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Research article

Environmental impacts of dietary quality improvement in China

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ABSTRACT

Dietary-related risks rank top among all the health risks in many countries. The 2nd United Nations Sustainable Development Goal aims to end hunger, achieve food security and improved nutrition and promote sustainable agriculture. Yet whether improving nutritional quality also benefits the environment is still under-explored, particularly for developing countries. China is an interesting and important case because of its rapidly changing dietary patterns distinct from the western countries studied in the literature, sub-national level heterogeneity, socio-economic characteristics and lifestyles, as well as its considerable population. This paper evaluates greenhouse gas (GHG) emissions, water consumption, and land appropriation resulting from shifting the Chinese population to healthy diets. We quantify the environmental impacts of individual diets using the latest available data of China Health and Nutrition Survey (2011), and compare them with the environmental impacts of suggested healthy dietary patterns in accordance with the 2016 Chinese Dietary Guidelines. If all Chinese would follow healthy diets rather than their current diets revealed in the survey, GHG emissions, water consumption, and land occupation would increase by 7.5% (63.9 Mt CO_2e annually), 53.5% (510 billion m^3), and 54.2% (1256 billion m^2), respectively. Urban and high-income groups have higher diet-related environmental impacts but could achieve less additional environmental impacts when moving to healthier diets. These findings indicate an expense of increased GHG emissions, and consumption of water and land resources in improving health. They also highlight the need to focus on the effects of improved economic conditions and urbanization in reconciling environmental impacts and human nutritional adequacy.

1. Introduction

The way we consume food is not only responsible for multiple malnutrition issues but is also contributing to detrimental environmental impacts. Global diets have been transitioning towards a more "western" style marked by excessive intake of sugar, trans fat, and red and processed meats, as well as insufficient consumption of vegetables, fruits, and whole grains (Micha et al., 2015; Popkin et al., 2012). These consumption patterns have been contributing to overweight or obesity in one-third of the world population (Ng et al., 2014; Bleich et al., 2007; Swinburn et al., 2009), inadequate intake of micronutrients ("hidden hunger") of 2 billion people (FoodOrganization, 2015; Haddad et al., 2015), and various food-related diseases including diabetes, stroke, and heart disease (Lim et al., 2012). At the same time, food consumption contributes significantly, directly and indirectly, to global environmental impacts. The global food system accounts for 19–29% of total anthropogenic GHG emissions (Vermeulen et al., 2012); more than 70% of the surface and groundwater consumption (Hoekstra and Mekonnen, 2012; Ranganathan, 2013), and uses 37% of the earth's land (Ranganathan, 2013; World Bank. (2016)). Adverse impacts are predicted to become more severe in the future due to further increasing consumption of animal products (Tilman and Clark, 2014).

Due to the links between nutritional and environmental issues, dietary change is expected to be a promising choice to simultaneously reduce environmental impacts and eliminate malnutrition (Tilman and Clark, 2014). A growing body of literature has investigated the environmental impacts of diets such as GHG emissions (Tilman and Clark, 2014; Masset et al., 2014; Vieux et al., 2013; Springmann et al., 2016; Song et al., 2017; Heller and Keoleian, 2015; Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2013; Eshel and Martin, 2006; Popp et al., 2010; Fazeni and Steinmüller, 2011), water consumption (Liu and Savenije, 2008;

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Vanham, 2012; Vanham et al., 2013; Capone et al., 2013), and land appropriation (Alexander et al., 2016; Kastner et al., 2012; Gerbens-Leenes and Nonhebel, 2002, 2005; Temme et al., 2013; Buzby et al., 2006). These studies predominantly focus on the developed world, including the United Kingdom (Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; WWF, 2011), Finland (Risku-Norja et al., 2009), Denmark (Saxe et al., 2013), France (Masset et al., 2014; Vieux et al., 2013; Vieux et al., 2012; balance of healthy, 2013), the United States (Eshel and Martin, 2006; Buzby et al., 2006; Peters et al., 2007, 2009, 2012), Austria (Fazeni and Steinmüller, 2011; Vanham, 2012), the Netherlands (Gerbens-Leenes and Nonhebel, 2002, 2005; Temme et al., 2013), Italy (Capone et al., 2013; Baroni et al., 2007), Spain (balance of healthy, 2013), Germany (Meier and Christen, 2012), Sweden (balance of healthy, 2013; Grabs, 2015), and New Zealand (Wilson et al., 2013). Some studies also explore whether the environmental impacts would be reduced if consumers in the study area switched to vegetarian diets (Springmann et al., 2016; Berners-Lee et al., 2012; Risku-Norja et al., 2009; Eshel and Martin, 2006; Vanham, 2012; Vanham et al., 2013; Baroni et al., 2007; Meier and Christen, 2012; Pathak et al., 2010), the so-called Mediterranean diet (Capone et al., 2013; Wilson et al., 2013; Wolf et al., 2011), or certain dietary recommendations (Fazeni and Steinmüller, 2011; Buzby et al., 2006; balance of healthy, 2013; Peters et al., 2007). Most studies agree that diets with less animal product consumption (particularly red meat) both reduce environmental impacts and benefit public health by reducing dietary-related health risks (Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2013; Eshel and Martin, 2006; Fazeni and Steinmüller, 2011; Vanham, 2012; Capone et al., 2013; Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes and Nonhebel, 2005; Temme et al., 2013; Buzby et al., 2006; WWF, 2011; balance of healthy, 2013; Peters et al., 2007; Peters et al., 2009; Peters et al., 2012; Baroni et al., 2007; Meier and Christen, 2012; Grabs, 2015; Wilson et al., 2013).

In contrast, studies focusing on developing countries such as China are rare and have been emerging only recently. The consequences of dietary change in these countries are worth special attention due to a number of reasons: First, diets in developing countries are substantially different from western diets and thus need more research in terms of environmental and health impacts. For instance, compared to many developed countries, Chinese have a much lower intake of milk but higher consumption of fruits and vegetables than many western countries (Singh et al., 2015). Meanwhile, Chinese have an overall lower intake of meat but prefer pork rather than beef that consumes more resources and generates higher GHG emissions (Micha et al., 2015; Heller et al., 2013; Wang et al., 2015). Furthermore, both environmental issues and malnutrition issues are worsening fast in many developing countries as their diets are westernizing with higher intake of animal products and processed foods, which create significant environmental impacts and are related to multiple diseases (Yang et al., 2013). Dietary risk factors have become the leading health risk factor in China, accounting for 16.3% of disability-adjusted life-years (DALYs) and 30.6% of deaths (Yang et al., 2013). China is suffering from obesity issues, with overweight and obesity rates reaching 30.1% and 11.9%, respectively, while deficiency of calcium is severe given the low consumption of dairy products (National Health and Family Planning Commission, 2015). In terms of environmental impacts, the food sector in China was responsible for 18% of direct and embedded GHG emissions (7.9–13.7% of global food-related emissions) (Vermeulen et al., 2012; Chen and Zhang, 2010), 64% of surface- and groundwater withdrawal in 2014 (Ministry of Water Recourc, 2015), and 12.7% of land use (Nath et al., 2015). All these issues are expected to become more critical in the future, as consumption of animal products, especially meat, is expected to rise with rapid economic development and urbanization (Liu and Savenije, 2008; Li et al., 2015; Yu et al., 2016). These trends have global implications given the considerable population of the country. Finally, the heterogeneous socio-economic contexts within the vast population add further complexity to the nutritional and environmental impact of dietary change. In China, urban residents consumed 52% more meat than their rural counterparts in 2002 (National Health and Family Planning Commission, 2013); the top 20% income group spent at least twice as much as the bottom 20% on food in 2011 (National Bureau of Statistics, 2012). These differences lead to distinct environmental and health outcomes as high socioeconomic status is associated with higher intake of protein, energy, and saturated fat particularly in low- and middle-income countries (Mayén et al., 2014; Wiedenhofer et al., 2017; Golley and Meng, 2012; Eriksson et al., 2014).

Recent studies have been addressing the extent to which dietary changes affect the environment and nutritional quality in developing countries, particularly China. For example, Song et al. quantified the carbon, water and ecological footprints of Chinese diets during 2004–2009 (Song et al., 2015). He et al. investigated the historical shift of the dietary patterns of various socio-economic groups over a decade in China and explored how the improvement or decline of nutritional quality over the observed period are linked to environmental impacts in terms of GHG emissions, water consumption, and land use (He et al., 2018). Scenario analysis was also conducted to show whether improving diets can result in environmental benefits. Song et al. found that changing dietary patterns to meet the latest national planning for food and nutrition can help mitigating climate change and benefit public health (Song et al., 2017). Similarly, Lei and Shimokawa explored the effect of promoting 2007 dietary guidelines in China on GHG emissions, energy use and water consumption (Lei and Shimokawa, 2017). While these studies offer informative discussion on how dietary change may result in interconnected environmental and nutritional outcomes, how results differ by socio-economic status and associated food consumption patterns is still under-explored. Individuals from different areas (e.g. urban versus rural) and income levels have different ability to access items from each food group which is reflected in the dietary patterns (He et al., 2018) and the associated environmental impacts. This heterogeneity needs to be taken into account when estimating environmental impacts of diets and shifts in dietary patterns such as adopting healthy dietary patterns.

In this research, we explore the environmental impacts of shifting to a healthy diet in China. We compare diets of 9980 individuals in 12 provinces in 2011 with the recommended 2016 Chinese Dietary Guideline to identify malnutrition issues of Chinese diets. Next, we quantify GHG emissions, water consumption and land appropriation of the diets of the sampled individuals in two scenarios by using lifecycle based analysis. To capture the uncertainty of agricultural production techniques, climate conditions, as well as consumers' choice, we use Monte Carlo simulation to evaluate uncertainties in environmental impacts in both scenarios. We take advantage of the rich details in socio-economic characteristics in our dataset to investigate whether the results differ by urban & rural status, age, sex, body weight and height, physical activity, dwelling area, income, and other socio-economic and demographic variables. Based on the results at the individual level, we extrapolate the results according to the distribution of age, sex, urban/rural status and personal income in China, and estimate the environmental impacts due to this nutritional improvement for the whole country. This study shows the environmental impacts of diets and their distance from healthy diets by different socio-economic groups at the subnational level, and the environmental trade-offs and win-win outcomes when moving towards healthy diets. These are prerequisites necessary for an informed policy decision. The study also demonstrates the usefulness of dietary guidelines as valuable policy tool not only for public health improvements at the sub-national level, which provides implications for policy design targeting individuals of heterogeneous socio-economic status, but also for promoting sustainable diets that benefit the ecological environment.

2. Methodology and data

2.1. Individual food intake

Individual food intake in habitual dietary patterns are derived from the latest China Health and Nutrition Survey (CHNS) in 2011. The dataset is provided by the Carolina Population Center of the University of North Carolina at Chapel Hill and the Chinese Center for Disease Control and Prevention (CCDC) available at http://www.cpc.unc.edu/projects/china. CHNS collects food intake, age, sex, body weight and height, physical activity, dwelling area, income, and other socio-economic and demographic characteristics through individual surveys. Its 2011 wave is sampled from 12 provinces of China with varying socio-economic contexts. Some descriptive statistics of demographics of the sample is available in Table S1.

CHNS collects food intake at the individual level by 24 h recall self-report for 3 consecutive days. This enables us to track all the types and weight of the food intake of each individual. The intake of cooking oil and condiments are estimated by differencing the weights of these items at the beginning and the end of the survey period for each family. We follow Du et al. (2004) to estimate the intake of each person. The CHNS can be directly associated with the Chinese Food Composition Tables (CFCTs) which contain the detailed nutrition content for each food item. For each food group, we adopt the average of the 3-day intake taken for each individual as her/his habitual intake. We also consider all records that exceed 4 times the group standard deviation as outliers and drop the corresponding individuals in our analysis.

2.2. Healthy dietary patterns

We define healthy dietary patterns as following the *Balanced Dietary Patterns* from *2016 Chinese Dietary Guideline*. As the latest recommendation from nutrition authorities in China, this guideline suggests a daily intake of 14 major food groups (refined grains, coarse cereals and pulse, tubers, dark-colored vegetables, light-colored vegetables, fruits, meat, eggs, seafood, dairy products, soybeans, nuts, oil, and salt) for healthy individuals, each specified for 11 different energy requirement levels ranging from 1000 kcals/day to 3000 kcals/day as shown in Table S5. All food groups considered in the Chinese Dietary Guideline were included in our analysis except for salt. Though salt is linked to high blood pressure which is considered a leading DALY health risk in China (Lim et al., 2012), its environmental impact is negligible due to both its low environmental impact factor when compared with other food groups (Life-cycle assessment soc, 2006; Gallen, 1996), and the small amounts actually consumed (Dongmei et al., 2016). Therefore, although reducing salt intake can bring about considerable health benefits in China, we choose to ignore it and concentrate the analysis on other major food groups in examining their GHG emissions, water consumption, and land use.

Healthy dietary patterns are designed based on a comprehensive consideration of the human requirement for both macro-nutrients including carbohydrate, fat, and protein, and micro-nutrients such as vitamins and minerals from the latest nutritional studies on China (Chinese Nutrition Society, 2013, 2016). With quantitative food-based suggestions, the guidelines aim at providing nation-specific operational and intuitive instructions for Chinese residents to improve their dietary quality. As healthy dietary patterns are energy-requirement-specific, we estimate the daily energy requirement of each individual in our sample based on body weight, age, gender and physical activity, and match the diet of each individual with the balanced dietary pattern of the nearest energy level.

2.3. Environmental impact evaluation

We link environmental impacts with individual daily food intake by food types to evaluate the impact of dietary patterns with a similar methodological framework as in (He et al., 2018). As the environmental impact factors can vary due to uncertainty associated with climatic conditions, geography and technology associated with food production, we adopt a Monte Carlo simulation to inspect if and how these factors affect our results. We assume lognormal distributions for GHG emissions based on the distribution of factors of our collection, and the normal distribution of water consumption and land appropriation. Based on these assumptions, we obtain the mean and standard deviation of the emission factors for simulation. For GHG emissions, we draw from over 100 lifecycle assessment (LCA) studies and use the mean and standard deviation of the emission factor of each type of food to characterize the distributions. These studies cover emissions from cradle to farm gate. A point to note is that we do not include the emissions from land use change when estimating the GHG emissions. As massive emissions are associated with the production of animal products in clearing the forest for pasture or feed production, the emissions per gram for these items can be much larger than plant-based products. In this way, our estimation of environmental benefits for GHG emissions can be conservative.

For water consumption, means of factors are based on the estimations provided by the Water Footprint Network. The data contain 1996–2005 average water consumption for 352 plant-based and 106 animal-based products. More information about this dataset can be found at http://waterfootprint.org/en/. This dataset does not include footprints for seafood, so we estimate the factors based on Pahlow et al. by accounting for the water consumption of feeds (Pahlow et al., 2015). However, information on the uncertainty of water footprints is rarely available. We assume the standard deviations for water consumption to be 15% of the means following the method in Zhuo et al. (Zhuo et al., 2014). The means of the land appropriation for plant-based food are calculated from the yield of each agricultural product during 1996–2005 from the Food and Agriculture Organization Statistics (FAOSTAT); we estimate the land appropriation required in producing animal-based food using factors that estimate the proportion of feeds converted to final animal products. Details of quantification of each environmental impact factor are included in the supporting information (SI). We adopt an assumption similar to the water footprints but use 5% of the means as the standard deviations due to the lack of uncertainty analysis and the observations of small changes in productivity over time in FAOSTAT.

It should be noted that the environmental impacts considered in this study are calculated within a boundary of cradle-to-gate, but do not include the emissions and resource use during food storage and cooking which may differ across food groups. For instance, specific food items such as dairy products must remain refrigerated, while others require a longer cooking time to become edible. Nevertheless, the literature shows that the production phase accounts for a dominant proportion of the environmental impacts for most food items according to Garnett (2008) and Sonesson et. Al (Pahlow et al., 2015). Therefore, we argue that the exclusion of these phases would not significantly change the results.

We also randomize individual's choices within each food group. We assume each individual independently and randomly select one item in the Chinese Food Content Tables (2002 & 2004 version) from each food group to follow the balanced dietary patterns. The probability that a specific food item is chosen is determined by the relative frequency of an individual's choice in the CHNS 2011 sample. In this way, it is assumed implicitly that they have different existing dietary patterns but similar preferences.

The simulation is repeated for 5000 trials. In each trial, environmental impact factors of each food item are generated. Next, one food item from each group is picked for each individual, and its intake in following a healthy diet is calculated. The food waste at the consumption phase is accounted for by inflating the intake with a series of waste ratio specified for food groups for industrialized Asian countries provided by FAO (Gustavsson et al., 2011). Finally, we multiply the consumed amount of a food item with its environmental impact factors to calculate its total environmental impact. The results of all trials compose our final sample. We calculate the percentage of deviation from the balanced dietary pattern (details included in the SI), and the total environmental impacts resulting from the dietary shift for each individual. We conduct regressions to test the effect of urban/rural status and per capita household income affects the malnutrition and dietary environmental impacts.

We finally extrapolate the environmental impact for the whole country using a reweighing method. Since the CHNS is sampled from 12 provinces, we generate a weight indicating the proportion of each sampled individual in the national population. The weights are constructed using another national household survey program, China Family Panel Studies (CFPS). Since 2010, this program investigates individuals from 25 provincial districts. The dataset includes individual-level demographic and socio-economic characteristics, as well as a weight for national representative estimation. We obtain the joint distribution of age, sex, urban/rural status and per capita household income in CFPS, and match the two samples using this distribution to map the weights to CHNS individuals. Details are included in the SI.

3. Results

3.1. Deviation from balanced dietary patterns

Chinese diets show a combination of over- and under-intake of important food categories. As shown in Fig. 1, there is a significant over-intake of meat, refined cereal, and cooking oil, when consumer behavior is contrasted against the guidelines. We also summarize how much individuals are over-consuming within each food group in Table S8 in the supporting information. On average, the sampled individuals consumed 175% more meat, 71% more refined cereal and 43% more cooking oil than in the recommended healthy diet per day. At the same time, the intake of dairy products was on average 93% lower than the recommended amount; the deficit amounted to 88% for coarse grains and pulses, 86% for nuts, 80% for fruits, 73% for tubers, and 71% for seafood 71%. Such unbalanced diet can result in significant health risks: The over-intake of meat and low consumption of milk are both correlated to colon and rectum cancers, the lack of nuts is associated with ischemic heart disease, and lack of fruits and vegetables can contribute to various types of cancer and strokes (Lim et al., 2012). These malnutrition issues have made the diet-related risks the leading health risks in China by 2010 (Yang et al., 2013).

Each socio-economic group distinguished by urban vs. rural, income level, and age shows surprisingly similar malnutrition issues including both over-intake of refined cereal, cooking oil, and meat, as well as insufficient consumption of other food groups. However, there are interesting differences to point out. We present the malnutrition patterns for each income and urban/rural group in Fig. 1, further separate the groups by age in Figure S3, and regress the socio-economic factors on the deviation from the balanced pattern for each food group in Table S9. Urban dwellers have a smaller over-intake level of cereal and less deficiency of other non-starchy food (10.4% less deficiency of milk, 11.7% less deficiency of egg, and 12.9% less deficiency of seafood than the rural residents as shown in Table S8), but show a more severe (48.1%) over-intake of meat. Per capita household income plays a similar role: an increase of every 10 thousand RMB leads to a decline of the deficiency of dairy products by 1.7%, egg by 3.7%, and seafood by

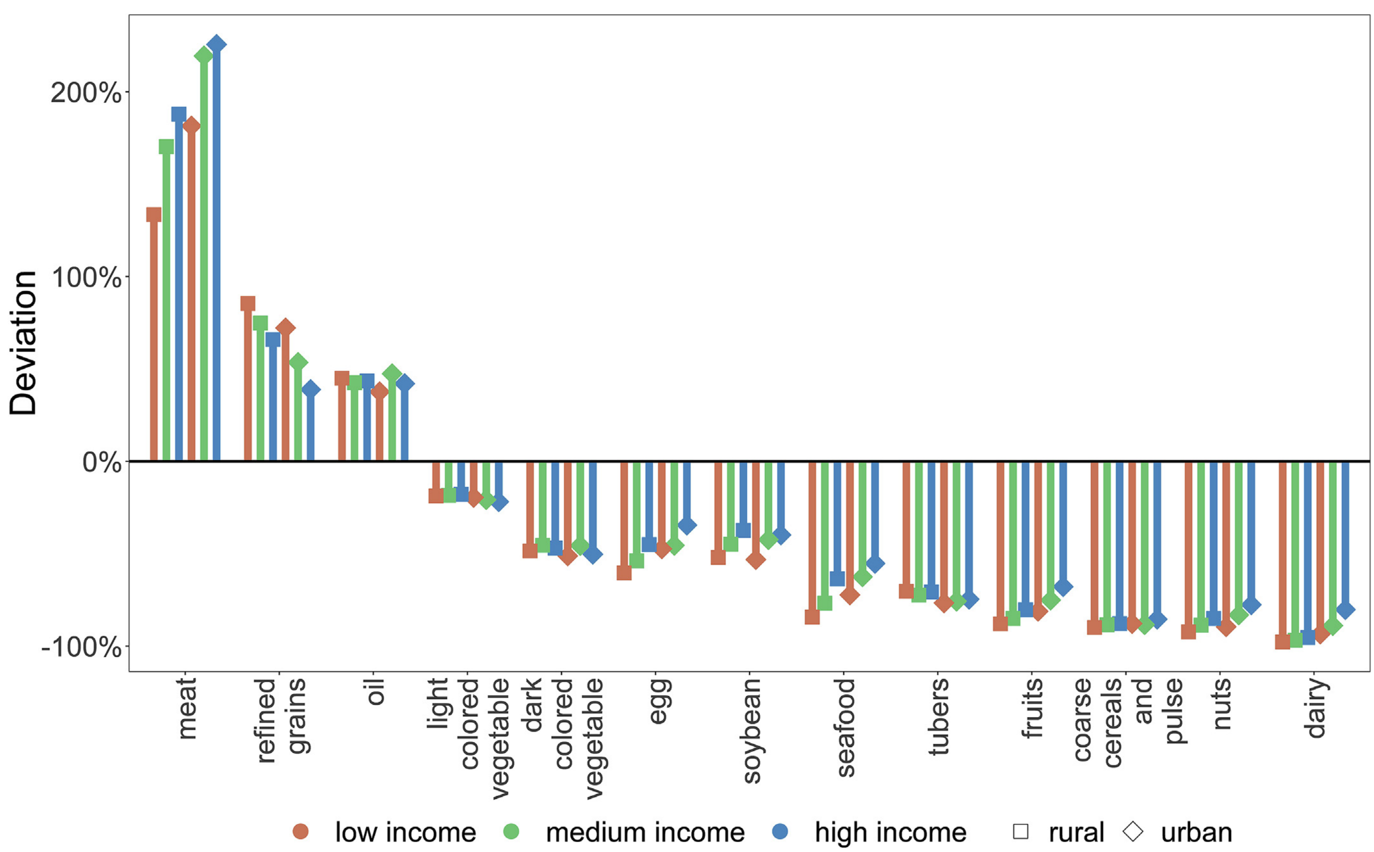

Fig. 1. Percentage deviation of food intake from recommended dietary patterns. Food groups on the x-axis are ranked by the level of malnutrition from the most severe over-intake to the most severe under-intake. The points and lines show average percentage of under-/over-intake of each food group for each socio-economic group. The horizontal red dashed line shows balanced diets without under-/over-intake issues. We conduct t-tests on the percentage deviation from the balanced dietary patterns, and all of them are statistically significant. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

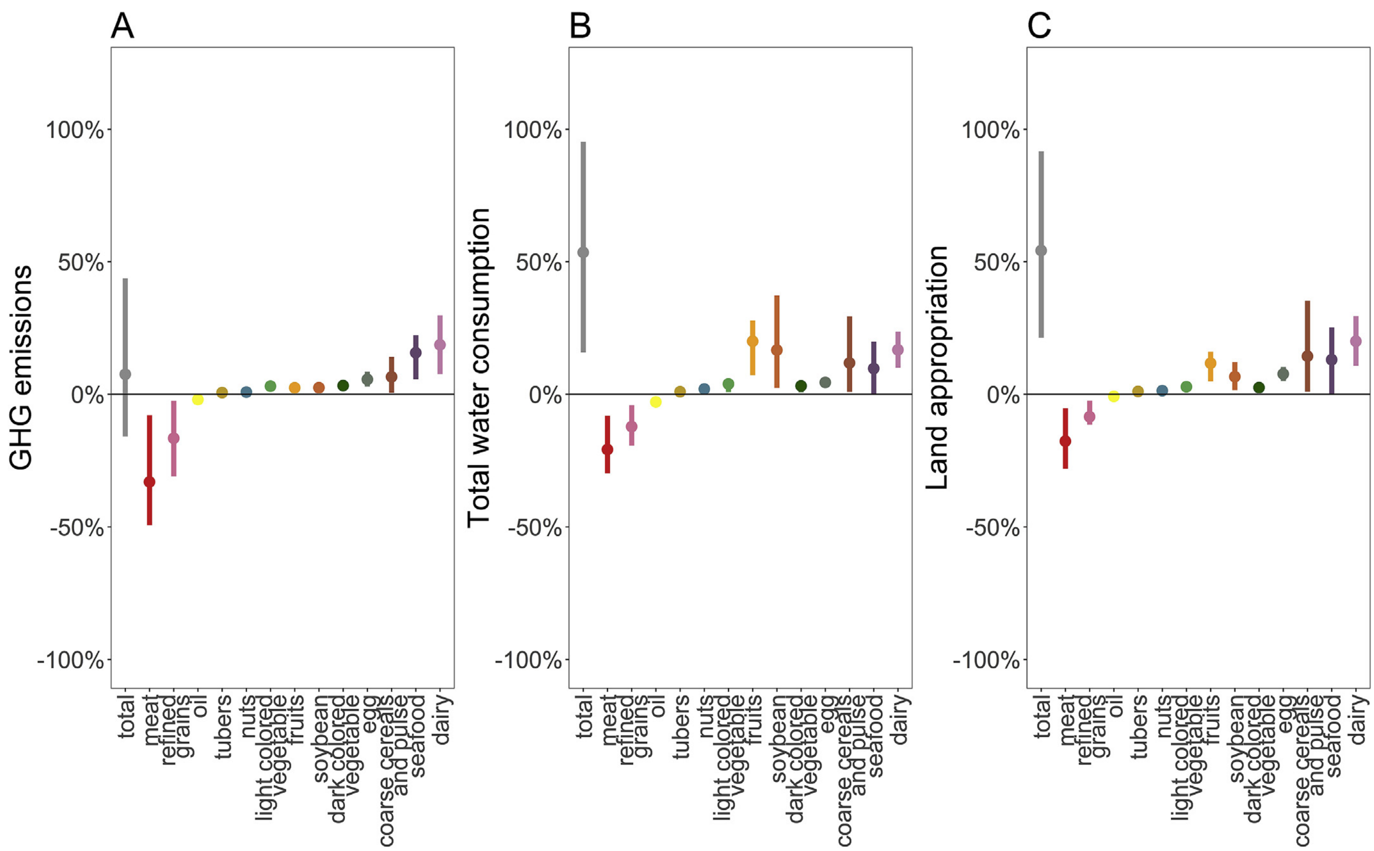

Fig. 2. Change of environmental impacts in following healthy diets at the national level. The vertical axis shows the percentage change in shifting to the healthy diets from the 5000 trials. Food groups (on the x-axis) are ranked by average from the lowest to the highest. (A) GHG emissions; (B) Total water footprint; (C) Land appropriation. The points show the average, and the line shows one standard deviation from the mean (16% and 84%).

4.2%, but also leads to additional over-intake of meat by 12.4%. On the other hand, age plays a role for all food groups except meat according to the significance of its coefficients in Table S9. Its effect is particularly critical for several food groups. Figure S3 and Table S9 show that the elders tend to have a more serious over-intake issue of refined grains and cooking oils, but less insufficiency of vegetables and soybeans. This may reflect the distinction of dietary habitat across different generations.

3.2. Environmental impacts of dietary change

In order to achieve a healthy diet as laid out in the 2016 Chinese Dietary Guideline, all socio-economic groups would have to reduce the intake of refined grains, meat, as well as cooking oil, and increase the intake of other food groups. Such dietary adjustments toward a healthy diet would create a different set of environmental impacts. We display the change in each type of environmental impacts due to the dietary shift in Fig. 2. The points show the percentage change for the whole country both in total and separated in food groups. Shifting to a healthy diet would lead to an increase in GHG by 7.5% (i.e. 63.9 Mt CO2e per year), water consumption by 53.5% (510 billion m^3), and land appropriation by 54.2% (1256 billion m^2). The increases of all three environmental impacts are significantly different from 0 (alpha = 0.01, and the p-values are less than $2.2*10^{-16}$ for all the tests), indicating possible trade-offs between nutrition and environment.

The different level of the total change for these environmental impacts are a result of not only the current patterns of consumption and thus the required change for each food group, but also the respective environmental impacts of each food group and the ratio of waste at the consumption phase. Since the change in quantities are the same across different impacts, the differences in total environmental impacts shown only reflect the underlying differences in emission and resource use factors by food group. Since meat is the major over-consumed food group and has high impacts in comparison to the insufficiently consumed food groups, the environmental outcomes would depend on how high the per-gram impact of meat is compared to those other groups. As shown in Figure S2, per-gram meat GHG emissions are much larger than other foods; for water consumption and land occupation, however, the contrast is weaker. Therefore, when individuals shift to healthy diets by reducing meat consumption, it would lead to a significant reduction of GHG emissions that could cancel out most increased emissions caused by increasing intake of dairy product, nuts, fruits, seafood, and other insufficiently consumed food items. For water and land, however, the benefit from the reduction of meat is more than compensated by the substantial increasing intake of other food groups. In addition, food waste also plays a role. In China, the proportion of waste at the consumption is considerable (15%) for fruits and vegetable, which is almost double the ratio for meat (8%) (Gustavsson et al., 2011). As a result, larger "extra" environmental impacts by increasing the consumption of fruits and vegetables further diminishes the environmental benefits of reducing meat consumption for GHG emissions, and lead to a larger increase of water consumption and land appropriation.

Individuals from different socio-economic groups contribute differently to environmental impacts. We display environmental impacts of current diets compared with the improved diet in Fig. 3, and explore the role of socio-economic status on impacts in Table S10. Both urban/rural status and per capita income have significantly negative coefficients when regressed on the change of the respective environmental impact, meaning that urban dwellers and high-income groups are usually related to a lower increase for all three environmental impacts or even a decrease for GHG emissions. This is a result of a higher intake

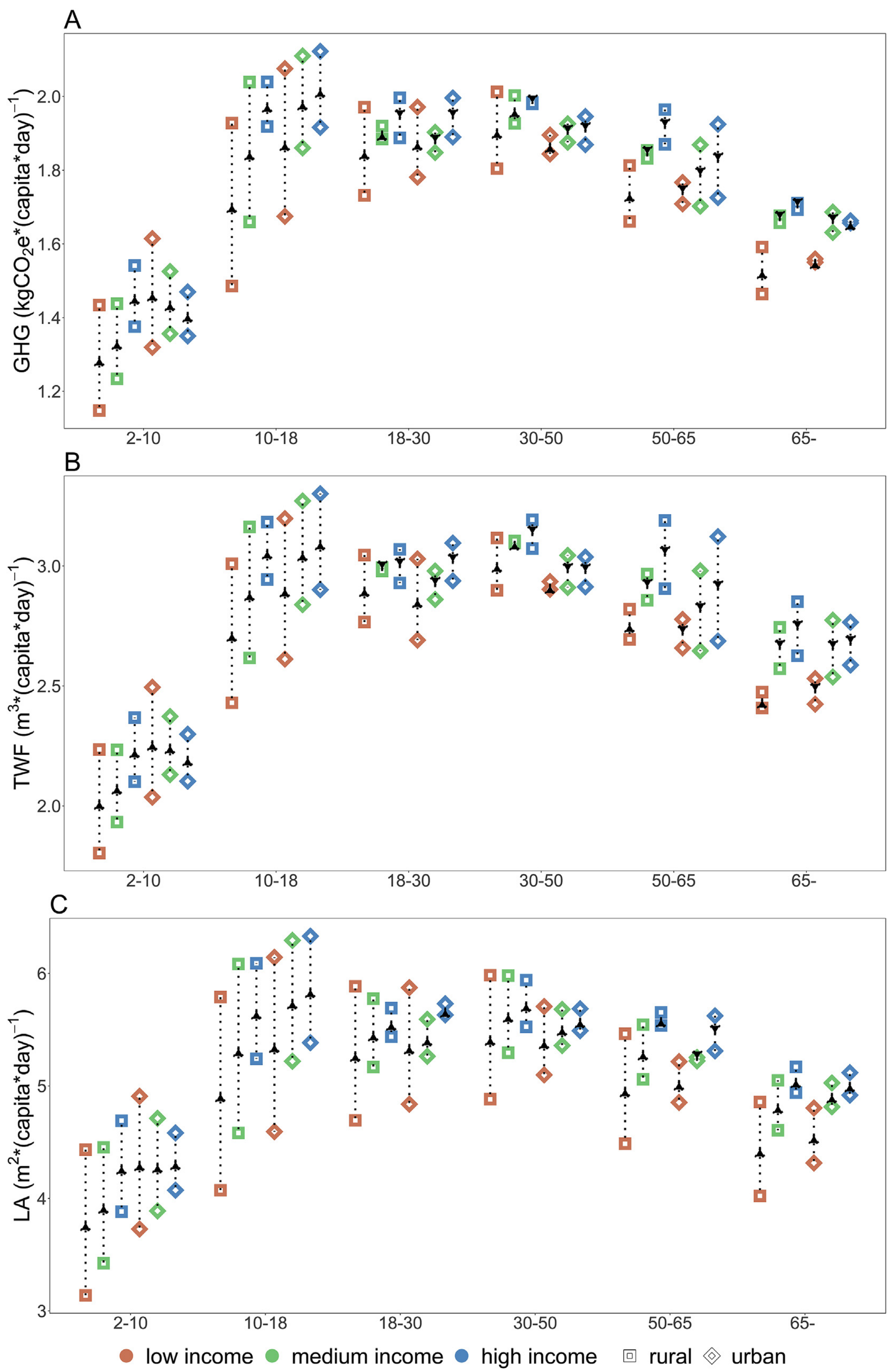

Fig. 3. Per capita environmental impacts of the existing and healthy diet for different socio-economic*age groups. Age groups on the x-axis. (A) GHG emissions; (B) Total water footprint; (C) Land appropriation. GHG = greenhouse gas, TWF = total water footprint, LA = land appropriation. The points show the average level, and the arrows (shown by the triangular points) show the direction of change (increase/decrease).

level of non-starchy foods, especially animal products, in urban and high-income groups. On one hand, individuals in the urban and high-income groups consume more meat than the rural and low-income groups, thus the adjustments would result in larger environmental benefits; on the other hand, they do not need as much food as rural and low-income groups to make up for intake deficiency, especially of non-meat animal products such as eggs and dairy products. The results vary by age as well. For example, shifting to healthy diets increases emissions for younger people of all socio-economic groups, with larger increases for lower income, as they require more dairy products, whereas it decrease emissions for older generations of medium and high income, as they mostly need to consume less meat. For water consumption and land occupation, children and adolescents also show a larger increase due to less plant-based food groups such as tubers, soybean, and vegetables.

4. Discussion

Our results add to the ongoing debate on whether improving nutritional dietary quality leads to environmental benefit or loss. To date, research has predominantly focused on developed countries, with most concluding that a change in food consumption behavior would be a competitive, low-cost means of realizing environmental sustainability and positive health outcomes (Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2013; Eshel and Martin, 2006; Fazeni and Steinmüller, 2011; Vanham, 2012; Capone et al., 2013; Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes and Nonhebel, 2005; Temme et al., 2013; Buzby et al., 2006; WWF, 2011; balance of healthy, 2013; Peters et al., 2007; Peters et al., 2009; Peters et al., 2012; Baroni et al., 2007; Meier and Christen, 2012; Grabs, 2015; Wilson et al., 2013). However, the conclusion of this line of inquiry is based on the fact that developed countries need to reduce consumption of animal products, particularly meat to a larger extent than the Chinese to follow a healthy diet. In this way, although typical Western diets are generally deficient in food groups such as vegetables and fruits, increasing the intake of these foods does cancel out the environmental benefits from reducing meat intake. By contrast, over-consumption of meat is less severe in China while the deficiency of dairy products is more critical (Lim et al., 2012). Along with other insufficiently consumed foods, their increase counteracts some of the environmental benefits from reducing meat consumption. This result shows that the environmental impact of dietary quality improvement may not always be positive, but depend on existing dietary patterns that individuals pursue. To date, there are very few studies examining the synergies between environmental and nutritional consequences of dietary change in developing countries, partly due to a lack of micro-level data.

Our results indicate that shifting to healthy diets does not necessarily benefit the environment as was found for many developed countries (Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2013; Eshel and Martin, 2006; Fazeni and Steinmüller, 2011; Vanham, 2012; Capone et al., 2013; Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes and Nonhebel, 2005; Temme et al., 2013; Buzby et al., 2006; WWF, 2011; balance of healthy, 2013; Peters et al., 2007; Peters et al., 2009; Peters et al., 2012; Baroni et al., 2007; Meier and Christen, 2012; Grabs, 2015; Wilson et al., 2013). They are also different from the previous global-level study of Springmann et al. involving China (Springmann et al., 2016). In the Springmann study, the scenario of the healthy diet is constructed according to dietary recommendations from the World Health Organization (WHO), which does not impose constraints on the intake of dairy products and seafood. These foods are rich sources of calcium and essential omega-3 fatty acid, respectively, but are rare in Chinese diets and lead to the insufficiency of the two nutrients (Lim et al., 2012), Increasing the intake of both would introduce considerable environmental impacts as shown in our results. Moreover, the study adopts dietary projections from FAO estimates as a business-as-usual scenario, which estimates per capita food supply based on national statistics but not micro-level individual dietary records (Details of FAOSTAT data preparation are included in Food Balance Sheets: A Handbook available at http://www.fao.org/docrep/003/X9892E/X9892E00.htm) and is thus less accurate. Such data differences may affect the evaluation results as well. So far, what constitutes a healthy diet is still an open question, on the other hand, there is agreement that there is more than one way to follow the dietary recommendations (Committee, 2016). As more research attempts evaluating the environmental impact of adopting healthy diets, scholars should put more emphasis on the question of how different definitions of healthy diets affect the conclusions with important implications for designing dietary guidelines and food policy.

The findings of this research highlight the necessity of a holistic perspective in addressing the two interconnected objectives of nutritional quality and ecological sustainability. Previous studies have connected nutritional and environmental outcomes of diets predominantly by focusing on a single type of environmental impact (Macdiarmid et al., 2012; Berners-Lee et al., 2012; Aston et al., 2012; Risku-Norja et al., 2009; Saxe et al., 2013; Eshel and Martin, 2006; Fazeni and Steinmüller, 2011; Vanham, 2012; Capone et al., 2013; Gerbens-Leenes and Nonhebel, 2002; Gerbens-Leenes and Nonhebel, 2005; Temme et al., 2013; Buzby et al., 2006; WWF, 2011; balance of healthy, 2013; Peters et al., 2007; Peters et al., 2009; Peters et al., 2012; Baroni et al., 2007; Meier and Christen, 2012; Grabs, 2015; Wilson et al., 2013). However, multiple environmental impacts from dietary adjustment can be different, and looking at each in isolation would lead to misleading conclusions and incomplete understanding of the various links. A lack of integrated perspectives can lead to inconsistent policies and inefficient use of resources and erroneous estimation on costs and benefits (Howells et al., 2013; Gingerich et al., 2017). As shown in this case, shifting to a healthy diet can result in synergies and trade-offs among different types of environmental impacts. This fact calls for integrative consideration of significant, if not all, environmental elements affected by dietary choice in managing the food-health-environment nexus. The Chinese government has developed national goals of improving nutrition quality (China General Office of t, 2014) as well as five-year plans of abating GHG emissions (The State Council of China, 2016), promoting water saving (National Development, 2017), and achieving the ecological sustainability during land use planning (Ministry of Land and Reso, 2016). The food-health-environment nexus thus provides a framework to systematically evaluate trade-offs across policy arenas. Our findings also suggest that policymakers should look into socio-economic diversity when addressing the nutrition-environment nexus. The differences across lifestyles and other socio-economic variables help explain diverse malnutrition issues and environmental impacts. Such differences have been observed across countries (Tilman and Clark, 2014; Springmann et al., 2016, 2017; Alexander et al., 2016), but still need more attention within countries or even regions given the socio-economic heterogeneities. As urban and high-income consumers pursue more westernized diets in China, policies that improve the nutritional quality of these consumers may result in an inevitable increase of environmental impacts. Available policy tools such as campaigns promoting healthy diets and food price adjustment can result in different environmental and nutritional outcome distributions given disparities in behavioral responses and price elasticities among various socio-economic groups (Andreyeva et al., 2010). Furthermore, it should be noted that the core data for the analysis was collected in 2011. Considering the rapid urbanization (the urbanization rate has increased from 51% in 2011 to more than 58% in 2017 according to the report of National Bureau of Statistics) and related changes in lifestyles, the potential to improve diets in China through policy intervention could also be on the rise. Rapid population ageing with their changing dietary patterns is also expected to have significantly increasing impact on health and the environment. While these issues should be addressed in future research, we hope this study will provide a starting point for recognizing the importance of the environmental and health impacts of the diets.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2019.03.106.

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