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Environmental and Human Health Trade-offs in Potential Chinese Dietary Shifts

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Summary Dietary shifts from staples towards meats, fruits and vegetables increase environmental impacts. Excessive red meat intake and micronutrient 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 $PM_{2.5}$, greenhouse gas emissions (GHGs), 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 the adoption of the Chinese Dietary Guideline (*CDG*) and EAT-Lancet diets, which avoid over 1 million premature deaths annually. However, both diets increase water use and GHGs. *CDG* also increases land use 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.

164 words.

Introduction

As countries become more affluent, dietary choices have shifted towards meats, fruit and vegetables that, compared to staples, have more taste appeal and diverse nutritional content[1,2]. Previous research reported that malnutrition and undernourishment rates in China dropped substantially over the past decade. However, at the same time, per capita GHG emissions, water and land use from Chinese food consumption have steadily increased[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%, while the consumption of starchy foods has decreased[5] (Fig. S1). 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, nuts 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 deaths[8–10]. Obesity and excess weight also are a growing concern, respectively affecting 89 and 320 million people[11].

Identifying food choices that can simultaneously benefit health and the environment is challenging and has been of great research interest in recent years. Research on diets in developed[19-27] and low- and middle-income countries[12–14] 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 (i.e. forage fish, bivalve mollusks, etc.) into total protein supply, as well as shifting away from rice towards wheat, coarse cereals, pulses and leafy vegetables, facilitates both GHG mitigation and dietary health. Studies estimate that agricultural GHG emissions can be reduced by 50% by changing diets in affluent economies[15] and by around 30% through dietary changes in China[14]. Alternative diets that embody the above environmental and health objectives include governmental balanced dietary recommendations, e.g. for China the Chinese Dietary Guideline (*CDG*) which emerged in 1989 and is updated every five years, the EAT-Lancet planetary health diet proposed in 2019, and environmental-friendly diets that replace beef with poultry, or replace meat with plant-based protein (*SRRM*)[16–18].

However, existing research remains incomplete. Although an increase in the consumption of fruit and vegetables are, in many ways, beneficial, they also require higher nitrogen (N) fertilizer input (in kg N/ha) than staple crops[19], which can result in additional N pollution. Beef, in particular, also has substantially higher N requirements per calorie than poultry, pork and crop products[20], as well as higher water and land requirements and GHG emissions. Atmospheric ammonia (NH_3) emissions, predominantly from agricultural nitrogen application and animal manure management, reacts with sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from transport, power, residential and industrial sectors to form secondary inorganic aerosols (SIAs), which dominate the inorganic fraction of health-damaging $PM_{2.5}$. NH_3 emissions contribute between10%-18% of China's $PM_{2.5}$[21] as well as drive the loss of ecosystem biodiversity[28-31]. Mitigation of NH_3 has recently been incorporated into Chinese air pollution policies[22] and in 2021 a quantitative target was set for animal farms in the Jing-Jin-Ji region [23].

The extent to which potential dietary shifts affect NH_3 emissions and the associated $PM_{2.5}$ air quality impacts remains unclear. Furthermore, previous studies that have evaluated climate impacts of various diets typically use traditional life-cycle calculations of GHG emissions[17,18,24,25]. However, this metric does not account for the inherent GHG costs of using land, which results in reduced carbon stored in vegetation and soils. Overall, the more land devoted to food production, the less carbon stored. In addition, previous dietary studies also mostly used food consumption data inferred from food production and balance statistics, instead of surveys of individual's 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; the EAT-Lancet diet; SRRM; and a US diet based on the U.S. National Health and Nutrition Examination Survey). We consider a wide range of health and environmental objectives (i.e., NH_3 emissions, $PM_{2.5}$ air quality and associated health impacts, greenhouse gas 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 soils to generate each food type[26] and addresses limitations associated with previous lifecycle GHG metrics. Furthermore, our empirical analysis utilizes food intake data from a 2011 Chinese dietary survey representative of actual diets[27]. We find that the dietary shift towards either 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 GHGs during food production, with the EAT-Lancet diet reducing COCs while CDG increases them. Adoption of the Soy Replaces Red Meat or EAT-Lancet diet can help mitigate NH_3 emissions and reduce air pollution associated premature deaths per year by 57,000. A shift towards Soy Replaces Red Meat diet can reduce all environmental damages examined and reduce premature deaths, although the diet-related health benefits appear much smaller than those from the CDG and EAT-Lancet diet, such that only ~300,000 premature deaths would be avoided each year. These findings are of great policy relevance since dietary health and air quality have received increasing policy attention in China[22,28], in addition to climate change mitigation and resource conservation. Moreover, 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 impacts of national dietary tendencies on reactive nitrogen burdens, health-damaging air pollution, climate, land use change, water utilization and public health.

Results

Four Potential Dietary Scenarios for China

We consider a shift of the 2011 population-wide Chinese *Baseline* diet towards four possible alternatives. These include two balanced diets, i.e., the *Chinese Dietary Guideline Diet (CDG;* 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, i.e., a westernized diet (*US;* a diet that matches intakes of key food categories in a typical US diet indicated from the U.S. National Health and Nutrition Examination Survey[30]) and a diet that replaces red meat protein in *Baseline* diet with soy protein (*SRRM;* a diet designed to zero health risks and environmental damages of red meat). Fig. 1 presents per capita intakes of various food products under the *Baseline* and four dietary scenarios, which all have comparable calorie supply. Fig. S2 and Table S1 present per capita intakes, and food loss & waste (FLW) along the supply chain for each diet, with more details provided in the Experimental Procedures and Tables S2-3.

The *US* and *Soy Replaces Red Meat (SRRM)* diets provide two relatively extreme cases for health and the environment. Compared to the *Baseline*, 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, as the Chinese are increasingly consuming foods that are typically found in western diets (e.g., steaks, dairy, cakes, sugar-sweetened drinks, etc.). In comparison, the *Soy Replaces Red Meat (SRRM)* diet replaces all *Baseline* red meat (goat, sheep, beef and pork) protein with the same amount of protein from soybeans, so that the health and environmental damages of red meat are eliminated[24,25]. Dietary scenarios with decreased animal protein supply, similar to *SRRM*, have been adopted for evaluation in many previous studies[16–18]. 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 diseases. However, red meat provides vitamin B_{12} and zinc so that people may have to find alternative sources of these micro-nutrients[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 thus 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* consumption of grains to decrease as much as the *CDG* diet. *EAT* provides a typical reference diet for all adults worldwide, yet *CDG's* dietary recommendations vary by individual's activity levels.

Health and Environmental Impacts of Different Diets

We evaluate the impacts 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 carbon opportunity costs (COCs), agricultural production-related greenhouse gas emissions, total water footprints, direct dietary health impacts associated with nutrient intakes and indirect health impacts through human exposure to $PM_{2.5}$ (see Experimental Procedures). Assumptions for international trade, food waste and loss, and animal feed crop production are detailed in 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 towards the *CDG* and *EAT* diets reduces premature deaths by 1.4 and 1.1 million/yr, respectively, accounting for 50% and 40% of the 2.77 million dietary risk-related premature deaths in China in 2012. Balanced diets benefit health through increasing intakes of fruit, vegetables and legumes and reducing excess intakes of red meat. Shifting towards the *SRRM* diet generates moderate dietary health benefits, decreasing premature deaths by 0.3 million/yr (11%).

Second, we find opportunities for mitigating NH_3 emissions and resulting $PM_{2.5}$ air pollution. The *SRRM* and *EAT* diet, respectively, reduce NH_3 emissions by 36% and 18%, thus reducing $PM_{2.5}$ by up to 10μg/m^3 locally. NH_3 emission reductions achieved by the *SRRM* diet results from a removal of red meat (pigs, goat and lamb) production and associated animal feed production. NH_3 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 Tg/yr (56%) mainly through reducing red meat consumption, and increases crop NH_3 emissions by 1.4 Tg/yr (26%) mainly due to increased fruit and vegetable production. Overall, the *EAT* diet provides NH_3 emission reductions of 2.5 (18%) Tg/yr. $PM_{2.5}$ mitigation and associated reductions in premature deaths are around 0.06 million/yr for both *SRRM* and *EAT*, which is orders of magnitude smaller than dietary health impacts. A comparison of dietary health and $PM_{2.5}$ impacts at regional scales requires future research, since 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*, both require increased consumption and production of fruit, vegetables and dairy, compared to the current Chinese diet. Increasing intakes of fruits and vegetables substantially improves dietary health, e.g., respectively avoiding 0.9 and 0.7 million premature deaths in the *CDG* diet.

However, increased fruit and vegetable production will involve intensive nitrogen fertilizer use and thus result in higher NH_3 emissions. The *EAT* and *CDG* diets result in 1.4 and 4.8 Tg/yr, respectively, higher NH_3 emissions than the *Baseline*. Furthermore, higher dairy intake, when not accompanied with decreases in other animal product intakes or production improvements, will likely increase environmental damages of the livestock sector. For example, *CDG* has 2.1 Gt CO_2-eq/yr higher land use COCs and 0.4 Gt CO_2-eq higher food production GHGs than the *Baseline*. In comparison, the *EAT* diet has more moderate increases in GHGs than the *Baseline*. This is because *EAT* requires smaller increases in dairy than *CDG* and cuts red meat consumption, which also results in lower livestock NH_3 emissions than the *CDG* diet.

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

Impacts 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 to those at present, but assuming no changes in NH_3 emission factors. Detailed assumptions about management practices and production patterns in dietary scenarios are provided in Experimental Procedures and Tables S4-5.

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%) due to its large production amount, followed by vegetables, goat, sheep, pork and dairy cattle production, which each contributes ~7-10%. Fruit and beef production, respectively, contribute to only 1% and 6% of total NH_3 emissions due to their low production levels, despite high NH_3 emission intensities.

Shifting from the *Baseline* diet towards the *US* diet leads to a 189% increase in NH_3 emissions. High NH_3 emissions in the *US* diet is due to its high beef and dairy consumption. Shifting towards 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 *CDG*'s lowered consumption of red meat, poultry and grains than the US diet. Still, overall, *CDG* has NH_3 emissions that are 110% higher than *Baseline.*

In contrast, shifting from the *Baseline* diet towards 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 (Fig. 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 to *Baseline*, 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%. To note, spotted areas in western China, the lower Yangtze River Basin and eastern China experience increased NH_3 emissions due to increased local crop production (Fig. 2).

Impacts 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 (WRF-Chem) with improved aerosol chemistry (see 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 towards the *US* diet increases SIA concentrations by up to 10 $\mu g/m^3$ locally (Fig. 3), particularly in wintertime eastern China and summertime over the North China Plain. Shifting towards the *CDG* diet also increases SIAs. However, shifting towards the *EAT* and *SRRM* diets achieves large SIA reductions in winter, e.g., up to 12 μg/m^3 reduction in central China. Figs. S3-4 provide impacts of dietary shifts on concentrations of ammonium, nitrate and sulfate aerosols in January and July.

Impacts of dietary shifts on food production GHGs

We account for life-cycle GHGs during food production (cradle to farm gate) at home and abroad that are needed to meet 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], since studies specifically for China are scarce. Shifting from the *Baseline* diet towards the *US* diet increases life-cycle GHGs by 20% (Table 1, Fig. 4A, Fig. S5A and Table S7), dominantly driven by increases in beef, eggs and dairy (Fig. S5A). Shifting towards the *CDG* diet leads to a 40% increase, dominantly driven by increases in aquatic products, vegetables and eggs and dairy (Fig. S5A). However, switching to the *SRRM* diet reduces emissions by 30%. Switching to the *EAT* diet leaves production emissions almost the same as *Baseline* (a 3% increase). This is because in the *EAT* scenario, although reduced consumption of meats generates reductions in GHG emissions, such savings are compensated for by increased GHG emissions associated with high consumption requirements for aquatic products.

Impacts of dietary shifts on land use GHGs

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, thus increasing yields or generating more food calories. In order to accommodate dietary changes, the 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 GHGs if they are imported from Brazil where ongoing net land use change (LUC) is occurring, but not if they are imported from long-cultivated fields in the United States (See Searchinger et al.[26]). The life-cycle GHG approach implies that animal feed production could have zero LUC GHG emissions even if they required land conversion from forests for production per kcal or gram of protein.

Here, instead, we calculate land use GHG emissions based on their “carbon opportunity costs” (COCs) and find substantial land use GHG consequences of dietary changes. In the *Baseline* diet, land use GHGs are already ~2.4 times the size of production GHGs at 2.4 Gt CO_2-eq/yr (Fig. 4 panel B vs. A; Fig. S5 panel B vs. A. and Table S8). As explained in Searchinger et al.[26], 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 GHGs 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 is already small in the *Baseline* diet. Most of the declines in red meat in the *EAT* diet, therefore, occur through declines in pork, which is more land-efficient than beef. COC declines in *EAT* driven by decreased intakes of red meat are offset by increased land demands for fish, fruit and pulses.

Impacts of dietary shifts on total water footprint

We account for total water use, including irrigation (blue) and rain (green) waters, during food production at home and abroad, in order to meet food demands in each dietary scenario (see Experimental Procedures). Inclusion of the total water footprint (TWF) metric delivers similar messages as factoring in production GHGs, i.e., except for *SRRM*, shifting towards all future diets increases water use. This is because producing beef, soybean, fruit and vegetables and dairy are all water-intensive. Thus, shifting from *Baseline* towards *SRRM*, although it saves water by cutting meat consumption, only generates small water savings due to large increases in soybean production (Fig. 4C and Fig. S5C). Shifting from *Baseline* towards the *US* diet requires more water due to high consumption of beef and dairy in the *US* diet. Shifting from *Baseline* towards the two balanced diets requires more water use due to increased consumption of eggs, dairy, aquatic products, fruit and vegetables.

Health implications of dietary shifts

Here we consider the impacts of changes in intakes of fruit, vegetables, legumes and red meat on premature mortalities from coronary heart disease (CHD), stroke, total cancers, Type II diabetes (T2DM), colon and rectum cancers, and lung cancer using cohort studies worldwide (see Experimental Procedures). We also consider the health impacts 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 lungs and bloodstreams, increasing risks of chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD) and ischemic stroke (see Experimental Procedures).

The health impacts of the four dietary shifts differ from the environmental impacts. 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 *EAT* due to *EAT*'s high fruit, vegetables and legumes consumption. The *CDG* diet is the most beneficial to health due to its even larger consumption of fruit, vegetable and legumes than *EAT*, although it slightly worsens air quality. *CDG* has lower pork and higher poultry consumption than the *Baseline*. *EAT* has even lower pork, beef and poultry than *CDG*. Overall *EAT* and *CDG* respectively reduces 1.4 and 1.6 million premature deaths per year (Table 1 and Fig. 5).

Solely focusing on dietary health, except for the *US* diet, all dietary shifts examined deliver dietary health benefits that range from 0.02 to 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 impacts, shifting from *Baseline* towards the *SRRM* and *EAT* diets each reduces premature mortalities due to exposure to $PM_{2.5}$ by roughly 0.06 million persons per year. By contrast, the *US* diet increases premature mortalities by 0.08 million and CDG by 0.06

million. The $PM_{2.5}$ health impacts of changing diets are smaller than dietary health impacts of changes in food intakes.

Uncertainties

Analyses of the kind in this paper face many uncertainties, including uncertainties in baseline Chinese diet estimations, dietary health impact 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. For example, according to these surveys and those in the US, fruit intake in China is even lower than in the US. Our results would differ if we used macro production statistics as many other studies have done[35–38].

The dietary surveys we use of food production, storage and non-food usages are all estimated through surveys conducted by localities. Survey data are then aggregated to the national level; errors are aggregated as well. National production statistics in China indicate substantially higher fruit and vegetable intakes 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 U.S.[40]. Given high-quality baseline diet data is 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 (i.e. intakes of fruits, vegetables, red meat and legumes) and premature mortalities from several end-point diseases (see Experimental Procedures and Table S10). These correlations have been used in previous studies[24]. 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, overweight, supply of micro-nutrients and quality of protein. For example, the *US* diet potentially results in higher calory supply per capita and thus higher incidences of overweight than the current Chinese diet[41].

Other uncertainties relate to the evaluation of environmental impacts. 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. Accuracy 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 above mentioned water consumption term can be almost equally important as water in farmed fish feed (Table S11). Water utilization also have large variations across production systems and locations[42]. We estimate that including these additional water usages indicated by Gephart et al.[42] will make the

CDG and *EAT* diets (the *US* diet) more (less) thirsty than currently estimated while 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 calculate the average of all available published LCA results for seafood.

Discussion

Growing populations in developing countries have shifted their dietary choices from staples towards fruit, vegetables and meats. Transitions of diets generate complex health and environmental consequences, since 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*), i.e. over 1 million/yr avoided premature deaths. 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/yr, 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 to that achieved through improving food production practices. For example, previous research estimated that combing multiple nitrogen management improvements in China achieves a 34% reduction in national NH_3 emissions and up to 7μg/m^3 reduction in $PM_{2.5}$ locally[34]. In addition, while 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 intakes of fruits and vegetables in the *CDG* diet, respectively, avoids 0.7 and 0.9 million premature deaths, however, NH_3 emissions and water use both increase. *CDG*'s dairy recommendations, much higher than the *Baseline* diet, also contribute to increasing environmental burdens. Dairy may protect against chronic diseases but are not associated with all-cause mortality[55] and have shortcomings as the majority of the Chinese population are lactose intolerant. A westernized diet, i.e., *US* diet, due to its high requirement for beef and dairy cattle production, increases livestock NH_3 emissions three-fold and thus increases $PM_{2.5}$-related mortalities by 0.08 million/yr. These increases occur with the assumption that increased beef and dairy demand is fulfilled with domestic production, such environmental impacts may be outsourced with food import from other countries. The evaluation of COCs emphasizes large land use change related GHG emissions resulting from additional consumption of beef, dairy, fruits and pulses. This means substantial cropland expansion will be needed to grow the crops or animal feed. Replacing red meat with soy decreases all environmental damages, however, its dietary health benefit is substantially lower than the balanced diets.

A potentially surprising result of our paper is that the *EAT* diet modestly increases greenhouse gas emissions from the food production process and 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 meats, such as pork and poultry, are offset by higher emissions from increased consumption of fruits and vegetables. Both diets substitute fruits and vegetables for starches, which have health benefits but cause more emissions. Only the *SRRM* diet results in reductions in production emissions. However, both the *SRRM* and *EAT* diets result in large reductions in land use carbon opportunity costs, which are also much larger than production emissions. The major greenhouse gas benefit of reduced meat consumption in China would therefore be in reduced land use.

Given 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 in China's fruits, vegetables and staple crop [34], and reductions in food loss and waste, estimated previously at 27% in China[43].

Our research demonstrates the rather complex impacts 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 environmental-health trade-offs, advocating for any specific dietary changes need to be made with caution. A healthy and sustainable food future requires food production technologies and food loss and waste 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 has been uploaded to Princeton University's DataSpace http://arks.princeton.edu/ark:/88435/dsp01nz8062179 (https://doi.org/10.34770/rnpp-4t33
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The Chinese *Baseline* diet and four future dietary scenarios

The ***Baseline*** diet is based on the China Health and Nutrition Survey (CHNS) for 2011[27], which sampled 10,000 random people in twelve provinces with distinct socioeconomic and demographic backgrounds. The survey tracked individual food intake (both food types and weights) over three consecutive days. We then estimate diets of individuals outside 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 the previous study . 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 socio-economic 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* per capita daily food intake.

The ***US*** Diet describes a diet in which the Chinese intake of nutrients will match those of a typical U.S. diet, by choosing among food products available on the Chinese market. Nutrient intake of Americans is from the U.S. Centers for Disease Control and Prevention's National Health and Nutrition Examination Survey (NHNAES)[30] during 2011-2012. The foods that 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 US, with definitions and more detailed information included in *Food Patterns Equivalents Database*[44].

The ***Soy Replaces Red Meat (SRRM)*** diet removes all red meat (goat, sheep, beef and pork) consumption. The decrease in animal protein is made up with increased intake of soybean products (equal protein substitution). This scenario potentially achieves environmental and health co-benefits, since reduced livestock production and corresponding animal feed production will lower environmental damages and reduced red meat intake will reduce health risks[45]. It is indeed a radical diet but has been widely adopted in previous dietary studies[16–18].

The ***Chinese Dietary Guideline Diet (CDG)*** is based on China's Balanced Dietary Patterns from the 2016 Chinese Dietary Guideline, 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.[46].

EAT-Lancet Dietary Recommendations (EAT*)* is based on dietary recommendations provided by the EAT-Lancet Commission[29], which apply universally to all adults regardless of age and country of origin. We thus assume the diets of people below <20 yrs of age are the same as in *Baseline.*

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 & 2004 version) 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 ~4000 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 intakes for food types with and without a standardization process. Among the ~5000 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 have fewer calories than one gram of grapes. Cooked rice and rice congee have substantially different calories. We thus standardize food items to allow better comparison following guidelines for calculating food weight equivalents provided by the Chinese Dietary Guidelines using methodology provided in He et al.[46].

Estimating food production in dietary scenarios

We estimate food production based on food intake and food loss & waste (FLW), while accounting for impacts of meat requirements on animal feed crops and international trade. We account for food losses during production, post-harvesting, food processing, packaging, distribution and food waste during consumption, using FLW ratios reported by FAO[47] (Table S2). We assume the ratio of FLW to total production stays the same for the *Baseline* and in future dietary scenarios. For example, if intake of one food product increases (or decreases) by X times in dietary scenarios compared to the *Baseline*, the amount lost and wasted in future dietary scenarios both will also increase (or decrease) by X times accordingly.

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* production level with a factor equal to the ratio of food consumption in dietary scenarios to that in the *Baseline*. The partitioning between net import and domestic production in dietary scenarios remains the same in the scenarios as partitioning in the *Baseline.* For example, if consumption of a non-animal feed food product i in a dietary scenario needs to be X times of that in *Baseline*, then both domestic production and net import of this food product i in the scenario will both be X times of those in the *Baseline.*

Animal feed crop production (maize, wheat, rice and soybean) requires slightly different treatment. Their production in future dietary scenarios should reflect both 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 to *B*aseline and assume animal feed production will scale up/down proportionally. Our results show that total meat (beef, goat, poultry and pork) consumption in *CDG* is 46% of that in *Baseline*, similarly in *EAT* 26%, in *US* 97%, and in *SRRM* 32.6%. Third, we follow the following formulas to calculate the ratio of production for each animal feed crop in dietary scenarios compared to *Baseline*:

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

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

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

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

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

For soybean, 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 *SRRM* is 5.8 times of that in *Baseline,* red meat production in *SRRM* is zero, which substantially decreases the demand of soybean for animal feed. Overall, the demand for soybean (from both animals and humans) in the *SRRM* scenario is only 75% of that in *Baseline.* So both net import and domestic production of soybean in *SRRM* can actually be only 75% of their *Baseline* levels. Impacts of soybean production abroad are included in our GHGs, land and water accounting but excluded in our NH_3 emission accounting. Table S3-4 summarize estimated changes in food consumption and production in alternative scenarios.

An overview of environmental impact evaluation

All of our environmental impact accounting is based on estimated food production, thus it addresses both food intake and food loss and waste.

Our accounting of land-use carbon opportunity costs (COCs), GHGs emissions and total water use footprints includes impacts of overseas production that is ultimately imported. If intake of one food increases by X times in dietary scenarios compared to the *Baseline*, land-use COCs, GHGs emissions and total water use footprints of this food type in the dietary scenario will also be X times that in *Baseline*. For GHGs and water evaluations, we assume that the impacts of any food produced outside 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 both are geographically-explicit, high-resolution and process-based models. The NH_3 emission model addresses dependence of emissions on agricultural production, management practices, climate and soil conditions. The air quality model addresses air pollutant formation influenced by emissions, meteorology and chemistry. In order 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 to the *Baseline*, we increase its production in each grid-box (1/4° ×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 impacts of China's domestic agricultural production only. Overseas NH_3 emissions will not have a significant impact 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.[48], which is an improved bottom-up high-resolution (1/4° ×1/4° latitude by longitude) NH_3 emission estimation tool for China. At each grid-box level, the model represents the production of eighteen crops (including maize, wheat, rice, potato, sweet potato, rapeseed, soybean, groundnut, tobacco, cotton, citrus, banana, grape, apple, pear, other fruit, vegetables), management practices, climate and soil conditions. Crop NH_3 emission factors are parametrized with fertilizer application timing, rate, type, 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 nitrogen (TAN) content produced by outdoor animals are subject to NH_3 volatilization and are 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 Weather Research and Forecasting – Chemistry (WRF-Chem) model v3.6.1, an online-coupled meteorology-chemistry model, to simulate $PM_{2.5}$ formation in *Baseline* and scenarios. WRF-Chem is widely used for air quality research [49,50]. We use improved secondary inorganic aerosol formation schemes provided in Chen et al.[51]. 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, RRTMG scheme for shortwave and longwave radiation, the Morrison scheme for cloud microphysics [52], the Yonsei University scheme for boundary layer mixing [53], and the Noah land surface model for land surface . Meteorological boundary conditions are from the 2012 National Centers for Environmental Prediction (NCEP) Final Analyses data for every 6 hours. 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) [55] and from HTAP (Hemispheric Transport of Air Pollutants) v2.2 outside 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 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 due to dietary changes. Each simulation set includes one month of simulation for January and one month of simulation for July (both after six days of spin-up) for the year 2012. The model resolution is 27 km by 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 50hPa. We turn off direct aerosol-climate feedback to minimize the impact of aerosol concentration change due to meteorology, which would in return provide feedback to simulated aerosol concentrations.

Estimate life-cycle food production GHG emissions, land-use carbon opportunity costs and water use

For the *Baseline* and each dietary scenario, production GHG emissions are estimated using 300 life-cycle assessments (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 the available GHG footprint studies (300 studies) from different countries following a previous study . The cradle to gate emissions include emissions during food production and during the production of agricultural chemical inputs (i.e. fertilizers and pesticides). It excludes emissions that occurred during food processing, transportation and retailing phases, and also excludes emissions that occurred during the production of agricultural tools needed for production. This is reasonable because GHGs of production phase dominates total GHG emission for most food items, evidenced by several previous studies[59]. Furthermore, post-production GHG emissions is likely to be small in China, due to its relatively short supply chain and widespread wet markets. We aggregate different types of GHGs (CO_2, CH_4, N_2O, O_3, and CFCs) reported in previous studies to CO_2-eq. 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 GHGs under *Baseline* diet.

Total water footprints are estimated using the China-specific data of green and blue water reported by the Water Footprint Network database[60]. The database reports for countries in the world their average water consumption for 352 plant-based and 106 animal-based products during the period of 1996-2005. Total water footprints include both green water footprint, i.e. the water from the precipitation, and the blue water footprint, i.e. the water from the surface and groundwater. This database reports footprints for China as national average value by food item. State-level data is not available as its 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 *Baseline* diet.

Water footprints for seafood were calculated following the method from a previous study[64], as 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. In order 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]. Lastly, 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 impacts of diets on the environment due to uncertainties in climate, technologies, errors from various evaluations, etc.. We run simulations repeated for 10000 trials. In each trial, environmental impact factors of each food group are generated from assumed distributions with a specific mean and standard deviation retrieved from the dataset of environmental impact 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 standard deviation 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 standard deviations for each product following a previous study [35]. For land appropriation, we assume normal distributions and 5% of the means from the FAOSTAT data as the standard deviations for each food group due to the observations of the flat change in productivity over time in FAOSTAT. We then link these generated factors to the CHNS dataset to evaluate the individual dietary environmental impacts.

Land use COCs are estimated using food-specific factors reported in Searchinger et al.[26]. 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 lifecycle 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 carbon opportunity cost metric addresses the land use costs and all other emissions of feed production. Table S8 summarizes COCs under the *Baseline* diet.

Health impacts of exposure to $PM_{2.5}$ and diets

Exposure to $PM_{2.5}$ air pollution degrades public health by increasing risks of premature deaths from four end-point diseases (chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD) and ischemic stroke).

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

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

where $Mort_{i,P}$ is the number of premature mortality in province P from disease *i*; POP_P is the number of adults in province P (≥ 25 y 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]; $RR_{i,P}$ is the relative risk factor for one disease *i* adopted from [69]. Relative risk factors for IHD and stroke are by age groups. There are 12 age groups considered, i.e. 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 y old. Relative risk factors for lung cancer and COPD are the same for all people ≥ 25 y old.

Among all dietary risks, we consider four major ones (intakes of red meat, vegetables, fruit and legumes) and evaluate impacts of changes in these risk factors on six end-point diseases (coronary heart disease (CHD), stroke, type II diabetes (T2DM), colon and rectum 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 mortalities from stroke, T2DM, and colon and rectum cancers. Vegetable and fruit intakes have been found to be negatively associated with mortalities 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 in analyzing the health effects of different diets. We use relative risk factors reported in Aune et al.[70], Kim et al.[71] and those used in Springmann et al.[24] (Table S10).

In cases where one disease is attributable to multiple risk factors, we assume 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 people’s 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 usages, 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 mis-reporting issues[38,72]. One study finds that increase of meat production reported by statistics during the1990s cannot be explained by stagnation of consumption and decline of livestock product exports. Given 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 since 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 suffers from similar issues[73] and that township and village enterprise output statistics are also overstated[2674].

FAO FBS’s data of per capita food supply includes food waste during food processing, cooking, and dining-out, and non-edible portions of food. Obtaining food intake has to involve using models to estimate food waste. A number of studies found that FAO data substantially overestimates individual’s total calorie intake, e.g. a Chinese diet of over 3000kcal/day/capita according to the FAO FBS, which is much higher than that reported by individuals during dietary surveys[75].

FAO data provides 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, i.e. Chinese Nutritional Guideline diet and US diet, diets vary depending on people’s 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 captures only diets for the nation on average. Macro statistics data (e.g. FAO Food Balance Sheet) of per capita food supply is the best suitable for cross-country comparison as they are estimated with relatively comparable methodologies using data reported.

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

Author contributions

Conceptualization, Y.G., P.H., and D.L.M.; Methodology, Y.G., P.H., Y.C. and M.Z.; Resources, Y.G., M.S., T.D.S., X.Z. and L.Z.. Formal Analysis, Y.G. and P.H.; Visualization, Y.G.; Supervision, D.L.M., T.D.S. and L.Z.; Project Administration, Y.G.; Writing – Original Draft, Y.G. and T.D.S.; Writing – Review & Editing, all authors.

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Declaration of interest

The authors declare no competing interests.

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Table 1. Environmental and health implications of Chinese dietary shifts from the 2011 *Baseline* diet towards four possible future diets. For each metric, both *Baseline* values and changes in dietary scenarios compared to *Baseline*, i.e., Scenario-*Baseline*, are provided. Negative values mean mitigation of environmental impacts or lives saved. The four potential dietary scenarios are *US* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission).

Environmental and health impacts	*Baseline*	*US - Baseline*	*SRRM - Baseline*	*CDG - Baseline*	*EAT - Baseline*
NH_3 emissions (Total; Tg/yr)	13.9	26.3	-5.1	15.8	-2.5
NH_3 emissions (Fertilizer; Tg/yr)	5.3	0.8	-1.1	4.8	1.4
NH_3 emissions (Manure; Tg/yr)	6.8	25.5	-4.1	11.1	-3.8
Production GHG emissions (Gt CO_2-eq/yr)	1	0.2	-0.3	0.4	0.03
Land-use carbon opportunity cost (Gt CO_2-eq/yr)	2.4	3.3	-0.7	2.1	-0.08
Total Water Footprint (Tera m^3/yr)	0.9	0.3	-0.05	0.6	0.6
Premature mortalities associated with exposure to $PM_{2.5}$ (k persons)	1700[a]	79	-57	60	-55
Premature mortalities associated with four dietary risks (k persons)	N/A[b]	-20	-293	-1364	-1109
Premature mortalities associated with fruit intake (k persons)	N/A[b]	-378	0	-913	-742
Premature mortalities associated with legume intake (k persons)	N/A[b]	-154	-253	-336	-376
Premature mortalities associated with red meat intake (k persons)	N/A[b]	-25	-56	-34	-53
Premature mortalities associated with vegetable intake (k persons)	N/A[b]	641	0	-685	-284
Premature mortalities associated with $PM_{2.5}$ and four dietary risks (k persons)	N/A[b]	81	-362	-1626	-1339

[a] We estimate that $PM_{2.5}$ concentrations in the year 2012 resulted in 1.7 million premature deaths. $PM_{2.5}$ concentrations depend nonlinearly on concentrations and emissions of many species (e.g. nitrogen oxides, sulfur dioxide, 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 due to changes in exposure.

Fig. 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* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission). Definitions of vegetables and fruit are based on Chinese habits, e.g. cucumber, tomato, loofah and zucchini are categorized as vegetables; watermelon and muskmelon as fruit. Intakes of alcohol, sugar, condiments and others are not presented in this figure.

Fig. 2. Changes in NH_3 emissions in potential dietary scenarios relative to *Baseline* NH_3 emissions in January and July of the year 2012. Colors indicate (NH_3 emissions in Scenario - NH_3 emissions in *Baseline)*/ NH_3 emissions in *Baseline* in (A-D) January and (E-H)) July of the year 2012. The four potential dietary scenarios are *US* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission).

Fig. 3. Changes in ground-level secondary inorganic aerosol (SIA) concentrations (in unit of $\mu g/m^3$; negative values mean reductions) in potential dietary scenarios compared to the *Baseline* in (A-D) January and (E-H)) July of the year 2012. The four potential dietary scenarios are *US* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission).

Fig. 4 Environmental impacts of food consumption in China in *Baseline* and four future dietary scenarios by food type. A) Life-cycle GHGs during food production from cradle to farm gate (Giga tonne CO_2-eq/yr); B) Land-use carbon emissions indicating the opportunity cost of land (Giga tonne CO_2-eq/yr). C) Food consumption-based total water footprint (TWF) (Tera m^3/yr); Numbers above each bar show the absolute value of the metric in each scenario; colored bars denote impacts of consumption of different food types. The four potential dietary scenarios are *US* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission).

Fig. 5 Lives saved (10k persons) from five diseases in four potential dietary scenarios compared to the *Baseline*, due to changes in food consumption and exposure to $PM_{2.5}$ air pollution. Colors of bars indicate risk factors and grey dots denote all individual risks combined. End-point diseases considered include stroke, ischemic heart disease (IHD), Type II Diabetes (T2DM), cancers (including colon and rectum cancers, lung cancer and other cancers, chronic obstructive pulmonary disease (COPD), and all these diseases. The four potential dietary scenarios are *US* (typical 2011 US diet), *Soy Replaces Red Meat (SRRM)* (All red meat replaced with soy products), *Chinese Dietary Guideline (CDG)* (Recommendation of Chinese Dietary Guidelines), and *EAT-Lancet Dietary Recommendations (EAT)* (healthy and sustainable diet recommended by Lancet EAT commission).