.40	0.020	−0.74, −0.06	−0.10	0.602	−0.49, 0.28
Important to me that foods I eat are healthy						
Disagree/Neutral	Ref.	—	—	Ref.	—	—
Somewhat agree	−0.32	0.422	−1.12, 0.47	−0.42	0.326	−1.27, 0.42
Strongly agree	−1.02	0.009	−1.79, −0.25	−1.18	0.005	−2.01, 0.36

[1]Model 1 = separate bivariate linear regression models with no mutual adjustment of covariates. Model 2 = a multivariate linear regression model adjusted for age, gender, race/ethnicity, income, education, and attitude towards heathy eating.

increase in energy-adjusted diet cost (β: 0.28; 95% CI: 0.06, 0.50).

The associations with animal protein consumption yielded contrasting results (Table 3). Higher quartiles of percentage energy from animal proteins was associated with significantly higher energy-adjusted diet costs (β: 0.52 for quartile 3 and 1.07 for quartile 4 with quartile 1 as the reference category). The associations remained strong and significant both in unadjusted and adjusted models. With HEI-2010, higher quartiles of animal protein consumption were associated with significantly lower HEI-2010 scores both in the unadjusted (β: −1.92 and −2.65 for quartile 3 and quartile 4, respectively, with quartile 1 as the reference category) and adjusted models (β: −2.43 and −3.24 for quartile 3 and quartile 4, respectively). Higher quartiles of animal protein were not associated with any significant increase in MAR. Additional bivariate and multivariate analyses showed that every

TABLE 3 Quartiles of plant compared with animal proteins in association with diet cost, HEI-2010, and nutrient density metrics: linear regression analyses[1]

	Quartile 1	Quartile 2	Quartile 3	Quartile 4	β per 3% increment (95% CI)
Percentage of energy from plant proteins					
n	451	451	451	451	1804
Mean ± SD	3.9 ± 0.6	5.1 ± 0.3	6.1 ± 0.3	8.2 ± 1.4	5.9 ± 1.7
Median (5th–95th percentile)	4.1 (2.6, 4.6)	5.2 (4.7, 5.6)	6.1 (5.6, 6.7)	7.7 (6.8, 11.2)	5.6 (3.4, 9.3)
Energy-adjusted diet cost					
Unadjusted model, coefficient (95% CI)	0 (Ref.)	0.26 (−0.02, 0.54)	0.37 (0.09, 0.65)**	0.64 (0.36, 0.92)***	0.41 (0.21, 0.61)***
Adjusted model, coefficient (95% CI)[2]	0 (Ref.)	−0.03 (−0.31, 0.24)	0.13 (−0.15, 0.42)	0.35 (0.04, 0.67)*	0.28 (0.06, 0.50)*
HEI-2010					
Unadjusted model, coefficient (95% CI)	0 (Ref.)	6.27 (5.12, 7.43)***	9.96 (8.80, 11.11)***	13.20 (12.05, 14.35)***	8.38 (7.61, 9.16)***
Adjusted model, coefficient (95% CI)[2]	0 (Ref.)	5.93 (4.68, 7.18)***	9.44 (8.21, 10.67)***	13.08 (11.85, 14.30)***	8.40 (7.62, 9.18)***
Nutrient density (MAR)					
Unadjusted model, coefficient (95% CI)	0 (ref)	2.86 (0.54, 5.18)*	5.16 (2.84, 7.49)***	7.36 (5.03, 9.68)***	4.96 (3.62, 6.30)***
Adjusted model, coefficient (95% CI)[2]	0 (ref)	2.19 (−0.28, 4.67)	3.92 (1.42, 6.42)**	6.05 (3.57, 8.53)***	4.18 (2.77, 5.59)***
Percentage of energy from animal proteins					
n	451	451	451	451	1,804
Mean ± SD	6.5 ± 1.7	9.7 ± 0.6	11.9 ± 0.7	15.6 ± 2.3	10.9 ± 3.6
Median (5th–95th percentile)	6.9 (2.9, 8.4)	9.7 (8.6, 10.6)	11.9 (10.8, 13.1)	14.9 (13.3, 20.5)	10.7 (5.2, 17.1)
Energy-adjusted diet cost					
Unadjusted model, coefficient (95% CI)	0 (Ref.)	0.21 (−0.05, 0.49)	0.58 (0.30, 0.85)***	1.18 (0.90, 1.46)***	0.40 (0.31, 0.49)***
Adjusted model, coefficient (95% CI)[3]	0 (Ref.)	0.26 (−0.01, 0.53)	0.52 (0.24, 0.79)***	1.07 (0.77, 1.36)***	0.37 (0.27, 0.46)***
HEI-2010					
Unadjusted model, coefficient (95% CI)	0 (Ref.)	−0.79 (−2.10, 0.52)	−1.92 (−3.23, −0.61)**	−2.65 (−3.96, −1.34)***	−0.98 (−1.38, −0.59)***
Adjusted model, coefficient (95% CI)[3]	0 (Ref.)	−0.64 (−2.04, 0.76)	−2.43 (−3.74, −1.11)***	−3.24 (−4.58, −1.91)***	−1.22 (−1.61, −0.82)***
Nutrient density (MAR)					
Unadjusted model, coefficient (95% CI)	0 (Ref.)	0.20 (−2.14, 2.54)	3.40 (1.05, 5.75)**	1.22 (−1.11, 3.57)	0.30 (−0.39, 0.99)
Adjusted model, coefficient (95% CI)[2]	0 (Ref.)	0.18 (−2.31, 2.68)	2.58 (0.30, 4.87)*	1.29 (−1.09, 3.68)	0.36 (−0.34, 1.07)

[1] Asterisks reflect P values from linear regression models: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$. HEI-2010, Healthy Eating Index 2010; MAR, mean adequacy ratio.

[2] A multivariate model mutually adjusted for age, gender, race/ethnicity, income, education and percentage of energy from plant proteins.

[3] A multivariate model mutually adjusted for age, gender, race/ethnicity, income, education, and percentage of energy from animal proteins.

3% increment in energy from animal proteins was associated with relatively higher diet costs (β: 0.37; 95% CI: 0.27, 0.46), with lower HEI-2010 scores (β: −1.22; 95% CI: −1.61, −0.82) and no significant change in MAR scores.

Characterizing plant and animal protein diets by MPEDs for each food group

Table 4 shows mean ± SD MPED values for each food group by quartiles of percentage energy from plant proteins compared with animal proteins. Diets with higher energy from plant proteins were characterized by a severalfold increase in the MPED values for soy products, a 193% increase in nuts and seeds, and a 171% increase in the consumption of legumes, with a significant drop in animal proteins. Among various sources of animal proteins, the highest decline was in the intake of red meats (60%), followed by total dairy (43%), with a 38% decline in poultry. The P-trend was <0.05 for each. There was a 7.5% decline in fish intake. Higher quartiles of plant-based diets were also associated with a 25–50% increase in total grains, fruits, and vegetables, and a significant decline in the intake of solid fats and added sugars. In contrast, higher quartiles of diets with animal proteins had the highest increase in the MPED values for red meats (by 258%), followed by poultry (204%), dairy (99%), and fish (83%), but significant decline in soy (−86%), legumes (−50%), and nuts and seeds (−48%). Animal-protein diets also tend to be higher in solid fats (21%) but lower in total fruits (−38%), vegetables (−12%), and total grains (−22%).

Discussion

This study examined the gradient in plant- compared with animal-protein consumption by sociodemographic and attitudinal measures, diet costs, and quality among US adults. The study findings are directly relevant to the recent efforts of the EAT-Lancet initiative (11).

Among sociodemographic and attitudinal measures, being a female, non-white, having higher education, and placing importance on healthy eating were significant correlates of plant-protein consumption. Education was positively associated with plant-protein diets, but income had no association whatsoever. Animal-based protein diets, on the other hand, were driven by higher incomes, lower education, and not placing importance on healthy eating. In terms of the strength of the associations, placing importance on healthy eating seemed to be the strongest correlate of plant-protein consumption, followed by education. A clear positive dose-response relation was observed. Higher income, on the other hand, seemed to drive animal-protein consumption, followed by attitudes. These data resonate with a Nielsen Global survey which suggested that people who perceive superior nutritional value and positive health effects

TABLE 4 Mean MPED values for each food group/subgroup by quartiles of plant- compared with animal-protein consumption[1]

MPED category	Quartile 1 ($n = 451$)	Quartile 2 ($n = 451$)	Quartile 3 ($n = 451$)	Quartile 4 ($n = 451$)	*P*-trend	% change from Q1 to Q4
Percentage of energy from plant proteins						
Total grains (number of ounce equivalents)	4.26 (2.98)	4.80 (2.59)	4.99 (2.79)	5.35 (2.94)	<0.001	26%
Total fruits group (number of cup equivalents)	1.31 (1.21)	1.51 (1.12)	1.77 (1.60)	1.74 (1.27)	<0.001	33%
Total vegetables group (number of cup equivalents)	1.69 (0.93)	1.96 (1.02)	2.23 (1.14)	2.52 (1.33)	<0.001	49%
Legumes (ounce equivalents)	0.07 (0.09)	0.09 (0.10)	0.12 (0.11)	0.19 (0.23)	<0.001	171%
Nuts and seeds (ounce equivalents)	0.56 (0.59)	0.81 (0.85)	1.12 (1.16)	1.64 (1.55)	<0.001	193%
Soy (ounce equivalents)	0.02 (0.04)	0.06 (0.13)	0.12 (0.25)	0.56 (0.92)	<0.001	2700%
Total milk group (number of cup equivalents)	2.29 (1.87)	1.76 (1.25)	1.59 (1.13)	1.31 (1.10)	<0.001	−43%
Eggs (ounce equivalents)	0.57 (0.67)	0.46 (0.53)	0.42 (0.41)	0.40 (0.48)	<0.001	−30%
Red meat (ounce equivalents)	2.18 (1.84)	1.88 (1.64)	1.49 (1.29)	0.87 (0.96)	<0.001	−60%
Poultry (ounce equivalents)	1.17 (1.18)	1.07 (0.90)	0.98 (0.84)	0.73 (0.73)	<0.001	−38%
Fish (ounce equivalents)	0.80 (0.88)	0.83 (0.83)	0.77 (0.75)	0.74 (0.78)	<0.05	−7.5%
Added sugar (teaspoon equivalents)	13.7 (11.2)	10.9 (7.4)	10.1 (6.0)	8.60 (5.0)	<0.001	−59%
Solid fats (gram equivalents)	40.3 (28.4)	32.2 (18.2)	28.9 (17.4)	23.7 (13.3)	<0.001	−41%
Percentage of energy from animal proteins						
Total grains (number of ounce equivalents)	5.31 (3.0)	5.05 (2.95)	4.90 (2.58)	4.14 (2.74)	<0.001	−22%
Total fruits group (number of cup equivalents)	1.97 (1.84)	1.62 (1.16)	1.51 (1.04)	1.23 (0.96)	<0.001	−38%
Total vegetables group (number of cup equivalents)	2.25 (1.33)	2.02 (1.06)	2.14 (1.12)	1.98 (1.07)	<0.01	−12%
Legumes (ounce equivalents)	0.16 (0.20)	0.12 (0.14)	0.11 (0.13)	0.08 (0.10)	<0.001	−50%
Nuts and seeds (ounce equivalents)	1.43 (1.44)	1.09 (1.19)	0.88 (0.97)	0.74 (0.86)	<0.001	−48%
Soy (ounce equivalents)	0.42 (0.87)	0.17 (0.44)	0.10 (0.25)	0.06 (0.17)	<0.001	−86%
Total milk group (number of cup equivalents)	1.16 (0.82)	1.59 (1.07)	1.88 (1.30)	2.31 (1.95)	<0.001	99%
Eggs (ounce equivalents)	0.36 (0.38)	0.44 (0.55)	0.49 (0.52)	0.56 (0.65)	<0.001	56%
Red meat (ounce equivalents)	0.70 (0.75)	1.29 (1.09)	1.92 (1.36)	2.51 (2.04)	<0.001	258%
Poultry (ounce equivalents)	0.47 (0.51)	0.90 (0.72)	1.15 (0.92)	1.43 (1.21)	<0.001	204%
Fish (ounce equivalents)	0.54 (0.58)	0.72 (0.64)	0.88 (0.80)	0.99 (1.05)	<0.001	83%
Added sugar (teaspoon equivalents)	11.40 (8.6)	11.90 (9.1)	10.80 (7.1)	9.20 (6.4)	<0.001	−19%
Solid fats (gram equivalents)	26.8 (15.8)	31.2 (21.3)	34.5 (21.2)	32.5 (24.1)	<0.001	21%

[1] *P*-trend values were obtained from a linear regression model. MPED, My Pyramid Equivalents Database; Q, quartile.

of plant-based proteins tend to gravitate towards higher plant-protein consumption (54). Data from Mintel also suggest that health-centric attributes were highly influential in the uptake of plant-based proteins (33). These findings provide insights into modifiable factors to promote plant-based dietary patterns.

The demographic drivers of overall protein consumption in the present study are consistent with findings from NHANES 1988–1991 (3) and that from a recent study based on French adults (31). However, the distinction made between plant and animal proteins in this study is new. Although there is some evidence of higher plant-protein intakes among younger age groups (36), no age effect was observed in this sample. This could be attributed to the underrepresentation of younger age groups in this study. Further studies with a wider age distribution of US adults could help fully investigate the effect of age on plant-protein compared with animal-protein diets.

Diets with higher energy from plant-based proteins were in turn found to be much higher quality. Such diets had significantly higher HEI scores and higher nutrient densities. Higher energy from animal proteins, on the contrary, had significantly lower HEI scores and no improvement in nutritional quality. Every 3% increment in percentage energy from plant proteins was associated with, on average, an 8.4-unit increase in HEI-2010 scores and a 4.1-unit increase in nutrient density. Consistent findings were obtained with the use of both HEI (a food group–based federal measure of diet quality) (48) and MAR [capturing nutrients of concern according to Federal Dietary Guidelines (39, 50)]. In a recent prospective cohort analyses based on 131,000 men and women with repeated dietary data from FFQs for ≤32 y, replacing 3% energy from varying sources of animal-based proteins with plant-based proteins was associated with substantial decline in overall mortality (4). Food group–level analyses revealed that such plant-based diets were constituted by a severalfold increase in soy products, nuts, and seeds, followed by legumes; and significantly lower amounts of red meats, poultry, and dairy in the present sample. Among different sources of animal proteins, red meats had the highest decline, followed by poultry. There was relatively a weaker decline in fish consumption. In the total dairy group, milk consumption also declined significantly, whereas yogurt and cheese consumption remained constant. Plant-protein diets were also significantly higher in fruits and vegetables as well as grains, but lower in solid fats and added sugars in this study. This may explain the observed positive effects of plant-protein diets on HEI-2010 scores and nutritional adequacy. In contrast, diets higher in animal proteins were severalfold higher in red meats, poultry, and milk, followed by fish. Those diets also tend to be high in solid fats, but significantly lower in fruits and vegetables, nuts, and seeds. These trends continue to follow the consumption patterns observed among US adults in NHANES 1988–1991 (3). The present findings also resonate with a recent systematic review that suggests that vegetarian diets have much higher HEI-2010 scores (4.5–16.4 points higher in 9 out of 12 studies) and are more likely to adhere to dietary recommendations for plant proteins, fruits, whole grains, and seafood (55). A positive association between plant-protein diets and dietary nutritional adequacy was also observed among French adults (31). The higher diet quality of plant-based diets may explain its association with improved health outcomes as consistently observed in the literature (11).

This is one of the first studies to compare plant-protein diets with animal-protein diets in terms of cost. In general, healthier diets have been linked with higher diet costs per calorie irrespective of the measure of diet quality used (38, 47, 56–59). However, the relation between plant-based diets and costs has not been explored much. The present study suggests that isocaloric diets higher in plant-based sources of proteins need not cost more. Diets with more energy provided by plant proteins were found to have a minimal increase in costs compared with diets containing lower energy from plant proteins. On the contrary, a stronger diet cost gradient was observed with higher consumption of animal protein. These diet cost estimates were based on FFQs, a standard, widely used technique in the literature (39, 47). This technique does reflect differences in diet costs due to differences in diet quality, and not merely due to price differences of the same food item across respondents. In a recent comprehensive review of food prices by Rao et al. (60), Mediterranean dietary patterns and patterns based on fruit and vegetable intake did not show significant price difference either. This could be attributed to the fact that plant-based sources of proteins, such as legumes, soy products, nuts, and seeds, provide relatively inexpensive ways of maximizing diet quality. This is consistent with findings from Bernstein et al. (38) based on data on 78,191 participants in the Nurses' Health Study with dietary data from FFQs. Greater spending on nuts and seeds, beans, soy, and whole grains was associated with much higher increase in Alternate Healthy Eating Index (AHEI) score, whereas higher spending on meats and dairy was associated with lower AHEI scores. These findings together suggest that plant-protein diets may be one approach to achieving higher-quality, nutritionally adequate diets with no or minimal increase in diet costs.

The study had some strengths and limitations: *1*) SOS is one of the few studies with rich data on sociodemographic and attitudinal measures, dietary intakes, and diet costs, allowing these factors to be studied simultaneously among a free-living sample of US adults. Although the findings from the present study are based on a relatively small sample, the distribution of total protein consumption (16% of the total dietary energy), and breakdown by plant compared with animal protein (6% compared with 10%, respectively) are highly consistent with large prospective cohort studies, namely the Nurses' Health Study and Health Care Professionals Cohort based on 131,342 adults (4). Consistent with the figures from NHANES 1988–1991 (3) and NHANES 2007–2010 (2), animal proteins continue to be the major source of proteins in the present sample as well (>60%), with ∼30% from plant proteins. *2*) The SOS sample was skewed by age, gender, income, and education, some of which are distinct characteristics of the Seattle population. We anticipate that the observed associations will be stronger with a more diverse sample in terms of sociodemographic variables. *3*) The role of attitudes was studied via a question that is a standard previously validated question from NHANES. Further studies with more data on attitudinal measures, including taste, cost, and convenience, will allow for a more in-depth investigation of the psychosocial factors involved. *4*) HEI-2010 was the most recent version of diet quality that was available for analyses. However, our findings from HEI-2010 are consistent with those observed with AHEI by Bernstein et al. (38). Sensitivity analyses with the most recent version of HEI (HEI-2015), which was available for only a subset of the study respondents, yielded consistent findings. *5*) Dietary data obtained from FFQs did not allow analyses of plant-protein compared with animal-protein diets by specific type of food or by name of the food item. Future studies based on 24-h recalls or actual food purchases will help to fully explore this domain. *6*) The diet cost estimates were based on the FHCRC FFQ dietary tool, a standard, previously validated procedure used in the literature to study diet costs and diet quality. However, further studies with additional data on actual food purchases and expenditures will help validate the low cost of plant-protein diets. *7*) The cross-sectional nature of the study does not allow causality to be established in the associations observed.

To summarize, the recent EAT-Lancet initiative promotes an immediate shift towards plant-based dietary patterns as a sustainable solution to healthier diets and planet (11). Such patterns are characterized by higher intakes of fruits, vegetables, nuts and seeds, legumes, and whole grains with limited intake of animal-based sources, saturated fats, and added sugars. Our findings suggest that it may indeed be feasible to achieve such diets at no additional cost. Promoting higher education and motivating consumers to place importance on healthy eating could be strategies to encourage the wider population to make such shifts. Further research is needed to identify those salient dietary patterns of plant-protein diets across wider representations of income, ethnicities, cultures, and geography. Parallel research is underway to evaluate the quality of plant-protein diets in terms of their amino acid content and adequacy in the population.

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