Environmental and human health trade-offs in potential Chinese dietary shifts

Graphical abstract

Highlights

- Balanced diets prevent more than one million premature deaths annually in China

- More fruit and vegetables benefit health but increase environmental burdens

- Dietary choices affect $PM_{2.5}$ air quality via NH_3 emissions from food production

- More soy protein reduces environmental impacts but has moderate health benefits

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In brief

Research shows that dietary shifts toward balanced diets and diets with more plant-based protein provide opportunities to address environmental and health challenges, but the effects on nitrogen pollution, associated air quality-related deaths, and land use-associated carbon storage remain unclear. We examine a shift in Chinese diets toward four hypothetical alternative diets and find opportunities to mitigate air pollution and reduce disease burdens. Pairing improved food production techniques with modified dietary practices can benefit health and the environment.

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Environmental and human health trade-offs in potential Chinese dietary shifts

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SCIENCE FOR SOCIETY Ensuring a secure supply of nutritious food within planetary boundaries is a global challenge, especially for China where improved agricultural practices feed the world's largest population but create multiple environmental challenges. Chinese diets are shifting toward more meat, fruit, and vegetables, generating compounded environmental and health consequences. Alternative diets have been studied for their climate and health impacts. However, research gaps remain, particularly regarding air pollution from nitrogen fertilizers and livestock manure and land-use change. Here, an analysis of four dietary alternatives is conducted to fill these gaps and finds that a diet high in beef, dairy, and fruit increases environmental effects with limited health benefits; diets with more fruit, vegetables, and legumes substantially reduce diet-related disease burdens but increase environmental effects unless dairy and red meat are reduced; diets that replace red meat with soy create multiple environmental benefits, but only moderate dietary health benefits.

SUMMARY

Dietary shifts from staples toward meats, fruits, and vegetables increase environmental impacts. Excessive red meat intake and micro-nutrient deficiencies also raise health concerns. Previous research examined environmental and health consequences of alternative diets but overlooked impacts on air pollution and land use change. Here we examine implications of four potential Chinese dietary shifts on ammonia and particulate matter ($PM_{2.5}$) air pollution, greenhouse gas (GHG) emissions, carbon storage loss associated with land-use change, water use, and human health. We show that a diet that replaces red meat with soy benefits the environment and avoids 57,000 $PM_{2.5}$-related premature deaths annually. Dietary health benefits, however, appear larger with adoption of the Chinese Dietary Guideline (CDG) and EAT-Lancet diets, which prevent over one million premature deaths annually. However, both diets increase water use and GHGs. CDG also increases COCs, but EAT-Lancet reduces it by cutting dairy and red meat. Complex benefits and trade-offs of dietary shifts emphasize the need for further improvements in agricultural management to enable larger health-environment co-benefits.

INTRODUCTION

As countries become more affluent, dietary choices have shifted toward meat, fruit, and vegetables, which, compared with staple foods, have more taste appeal and diverse nutritional content.[1,2]

Previous research has shown that malnutrition and undernourishment rates in China have dropped substantially over the past decade. However, at the same time, per-capita greenhouse gas (GHG) emissions and water and land use from Chinese food consumption have increased steadily.[3,4] These increases are

largely associated with increased consumption of meat products.[3,4] Between 1998 and 2012, Chinese per-capita meat consumption, dominated by pork, has increased by ∼50%, whereas consumption of starchy foods has decreased (Figure S1).[5] In addition to the environmental concerns associated with this dietary shift, large disease burdens in China (i.e., 3.4 million premature deaths in 2017) are attributable to dietary risks, including low fruit, nut, and coarse-grain intake and high intake of oil and salt.[6,7] Intake of red meat, when in excess, has been found to be associated with increased risks of cardiovascular diseases, type 2 diabetes, colorectal cancer, and premature death.[8–10] Obesity and excess weight also are a growing concern, affecting 89 and 320 million people, respectively.[11]

Identifying food choices that can simultaneously benefit health and the environment is challenging and has been a great research interest in recent years. Research on diets in developed[12–20] and low- and middle-income countries[21–23] has shown that decreasing intake of meat (especially beef) and dairy and increasing the share of plant-based protein and low-food-chain animal protein (forage fish, bivalve mollusks, etc.) in the total protein supply, as well as shifting away from rice toward wheat, coarse cereals, pulses, and leafy vegetables, facilitates GHG mitigation and dietary health. Studies estimate that agricultural GHG emissions can be reduced by 50% by changing diets in affluent economies[24] and by around 30% through dietary changes in China.[23] Alternative diets that embody the above environmental and health objectives include balanced dietary recommendations (e.g., for China, the Chinese Dietary Guideline (CDG), which emerged in 1989 and is updated every 5 years; the EAT-Lancet planetary health diet, proposed in 2019; and environmentally friendly diets that replace beef with poultry or meat with plant-based protein (Soy Replaces Red Meat [SRRM]).[25–27]

However, existing research remains incomplete. Although an increase in consumption of fruit and vegetables is in many ways beneficial, it also requires higher nitrogen (N) fertilizer input (in kg N/hectare) than staple crops,[12] which can result in additional N pollution. Beef in particular also has substantially higher N requirements per calorie than poultry, pork, and crop products,[13] as well as higher water and land requirements and GHG emissions. Atmospheric ammonia (NH_3) emissions, predominantly from agricultural N application and animal manure management, reacts with sulfur dioxide (SO_2) and N oxides (NO_x) from transport, power, residential, and industrial sectors to form secondary inorganic aerosols (SIAs), which dominate the inorganic fraction of health-damaging $PM_{2.5}$ (fine particulates with aerodynamic diameters of <02.5 μm) NH_3 emissions contribute between 10% and 18% of China's $PM_{2.5}$[14] and drive the loss of ecosystem biodiversity.[28–31] Mitigation of NH_3 has recently been incorporated into Chinese air pollution policies,[15] and in 2021, a quantitative target was set for animal farms in the Jing-Jin-Ji region.[16]

The extent to which potential dietary shifts affect NH_3 emissions and the associated $PM_{2.5}$ air quality effects remains unclear. Furthermore, previous studies that have evaluated climate effects of various diets typically use traditional life cycle calculations of GHG emissions.[26,27,17,18] However, this metric does not account for the inherent GHG costs of using land, which results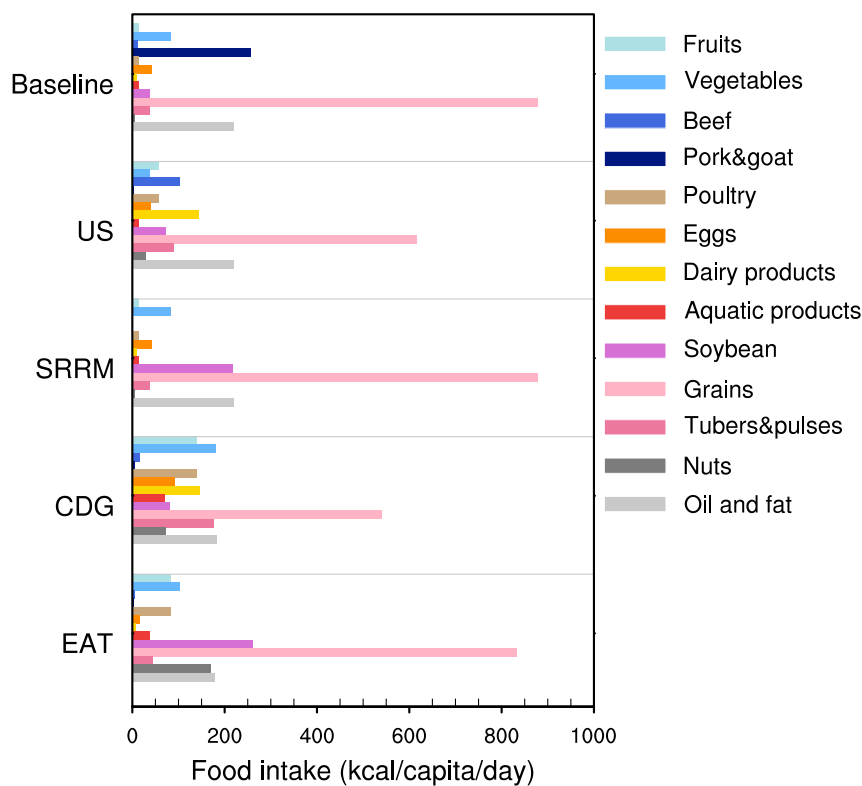 in reduced carbon stored in vegetation and soil. Overall, the more land is devoted to food production, the less carbon is stored. Previous dietary studies also mostly used food consumption data inferred from food production and balance statistics instead of surveys of individuals' real diets, which can skew results.

Here we analyze the environmental and human health trade-offs and co-benefits associated with the current Chinese diet and potential future diets (the CDG diet, EAT-Lancet diet, SRRM, and the United States (US) diet). We consider a wide range of health and environmental objectives (NH_3 emissions, $PM_{2.5}$ air quality and associated health effects, GHG emissions, land use carbon opportunity costs (COCs), water use, and dietary health) and provide a comprehensive picture of the human health and environmental consequences of dietary shifts. We adopt the carbon opportunity costs (COCs) concept, which estimates a global annual average carbon storage loss from terrestrial vegetation and soil to generate each food type[19] and addresses limitations associated with previous life-cycle GHG metrics. Our empirical analysis utilizes food intake data from a 2011 Chinese dietary survey representative of actual diets.[20] We find that the dietary shift toward the CDG or EAT-Lancet diet would reduce premature deaths by more than one million per year. However, these dietary shifts would be associated with additional water consumption and GHG emissions during food production, with the EAT-Lancet diet reducing COCs by reducing beef and dairy production and CDG by increasing them. Adoption of the SRRM or EAT-Lancet diet can help mitigate NH_3 emissions and reduce air pollution associated premature deaths per year by 57,000 and 55,000, respectively. A shift toward the SRRM diet can reduce all environmental damages examined and reduce premature deaths, although the diet-related health benefits appear to be much smaller than those from the CDG and EAT-Lancet diets so that only ∼300,000 premature deaths would be prevented each year. These findings are of great policy relevance because dietary health and air quality as well as greenhouse gas mitigation and resource conservation are receiving increasing policy attention in China.[15,28] Given that China produces food that feeds 18% of the world's population, our research provides important evidence to help facilitate sustainable transitions of the food sector. Chinese dietary transitions and the associated environmental and health consequences are representative of those in other emerging economies. Our analyses can also foster future research in other countries to analyze the effects of national dietary tendencies on reactive N burdens, health-damaging air pollution, climate, land use change, water use, and public health.

RESULTS

Four potential dietary scenarios for China

We consider a shift of the 2011 population-wide Chinese Baseline diet toward four possible alternatives. These include two balanced diets: the CDG diet, a balanced diet recommended by the Chinese government, and the EAT-Lancet diet (EAT; a balanced and sustainable diet recommended by the EAT-Lancet Commission[29]). We also consider two relatively extreme cases: a westernized diet (US; a diet that matches intakes of key food categories in a typical United States diet as indicated by the US National Health and Nutrition Examination Survey[30]), and a diet that

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Figure 1. Food intake (kcal/person/day) by food type for the 2011 Baseline Chinese diet and the four dietary scenarios

The four dietary scenarios are US (a typical 2011 United States diet), Soy Replaces Red Meat (SRRM; all red meat is replaced with soy products), Chinese Dietary Guideline (CDG; recommendation of the CDG), and EAT-Lancet Dietary Recommendations (EAT; a healthy and sustainable diet recommended by the Lancet EAT Commission). Definitions of vegetables and fruit are based on Chinese habits; e.g., cucumber, tomato, loofah, and zucchini are categorized as vegetables and watermelon and muskmelon as fruit. Intake of alcohol, sugar, condiments, and other food is not presented in this figure.

replaces red meat protein in the Baseline diet with soy protein (SRRM; a diet designed to eliminate the health risks and environmental damage of red meat). Figure 1 presents per-capita intake of various food products under the Baseline and four dietary scenarios, which all have a comparable calorie supply. Figure S2 and Table S1 present per-capita intake and food loss and waste (FLW) along the supply chain for each diet, with more details provided in the experimental procedures and Tables S2 and S3.

The US and SRRM diets provide two relatively extreme cases for health and the environment. Compared with the Baseline diet, the US diet has higher consumption of poultry, fruit, beef, and dairy but lower consumption of grains, vegetables, and pork. This scenario illustrates the consequences of a continuing westernization of Chinese diets because the Chinese people are increasingly consuming foods that are typically found in western diets (e.g., steak, dairy, cake, sugar-sweetened drinks, etc.). In comparison, the SRRM diet replaces all Baseline diet red meat (goat, sheep, beef, and pork) protein with the same amount of protein from soybeans, so that the health and environmental damage of red meat is eliminated.[17,18] Dietary scenarios with decreased animal protein supply, similar to SRRM, have been adopted for evaluation in many previous studies.[25–27] China has a long history of consuming soy and fermented soy products, and increases in soy intakes are associated with decreased risks of breast cancer,[31] depression,[32] and ischemic heart disease. However, red meat provides vitamin B_{12} and zinc, so people may have to find alternative sources of these micronutrients.[33]

The CDG and EAT diets represent balanced dietary patterns. The CDG diet requires greater consumption of fruit, vegetables, aquatic products, eggs, and dairy than the Baseline diet and

less pork, goat, and refined grains. In comparison, the EAT diet promotes environmental sustainability in addition to dietary health; it recommends higher consumption of soybeans and nuts and lower consumption of red meat and vegetables than the CDG diet. It also does not require the Baseline diet consumption of grains to decrease as much as the CDG diet. The EAT diet is a typical reference diet for all adults worldwide, but CDG diet recommendations vary according to an individual's activity level.

Health and environmental effects of different diets

We evaluate the effects of diets on food demand and, therefore, agricultural production and the associated health and environmental implications. We account for NH_3 emissions and associated $PM_{2.5}$ air pollution, land use COCs, agricultural production-related GHG emissions, total water footprints, direct dietary health effects associated with nutrient intake, and indirect health effects through human exposure to $PM_{2.5}$ (experimental procedures). Assumptions for international trade, FLW, and animal feed crop production are detailed in the experimental procedures.

Our analyses unveil several major findings that are absent from previous studies (Table 1). First, we find substantial dietary health benefits associated with balanced diets at the national scale. Shifting toward the CDG and EAT diets reduces premature deaths by 1.4 and 1.1 million/year, respectively, accounting for 50% and 40% of the 2.77 million dietary risk-related premature deaths in China in 2012. Balanced diets benefit health by increasing intake of fruit, vegetables, and legumes and reducing excess intake of red meat. Shifting toward the SRRM diet generates moderate dietary health benefits, decreasing premature deaths by 0.3 million/year (11%).

Second, we find opportunities for mitigating NH_3 emissions and resulting $PM_{2.5}$ air pollution. The SRRM and EAT diets reduce NH_3 emissions by 36% and 18%, respectively, reducing $PM_{2.5}$ by up to 10 μg/m^3 locally. NH_3 emission reductions achieved by the SRRM diet results from removal of red meat (pork, goat, and lamb) production and associated animal feed production. NH_3

Table 1. Environmental and health implications of Chinese dietary shifts from the 2011 Baseline diet toward four possible future diets

Environmental and health impacts	Baseline	US-Baseline	SRRM-Baseline	CDG-Baseline	EAT-Baseline
NH_3 emissions (total, Tg/year)	13.9	26.3	−5.1	15.8	−2.5
NH_3 emissions (fertilizer, Tg/year)	5.3	0.8	−1.1	4.8	1.4
NH_3 emissions (manure, Tg/year)	6.8	25.5	−4.1	11.1	−3.8
Production GHG emissions ($Gt\ CO_2$-equiv/year)	1	0.2	−0.3	0.4	0.03
Land use COC ($Gt\ CO_2$-equiv/year)	2.4	3.3	−0.7	2.1	−0.08
TWF (tera m^3/year)	0.9	0.3	−0.05	0.6	0.6
Premature mortalities associated with exposure to $PM_{2.5}$ (1,000 persons)	1,700[a]	79	−57	60	−55
Premature mortalities associated with four dietary risks (1,000 persons)	N/A[b]	−20	−293	−1,364	−1,109
Premature mortalities associated with fruit intake (1,000 persons)	N/A[b]	−378	0	−913	−742
Premature mortalities associated with legume intake (1,000 persons)	N/A[b]	−154	−253	−336	−376
Premature mortalities associated with red meat intake (1,000 persons)	N/A[b]	−25	−56	−34	−53
Premature mortalities associated with vegetable intake (1,000 persons)	N/A[b]	641	0	−685	−284
Premature mortalities associated with $PM_{2.5}$ and four dietary risks (1,000 persons)	N/A[b]	81	−362	−1,626	−1,339

For each metric, Baseline values and changes in dietary scenarios compared with Baseline (i.e., scenario-Baseline) are provided. Negative values mean mitigation of environmental effects or lives saved. The four potential dietary scenarios are US (a typical 2011 US diet), Soy Replaces Red Meat (SRRM; all red meat is replaced with soy products), Chinese Dietary Guideline (CDG; recommendation of CDG), and EAT-Lancet Dietary Recommendations (EAT; a healthy and sustainable diet recommended by the Lancet EAT Commission).

[a]We estimate that $PM_{2.5}$ concentrations in 2012 resulted in 1.7 million premature deaths. $PM_{2.5}$ concentrations depend nonlinearly on concentrations and emissions of many species (e.g., NO_x, SO_2, and primary $PM_{2.5}$) emitted by residential, energy, industry, and transportation sectors, in addition to NH_3, which is dominantly from agricultural sources.

[b]Dose-response relationships for dietary intake risks only provide estimates of changes in health risks because of changes in nutrient intake levels.

volatilization in animal houses, during animal manure storage and management processes, and from nitrogenous fertilizer application for animal feed crops are reduced. Although soybean production increases, it has little effect on NH_3 emissions. In comparison, the EAT diet decreases livestock NH_3 emissions by 3.8 Teragrams/year (Tg/year) (56%), mainly by reducing red meat consumption, and increases crop NH_3 emissions by 1.4 Tg/year (26%), mainly because of increased fruit and vegetable production. Overall, the EAT diet provides NH_3 emission reductions of 2.5 (18%) Tg/year. $PM_{2.5}$ mitigation and associated reductions in premature deaths are around 0.06 million/year for the SRRM and EAT diets, which is orders of magnitude smaller than dietary health effects. A comparison of dietary health and $PM_{2.5}$ effects at regional scales requires future research because agricultural production activities may be concentrated in specific areas.
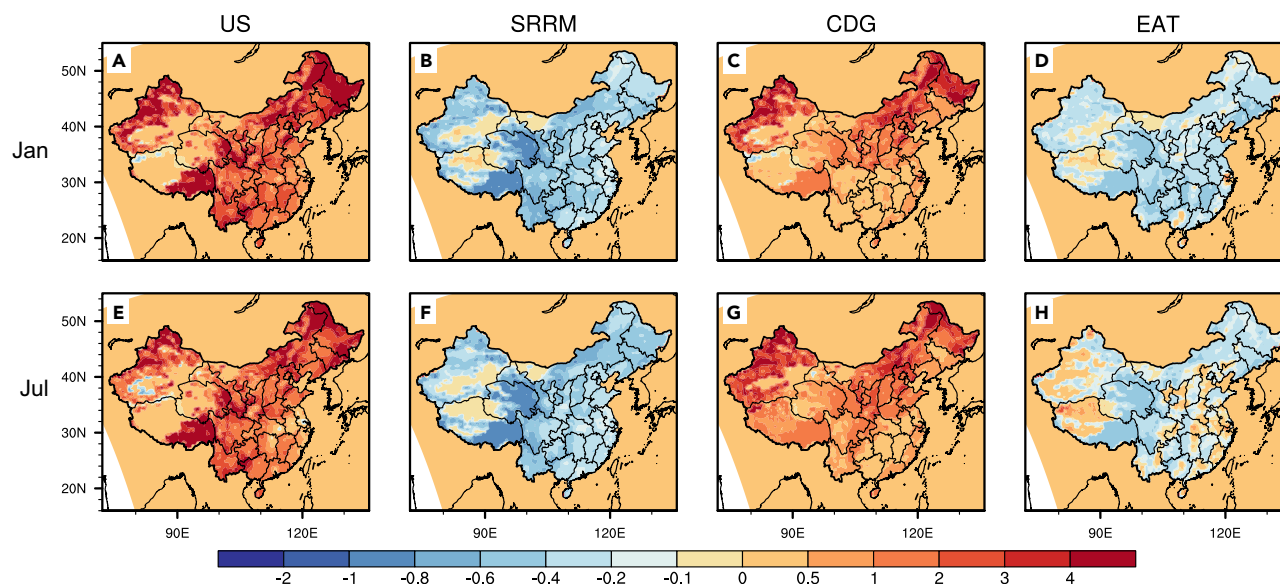
Third, we find rather complex trade-offs for health and the environment in increased consumption and production of fruit, vegetables, and dairy. The two balanced diets examined, CDG and EAT, require increased consumption and production of fruit, vegetables, and dairy compared with the current Chinese diet. Increasing intake of fruit and vegetables substantially improves dietary health, preventing 0.9 and 0.7 million premature deaths in the CDG diet.

However, increased fruit and vegetable production will involve intensive N fertilizer use and result in higher NH_3 emissions. The

EAT and CDG diets result in 1.4 and 4.8 Tg/year, respectively, higher NH_3 emissions than with the Baseline diet. Higher dairy intake, when not accompanied by decreases in intake of other animal products or production improvements, will likely increase the environmental damage of the livestock sector. For example, the CDG diet has 2.1 $Gt\ CO_2$-equiv/year higher land use COCs and 0.4 $Gt\ CO_2$-equiv higher food production GHG emissions than the Baseline diet. In comparison, the EAT diet has more moderate increases in GHG emissions than the Baseline diet. This is because the EAT diet requires smaller increases in dairy than the CDG diet and cuts red meat consumption, which also results in lower livestock NH_3 emissions than the CDG diet.

The SRRM diet mitigates all environmental damage examined but generates moderate dietary health benefits of 0.3 million/year prevented premature deaths, which is substantially smaller than that achieved by the balanced diets. In addition, the SRRM diet is also the only alternative diet that decreases water use. However, the SRRM diet's reduction in environmental damage is achieved at the opportunity cost of dietary health relative to balanced diets. Last, the US diet increases all environmental burdens and health risks compared with the Baseline diet, mainly because of its high intake of beef and low intake of vegetables. It also has the smallest dietary health benefit and the largest $PM_{2.5}$-related health damage. Below, we elaborate the effects of dietary shifts on each environmental and health objective.

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Figure 2. Changes in NH_3 emissions in potential dietary scenarios relative to Baseline diet NH_3 emissions in January and July of 2012
(A–H) Colors indicate (NH_3 emissions in Scenario − NH_3 emissions in Baseline diet)/NH_3 emissions in Baseline diet in (A–D) January and (E–H) July of 2012. The four potential dietary scenarios are US, SRRM, CDG, and EAT.

Effects of dietary shifts on NH_3 emissions

We account for NH_3 emissions from domestic food production, including NH_3 emitted during nitrogenous fertilizer use in human and animal feed crop production and during livestock manure handling and management. When estimating food-related NH_3 in future dietary scenarios, we address changes in food production levels compared with those at present but assume no changes in NH_3 emission factors. Detailed assumptions about management practices and production patterns in dietary scenarios are provided in the experimental procedures and Tables S4 and S5.

Under the Baseline diet, China's national total NH_3 emissions are 13.9 Tg NH_3, with crop N fertilizer use contributing to 37%, livestock manure management contributing to 49%, and other anthropogenic sources (transportation and sewage) contributing to 14% of total NH_3 emissions (Table S6). The largest contributor is cereals (17%) because of the large production amount, followed by vegetables, goat, sheep, pork, and dairy cattle production, which each contributes ∼7%–10%. Fruit and beef production contribute to only 1 and 6% of total NH_3 emissions, respectively, because of their low production levels, despite high NH_3 emission intensities.

Shifting from the Baseline diet toward the US diet leads to a 189% increase in NH_3 emissions. High NH_3 emissions in the US diet are due to its high beef and dairy consumption. Shifting toward the CDG diet leads to a 110% increase. High consumption of fruit, vegetables, eggs, and dairy products in the CDG diet contributes to increased NH_3 emissions. Such effects are offset by the CDG diet's lowered consumption of red meat, poultry, and grains compared with the US diet. Still, overall, the CDG diet has NH_3 emissions that are 110% higher than those of the Baseline diet.

In contrast, shifting from the Baseline diet toward the SRRM and EAT diets significantly decreases NH_3 emissions by 36% and 18%, respectively. The SRRM diet removes the N-intensive production of pigs, beef cattle, and goats. Associated animal

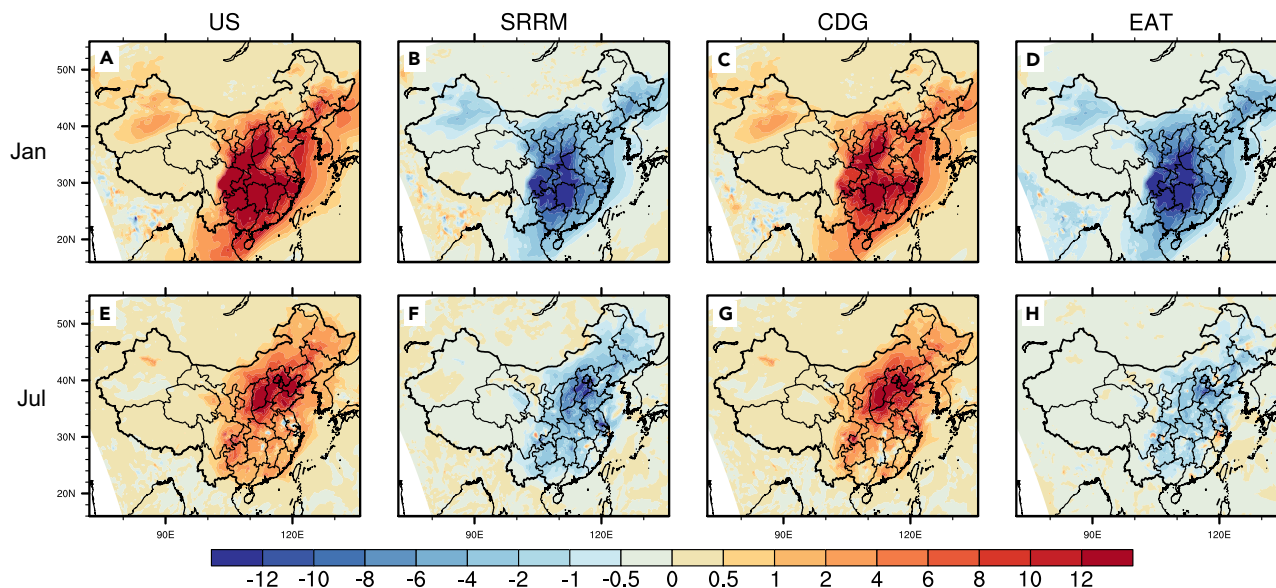feed production also decreases; e.g., maize (46% decrease), wheat (28% decrease), and rice (6% decrease). Locally, NH_3 emission reductions can be as high as 20% in eastern China and 60% in northeastern, middle, and western China, where animal densities are high (Figure 2). As for the EAT diet, although it requires substantial (moderate) increases in consumption of fruit, soy products, and nuts (vegetables and root vegetables) compared with the Baseline diet, it dramatically cuts consumption of animal products; e.g., a 77% reduction in red meat. Locally, NH_3 emission reductions can be as much as 60%. Some areas in western China, the lower Yangtze River Basin, and eastern China experience increased NH_3 emissions because of increased local crop production (Figure 2).

Effects of dietary shifts on $PM_{2.5}$ air quality

We estimate changes in $PM_{2.5}$ concentrations driven by NH_3 emission changes in China using a regional atmospheric chemistry model (Weather Research and Forecasting – Chemistry [WRF-Chem]) with improved aerosol chemistry (experimental procedures). Evaluations of simulated NH_3 and speciated $PM_{2.5}$ can be found in a previous article.[34] Shifting from the Baseline diet toward the US diet increases SIA concentrations by up to 10 $\mu g/m^3$ locally (Figure 3), particularly in wintertime eastern China and summertime over the North China Plain. Shifting toward the CDG diet also increases SIAs. However, shifting toward the EAT and SRRM diets achieves large SIA reductions in winter; e.g., an up to 12 $\mu g/m^3$ reduction in central China. Figures S3 and S4 show effects of dietary shifts on concentrations of ammonium, nitrate, and sulfate aerosols in January and July.

Effects of dietary shifts on food production GHG emissions

We account for life cycle GHG emissions during food production (cradle to farm gate) at home and abroad that are needed to meet

Figure 3. PM$_{2.5}$ air quality impacts of shifting from the Baseline diet towards four potential diets
(A–H) Changes in ground-level secondary inorganic aerosol (SIA) concentrations (in units of $\mu g/m^3$; negative values mean reductions). in potential dietary scenarios compared to the Baseline diet in (A–D) January and (E–H) July of 2012. The four potential dietary scenarios are US, SRRM, CDG, and EAT.

Chinese food demands in each dietary scenario. We use 300 life cycle assessments (LCAs) covering the emissions from cradle to farm gate worldwide following the methodology in He et al.[3] because studies specifically for China are scarce. Shifting from the Baseline diet toward the US diet increases life cycle GHG emissions by 20% (Figures 4A and S5A; Tables 1 and S7), dominantly driven by increases in beef, eggs, and dairy (Figure S5A). Shifting toward the CDG diet leads to a 40% increase, dominantly driven by increases in aquatic products, vegetables, eggs, and dairy (Figure S5A). However, switching to the SRRM diet reduces emissions by 30%. Switching to the EAT diet leaves production emissions almost the same as for the Baseline diet (a 3% increase). This is because in the EAT diet scenario, although reduced consumption of meat generates reductions in GHG emissions, such savings are compensated for by increased GHG emissions associated with high consumption requirements for aquatic products.

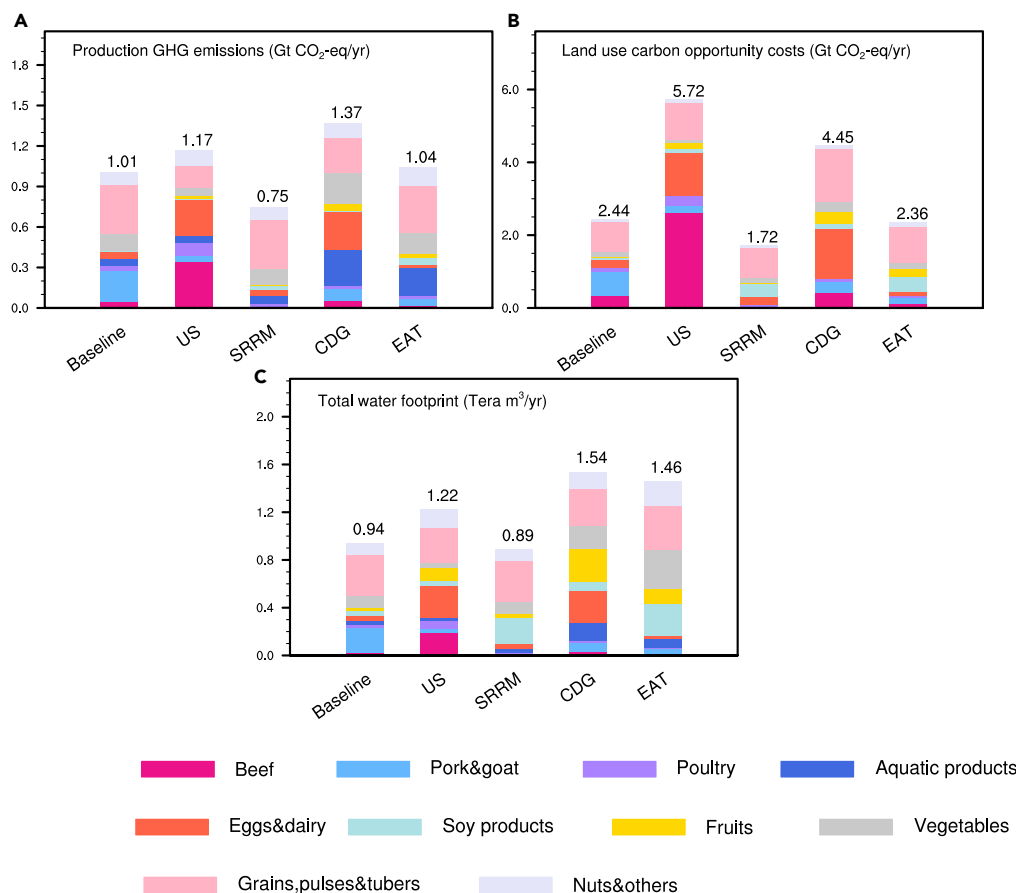**Effects of dietary shifts on land use GHG emissions**
Land has opportunity costs for global carbon storage. A piece of land could remain forested as for global carbon storage purposes or could be used to grow another type of food/biofuel more efficiently, increasing yields or generating more food calories. To accommodate dietary changes, expansion of agricultural land may occur when intensification is not sufficient or realistic. Following the life cycle GHG approach above, dietary choices that greatly increase or reduce global land use demands are not necessarily assigned a GHG cost or saving. For example, in previous life cycle studies, GHG emissions from soybeans are assigned life cycle GHG emissions when they are imported from Brazil, where ongoing net land use change (LUC) is occurring, but not when they are imported from long-cultivated fields in the United States (see Searchinger et al.[19]). The life cycle GHG approach implies that animal feed production could have zero

LUC GHG emissions even when they required land conversion from forests for production per kilocalorie or gram of protein.

Here, instead, we calculate land use GHG emissions based on their COCs and find substantial land use GHG consequences of dietary changes. In the Baseline diet, land use GHG emissions are already ~2.4 times the size of production GHG emissions at 2.4 Gt CO$_2$-equiv/year (Figure 4B versus Figure 4A; Figure S5B versus Figure S5A; Table S8). As explained in Searchinger et al.,[19] this comparison indicates that the land required to produce the Baseline diet, if not used for food, could be used to globally store vegetative and soil carbon at a level equal to 240% of the GHGs emitted during food production and processing for more than 30 years. COCs rise to 5.7 Gt under the US diet primarily because of the large increase in beef consumption. Even under the CDG diet, land use GHG emissions rise to 4.1 Gt because of the large increase in dairy but also in part because of increases in fruit and pulses, both of which have larger land use demands per kilogram fresh weight than cereals. These costs decline significantly under the SRRM scenario, mostly because of the decline in beef. These costs decline by only 3% under the EAT scenario. That is because beef consumption is already low in the Baseline diet. Most of the decline in red meat in the EAT diet, therefore, occurs through decline in pork, which is more land-efficient than beef. COC decline in the EAT diet, driven by decreased intake of red meat, is offset by increased land demand for fish, fruit, and pulses.

Effects of dietary shifts on total water footprint
We account for total water use, including irrigation (blue) and rain (green) water, during food production at home and abroad to meet food demands in each dietary scenario (experimental procedures). Inclusion of the total water footprint (TWF) metric delivers similar messages as factoring in production GHG emissions; i.e., except for the SRRM diet, shifting toward all future

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Figure 4. Environmental effects of food consumption in China in the Baseline diet and four future dietary scenarios by food type
(A) Life cycle GHG emissions during food production from cradle to farm gate (gigaton CO_2-equiv/year).
(B) Land use carbon emissions indicating the opportunity cost of land (gigaton CO_2-equiv/year).
(C) Food consumption-based total water footprint (TWF) (tera m^3/year).
Numbers above each bar show the absolute value of the metric in each scenario. Colored bars denote effects of consumption of different food types. The four potential dietary scenarios are US, SRRM, CDG, and EAT.

diets increases water use. This is because producing beef, soybean, fruit, vegetables, and dairy is water intensive. Thus, shifting from the Baseline diet toward the SRRM diet, although it saves water by cutting meat consumption, only generates small water savings because of large increases in soybean production (Figures 4C and S5C). Shifting from the Baseline toward the US diet requires more water because of high consumption of beef and dairy in the US diet. Shifting from the Baseline diet toward the two balanced diets requires more water use because of increased consumption of eggs, dairy, aquatic products, fruit, and vegetables.
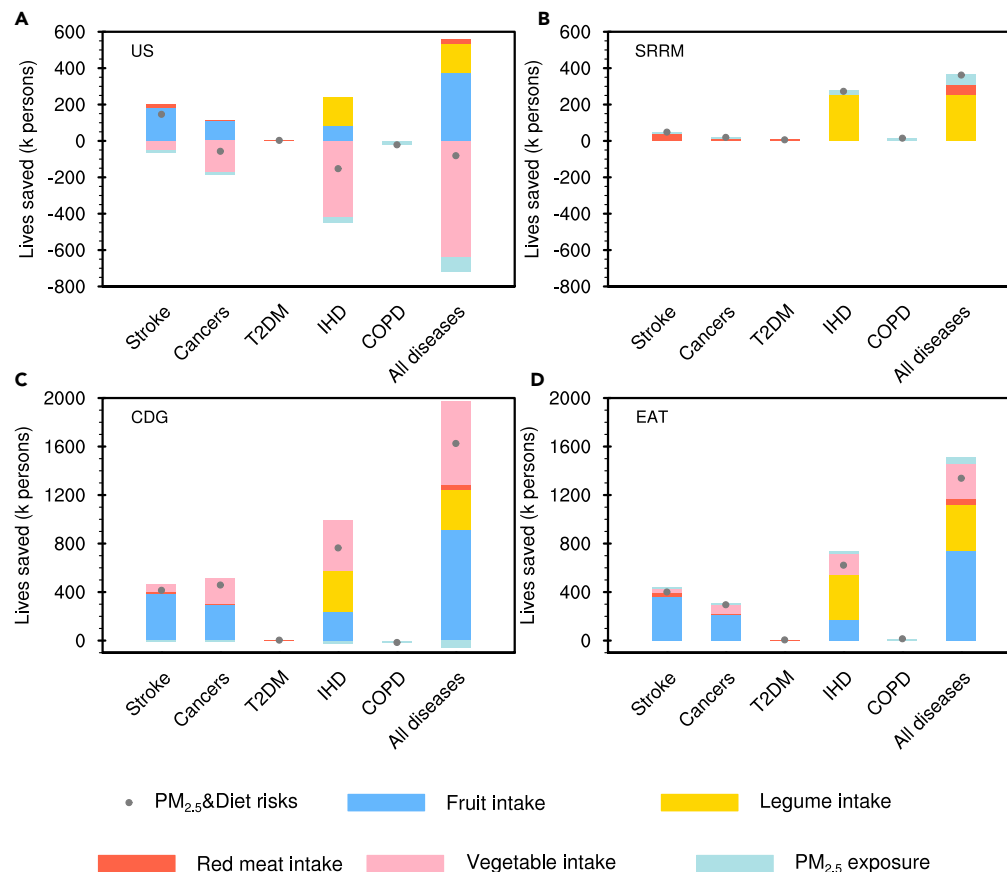
Effects of dietary shifts on health
Here we consider the effects of changes in intake of fruit, vegetables, legumes, and red meat on premature mortality from coronary heart disease (CHD), stroke, total cancers, type II diabetes mellitus (T2DM), colon and rectal cancers, and lung cancer using cohort studies worldwide (experimental procedures). We also consider the health effects of changes in $PM_{2.5}$ air pollution levels resulting from changes in food production levels to accommodate the food demands of various diets. $PM_{2.5}$ can

penetrate into the lungs and bloodstream, increasing risks of chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD) and ischemic stroke (Experimental procedures).

The health effects of the four dietary shifts differ from the environmental effects. Overall, the US diet increases premature deaths by 0.08 million persons per year. It provides dietary health disbenefits resulting from low vegetable consumption and health disbenefits through increased $PM_{2.5}$ levels resulting from N-intensive beef and dairy production. The SRRM diet is modestly beneficial for dietary health but dramatically less beneficial than the EAT diet because of the EAT diet's high fruit, vegetable, and legume consumption. The CDG diet is the most beneficial to health because of its even higher consumption of fruit, vegetable, and legumes compared with that in the EAT diet, although it slightly worsens air quality. The CDG diet has lower pork and higher poultry consumption than the Baseline diet. EAT has even lower pork, beef, and poultry consumption than the CDG diet. Overall, the EAT and CDG diets reduce 1.4 and 1.6 million premature deaths per year, respectively (Table 1; Figure 5).

Figure 5. Lives saved (10,000 persons) from five diseases in four potential dietary scenarios compared with the Baseline diet because of changes in food consumption and exposure to PM$_{2.5}$ air pollution
Colors of bars indicate risk factors, and gray dots denote all individual risks combined. Endpoint diseases considered include stroke, ischemic heart disease (IHD), type II diabetes mellitus (T2DM), cancer (including colon and rectal cancers, lung cancer, and other cancers), chronic obstructive pulmonary disease (COPD), and all of these diseases. The four potential dietary scenarios are US (A), SRRM (B), CDG (C), and EAT (D).

Solely focusing on dietary health, except for the US diet, all dietary shifts examined deliver dietary health benefits that range from 0.02–1.4 million persons per year. Although changes in red meat consumption play a role, increased intake of fruit, vegetables. and legumes dominate health benefits.

Solely focusing on air quality effects, shifting from the Baseline diet toward the SRRM and EAT diets reduces premature mortality because of exposure to PM$_{2.5}$ by roughly 0.06 million persons per year. In contrast, the US diet increases premature mortality by 0.08 million and the CDG diet by 0.06 million. The PM$_{2.5}$ health effects of changing diets are smaller than dietary health effects of changes in food intake.

Uncertainties
Analyses of the kind in this paper face many uncertainties, including uncertainties regarding the current Chinese diet (experimental procedures), dietary health effects evaluation, emission estimations for other SIA precursors (i.e. SO$_2$ and NO$_x$), water footprint data, and environmental accounting of seafood. Our results are heavily influenced by the low estimates of fruit and vegetables in Chinese nutrition surveys in the current Chinese diet, consistent and supported by the Global Dietary

Database. For example, according to these surveys and those in the United States, fruit intake in China is even lower than in the United States. Our results would differ if we used macro production statistics, as many other studies have done.[26,27]

We chose the Chinese nutritional surveys to construct baseline Chinese diets in order to avoid "human" errors in Chinese national macro statistics. Macro statistics calculate human food consumption from food production, import and export, stock change, and non-food use, which are estimated through surveys conducted by localities. Survey data are then aggregated to the national level; errors are aggregated as well. In addition, previous research reported over-reporting of livestock production.[35–38] National production statistics in China indicate substantially higher fruit and vegetable intake than nutritional surveys (Table S9). This discrepancy/inconsistency between macro-level statistics and micro-level survey data is not uncommon; many countries estimate higher food consumption from national statistics than from nutritional surveys, including higher estimation of livestock products and lower estimation of grain intake.[39] Indeed, dietary surveys can be vulnerable to under-reporting, which has been shown to be especially serious among severely obese populations in the United States.[40] Given high-quality

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baseline diet data are critical for estimating the gap between current diet and healthy/sustainable diets, future research is needed to understand the gap between diets estimated from micro-surveys and macro-statistics.

Another area of uncertainty involves the health effects of different diets. Our dietary health evaluation considers the correlations between four dietary risk factors (intake of fruits, vegetables, red meat, and legumes) and premature mortality from several endpoint diseases (Experimental procedures' Table S10). These correlations have been used in previous studies.[17] However, these correlations do not infer causal relationships and potentially vary across populations with different lifestyles (sports, smoking, etc.). We also exclude health indicators such as obesity, being overweight, supply of micro-nutrients, and quality of protein. For example, the US diet potentially results in a higher calory supply per capita and, thus, higher incidences of being overweight than the current Chinese diet.[41]

Other uncertainties relate to the evaluation of environmental effects. Contribution of NH_3 to formation of SIAs depends on the abundance of SO_2 and NO_x which primarily originate from combustion, transportation, and residential sources. The cccuracy of these emission estimates and their geographical locations will affect the accuracy of the air quality modeling results. We used the water footprint database for the time period of 1996–2005 because it is the most recent food product-level water use database. Updated data, when available, can be used for future studies. Our water use accounting includes water used to grow the feed for farmed fish by fish species. It excludes water losses via evaporation, infiltration, and dilution in farmed aquaculture or water associated with feed for wild capture. Recent research found that each abovementioned water consumption term can be almost as important as water in farmed fish feed (Table S11). Water utilization also has large variations across production systems and locations.[42] We estimate that including these additional water uses indicated by Gephart et al.[42] will make the CDG and EAT diets (the US diet) more (less) thirsty than currently estimated, whereas water savings achieved by the SRRM scenario will not change (Table S12). Our current conclusions for water use still hold, but the magnitude of changes in alternative diets relative to the Baseline diet would be different. Furthermore, GHG emissions associated with seafood production also vary across production systems. However, we did not discriminate between farming and capture fisheries but calculated the average of all available published LCA results for seafood.

DISCUSSION

Growing populations in developing countries have shifted their dietary choices from staple foods toward fruit, vegetables, and meats. Transitions of diets generate complex health and environmental consequences because various foods are associated with varying pollutant emission intensities, resource requirements, micro-nutrient contents, and dietary health effects. Understanding the nexus of diet, health, and environment is essential for creating a nutritious and sustainable food future. Our analyses for China find substantial dietary health benefits associated with balanced diets (CDG and EAT): more than one million prevented premature deaths per year. Thus, the government, non-governmental organizations, and the private sector could consider strengthening

public education of the health benefits of balanced dietary patterns and facilitating wiser consumer food decisions. We also find opportunities for mitigating NH_3 emissions and, thus, $PM_{2.5}$-related premature deaths by ~0.06 million/year through uptake of the SRRM and EAT diets. Such air quality benefits are smaller than those derived from healthy diets but are still large and comparable with that achieved through improving food production practices. For example, previous research estimated that combining multiple N management improvements in China achieves a 34% reduction in national NH_3 emissions and up to a 7 $\mu g/m^3$ reduction in $PM_{2.5}$ locally.[34] In addition, although wise food choices are personal, clean air is a public good.

We also find rather complex trade-offs in production and consumption of fruit, vegetables, and dairy for health and the environment. Increasing intake of fruits and vegetables in the *CDG* diet, respectively, avoids 0.7 and 0.9 million premature deaths, but NH_3 emissions and water use increase. The CDG diet's dairy recommendations, much higher than those of the Baseline diet, also contribute to increasing environmental burdens. Dairy may protect against chronic diseases but is not associated with all-cause mortality[43] and has shortcomings because the majority of the Chinese population is lactose intolerant. A westernized diet (i.e., the US diet), because of its high requirement for beef and dairy cattle production, increases livestock NH_3 emissions 3-fold and, thus, increases $PM_{2.5}$-related mortalities by 0.08 million/year. These increases occur with the assumption that increased beef and dairy demand is fulfilled with domestic production; such environmental effects may be outsourced with food import from other countries. The evaluation of COCs emphasizes large LUC-related GHG emissions resulting from additional consumption of beef, dairy, fruits, and pulses. This means that substantial cropland expansion will be needed to grow crops or animal feed. Replacing red meat with soy decreases all environmental damage, but its dietary health benefit is substantially lower than that of the balanced diets.

A potentially surprising result of our study is that the EAT diet modestly increases GHG emissions from the food production process and that the CDG diet increases them substantially. That is likely because the existing Chinese diet has little consumption of dairy and beef, and reductions in emissions as a result of less consumption of meat, such as pork and poultry, are offset by higher emissions from increased consumption of fruit and vegetables. Both diets substitute fruit and vegetables for starches, which has health benefits but causes more emissions. Only the SRRM diet results in reductions in production emissions. However, the SRRM and EAT diets result in large reductions in land use COCs, which are also much larger than production emissions. The major GHG benefit of reduced meat consumption in China would therefore be in reduced land use.

Given the limited effects on production emissions from the different diets, except for those resulting from elimination of red meat, other environmental solutions would also be necessary to reduce environmental costs associated with food production. Possible examples include dietary supplements for cattle; reducing excess N application to China's fruit, vegetable, and staple crops;[34] and reductions in FLW, estimated previously at 27% in China.[44]

Our research demonstrates the rather complex effects of four hypothetical Chinese dietary shifts on dietary health and multiple

environmental objectives. We find opportunities for mitigating NH_3 emissions and associated $PM_{2.5}$ pollution as well as opportunities for improving dietary health. Given clear environment-health trade-offs, advocating any specific dietary changes needs to be done with caution. A healthy and sustainable food future requires food production technologies and FLW mitigation in addition to dietary change strategies.

EXPERIMENTAL PROCEDURES

Resource availability
Lead contact
Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Denise L. Mauzerall (mauzerall@princeton.edu).

Materials availability
This study did not generate new unique materials.

Data and code availability
Data and code have been uploaded to Princeton University's DataSpace (http://arks.princeton.edu/ark:/88435/dsp01nz8062179; https://doi.org/10.34770/rnpp-4t33).

The Chinese Baseline diet and four future dietary scenarios
The Baseline diet is based on the China Health and Nutrition Survey (CHNS) for 2011,[20] which sampled 10,000 random people in 12 provinces with distinct socioeconomic and demographic backgrounds. The survey tracked individual food intake (food types and weights) over 3 consecutive days. We then estimate diets of individuals outside of the sample areas by matching diets of sampled individuals with individuals in each area based on similarities in socioeconomic conditions (indicated by income) and eating habits (indicated by the province of residence), following the same matching processes used in He et al.[45] The demographic information of the CHNS sample and of all Chinese is from the China Family Panel Studies (CFPS). The CFPS program provides individual-level demographic information and socioeconomic characteristics representative of 25 provincial districts as well as a weight for national representative estimation since 2010. We obtain the joint distribution of a number of variables, such as age, sex, urban/rural status, and per-capita household income, from CFPS and match the CHNS sample to the nationwide population. Table S1 provides Baseline diet per-capita daily food intake.

The US diet is a diet in which the Chinese intake of nutrients matches that of a typical United States diet by choosing among food products available on the Chinese market. Nutrient intake of Americans is from the Centers for Disease Control and Prevention National Health and Nutrition Examination Survey (NHNAES)[30] during 2011–2012. The foods we matched were from the following categories: total fruit, dark-colored vegetables, light-colored vegetables, starchy vegetables – potatoes, starchy vegetables – others, total dairy products, protein foods – eggs, protein foods – livestock products, protein foods – poultry products, protein foods – seafoods, protein foods – nuts and seeds, protein foods – soybean, refined grains, and whole grains. These are the food categories used for dietary quality evaluation in the United States, with definitions and more detailed information included in the Food Patterns Equivalents Database.[46]

The SRRM diet removes all red meat (goat, sheep, beef, and pork) consumption. The decrease in animal protein is made up by increased intake of soybean products (equal protein substitution). This scenario potentially achieves environmental and health co-benefits because reduced livestock production and corresponding animal feed production will lower environmental damage, and reduced red meat intake will reduce health risks.[47] It is a radical diet but has been widely adopted in previous dietary studies.[25–27]

The CDG diet is based on China's Balanced Dietary Patterns from the 2016 CDG, which includes intake quantities for 14 food groups (e.g., fruit, leafy vegetables, whole grains) for people at 11 energy requirement levels. More details can be found in He et al.[45]

The EAT diet is based on dietary recommendations provided by the EAT-Lancet Commission[29] that apply universally to all adults regardless of age and country of origin. We thus assume the diets of people below 20 years of age are the same as in the Baseline diet.

In all four future dietary scenarios, we determine each individual's exact combination of food choices in sub-food groups (the Chinese Food Content Tables, 2002 and 2004 versions) by randomizing their choices within each major food group through Monte Carlo simulations. In the simulation, we keep an individual's dietary preferences among each sub-food group item the same as preferences indicated by the Baseline diet. The Chinese Food Content Tables include a sum of ∼4,000 Chinese food products. The Chinese Food Content Tables discriminates among different types of snacks, different cooking methods for one food product, and different types of meat (e.g. pork neck, butt, loin, etc.).

We consider food intake for food types with and without a standardization process. Among the ∼5,000 types of Chinese food products we model, food products under the same food group can vary significantly in nutritional composition. Cooking methods of a food also affect nutrition and energy supply. For example, different types of pork have substantially different fat, protein, and energy content. One gram of strawberries has fewer calories than one gram of grapes. Cooked rice and rice congee have substantially different amounts of calories. We thus standardize food items to allow better comparison, following guidelines for calculating food weight equivalents provided by the CDG using methodology provided in He et al.[45]

Estimating food production in dietary scenarios
We estimate food production based on food intake and FLW while accounting for effects of meat requirements on animal feed crops and international trade. We account for food losses during production, after harvesting, food processing, packaging, distribution, and food waste during consumption using FLW ratios reported by the Food and Agriculture Organization (FAO)[48] (Table S2). We assume that the ratio of FLW to total production stays the same for the Baseline diet and in future dietary scenarios. For example, if intake of one food product increases (or decreases) by X times in dietary scenarios compared with the Baseline diet, then the amount lost and wasted in future dietary scenarios will also increase (or decrease) accordingly by X times.

Baseline agricultural production by food products and their geographical distribution for the year 2012 is obtained from the Chinese Statistical Yearbook. Production of each non-animal feed food product in dietary scenarios is estimated by scaling the Baseline diet production level with a factor equal to the ratio of food consumption in dietary scenarios to that in the Baseline diet. The partitioning between net import and domestic production in dietary scenarios remains the same in the scenarios as partitioning in the Baseline diet. For example, if consumption of a non-animal feed food product i in a dietary scenario needs to be X times of that in the Baseline diet, then domestic production and net import of this food product i in the scenario will be X times of those in the Baseline diet.

Animal feed crop production (maize, wheat, rice, and soybeans) requires slightly different treatment. Their production in future dietary scenarios should reflect changes in human demand for food as well as changes in animal demand for feed, which is affected by human demand for meat. We follow three steps to estimate animal feed crop production in dietary scenarios. First, we obtain the partitioning between crop production for animal feed, human food, and other purposes from the 2011 FAO Food Balance Sheet (Table S5). Second, we calculate how total meat (beef, goat, poultry, and pork) consumption changes in dietary scenarios compared with the Baseline diet and assume that animal feed production will scale up/down proportionally. Our results show that total meat (beef, goat, poultry, and pork) consumption in the CDG diet is 46% of that in the Baseline, in the EAT diet 26%, in the US diet 97%, and in the SRRM diet 32.6%. Third, we use the following formulas to calculate the ratio of production for each animal feed crop in dietary scenarios compared with the Baseline diet.

For one crop, P denotes production. C denotes consumption. Base denotes Baseline diet conditions, and scenario denotes an alternative dietary scenario. Equations 1, 2, and 3 indicate how production in scenarios are calculated:

$$P_{base} = P_{base_{animalfeed}} + P_{base_{humanfood}} + P_{base_{others}} \qquad \text{(Equation 1)}$$

$$P_{scenario} = P_{base_{animalfeed}} \times \frac{C_{scenario_{meat}}}{C_{base_{meat}}} + P_{base_{humanfood}} \times \frac{C_{scenario}}{C_{base}} + P_{base_{others}}$$
$$\text{(Equation 2)}$$

$$\frac{P_{scenario}}{P_{base}} = \frac{P_{base_{animalfeed}}}{P_{base}} \times \frac{C_{scenario_{meat}}}{C_{base_{meat}}} + \frac{P_{base_{humanfood}}}{P_{base}} \times \frac{C_{scenario}}{C_{base}} + \frac{P_{base_{others}}}{P_{base}}$$
$$\text{(Equation 3)}$$

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Import of animal feed crops is a small share of domestic production except for soybeans. For wheat, net import is 0.4% of domestic production, for maize 2%, for rice 3%, and for soybeans 377% (Table S5). We assume that the ratio of import to domestic production stays unchanged in all dietary scenarios as that in the Baseline diet.

For soybeans, the trade assumption will not result in unrealistically high soybean import from other countries under the SRRM scenario. This is because, although human consumption for soybean in the SRRM diet is 5.8 times of that in the Baseline diet, red meat production in the SRRM diet is zero, which substantially decreases the demand of soybeans for animal feed. Overall, the demand for soybeans (from animals and humans) in the SRRM scenario is only 75% of that in the Baseline diet. So net import and domestic production of soybeans in the SRRM diet can actually be only 75% of their Baseline diet levels. Effects of soybean production abroad are included in our GHG emission and water accounting but excluded in our NH_3 emission accounting. Tables S3 and S4 summarize estimated changes in food consumption and production in alternative scenarios.

An overview of environmental effect evaluation

All of our environmental effect accounting is based on estimated food production; thus, it addresses food intake and FLW.

Our accounting of land use COCs, GHG emissions and total water use footprints include effects of overseas production that is ultimately imported. If intake of one food increases by X times in dietary scenarios compared with the Baseline diet, land use COCs, GHG emissions and total water use footprints of this food type in the dietary scenario will also be X times that in the Baseline diet. For GHG emissions and water evaluations, we assume that the effects of any food produced outside of China and later imported for Chinese consumption will have the same emission factors during foreign production as they would if they were produced within China.

NH_3 emissions and $PM_{2.5}$ air quality modeling are slightly different. They are geographically explicit, high-resolution, and process-based models. The NH_3 emission model addresses dependence of emissions on agricultural production, management practices, and climate and soil conditions. The air quality model addresses air pollutant formation influenced by emissions, meteorology, and chemistry. To fulfill food demand in dietary scenarios, we scale current food production up or down. For example, if intake of one food increases by X times in dietary scenarios compared with the Baseline diet, we increase its production in each grid box ($1/4° \times 1/4°$ latitude by longitude) by X times and run the NH_3 emission model to estimate the associated increases in NH_3 emissions. This approach indicates that we assume no cropland expansion, no changes in the relative geographical distribution of food production, and no technological advancements and, thus, no changes in NH_3 emission factors. Although improvements in management practices may lower NH_3 emissions associated with future diets, it is out of the scope of this research focusing on dietary strategies. NH_3 emission modeling also addresses effects of China's domestic agricultural production only. Overseas NH_3 emissions will not have a significant effect on China's air quality.

Production-based NH_3 emission model for China

We utilize an NH_3 emission model published in Zhang et al.,[49] which is an improved bottom-up, high-resolution ($1/4° \times 1/4°$ latitude by longitude) NH_3 emission estimation tool for China. At each grid box level, the model represents the production of 18 crops (including maize, wheat, rice, potato, sweet potato, rapeseed, soybean, groundnut, tobacco, cotton, citrus, banana, grape, apple, pear, other fruit, and vegetables), management practices, and climate and soil conditions. Crop NH_3 emission factors are parametrized with fertilizer application timing, rate, type, and method as well as a number of climate (temperature, wind, etc.) and soil (pH) conditions. The model represents the production of major animals (cattle, goat, sheep, pig, and poultry) in grazing, intensive, and free-range systems. Total ammonium N (TAN) content produced by outdoor animals is subject to NH_3 volatilization and is without further management. TAN produced by indoor animals goes through several stages of management (i.e., animal housing, manure storage, and manure spreading), with each stage subject to NH_3 volatilization. Table S6 provides NH_3 emission budgets by food products for China in 2012.

Air quality simulation

We use the WRF-Chem model v.3.6.1, an online-coupled meteorology-chemistry model, to simulate $PM_{2.5}$ formation in the Baseline and other scenarios. WRF-Chem is widely used for air quality research.[50,51] We use improved SIA formation schemes provided in Chen et al.[52] The physical and chemical schemes used are Carbon-Bond Mechanism Version Z (CBMZ) for gas-phase chemistry, 4-bin Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) for aerosol chemistry, the RRTMG scheme for shortwave and long-wave radiation, the Morrison scheme for cloud microphysics,[53] the Yonsei University scheme for boundary layer mixing,[54] and the Noah land surface model for land surfaces.[55] Meteorological boundary conditions are from the 2012 National Centers for Environmental Prediction (NCEP) final analyses data for every 6 h. Chemical initial and boundary conditions are a 2012 simulation of the global chemical transport model, Model for Ozone and Related Tracers Version 4 (MOZART-4).

Anthropogenic emissions of air pollutants are from the Multi-resolution Emission Inventory for China (MEIC) (http://www.meicmodel.org)[43] and from HTAP (Hemispheric Transport of Air Pollutants) v.2.2 outside of China.[56] Biogenic emissions are calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) scheme,[57] and open biomass burning emissions are from the Global Fire Emission Database version 4.[58]

We conduct five sets of simulations: one baseline and four future dietary scenarios, where the only difference from the baseline simulation is modified NH_3 emissions because of dietary changes. Each simulation set includes 1 month of simulation for January and 1 month of simulation for July (both after 6 days of spin-up) for the year 2012. The model resolution is 27×27 km with the domain covering China and parts of other Asian countries (9°N-58°N, 60°E−156°E) and with 37 vertical levels extending from the surface to 50 hectopascal (hPa). We turn off direct aerosol-climate feedback to minimize the effect of aerosol concentration change because of meteorology, which, in return, would provide feedback to simulated aerosol concentrations.

Estimated life cycle food production GHG emissions, land use COCs, and water use

For the Baseline diet and each dietary scenario, production GHG emissions are estimated using 300 LCAs covering the emissions from cradle to farm gate worldwide following the methodology in He et al.[3] Ideally, we should use LCA studies for China representative of the production efficiency and technologies in China. However, these studies are of limited number, and, thus, we used an average of all available GHG footprint studies (300 studies) from different countries following He et al.[3] The cradle-to-gate emissions include emissions during food production and during production of agricultural chemical inputs (i.e., fertilizers and pesticides). They exclude emissions that occurred during food processing, transportation, and retailing phases and those that occurred during production of agricultural tools needed for production. This is reasonable because GHG emissions of the production phase dominate total GHG emissions for most food items, as evidenced by several previous studies.[59] Post-production GHG emissions are likely to be small in China because of its relatively short supply chain and widespread wet markets. We aggregate different types of GHG emissions (CO_2, CH_4, N_2O, O_3, and chlorofluorocarbons) reported in previous studies to CO_2-equiv. For seafood, we do not differentiate production systems (farmed or wild capture) and aggregate all available LCAs for seafood. Table S7 provides the estimated life cycle GHG emissions under the Baseline diet.

TWFs are estimated using the China-specific data of green and blue water reported by the Water Footprint Network database.[60] The database reports the average water consumption of countries for 352 plant-based and 106 animal-based products during the period of 1996–2005. TWFs include the green water footprint (i.e., water from precipitation) and the blue water footprint (i.e., water from the surface and groundwater). This database reports footprints for China as national average value by food item. State-level data are not available because their estimation requires tracking the flow of food items from where they are produced to where they are consumed. For plant-based products, the database uses a grid-based dynamic water model to quantify irrigation water use and excludes water use during upstream production processes, such as fertilizer production.[61] For animal products, the metric includes water consumption for animal feed production and animal direct water consumption.[62] For processed food types, the metric accounts for water consumption for

unprocessed food product production and additional water use during processing steps.[63] Table S7 provides the estimated water footprints under the Baseline diet.

Water footprints for seafood were calculated following the method from a previous study[64] because it is not included in the Water Footprint Network database. We account for water used for feed production for farmed fish, excluding water use for marine capture or during evaporation, infiltration, and dilution of farmed aquaculture. To estimate the feed-related water uses for farmed fish, we first obtain from FAO fishery statistics[65] the annual field of farming and capture fisheries to obtain the proportion of aquaculture for different species. Based on the proportion, we retrieve the feed conversion ratio (kg of feed/kg of product, indicating the weight of feed needed in producing per unit of each food item) from the literature to estimate the feed required for producing the seafoods.[66] Last, we use the Water Footprint Network database to calculate the resources needed for producing the feed.

We use Monte Carlo simulations to estimate the uncertainty of the effects of diets on the environment because of uncertainties in climate, technologies, errors from various evaluations, etc. We run simulations repeated for 10,000 trials. In each trial, environmental effect factors of each food group are generated from assumed distributions with a specific mean and standard deviation (SD) retrieved from the dataset of environmental effect factors. We assume log normal distributions for GHG emissions of each food group based on the distribution of factors of our collection of LCA studies and retrieve the mean and SD for each food group. For water consumption, we assume a normal distribution for each of the 352 plant-based and 106 animal-based products from the Water Footprint Network database and use 15% of the means as the SD for each product following a previous study.[35] We then link these generated factors to the CHNS dataset to evaluate the individual dietary environmental effects.

Land use COCs are estimated using food-specific factors reported in Searchinger et al.[19] This metric measures the carbon cost of land devoted to each food's production based on the average quantity of carbon lost from native vegetation to generate the agricultural land used to produce a kilogram (or calorie) of that food. Just as life cycle analyses factor in the fixed cost in emissions for constructing a factory used to produce a good, such as a car, COCs calculate the costs of "producing" agricultural land. When applied to different diets, the difference in COCs estimates the differences in the annualized quantity of carbon that could be stored in native vegetation and soils in one diet versus another. For meat, milk, and seafood products, the COC metric addresses the land use costs and all other emissions of feed production. Table S8 summarizes COCs under the Baseline diet.

Health effects of exposure to PM₂.₅ and diets

Exposure to $PM_{2.5}$ air pollution degrades public health by increasing the risks of premature death from four endpoint diseases (COPD, lung cancer, IHD, and ischemic stroke).

For each province in China, we calculate the number of premature deaths of each disease based on Equation 4:

$$Mort_{i,P} = POP_P \times MortBase_{i,P} \times \left(1 - \frac{1}{RR_{i,P}}\right), \quad \text{(Equation 4)}$$

where $Mort_{i,P}$ is the number of premature mortalities in province P from disease i, POP_P is the number of adults in province P ($\geq$25 years old) in 2012 from the 2013 China Statistical Yearbook,[67] $MortBase_{i,P}$ is the baseline mortality rate in province P for disease i in 2012 from the Global Burden of Disease study,[68] and $RR_{i,P}$ is the relative risk factor for one disease i adopted from Burnett et al.[69] Relative risk factors for IHD and stroke are by age groups. There are 12 age groups considered: 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, and over 80 years old. Relative risk factors for lung cancer and COPD are the same for all people 25 years of age or older.

Among all dietary risks, we consider four major ones (intake of red meat, vegetables, fruit, and legumes) and evaluate effects of changes in these risk factors on six endpoint diseases (CHD, stroke, T2DM, colon and rectal cancers, lung cancer, and other cancers) based on available epidemiological studies. In detail, total red meat intake has been found to be positively associated with premature mortality from stroke, T2DM, and colon and rectal cancers. Vegetable and fruit intake has been found to be negatively associated with mortality from CHD, stroke, total cancer, and lung cancer. Legume intake

has been found to be negatively associated with CHD. We estimate the mortality attributable to dietary risk factors by calculating population-attributable fractions (PAFs) following Equation 5:

$$PAF = \frac{\int RR(x)P(x)dx - \int RR(x)P'dx}{\int RR(x)P(x)dx} \quad \text{(Equation 5)}$$

There are uncertainties when analyzing the health effects of different diets. We use relative risk factors reported in Aune et al.,[70] Kim et al.,[71] and Springmann et al.[17] (Table S10).

In cases where one disease is attributable to multiple risk factors, we assume that PAFs combine multiplicatively following Equation 6:

$$PAF_{TOT} = 1 - \prod_i (1 - PAF_i). \quad \text{(Equation 6)}$$

Uncertainties in data sources for estimating the Baseline Chinese diet

This study adopted nutritional surveys to estimate baseline Chinese diets. Alternatively, macro-statistics from the FAO Food Balance Sheet (FBS) can be used to estimate baseline Chinese diets. However, in this study, we decided to rely on the micro-level nutritional survey approach for two reasons. First, the quality of Chinese national statistics of agricultural production and supply has been criticized by previous research. Second, nutritional survey data more realistically capture variations in peoples' dietary preferences depending on age, sex, and region and more accurately estimate food waste.

FAO FBS estimation of per-capita food supply in China is estimated by subtracting non-human food use (e.g., food for animal feed, food for export, food for seed, food for processing, etc.) from total agricultural production reported by the Chinese State Statistics Bureau. China's official statistics, in nature, rely on household and enterprise surveys. In particular, a number of studies pointed out severe misreporting issues.[38,72] One study finds that the increase in meat production reported by statistics during the 1990s cannot be explained by stagnation of consumption and decline of livestock product exports. Given the lack of refrigerated storage facilities, particularly in rural China, stock holdings are less likely to be able to explain the discrepancies.[35] The research, through interviews, also finds that "human errors" probably remain the most important source of data errors because the central government had set regional government targets for agricultural production. In addition, food production levels had frequently been used to assess the political performance of bureaucrats at regional and village levels.[35] Additional research echoes the finding that China's official livestock production data have been two to three times as high as its consumption data since the year 1999, and official statistics over many years fell short of various statistical tests, indicating poor data quality and consistency.[36] Other research finds that fishery output data suffer from similar issues[73] and that township and village enterprise output statistics are also overstated.[19,74]

FAO FBS data of per-capita food supply include food waste during food processing, cooking, and dining out and non-edible portions of food. Obtaining food intake data has to involve using models to estimate food waste. A number of studies found that FAO data substantially overestimate an individual's total calorie intake; e.g., a Chinese diet of over 3,000 kcal/day/capita according to the FAO FBS, which is much higher than that reported by individuals during dietary surveys.[75]

FAO data provide national per-capita food consumption, excluding substantial dietary variations among people in different age groups, of different sexes, at different income levels, and with rural or urban backgrounds. Instead, in two of our dietary change scenarios (The Chinese Nutritional Guideline diet and US diet), diets vary depending on peoples' sex, age, daily calorie intake, and activity level. It is thus infeasible to model each person's dietary transitions to these two diets based on FAO data, which capture only diets for the nation on average. Macro-statistics data (e.g., FAO FBS) of per-capita food supply is most suitable for cross-country comparison because they are estimated with relatively comparable methodologies using data reported.

Similar to previous findings for other regions, we find that for China's FAO food consumption data, compared with nutritional survey data mapped to the nationwide population, overestimates consumption of livestock products but underestimates consumption of grains (Table S9).[39]

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