Health and environmental impacts of plant-rich dietary patterns: a US prospective cohort study

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Summary

Background Diets that are rich in animal-based foods threaten planetary and human health, but plant-rich diets have varied health and environmental effects. We aimed to characterise a healthy dietary index and three plant-based indices by their environmental impacts and associations with risk of cardiovascular disease.

Methods In this prospective cohort study, we used data from a food-frequency questionnaire in the US-based Nurses' Health Study II. Participants were categorised by quintiles of four dietary indices, including the alternative healthy eating index-2010 (AHEI), plant-based diet index (PDI), unhealthy PDI, and healthy PDI. We calculated environmental impacts (greenhouse gas emissions and irrigation water, nitrogenous fertiliser, and high-quality cropland needs), and relative risks (RRs) of cardiovascular disease from 1991–2017, comparing quintiles.

Findings We included 90,884 participants in the health-impact analysis and 65,625 participants in the environmental-impact analysis. Comparing the top and bottom quintiles, higher AHEI scores were associated with a decreased cardiovascular disease risk (relative risk 0·77 [95% CI 0·66–0·89]); 30% lower greenhouse gas emissions (Q5 2·6 kg CO₂ equivalent vs Q1 3·7 kg CO₂ equivalent); and lower fertiliser, cropland, and water needs (all pₚₚₚₚ<0·0001). Similarly, the highest healthy PDI and PDI quintiles were associated with a decreased cardiovascular disease risk (healthy PDI 0·71 [0·60–0·83] and PDI 0·74 [0·63–0·85]) and lower environmental impacts (PDI water needs pₚₚₚₚ<0·0014; all other pₚₚₚₚ<0·0001). Conversely, the highest unhealthy PDI quintile had a higher cardiovascular disease risk compared with the lowest unhealthy PDI quintile (1·15 [1·00–1·33]; pₚₚₚₚ=0·023) and required more cropland (pₚₚₚₚ<0·0001) and fertiliser (pₚₚₚₚ<0·0008).

Interpretation Dietary patterns that are associated with better health had lower greenhouse gas emissions and nitrogenous fertiliser, cropland, and irrigation water needs. Not all plant-based diets conferred the same health and environmental benefits. US dietary guidelines should include nuanced consideration of environmental sustainability.

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Introduction The global food system has enormous impacts on freshwater and land use, nitrogen cycles, and climate change. The food-supply chain is responsible for approximately 25% of all human-generated greenhouse gas emissions, and uses approximately 70% of the planet’s consumptive freshwater withdrawals and nearly 40% of global land. Food systems’ detrimental impacts are not limited to the environment. An increase in unhealthy diets that are rich in heavily processed and animal-based foods (eg, red meat) is threatening both planetary and human health, contributing to increased rates of obesity, type 2 diabetes, and other non-communicable diseases worldwide. Because adverse associations between diets that are rich in animal-based foods and human and environmental health are well established, widespread adoption of healthier plant-rich diets has the potential to reduce disease risk and environmental degradation.

Dietary patterns that are rich in plant-based foods differ in the types of foods they include and the extent to which they exclude animal-based foods, and thus have varied associations with health. Dietary indices can be used to differentiate plant-based dietary patterns and quantify their associations with health across graded differences in diets. For instance, the overall plant-based diet index (PDI) emphasises consumption of all plant-based foods regardless of nutritional value, and higher PDI scores have been associated with lower risks of several chronic diseases, including coronary heart disease. The unhealthy PDI emphasises consumption of plant-based foods that are rich in refined grains and added sugars; diets with higher unhealthy PDI scores are associated with a higher risk of coronary heart disease compared with plant-based diets that are rich in whole grains, legumes, nuts, fruits, and vegetables, which have higher scores on the healthy PDI. Another diet index that emphasises plant-based foods is the alternative healthy eating index (AHEI), which provides higher scores for healthy plant-based foods, and also for some animal-sourced foods such as fish. Diets with higher AHEI scores are associated with a lower risk of major chronic disease.
Research in context

Evidence before this study
We did not do a formal literature review before undertaking this research. Previous research has documented heterogeneous health effects of different plant-based dietary patterns. Prospective cohort studies have found that the alternative healthy eating index-2010 (AHEI), plant-based diet index (PDI), and healthy PDI are all associated with a reduced risk of chronic disease, whereas the unhealthy PDI is associated with an increased risk of chronic disease. Other studies have modelled the environmental impacts of various dietary patterns that are rich in plant-based foods, such as vegetarian diets, but research that simultaneously examines environmental and health impacts of plant-rich diets is scarce.

Added value of this study
We characterised the health and environmental impacts associated with high versus low scores on various plant-rich dietary indices in a US cohort. To our knowledge, this is the first study to directly link multiple indicators of environmental impact and health effects with multiple diet indices in the same longitudinal cohort. We found that participants in the highest AHEI and healthy PDI score quintiles had a reduced risk of cardiovascular disease; reduced greenhouse gas emissions; and reduced use of cropland, irrigation water, and nitrogenous fertiliser. Participants in the highest unhealthy PDI score quintile had an increased risk of cardiovascular disease, and their diets required more cropland and fertiliser, compared with those in the lowest unhealthy PDI score quintile.

Implications of all the available evidence
Plant-based dietary patterns that are associated with better human health are also associated with better environmental health. Future US dietary guidelines should include consideration of environmental sustainability and recognise the human and environmental health co-benefits of more sustainable diets, but also that not all plant-based diets confer the same health and environmental benefits.

Although the health effects of different plant-based dietary patterns have been widely studied, less research has addressed the environmental impacts of these dietary patterns. Previous studies have modelled the environmental impacts of various dietary patterns that are rich in plant-based foods (eg, vegetarian diets), and some work has addressed specific protective or deleterious dietary components, such as red meat. But, to our knowledge, no study has directly linked multiple metrics of environmental impacts of multiple dietary patterns with long-term health outcomes in the same cohort of participants. We aimed to characterise the health and environmental impacts of various plant-rich dietary patterns within a longitudinal US cohort. For environmental outcomes, we primarily measured greenhouse gas emissions, but also measured irrigation water use, nitrogenous fertiliser use, and high-quality cropland use, all of which have substantial environmental impacts but are more dependent on local circumstances than greenhouse gas emissions are.

Methods
Study population and dietary assessment
In this prospective cohort study, we used data from the Nurses’ Health Study II, which began in 1989 when 116430 US female nurses aged 25–42 years completed a posted questionnaire regarding their medical history and lifestyle practices. This cohort has been followed up via self-administered questionnaires to update information on lifestyle and medical history and ascertain clinical outcomes every 2 years, with a follow-up rate of approximately 90% per cycle. The study protocol was approved by the Institutional Review Boards of the Brigham and Women’s Hospital and the Harvard T H Chan School of Public Health.

Starting in 1991, diet was assessed every 4 years using a previously validated semi-quantitative food-frequency questionnaire. For each of approximately 150 listed food items, participants reported their usual intake of a standard portion of each food item during the previous year. These responses were translated to daily nutrient intake using the Harvard Food Composition Database derived from US Department of Agriculture (USDA) nutrient data. The reproducibility and validity of nutrient, food, and dietary pattern measurements using the food-frequency questionnaire in the Nurses’ Health Study have been described previously in detail. We did the health-impact analysis using longitudinally collected data from the baseline (1991) until 2017 in the Nurses’ Health Study II, based on our previously published work. We excluded participants with a cancer diagnosis at baseline and cardiovascular disease, and those who reported implausible calorie intakes of below 500 kcal/day or greater than 3500 kcal/day. The environmental-impact analysis was further restricted to participants within the health-impact-analysis population who completed the 2011 food-frequency questionnaire, which we used because it was the most detailed food-frequency questionnaire and showed recent dietary information available from that cohort.

The AHEI-2010 was developed as a measure of diet quality, with higher index scores associated with lower risk of major chronic diseases. This index scores individuals on the basis of their intake of 11 food groups related to health outcomes, with scores ranging from 0 to 10 for each item. We excluded alcoholic beverages from the indices because epidemiological evidence has found alcohol...
consumption to be associated both positively and negatively with several health outcomes, depending on intake level. Higher intake of vegetables, fruits, whole grains, nuts and legumes, long chain n-3 fats, and polyunsaturated fats are scored positively, whereas sugary beverages, red and processed meat, trans fat, and sodium are scored negatively. The total score for an individual could range from 0 (worst diet) to 100 (best diet).

The overall PDI and its healthy and unhealthy sub-indices were calculated using methods described previously.14 Briefly, the PDI scores dietary patterns using 18 food groups on the basis of nutrient and culinary similarities. These groups are seven healthy plant food groups (whole grains, fruits, vegetables, nuts, legumes, vegetable oils, and tea and coffee), five unhealthy plant food groups (fruit juices, sugar-sweetened beverages, refined grains, potatoes, and sweets and desserts), and six animal food groups (animal fats, dairy, eggs, fish and seafood, meat including poultry and red and processed meat, and miscellaneous other animal-based foods). We summed intakes of these 18 food groups, scored as quintiles, to obtain overall scores, with a possible range of 18–90. For the overall PDI, intake of healthy and unhealthy plant foods increases the index score, whereas intake of animal foods reduces the score. For the healthy PDI, only the intake of healthy plant foods increases the score, whereas for the unhealthy PDI, only the intake of unhealthy plant foods increases the score; intake of the other two food groups in each index reduces each score. For all three plant-based diet indices, higher scores reflect lower animal-based food intake. We excluded margarine because of the changes in trans-fat content over time. However, we adjusted for alcoholic beverages and margarine consumption as covariates in the analyses.

Assessment of environmental impact
We estimated greenhouse gas emissions and use of high-quality cropland (as distinct from rangeland or grassland), reactive nitrogen (from fertiliser) and irrigation water from field to farm gate (impact of food production measured until the food is ready for consumption, but before it is transported or consumed) for each of the 156 items included in the 2011 Nurses’ Health Study II food-frequency questionnaire. Our analysis excluded post-farm-gate environmental impacts (eg, transportation and waste). Our full food-frequency questionnaire environmental database provides detailed background, data, assumptions, and citations regarding all food items’ environmental impacts.15

Environmental impacts were primarily derived from previously reported values that were based on lifecycle assessment studies16 and supplemented by other published values.17,18 For the five key livestock categories—beef, dairy, poultry, pork, and eggs—we relied on analyses of national consumption and production statistics.19,20 For most other items, we mostly relied on several lifecycle assessments that represent key producing areas. For water use when no lifecycle assessment results were available, we used the USDA and other sources, including supplementary text and data files from Eshel and colleagues.15,25 Additionally, when environmental impact estimates were unavailable for a particular food, we used data for similar food items with similar agricultural resource use. For example, “other carbonated beverage” was equated to Coca-Cola, and parsley to spinach; we also used the same values for regular and decaffeinated coffee. Additionally, the environmental impacts for some foods were calculated on the basis of the conversion of one constituent ingredient to another (eg, corn oil, corn syrup, or popcorn were derived from the environmental attributes of corn, accounting for corn mass used derived from fat content, augmented for intermediate processing).

The food-frequency questionnaire included 88 compound foods made of two or more food items (eg, sweetened yogurt or mixed dried fruit). Environmental attributes of each compound food were estimated on the basis of each food’s individual constituent components, with the relative amounts of the components of the compound foods weighted on the basis of US consumption patterns at that time. Nutrient profiles and recipes for food-frequency questionnaire food items were derived from USDA data and product label information.

Statistical analysis
We calculated the environmental impact per person for each food-frequency questionnaire item by multiplying each individual’s serving intake level by the environmental impact associated with a one-serving increment in the intake of that food-frequency questionnaire item. We then summed those environmental impacts across all food-frequency questionnaire items for each individual, obtaining cropland, reactive nitrogen, and irrigation water use, and greenhouse gas emissions per person per day. To calculate the environmental impacts attributable to a specific food group, we summed the environmental impacts within each food group and calculated the percentage contribution to each environmental impact metric by each food group. To quantify the associations of diet healthiness with environmental attributes, we first categorised participants by index score quintiles for each of the four dietary indices (AHEI, PDI, unhealthy PDI, and healthy PDI). We then applied general linear models with environmental attributes as dependent variables and quintiles of dietary indices and total energy intake as independent variables to calculate the energy-adjusted mean environmental impact in each quintile of dietary indices and standardised the mean values to a total energy intake of 2000 kcal daily.

We estimated relative risks (RRs) for incidence of cardiovascular disease (the leading cause of death in the USA)1 across quintiles of dietary indices using Cox
proportional hazards models adjusted for age, race and ethnicity, marriage status, living status (living alone or not), family history of myocardial infarction, menopausal status, oral contraceptive use, multivitamin use, aspirin use, total energy intake, smoking status, alcohol drinking, physical activity, and body-mass index (BMI) in the Nurses’ Health Study II (1991–2017). We calculated cumulative means to the start of each 2-year follow-up interval to best represent long-term dietary patterns and reduce within-person variation; we then included the cumulative means as main exposures in the Cox proportional hazards models. We calculated person-years of follow-up from the earliest of time of death, cardiovascular disease, loss to or unavailability for follow-up, or the end of follow-up. In secondary analyses, we estimated RRs for incidence of and mortality from cancer, coronary heart disease (non-fatal myocardial infarction plus death due to coronary heart disease), stroke, type 2 diabetes, cardiovascular disease (excluding coronary heart disease), respiratory and neurodegenerative diseases, and total mortality. We calculated RRs by multiplying across-quintile differences in AHEI by multivariable-adjusted RRs associated with a one-unit increment in the dietary index. These multivariable-adjusted RRs were estimated from the Nurses’ Health Study and Health Professionals Follow-Up Study and previously published.4,22,23 The methods for follow-up and documentation of disease and mortality outcomes in the cohorts have been described in detail.4,22,23 To estimate the uncertainty (95% CI) of the RRs, we used Monte-Carlo simulations to take 1000 draws from the distribution of differences in dietary index and the RRs simultaneously, propagating the uncertainty in the dietary index and RRs into the final estimates. We did all analyses at a two-tailed α of 0·05, using SAS (version 9.4) and R (version 4.0.3).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The health outcomes analysis included 90 884 participants, and the environmental impact analysis included 65 625 participants. Participants with diets in the highest quintiles of greenhouse gas emissions, land use, fertiliser inputs, and water use generally had higher BMIs (28·5–29·4 kg/m²) and lower levels of physical activity (16·4–18·4 metabolic equivalents (METs) × h per week) than those in the lowest quintiles (BMI 25·4–26·8 kg/m²; physical activity 21·2–24·7 METs × h per week; table 1). Furthermore, those in the highest quintiles of all four environmental attributes were more likely to be current smokers (7·5–9·4%) and have hypertension (33·8–35·6%) and type 2 diabetes (8·4–10·2%) compared

### Table 1: Age-adjusted characteristics of study population included in the environmental impact analysis (n=65 625)

| Environmental attribute* | Quintiles of greenhouse gas emission | Quintiles of cropland needs | Quintiles of fertiliser needs | Quintiles of irrigation water needs |
|---------------------------|--------------------------------------|-----------------------------|-------------------------------|------------------------------------|
|                           | Q1 (94·2%) | Q3 (95·6%) | Q5 (96·9%) | Q1 (94·9%) | Q3 (96·0%) | Q5 (95·0%) | Q1 (95·6%) | Q3 (95·3%) | Q5 (94·0%) | Q1 (95·5%) | Q3 (95·9%) | Q5 (94·0%) |
| Age, years†              | 56·7 (95·6%) | 56·5 (95·6%) | 56·5 (95·6%) | 56·9 (95·6%) | 56·5 (95·6%) | 56·4 (95·6%) | 56·8 (95·6%) | 56·4 (95·6%) | 56·8 (95·6%) | 56·5 (95·6%) | 56·3 (95·6%) |
| BMI, kg/m²               | 25·9 (67·7%) | 27·6 (73·5%) | 28·9 (71·6%) | 25·4 (66·9%) | 27·6 (73·8%) | 29·4 (72·5%) | 26·1 (68·6%) | 27·5 (73·3%) | 29·0 (71·2%) | 26·8 (66·2%) | 27·4 (72·9%) |
| Ethnicity‡               | White      | 12·367 (94·2%) | 12·550 (95·6%) | 12·456 (94·9%) | 12·310 (93·9%) | 12·590 (96·0%) | 12·474 (95·0%) | 12·552 (95·6%) | 12·514 (95·3%) | 12·337 (94·0%) | 12·536 (95·5%) | 12·532 (94·0%) |
|                         | Married    | 8886 (67·7%) | 9648 (73·5%) | 9394 (71·6%) | 8780 (66·9%) | 9691 (73·8%) | 9519 (72·5%) | 9010 (68·6%) | 9626 (73·3%) | 9349 (71·2%) | 8882 (66·2%) | 9609 (72·9%) |
| Current smoker           | 446 (3·4%)  | 638 (4·9%)  | 1094 (8·3%) | 367 (2·8%)  | 697 (5·3%)  | 1048 (8·0%) | 357 (2·7%)  | 610 (4·6%)  | 1230 (9·4%) | 590 (4·5%)  | 632 (4·8%)  | 984 (7·5%)  |
| Physical activity, metabolic equivalents × h per week | 22·9 (4·5%) | 20·1 (6·1%) | 17·7 (9·0%) | 24·7 (3·6%) | 19·7 (6·1%) | 16·4 (10·2%) | 23·2 (4·5%) | 20·4 (6·1%) | 16·8 (9·0%) | 21·2 (5·4%) | 20·6 (6·1%) | 18·4 (8·4%) |
| Energy intake, kcal/day  | 1718 (32·4%) | 1720 (37·0%) | 1740 (36·6%) | 1705 (32·4%) | 1707 (36·4%) | 1751 (39·7%) | 1717 (33·5%) | 1710 (36·4%) | 1728 (39·7%) | 1698 (29·2%) | 1722 (36·7%) |
| Multivitamin use         | 5450 (41·5%) | 5361 (40·8%) | 5698 (43·4%) | 5204 (39·7%) | 5380 (41·0%) | 5927 (42·2%) | 5321 (40·5%) | 5400 (41·1%) | 5825 (44·4%) | 5308 (40·4%) | 5442 (41·5%) | 5759 (43·9%) |
| Hypertension             | 3062 (23·3%) | 3916 (30·0%) | 4655 (35·5%) | 3984 (22·0%) | 3895 (29·7%) | 4669 (35·6%) | 3227 (23·8%) | 3857 (29·4%) | 4585 (34·9%) | 3272 (29·2%) | 3872 (29·3%) | 4442 (33·8%) |
| Hypercholesterolaemia    | 4534 (34·5%) | 4857 (37·0%) | 5066 (38·6%) | 4257 (32·4%) | 4784 (36·4%) | 5233 (39·7%) | 4938 (33·3%) | 4845 (36·9%) | 5702 (39·6%) | 4657 (35·2%) | 4821 (36·7%) | 5015 (38·2%) |
| Type 2 diabetes          | 585 (4·5%)  | 801 (5·6%)  | 1186 (9·0%) | 471 (3·6%)  | 796 (6·1%)  | 1336 (10·2%) | 593 (4·5%)  | 803 (6·1%)  | 1186 (9·0%) | 708 (5·4%)  | 824 (6·1%)  | 1100 (8·4%) |

Data are means for continuous variables and n (%) for categorical variables. Quintiles were calculated on the basis of energy residuals of environmental variables. *Values are mean daily CO2 equivalent of greenhouse gas emitted (kg), high-quality cropland required (m²), nitrogenous fertiliser (g), and irrigation water (m³)†Not age-adjusted values. ‡Further disaggregated race and ethnicity data were not available.

Table 1: Age-adjusted characteristics of study population included in the environmental impact analysis (n=65 625)
with those in the lowest quintiles (current smokers 2·7–4·5%, hypertension 22·0–25·7%, and type 2 diabetes 3·6–5·4%; table 1).

During 2 306 769 person-years of follow-up, we found 2166 incident cases of cardiovascular disease (table 2). Higher AHEI scores were associated with a lower risk of cardiovascular disease (RR comparing top versus bottom quintiles 0·77 [95% CI 0·66–0·89]; p\textsubscript{least}<0·0001) and lower greenhouse gas emissions (Q5 2·6 kg CO\textsubscript{2} equivalent vs Q1 3·7 kg CO\textsubscript{2} equivalent; p\textsubscript{least}<0·0001; figure 1; table 2). As previously reported,\textsuperscript{12,23} higher AHEI scores were strongly associated with other positive health outcomes, including significantly lower risks of coronary heart disease, stroke, and type 2 diabetes, as well as total mortality and mortality from cancer and cardiovascular, respiratory, and neurodegenerative diseases (appendix pp 2–3). Nitrogenous fertiliser inputs, cropland use, and irrigation water use were also significantly lower for those in the highest quintile of AHEI scores compared with those in the lowest (all p\textsubscript{least}<0·0001). We found similar trends for the healthy PDI, with participants scoring the highest having a lower risk of cardiovascular disease (RR 0·71 [95% CI 0·60–0·83]) and lower greenhouse gas emissions and nitrogenous fertiliser, cropland, and irrigation water use (all p\textsubscript{least}<0·0001). For unhealthy PDI, those in the highest score quintile had a higher risk of cardiovascular disease (RR 1·15 [95% CI 1·00–1·33]; p\textsubscript{least}=0·023) and a diet requiring significantly more cropland (p\textsubscript{least}<0·0001) and fertiliser (p\textsubscript{least}=0·0008; table 2; appendix pp 4–7). We found no significant differences in greenhouse gas emissions or

| Overall plant-based diet index | Q1 | Q2 | Q3 | Q4 | Q5 | P\textsubscript{least} |
|-------------------------------|----|----|----|----|----|----------------------|
| Median diet score (IQR)       | 47 | 51 | 55 | 58 | 62 | 0·87                  |
| Greenhouse gas emissions, kg CO\textsubscript{2} e* | 3·6 | 3·3 | 3·0 | 2·6 | 2·6 | <0·0001               |
| Fertiliser needs, gNr*        | 89 | 86 | 82 | 78 | 78 | 9·77 (7·4–8·2)        |
| Cropland needs, m\textsuperscript{2} * | 32 | 28 | 26 | 23 | 19 | <0·0001               |
| Irrigation water needs, m\textsuperscript{3} * | 0·72 | 0·70 | 0·69 | 0·68 | 0·66 | 0·0014               |
| RR of CVD (95% CI)†          | 0·87 | 0·83 | 0·75 | 0·70 | 0·66 | 0·0005               |

| Healthy plant-based diet index | Q1 | Q2 | Q3 | Q4 | Q5 | P\textsubscript{least} |
|-------------------------------|----|----|----|----|----|----------------------|
| Median diet score (IQR)       | 45 | 51 | 54 | 58 | 64 | 0·87                  |
| Greenhouse gas emissions, kg CO\textsubscript{2} e* | 3·5 | 3·3 | 3·0 | 2·7 | 2·7 | <0·0001               |
| Fertiliser needs, gNr*        | 91 | 86 | 81 | 76 | 76 | 9·76 (7·5–8·0)        |
| Cropland needs, m\textsuperscript{2} * | 32 | 29 | 26 | 23 | 18 | <0·0001               |
| Irrigation water needs, m\textsuperscript{3} * | 0·70 | 0·67 | 0·66 | 0·65 | 0·66 | 0·0001               |
| RR of CVD (95% CI)†          | 0·87 | 0·83 | 0·80 | 0·70 | 0·70 | 0·0003               |

| Unhealthy plant-based diet index | Q1 | Q2 | Q3 | Q4 | Q5 | P\textsubscript{least} |
|-------------------------------|----|----|----|----|----|----------------------|
| Median diet score (IQR)       | 46 | 51 | 55 | 59 | 64 | 0·87                  |
| Greenhouse gas emissions, kg CO\textsubscript{2} e* | 3·2 | 3·1 | 3·0 | 2·9 | 2·7 | <0·0001               |
| Fertiliser needs, gNr*        | 83 | 82 | 81 | 79 | 79 | 9·79 (8·4–9·0)        |
| Cropland needs, m\textsuperscript{2} * | 24 | 23 | 22 | 20 | 17 | <0·0001               |
| Irrigation water needs, m\textsuperscript{3} * | 0·69 | 0·67 | 0·67 | 0·65 | 0·65 | 0·0004               |
| RR of CVD (95% CI)†          | 0·87 | 0·83 | 0·80 | 0·70 | 0·70 | 0·0003               |

| AHEI-2010                      | Q1 | Q2 | Q3 | Q4 | Q5 | P\textsubscript{least} |
|-------------------------------|----|----|----|----|----|----------------------|
| Median diet score (IQR)       | 33 | 40 | 45 | 50 | 58 | 0·87                  |
| Greenhouse gas emissions, kg CO\textsubscript{2} e* | 3·7 | 3·4 | 3·1 | 2·9 | 2·6 | <0·0001               |
| Fertiliser needs, gNr*        | 97 | 88 | 83 | 79 | 79 | 9·79 (7·1–7·5)        |
| Cropland needs, m\textsuperscript{2} * | 35 | 30 | 26 | 22 | 16 | <0·0001               |
| Irrigation water needs, m\textsuperscript{3} * | 0·77 | 0·72 | 0·68 | 0·66 | 0·66 | 0·0005               |
| RR of CVD (95% CI)†          | 0·87 | 0·83 | 0·80 | 0·70 | 0·70 | 0·0003               |

AHEI=alternate healthy eating index. CO\textsubscript{2} e=CO\textsubscript{2} equivalent. CVD=cardiovascular disease. gNr=grams of reactive nitrogen. RR=risk ratio.*Values are adjusted daily means (never, past, or current use), multivitamin use (yes or no), aspirin use (yes or no), smoking status (never smoker, former smoker, or current smoker: 1·14–1·24, or ≥2·5 cigarettes per day), alcohol drinking (0, 0·1–0·4, 0·5–0·9, 1·0–1·4, 1·5–1·9, 2·0–2·4, or ≥2·5 g/day), physical activity (quintile), and body-mass index (>21, 21 to >25, 25 to >30, 30 to >35, ≥35 kg/m\textsuperscript{2}) in the Nurses’ Health Study II (1991–2017). The RRs of CVD across quintiles of the healthy plant-based diet index are from Shan et al.\textsuperscript{1}

Table 2: Associations of dietary patterns with daily calorie intake-adjusted environmental impacts and the risk of CVD by quintile
irrigation water needs between extreme unhealthy PDI quintiles (table 2).

The food groups that contributed the most to greenhouse gas emissions associated with participants' dietary intake were all animal-based and included red and processed meat (31.0% of all participants' dietary greenhouse gas emissions), dairy (13.2%), poultry (9.3%), and fish (5.6%; figure 2). Plant-based food groups with the highest greenhouse gas emissions based on participant intakes included fruit juice (4.9%), vegetables (4.6%), and fruit (3.2%; figure 2). Red and processed meat also contributed the most to use of cropland (59.4% of all cropland use for participants' diets), irrigation water (26.3%), and fertiliser (25.0%; figure 2). Dairy was also resource-intensive, responsible for 8.6% of use of cropland, 6.6% of irrigation water, and 8.5% of fertiliser (figure 2). Aside from meat and dairy, vegetable intake was responsible for 24.6% of irrigation water use (with fruit contributing 6.5% and nuts 5.1% of total irrigation water use; figure 2). Plant-based foods that were responsible for the highest fertiliser use were vegetables (11.4%), whole grains (6.6%), refined grains (5.1%), and fruit (4.0%; figure 2).

Higher AHEI scores were associated with greater greenhouse gas emissions from whole grains, fruit,
vegetables, nuts, legumes, fish, poultry, and tea and coffee, but ultimately resulted in an overall lower level of greenhouse gas emissions that was largely driven by lower consumption of red and processed meat (41·1% of all emissions in Q1 vs 17·1% of all emissions in Q5) and fruit juice (Q1 6·8% vs Q5 2·5%; figure 3; appendix p 8).

**Discussion**

Our results show that higher dietary quality, as indicated by AHEI score in a prospective US cohort, is associated with benefits for human and environmental health. Such benefits include reduced risks of cardiovascular disease, other chronic diseases, and mortality, and also significantly reduced greenhouse gas emissions and need for cropland, irrigation water, and nitrogenous fertiliser. Reduced red and processed meat consumption was the largest contributor to these observed beneficial effects. Long-term health benefits of dietary patterns with higher AHEI scores have been similarly documented in other cohorts.1 Previous research investigating the environmental impacts of the AHEI using different methodology produced similar results to ours.24 We also examined the health and environmental impacts of plant-based dietary patterns (measured by PDI, healthy PDI, and unhealthy PDI scores), which have repeatedly been associated with far lower greenhouse gas emissions than animal-based diets have, especially those high in red meat.1 Our findings, however, highlight important differences between healthy and unhealthy plant-based dietary patterns. Whereas healthy plant-based patterns were associated with indicators of better human and environmental health, including significantly reduced cardiovascular disease risk; greenhouse gas emissions; and use of cropland, irrigation water, and fertiliser; unhealthy plant-based patterns were associated with adverse human and environmental health effects, including significantly increased cardiovascular disease risk and use of cropland and fertiliser. Our findings are consistent with previously documented associations with cardiovascular risk factors for the food groups in each dietary index.25 To our knowledge, however, this is the first study to directly link multiple indicators of environmental impact and health effects with multiple diet indices in the same longitudinal cohort.

Our results further illuminate the large differences in environmental impacts among food categories based on participant dietary intake. Animal-based foods—especially red and processed meat—contributed most to greenhouse gas emissions and use of cropland, irrigation water, and fertiliser. Although nut production is often noted as having high water needs, nut consumption only contributed 5·1% of total water use in participants’ diets, compared with 26·3% contributed by red and processed meat and 24·6% contributed by vegetables. Nuts required proportionally less water because participants consumed them in smaller amounts than they did red and processed meat and vegetables, and nuts had lower water needs per calorie compared with those of red meat. We also found that some foods that are discouraged in the AHEI because of associations with increased chronic disease risk—including sugar-sweetened beverages, refined grains, sweets, and potatoes—had lower greenhouse gas emissions than many other food categories did but required more fertiliser.

These findings highlight the importance of considering the environmental and health impacts of diet simultaneously. For the first time, the Advisory Committee for the 2015–20 US Dietary Guidelines for Americans (DGA) recommended the incorporation of sustainability as a factor for dietary consideration, with a specific recommendation to reduce red and processed meat consumption.26 The meat industry lobbied Congress,27 which subsequently directed the USDA and Department of Health and Human Services to omit sustainability from the 2015–20 DGA, asserting that the topic was outside the scope of their mandate to provide nutritional and dietary information.28 Recommendations for the inclusion of sustainability as a consideration for dietary guidelines have continued, however, in both a 2017 report from the National Academies of Sciences, Engineering, and Medicine29 and in the 2020–25 DGA Advisory Committee.

Figure 3: Greenhouse gas emissions across quintiles of the AHEI-2010 by different food groups (n=65 625)

Values are adjusted means (95% CI) estimated from general linear models with greenhouse gas emission as dependent variables and quintiles of AHEI-2010 and total energy intake as independent variables. All the values were standardised on the basis of total energy intake of 2000 kcal/day. Other foods include artificial sweeteners; beer, snack bars; chowder or cream soup; non-dairy coffee whitener (excluding fat free); energy bars; meal-replacement drinks; still bottled, sparkling, or tap water; high-protein bars; ketchup or red chilli sauce; light beer; liquor; beef, calf or pork liver; chicken or turkey liver; low-fat or fat-free mayonnaise; regular mayonnaise; pizza; red wine; diet nutrition drinks; white wine; low-calorie beverage with caffeine; or other low-calorie beverage without caffeine. AHEI-2010=alternate healthy eating index 2010. CO₂e=CO₂ equivalent.
This analysis has limitations. First, the analysis is only as robust as the environmental indicators on which it is based. A synthetic compilation of lifecycle analysis data found some variation in estimated environmental impacts for different food groups, but this within-group variation was minimised by the large mean differences between animal-sourced and plant-sourced foods. For example, the greenhouse gas emissions per serving for beef are roughly 160 times greater than those for legumes, whereas greenhouse gas emissions from pork and dairy are 30–40 times greater than those for legumes. We are therefore confident that the uncertainty of our estimated environmental impacts is far smaller than the range spanned by the extreme quintiles that we report. The environmental impacts quantified in this analysis are lower estimates of the likely actual impact of food production, because of the omission of post-farm-gate considerations (eg, food loss and waste or transportation) in our calculations. Finally, the generalisability of our results is somewhat limited by the demographics of the Nurses’ Health Study II, which is limited to mostly White US female nurses. Although the relative risks are likely to be largely generalisable because they are based on biological relationships, the distributions of dietary variables will vary across demographic subgroups, and stronger associations might be observed in a nationally representative population with a more heterogeneous diet.

In summary, our findings document that dietary patterns that are associated with better health outcomes can simultaneously improve planetary health by reducing greenhouse gas emissions and use of cropland, irrigation water, and nitrogenous fertiliser. Because human health is ultimately dependent on planetary health, future national dietary guidelines should include consideration of environmental sustainability and recognise that not all plant-based diets confer the same health and environmental benefits.

Contributors
MJS, GE, and WW conceptualised the study. MJS obtained funding, overviewed data collection and analysis, and provided critical manuscript revisions. GE and MJ created the environmental attribute database and provided critical manuscript revisions. DDW analysed and interpreted the data and provided critical manuscript revisions. AAM interpreted the report’s repeated recognition of the importance of food-system sustainability. Although sustainability was omitted from the 2020–25 DGA, our findings suggest that future DGAs could benefit from the incorporation of dietary sustainability; such a change could both educate consumers and influence tens of millions of Americans’ diets through updated standards in federal feeding programs. This recommendation is supported by the EAT-Lancet Commission’s 2019 report findings, which highlighted the need for a global food-system transformation to ensure that the world’s rapidly growing population can be fed healthy diets from sustainable food systems. Indeed, other countries such as Denmark have already incorporated sustainability into their dietary guidelines.

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