Plant-based and planetary-health diets, environmental burden, and risk of mortality: a prospective cohort study of middle-aged and older adults in China

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Summary

Background Plant-based diets (PBDs) and planetary-health diets (PHDs) are recommended for their potential health and environmental benefits, but population-based evidence in diverse cultures is scarce.

Methods We included 9364 adults aged 45 years and older (52·3% female, 47·7% male) from the open cohort of the China Health and Nutrition Survey. Dietary intake was assessed using 3-day 24 h dietary recalls combined with weighing methods from 1997 to 2011, and mortality was documented from 1997 to 2015. We calculated the overall PBD index (PDI), healthful PBD index (hPDI), and unhealthful PBD index (uPDI; ranges 18–90), and the PHD score (range 0–140). We also estimated the related greenhouse gas emissions, land appropriation, and total water footprint and examined their associations with mortality.

Findings PBD indices were inversely related to greenhouse gas emissions, land appropriation, and total water footprint, whereas higher PHD score was related to higher environmental burdens (p<0·0001). During follow-up (mean 9·2 years), 792 (8·5%) death cases were documented. PDI (HR 1·08 [95% CI 0·88–1·32]) and hPDI (0·98 [0·80–1·21]) were not significantly associated with mortality, whereas higher uPDI was related to a higher mortality risk (1·55 [1·26–1·91]). In contrast, higher PHD score was associated with lower mortality risk (0·79 [0·63–0·99]).

Interpretation The PBDs showed environmental benefits, but are not necessarily associated with lower mortality risk. The PHD, developed mainly in western populations, was related to lower mortality risk but higher environmental burdens in the Chinese population.

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Introduction

Environmental sustainability and human wellbeing are both major concerns in the context of world development.[1–3] In a sense, the agendas of planetary and human health are highly interconnected, and food system transformation has been proposed as a potential solution for both.[4] For example, compared with animal-based foods such as red and processed meat, legumes, nuts, fruits, and vegetables benefit human health[5–7] and have lower environmental impacts.[8,9] Recent studies further investigated dietary patterns aimed at reducing environmental impacts while promoting human health, such as plant-based diets (PBDs).[10,11] In 2019, the EAT–*Lancet* Commission devised a planetary-health reference diet (PHD) to promote human and environmental health simultaneously,[4,12] which provided more specific recommendation intake levels for food groups compared with PBDs. In previous investigations, primarily in the western populations, the plant-rich dietary patterns[13] and PHD[14] had co-benefits to population health and the environment.

However, several questions remain unsolved. First, there is little population-based evidence on the health and environmental benefits of these dietary patterns for developing countries with distinct diet, genetic, and disease profiles.[15,16] China is facing substantial environmental pressure, and its food system is currently a major driver of environmental burdens.[17] The ongoing transition from carbohydrate-dominated diets towards affluent diets rich in animal-sourced foods, if not modified, could further exacerbate pressure on the environment and land in China. The dietary pattern in China remains suboptimal with respect to human health, and accounts for a large proportion of premature deaths.[18] Therefore, investigations are needed into the environmental impacts of the PBDs and PHD for further optimisation of the dietary structure in China to reduce environmental burdens while promoting population health. Most studies evaluating the environmental impacts of dietary patterns used summary data of the populations, potentially masking important differences

Research in context

Evidence before this study

We searched PubMed for research articles published between database inception and Feb 8, 2022, with no language restrictions, using the search term ((Plant-based diet) OR (Plant-based dietary pattern) OR (EAT-Lancet) OR (planetary health diet)) AND ((Mortality) OR (greenhouse gas emission) OR (land use) OR (water footprint)), retrieving 998 results. In previous studies, plant-based and planetary-health dietary patterns have been promoted as a solution to environmental issues. Several cohort studies have examined their associations with risk of mortality and environmental burdens, primarily in western countries. However, evidence on the relationship between plant-based and planetary-health dietary patterns and human health and the environment in different cultural backgrounds is still scarce.

Added value of this study

This is one of the few population-based studies that examines the associations of a panel of plant-based and planetary-health dietary patterns with environmental burdens and the risk of mortality. In this large prospective cohort of middle-aged and older adults in China, the environmentally friendly plant-based diets were not necessarily associated with lower mortality risk. Our findings do not cast doubt on all plant-based diets, but rather highlight the importance of the composition of plant-based diets and the potential detrimental effects of unhealthy plant-based foods. Although adhering to the planetary-health reference diet proposed by the EAT–*Lancet* Commission was associated with a lower risk of mortality, it might result in higher environmental burdens in the study population.

Implications of all the available evidence

Further studies are warranted to identify the optimal dietary pattern with dual benefits for the environment and population health in China. An integrated and balanced approach promoting both environmental sustainability and human health is needed in policy making on food system transformations.

between individuals or subgroups and often generating conflicting results.[19,20] In a previous study, theoretical dietary patterns conforming to the Chinese Dietary Guideline (CDG) and EAT–*Lancet* Commission recommendations increased greenhouse gas emissions and water usage[21] compared with current consumption patterns in China, and another study showed a moderate decrease in the indicators.[22]

To address several evidence gaps of PBDs and PHD with environmental impacts and mortality, we conducted prospective analyses based on a population-based cohort in China. We hypothesised that overall and healthy PBDs and PHD are related to a lower risk of mortality among adults aged 45 years and older in China, unhealthy PBD is associated with higher risk, and all these diets are associated with lower environmental burden measures.

Methods

Study design and participants

The China Health and Nutrition Survey (CHNS) is a nationally representative dynamic cohort in China[23] commenced in 1989. The CHNS enrolled more than 30 000 individuals in nine provinces and municipal cities using multistage random-cluster sampling methods, with 85% being Han Chinese and 15% being other east Asian ethnic groups. In the current study, dietary intake was assessed in 1997, 2000, 2004, 2006, 2009, and 2011, and mortality was documented from Jan 15, 1997 to Dec 31, 2015. More than 90% of the participants participated at least twice.

See Online for appendix

Among the 10 161 middle-aged and older participants aged 45 years and older with at least one valid dietary assessment (total energy in 500–4500 kcal) in 1997–2011, we excluded participants who had a history of cardiovascular disease (stroke or myocardial infarction) or cancer at or before baseline, and who died within the first 2 years of follow-up, to reduce reverse causation (figure 1).[24] We included participants aged 45 years and older because younger participants are less likely to have nutrition-associated causes of deaths within the time frame of follow-up.[25–27] The formal analysis included 9364 participants.

Each participant has provided written informed consent, and the CHNS was approved by institutional review boards at the University of North Carolina at Chapel Hill and the National Institute of Nutrition and Food Safety.[28] The current study is approved by the Zhejiang University School of Public Health (NO. ZGL202005–02).

Procedures

The primary exposures included overall PBD index (PDI), healthful PBD index (hPDI), unhealthful PBD index (uPDI), and the PHD score derived from 3-day 24 h dietary recalls combined with weighing methods (appendix p 2). For overall PDI, quintiles of seven healthful and five unhealthful plant-based food groups were assigned scores of 1–5, and reversely for quintiles of six animal-based food groups.[29] We then summed scores from all food groups as the PDI (possible range 18–90). Based on this criteria, hPDI reversely assigned scores to unhealthful food groups, and uPDI reversely assigned scores to healthful food groups (appendix p 3). The PHD score (possible range 0–140) was based on the 14 key recommendations of the EAT–*Lancet* Commission.[12] The food groups were categorised into recommended, moderate, and restricted groups and assigned scores of 0–10 according to their energy-adjusted intake levels (appendix p 4). We also adopted a previous strategy that defined a PHD score ranging from 0 to 14 for sensitivity analysis.[30]

In this study, we referred to the Chinese Food Life Cycle Assessment Database (CFLCAD) to calculate individual-level diet-related environmental impacts,[29] including greenhouse gas emissions, total water footprint (TWF), and land appropriation per 2000 kcal per day. The CFLCAD included greenhouse gas emissions for 80 food items, TWF for 93 food items, and land appropriation for 50 food items through a systematic literature review. The system boundary of cradle to the post-farm gate included the production, storage, processing, packaging, transportation, and preparation at home stages. This energy adjustment approach ensured that the differences detected in the environmental burdens reflected the overall dietary composition rather than the confounding of total energy intake. Briefly, we combined product-based environmental impacts with food items in the CHNS, multiplying averaged environmental impacts per g of each food item by individual-level food consumption. We also incorporated the data from a previous study with China-specific estimates[30] for food items that were not included in the CFLCAD.

The primary outcome of interest was all-cause mortality. The information on mortality in CHNS is available from the household register completed at each face-to-face follow-up (approximately every 2–4 years) from Jan 15, 1997, to Dec 31, 2015. Individuals were listed as alive and present, moved, or died. If there was a move or a death, the month of the event was recorded. The age-specific death rates in the CHNS were consistent with the 2000 Chinese census and the 2002 Demographic Yearbook.[31] We calculated person-time from the study baseline (date of the first wave of dietary assessment) to date of death, loss to follow-up, or the end of follow-up (Dec 31, 2015), whichever came first.

We included multiple covariates collected at baseline and updated at follow-ups, including sociodemographic factors and lifestyle-related and health-related factors. Sociodemographic variables included age, sex (self-reported in the face-to-face interviews), the highest level of education (high school or above *vs* below high school), family income, and residency (rural resident *vs* urban resident). Lifestyle factors included smoking status (ever smoker *vs* never smoker), alcohol drinking (current drinker *vs* non-drinker) and physical activity (metabolic equivalent of task [MET] h). Health-related variables included objectively measured BMI (appendix p 2), self-reported hypertension, and self-reported diabetes.

Statistical analysis

We described baseline characteristics of participants using mean (SD) for continuous variables and n (%) for categorical variables. In the primary analysis, we assessed the relations of PBD indices and PHD score to all-cause mortality with Cox proportional hazards models stratified by baseline wave, with sequential adjustments for baseline sociodemographic factors and lifestyle-related and health-related factors. Diet scores are updated as cumulative average values and included in the Cox models as time-varying covariates, because long-term diet might be more important and relevant to health outcomes than short-term diet.[32] In an exploratory analysis, we regressed mortality risk against environmental burdens from dietary intake using the fully adjusted model as stated previously, according to a previous study by Laine and colleagues.[14] We further tested for non-linearity when examining the associations of the dietary patterns with the risk of mortality using restricted cubic splines. We presented the distributions of environmental burden indicators according to the quartiles of diet scores using box plots and assessed their associations using *t* tests.

To assess whether the associations differed by other covariates, we performed prespecified stratified analyses by age (aged <65 *vs* ≥65 years), sex (female *vs* male), smoking status (ever *vs* never), BMI categories (underweight or normal weight *vs* overweight or obesity), residence (urban *vs* rural), current alcohol consumption (yes *vs* no), physical activity (low *vs* high), and the existence of chronic conditions such as hypertension and diabetes (yes *vs* no). P values for interactions were calculated by adding a multiplicative interaction term between the subgroup variable and the diet score into the primary model.

We conducted several sensitivity analyses to test the robustness of our primary findings. First, we excluded death cases in the first 4 years to further account for reverse causation caused by changes in dietary behaviour before death. Second, we adjusted the models for the province indicators to account for regional differences in diet and mortality. Third, we used baseline or the most recent diet score, rather than cumulatively averaged diet scores, as exposures. Fourth, we assessed the association

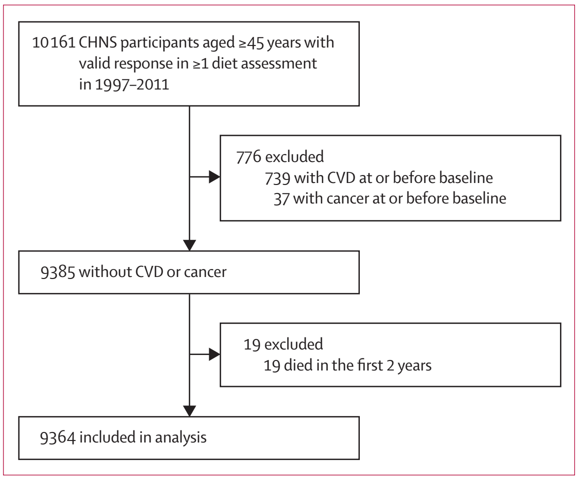

Figure 1: **Participant inclusion from the CHNS**
CHNS=China Health and Nutrition Survey. CVD=cardiovascular disease.

	Overall (n=9364)	Male (n=4462)	Female (n=4902)
Total energy intake, kcal	2125·3 (655·4)	2294·1 (675·0)	1971·5 (596·8)
Age, years	54·5 (9·4)	54·5 (9·2)	54·5 (9·5)
Urban resident	3786 (40·4%)	1778 (39·8%)	2008 (41·0%)
BMI category			
Underweight (<18·5 kg/m²)	490 (5·2%)	214 (4·8%)	276 (5·6%)
Normal (18·5–23·9 kg/m²)	4985 (53·2%)	2535 (56·8%)	2450 (50·0%)
Overweight (24·0–27·9 kg/m²)	2957 (31·6%)	1333 (29·9%)	1624 (33·1%)
Obesity (≥28·0 kg/m²)	932 (10·0%)	380 (8·5%)	552 (11·3%)
High school degree	2153 (23·0%)	1255 (28·1%)	898 (18·3%)
Household income per capita, Chinese Yuan	10 122·1 (14 075·5)	10 226·6 (13 669·5)	10 027·0 (14 436·0)
Physical activity			
Tertile 1	800 (34·8%)	368 (39·2%)	432 (31·8%)
Tertile 2	828 (36·0%)	325 (34·6%)	503 (37·0%)
Tertile 3	670 (29·2%)	246 (26·2%)	424 (31·2%)
Ever smoker	3114 (33·3%)	2859 (64·1%)	255 (5·2%)
Current alcohol drinker	3320 (35·5%)	2796 (62·7%)	524 (10·7%)
Hypertension	1194 (12·8%)	555 (12·4%)	639 (13·0%)
Diabetes	301 (3·2%)	147 (3·3%)	154 (3·1%)
Diet scores			
Plant-based diet index	41·0 (4·8)	40·8 (4·7)	41·2 (4·8)
Healthful plant-based diet index	54·8 (4·7)	54·7 (4·6)	54·9 (4·8)
Unhealthful plant-based diet index	62·5 (5·7)	62·6 (5·6)	62·3 (5·7)
Planetary-health diet score	53·8 (10·8)	53·5 (10·7)	54·0 (10·9)
Daily diet-related environmental burdens			
GHG emissions, kg CO_2e	1·8 (0·9)	2·0 (1·0)	1·7 (0·8)
Total water footprint, m³	2·3 (1·1)	2·5 (1·2)	2·1 (1·0)
Land appropriation, m²	1·9 (1·0)	2·1 (1·1)	1·7 (0·9)

Data shown are mean (SD) or n (%). CHNS=China Health and Nutrition Survey. GHG=greenhouse gas.

***Table 1:* Baseline characteristics of the study population in CHNS (n=9364)**

of the alternatively defined PHD score (range 0–14) with risk of mortality. Last, we used age rather than calendar time as the time scale in the Cox model. A two-sided p value of >0·05 was considered an indicator of statistical significance. Statistical analyses were performed using R 4.1.0.

Role of the funding source

The funders had no role in the study design, data collection, data analysis, data interpretation, writing of the report, or decision to submit for publication.

Results

In this study, we included a total of 9364 participants from CHNS (mean age 54·5 years, 52·3% female, 47·7% male; table 1). Among them, 40·4% lived in urban areas, 41·6% were overweight or had obesity, 33·3% were ever smokers, and 35·5% were current alcohol drinkers. The mean (SD) values at baseline were 41·0 (4·8) for PDI, 54·8 (4·7) for hPDI, 62·5 (5·7) for uPDI, and 53·8 (10·8) for PHD score (appendix p 9). Of the overall participants, mean (SD) environmental burdens for daily food consumption were 1·8 kg CO_2e (0·9) greenhouse gas emissions, 2·3 m³ (1·1) total water footprint, and 1·9 m² (1·0) land appropriation. The distributions of the PBD indices did not show a substantial change during follow-up, whereas PHD scores of the participants were slightly higher in later waves (appendix p 10).

Higher adherences to overall, healthful, and unhealthful PBDs were related to lower greenhouse gas emissions, total water footprint, and land appropriation (p<0·0001; figure 2, appendix p 5). In contrast, the PHD score was positively associated with higher greenhouse gas emissions (0·22 kg CO_2e comparing highest *vs* lowest quartiles; 95% CI 0·19–0·25), higher total water footprint (0·53 m³, 0·49–0·56), and land appropriation (0·27 m², 0·23–0·30). Among food groups, animal-based foods (eg, poultry, red and processed meat, and dairy foods) were the main contributors (appendix p 11). The positive association between PHD score and environmental burdens could be partly explained by the large gaps between intake level of dairy foods with the EAT–*Lancet* planetary-health recommendations (appendix p 12).

During follow-up (mean 9·2 years), 792 (8·5%) death cases were documented (table 2). In the multivariable-adjusted models, PDI and hPDI showed a non-significant association with risk of mortality (hazard ratio [HR] comparing highest *vs* lowest quartiles: 1·08 [95% CI 0·88–1·32], p=0·740; HR for hPDI: 1·01 [0·91–1·12], p=0·985). On the contrary, uPDI was significantly related to a higher risk of mortality, with HR comparing highest versus lowest quartiles being 1·55 (1·26–1·91, p<0·0001). We observed a significantly lower risk of mortality in participants with a higher PHD score (HR 0·79 [95% CI 0·63–0·99], p=0·008), and the association showed significant non-linearity (p=0·008; figure 3), all passing Benjamini–Hochberg adjustments for multiplicity.

Lower diet-related environmental burdens were associated with a higher risk of mortality (table 3). In the subgroup analyses, the associations of dietary scores with mortality were generally consistent (appendix p 6). The relations of PDI and hPDI to environmental impacts were not modified by any of the covariates of interest (p>0·05 for all tests) and were not significant in any subgroups of study participants. The detrimental association of uPDI with mortality was more pronounced in male participants than female participants (HR comparing extreme quartiles: 2·10 [95% CI 1·56–2·84] for males, 1·12 [0·82–1·51] for females, p for interaction=0·002). The association of PHD score was stronger among urban residents (0·59 [0·40–0·86], p for interaction=0·014) than rural residents and ever smokers (0·63 [0·42–0·93], p for interaction=0·039) than never smokers. The associations of diet-related environmental burdens with mortality risk were generally consistent across study subgroups (appendix p 7).

In the sensitivity analyses, the observed associations were consistent (appendix p 8). For example, HRs

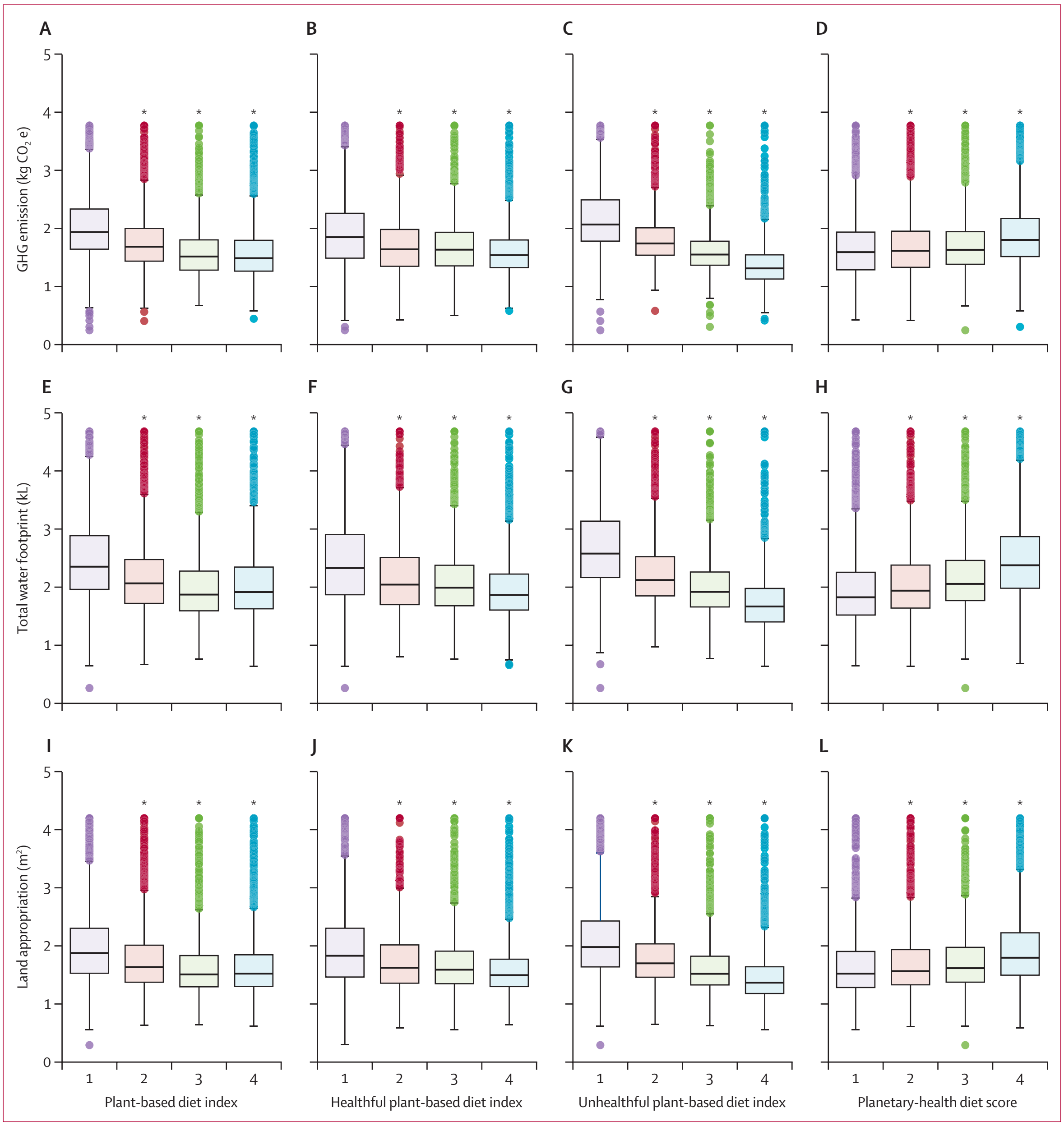

Figure 2: **Total energy intake-adjusted GHG emissions, total water footprint, and land appropriation according to quartiles of plant-based diet indices and planetary-health diet score**

GHG=greenhouse gas. *p<0·001.

(95% CIs) for each 5-unit increment in the PHD score were 0·91 (0·86–0·96) when we exclude participants who died in the first 4 years of follow-up, 0·96 (0·92–1·01) when we adjusted the models for province indicators, 0·94 (0·92–0·96) for the baseline score, 0·93 (0·91–0·95) for the most recent score, and 0·93 (0·90–0·95) when we used age rather than calendar year as the time scale.

Discussion

In this cohort study, higher adherence to PBDs was associated with lower environmental burdens. Among the PBD indices, PDI and hPDI did not show significant associations with mortality risk, whereas higher uPDI was associated with higher risk of mortality. In contrast, adherence to the PHD was related to lower mortality risk but higher environmental burdens. The associations were consistent across most study subgroups. Our findings imply that dietary patterns with dual benefit for environmental sustainability and human wellness deserve further investigations across diverse populations.

This is one of the few population-based studies to comparatively examine the relations of a panel of PBDs

	Median	Deaths/ person-years	Model 1	Model 2	Model 3
Plant-based diet index (18–90)					
Quartile 1	37	199/21 592	1·00 (reference)	1·00 (reference)	1·00 (reference)
Quartile 2	40	209/21 906	1·08 (0·89–1·31)	1·02 (0·84–1·24)	1·02 (0·84–1·24)
Quartile 3	42	190/20 741	1·01 (0·83–1·23)	0·91 (0·74–1·12)	0·91 (0·75–1·12)
Quartile 4	45	194/21 679	1·22 (1·00–1·49)	1·07 (0·88–1·31)	1·08 (0·88–1·32)
Per 5-unit	NA	NA	1·09 (0·99–1·20)	1·02 (0·93–1·13)	1·03 (0·93–1·13)
p value	NA	NA	0·113	0·776	0·740
Healthful plant-based diet index (18–90)					
Quartile 1	51	203/24 339	1·00 (reference)	1·00 (reference)	1·00 (reference)
Quartile 2	55	192/20 322	0·99 (0·81–1·21)	0·91 (0·75–1·11)	0·91 (0·75–1·11)
Quartile 3	57	225/23 109	1·07 (0·88–1·29)	0·95 (0·78–1·15)	0·96 (0·79–1·16)
Quartile 4	60	172/18 148	1·12 (0·92–1·38)	0·98 (0·79–1·20)	0·98 (0·80–1·21)
Per 5-unit	NA	NA	1·09 (0·98–1·20)	1·00 (0·91–1·11)	1·01 (0·91–1·12)
p value	NA	NA	0·198	0·904	0·985
Unhealthful plant-based diet index (18–90)					
Quartile 1	58	153/23 709	1·00 (reference)	1·00 (reference)	1·00 (reference)
Quartile 2	62	189/22 038	1·20 (0·97–1·49)	1·07 (0·86–1·32)	1·07 (0·86–1·33)
Quartile 3	65	203/19 578	1·48 (1·20–1·82)	1·28 (1·04–1·59)	1·29 (1·04–1·60)
Quartile 4	69	247/20 593	1·91 (1·56–2·34)	1·54 (1·25–1·90)	1·55 (1·26–1·91)
Per 5-unit	NA	NA	1·39 (1·29–1·51)	1·29 (1·19–1·40)	1·29 (1·19–1·40)
p value	NA	NA	<0·0001	<0·0001	<0·0001
Planetary-health diet score (0–140)					
Quartile 1	44	257/21 481	1·00 (reference)	1·00 (reference)	1·00 (reference)
Quartile 2	50	210/21 392	0·92 (0·77–1·10)	0·97 (0·81–1·17)	0·97 (0·81–1·17)
Quartile 3	55	201/21 247	0·79 (0·65–0·95)	0·86 (0·71–1·04)	0·86 (0·71–1·03)
Quartile 4	62	124/21 798	0·60 (0·48–0·74)	0·80 (0·64–1·01)	0·79 (0·63–0·99)
Per 5-unit	NA	NA	0·90 (0·86–0·93)	0·94 (0·90–0·99)	0·94 (0·90–0·98)
p value	NA	NA	<0·0001	0·011	0·008

All models were stratified by baseline wave. Model 1 was adjusted for age, age-square, and sex; model 2 was adjusted for age, age-square, sex, residence, education, household income per capita, total energy intake, smoking status, alcohol intake, and physical activity; model 3 was adjusted for age, age-square, sex, residence, education, household income per capita, total energy intake, smoking status, alcohol intake, physical activity, hypertension, and diabetes. p values for trends were calculated by assigning the median value to each quartile and modelling it as a continuous variable.

***Table 2:* Multivariable adjusted hazard ratios and 95% CIs for mortality according to plant-based diet indices and planetary-health diet score**

and PHD to environmental burdens. Previous studies in western countries suggested that dietary changes towards the EAT–*Lancet* recommendation might be beneficial for the environment[14] and human health.[33,34] For example, a European cohort study reported that targeting a dietary shift towards EAT–*Lancet* recommendations could bring about both health and environmental benefits.[14] In the current study, Higher PBDs are associated with lower greenhouse gas emissions, lower total water footprint, and less land appropriation, while a higher PHD score was associated with higher environmental burdens. Our findings are consistent with a previous analysis using summary data of the CHNS,[21] but differ from another study based on data at the retailing stage,[22] potentially because of a longer timeframe and individual-level dietary assessments in this study.

Overall and healthful PBDs have been associated with lower risk of adverse health outcomes, such as type 2 diabetes[11] and cardiovascular diseases,[35] primarily in the western populations. In our previous investigation, higher PDI and hPDI were associated with lower mortality risk in older Chinese adults, whereas uPDI showed a detrimental association.[36] In this study, we confirmed that higher uPDI was related to higher mortality risk, but PDI and hPDI did not show a significant association. The differences in overall dietary structures and age distributions might partially explain the discrepancies. PBD scores are based on population intake distributions rather than predefined cutoffs, which might hinder the comparability of study findings across different populations. Future studies are needed to assess the potential health effects of PBDs across countries under a comparative framework. Furthermore, we added that adherence to the PHD was related to lower mortality risk, which is consistent with the previous study using summary data of the CHNS[21] and a cohort study in a European population.[30] The underlying driving factors for this protective association might come from the emphasis on specific food groups. For example, vegetables and wholegrains are well established protective factors against mortality—potential contributing components include antioxidants[37] and dietary fibre.[38] On the contrary, red and processed meat could be the main detrimental component associated with higher adipose and inflammation risk.[39] Importantly, our findings do not cast doubt on all PBDs, but rather highlight the importance of the composition of PBDs and the potential detrimental effects of unhealthy plant foods.

In contrast to western populations, for whom environmentally friendly dietary patterns were usually beneficial for both enviorment and human health, the diverse Chinese population might be faced with a trade-off between environmental sustainability and human wellness in the food system transformation. Individuals with low PHD scores in China and western countries are scoring low for different reasons: those with low PHD scores in China tended to have a high intake of carbohydrate-rich food, whereas those with low PHD scores in western countries might consume more animal-based foods than recommended. This difference might reflect the large gap in dairy foods intake between the CHNS population and the planetary health recommendations, and lower average diet-related environmental burden indices in this study compared with previous studies in western countries.[14] Consequently, our study showed that lower diet-related environmental burdens seemed associated with higher mortality risk for individuals. This finding also resonated with the EAT–*Lancet* report: for populations with carbohydrate-staple-dominant diets and relatively low per capita environmental footprints, adopting more diverse diets such as the proposed PHD would have favourable health impacts but some adverse environmental impacts.

Our subgroup analysis also found that the associations between PHD score and mortality were stronger for ever smokers (*vs* never smokers) and urban residents (*vs* rural residents). This finding implied that the PHD might bring more benefits for populations with sufficient food access and overnutrition than those with undernutrition status, as rural participants in this study were probably at relatively early stages of the nutritional transition and were not yet experiencing the full consequences of their current diets. Localised adaptation of the PHD is necessary for healthy and sustainable food systems taking into account the country-specific dietary structure and cultural backgrounds.[22,40–42] Furthermore, the dynamics of the food system, environment, and human wellness merit continued investigation.[43] Environmental sustainability also influences the quality and safety of food. Pollution of agricultural land and water sources can result in contaminated crops and livestock, leading to potential foodborne illnesses and inadequate nutrition. In all, a diet that is more environmentally friendly (such as healthful PBD) might eventually benefit human health by reducing the environmental burdens, even when the direct health benefit from dietary intake might not be evident at an individual level. Additionally, the detrimental association of uPDI with mortality was more pronounced in male participants than female participants. This finding deserves specific attention as it might reflect both socioeconomic and biological differences between sexes in our study population.

Currently, most studies are conducted in western populations with high consumption of animal-based foods and processed foods. However, in the Chinese population, the long tradition of PBD[44] cannot be neglected when examining the associations of PHD with human health. As one of the most populated countries worldwide, China's surging economy has brought about rapid dietary shifts in the past decades,[45] leading to complex diet–environment–health interactions.[46] Although the diet scores and environmental burdens did not change rapidly in this study, a previous study reported secular trends in the consumption of specific food groups.[45] Therefore, whether or not evidence generated from western populations can be applied to low-income and middle-income countries deserves attention. Apart from the environmental sustainability and health effects, other factors (eg, affordability[47,48]) should be considered while advocating specific dietary changes. Because our study population was solely Asian Chinese, whether our findings extend to individuals with other ethnic, socioeconomic, and regional backgrounds warrants examination.

Our findings should be interpreted with caution due to some limitations. First, a 3-day recall period might not fully capture a person's long-term dietary habits, and could be influenced by various factors such as special occasions, season, and temporary dietary changes. Despite these factors, the cumulative average of the 3-day recall data could be used to represent long-term dietary

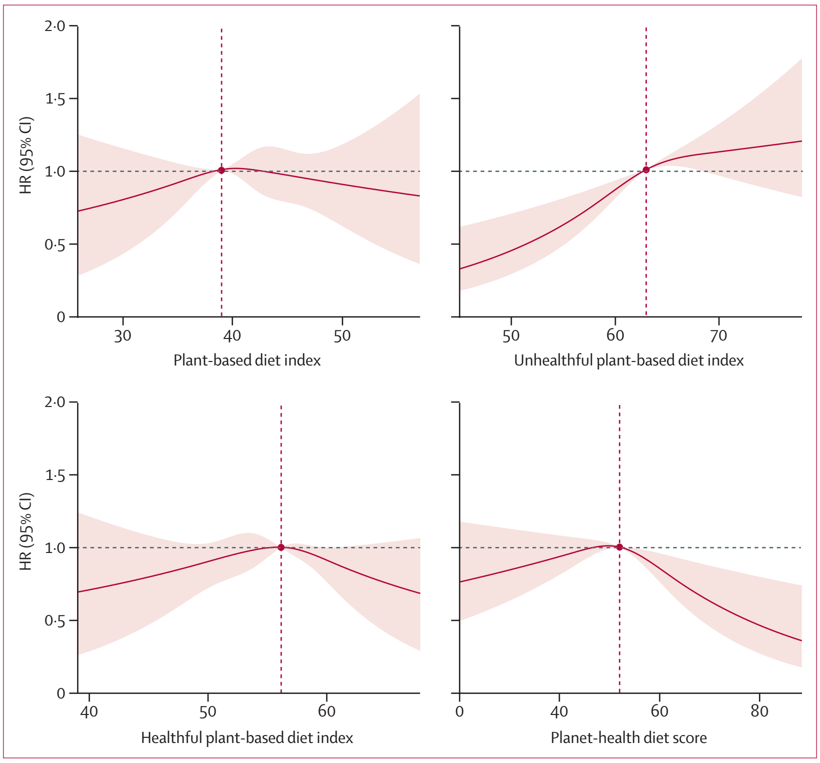

Figure 3: **Restricted cubic splines for the associations of the plant-based diet indices and planetary-health diet score with risk of mortality**

The splines were estimated using Cox-proportional hazard models adjusted for age, age-square, sex, residence, education, household income per capita, total energy intake, smoking status, alcohol intake, physical activity, hypertension, and diabetes. The nominal p values for non-linearity were 0·244 (overall plant-based diet index), 0·063 (healthful plant-based diet index), 0·054 (unhealthful plant-based diet index), and 0·008 (planetary-health diet score).

	Median	Deaths/person-years	HR (95% CI)	p value
GHG emission, kg CO_2e				
Quartile 1	0·98	252/21 482	1·33 (1·08–1·65)	..
Quartile 2	1·36	218/21 632	1·27 (1·03–1·57)	..
Quartile 3	1·72	163/21 403	0·99 (0·80–1·24)	..
Quartile 4	2·39	159/21 271	1·00 (reference)	0·0038
Total water footprint, m³				
Quartile 1	1·19	265/21 636	1·47 (1·18–1·82)	..
Quartile 2	1·67	186/21 501	1·18 (0·95–1·47)	..
Quartile 3	2·14	194/21 281	1·27 (1·02–1·58)	..
Quartile 4	3·02	147/21 370	1·00 (reference)	0·0047
Land appropriation, m²				
Quartile 1	1·00	260/21 325	1·36 (1·10–1·69)	..
Quartile 2	1·33	190/21 221	1·15 (0·92–1·43)	..
Quartile 3	1·69	194/21 456	1·22 (0·99–1·51)	..
Quartile 4	2·47	148/21 786	1·00 (reference)	0·0014

HRs (95% CIs) were calculated from Cox models stratified by baseline wave and adjusted for age, age-square, sex, residence, education, household income per capita, total energy intake, smoking status, alcohol intake, physical activity, hypertension, and diabetes. p values for trend were calculated by assigning the median value to each quartile and modelling it as a continuous variable. GHG=greenhouse gas. HR=hazard ratios.

Table 3: **Multivariable adjusted HRs and 95% CIs for mortality according to total energy-adjusted GHG emission, total water footprint, and land appropriation from dietary intake**

assessment.[49] Although we have tried to reduce the within-person errors using data from repeated assessments, non-significant associations in our study should be interpreted with caution because of the widened CIs. Second, our findings on the mortality outcome might not accurately reflect causality because of the observational nature of this study. Third, younger participants had a lower frequency of dietary assessments, and the average time intervals between two consecutive dietary assessments were 3·8 years for participants younger than 65 years and 3·1 years for participants aged 65 years and older. Theoretically, this difference might lead to biased results; however, the sensitivity analysis using the baseline rather than updated dietary scores showed consistent findings. Last, in addition to the baseline major conditions that were accounted for in the current study, other non-communicable diseases and other unmeasured confounding variables can also influence the associations of interest, but we were unable to take them into account because they were not measured at baseline of the current study.

In conclusion, the environmentally friendly PBDs are not necessarily associated with lower mortality risk. The PHD, developed mainly in western populations, was related to lower mortality risk but higher environmental burdens in the Chinese population. Further studies are warranted to identify the optimal dietary pattern with co-benefits for global environment and population health, taking into account the diverse and country-specific dietary cultures.

Contributors

CY and XW designed and conceptualised the study; HC, LH, and CY had access to the raw data; HC and LH verified the data and performed statistical analysis; XW, JSJ, and YW interpreted the findings; HC drafted the manuscript; and XW, JSJ, YQ, PH, YL, BLB, CM, and WCW revised the manuscript. All coauthors critically reviewed this manuscript. CY had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Data used for this study, including individual participant data and data dictionaries, are publicly available on the CHNS website (https://www.cpc.unc.edu/projects/china). We plan to disseminate our findings to the general public in a press release.

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