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Environmental effects of sustainability-oriented diet transition in China

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ABSTRACT

Dietary adjustment is widely recognized as an effective way to solve the environment/ health predicament, and a more sustainable diet is the final target. The environmental effects of the sustainable oriented diet transition deserve considered, especially given the severe food waste. Here, we explored the links between food supply, food consumption, and food demand of recommended diet from 1990 to 2015 at the individual and national level in China, and then quantified the effects of dietary transition on nitrogen footprints (NF), phosphorus footprints (PF), carbon footprints (CF), and water footprints (WF). Results show that cereal consumption decreased at a rate of 1.6% annually, but it was still higher than the dietary guidelines in 2015. Meat consumption went up and almost 1.5 times the maximum recommended level (Max_RL) in 2015. Milk consumption accounted to 10% of the minimum recommended level (Min_RL). Cereal and meat supplies had exceeded the Max_RL demands by 34% and 47%, respectively. The ratios of food supply to consumption varied from 1.3 for meat to 4.3 for vegetables from 1990 to 2015. For environmental effects, NF, PF, and CF would decrease by 36%,22%, and 29%, but WF increased by 3% when current food consumption in 2015 completely meet with the Min_RL. While NF, PF, CF, and WF would increase by 22%,63%,22% and 65% when food supply meet with the food demand of the Max_RL. We would underestimated NF by 4%, but overestimate PF, CF, and WF by 12%, 3%, and 20% if without considering gaps between food supply and consumption. We conclude that ignore the gaps between food supply and consumption would overestimate the environmental impacts when current food consumption transitions to the recommended diet. Measures facilitating the realization of the sustainability-oriented diet rely on dietary patterns adjustment and improving the efficiencies of food supply chain.

1. Introduction

Food consumption is connected to human health, resource utilization, and environmental sustainability (Kearney, 2010). For the world as a whole, food consumption is undergoing dietary transition toward unhealthful diets, such as higher consumption of oils, meat, and refined sugar, which is one of the top five health risk factors in China as well as worldwide (Lim et al., 2012; Tilman and Clark, 2014). It has been found that 11 million deaths and 255 million disability-adjusted life years (DALYs) are attributable to dietary risk factors (Afshin et al., 2019). Too low intake of fruits and vegetables have resulted in 6.7 million deaths and 5.7% of global DALYs, and diets containing little animal-sourced food are likely to decrease the number of deaths in 2010 (Lim et al., 2012). Meanwhile, the food system accounts to 19–29% of total anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012), more than 23% of reactive nitrogen (Nr) emissions (Oita et al., 2016), ~70% of the surface and groundwater consumption (Hoekstra and Mekonnen, 2012), and about 90% of rock phosphate demands (Rosemarin, 2004). Without technological improvements and dedicated measures in food production, resources consumption will surpass the planetary boundaries in the near future (Springmann et al., 2018).

The situation is expected to be worse as a growing and wealthier population is experiencing dietary transition throughout the world, resulting in resource over-consumption and environmental degradation (Tilman and Clark, 2014). Facing the human health/environmental dilemma, dietary adjustment might be a promising solution which attracts a vast amount of attention. One group of studies has assessed the environmental effects of food production and consumption around the world. For instance, Cui et al. (2016) found that China's nitrogen footprint (NF) from the food system increased from 30.3 Tg in 1990 to

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54.0 Tg in 2009. Lin et al. (2015) determined that the total carbon footprint (CF) of food production in China doubled during 1979–2009. The second group of studies has evaluated the environmental impacts of many typical diets, such as the recommended diet of the World Health Organization, the USA, Australia, Canada, Germany, the UK, China, and India (Horgan et al., 2016; Ritchie et al., 2018); the vegetarian diet (White and Hall, 2017) and the Mediterranean diet (Castañé and Antón, 2017). Ritchie et al. (2018) compared many different dietary guidelines and suggested that a wide disparity existed among them, ranging from 687 kg of carbon dioxide equivalents (CO_2e) capita^{-1}yr^{-1} for the Indian diet guidelines to the 1579 kg CO_2e capita^{-1}yr^{-1} in the USA. The third group of studies has focused on assessing the environmental impacts of dietary adjustments, such as reducing meat consumption and increasing vegetable and fruit consumption (Scarborough et al., 2012; Aleksandrowicz et al., 2019). A 50% reduction in meat and dairy and replaced by fruit, vegetables, and cereals, could result in a 19% reduction in GHG emissions and 36,910 deaths delayed or averted per year in the UK (Scarborough et al., 2012). In global terms, human mortality rates could be reduced by 6% −10%, and food-related GHG emissions reduced by 29% - 70% in 2050 compared with current food consumption pattern (Springmann et al., 2018).

Among various dietary patterns, dietary guidelines are put forward from the perspectives of residents' nutrition and health as well as environmental friendly. Adherence to the Chinese or US dietary guidelines, the risks of cardiovascular disease, cancer, and diabetes mortality would be decreased, mainly in men (Yu et al., 2014). Moreover, higher Alternate Healthy Eating Index (AHEI) scores were associated with impressive reductions in the risk of primary chronic disease (McCullough et al., 2002). Furthermore, recommended diets contributed to decrease the effects on GHG, land use, and eutrophication of 24.8%,21.3%, and 17.6%, respectively, particularly in high-income nations (Behrensa et al., 2017). The recommended diet is a type of sustainability-oriented diet and the suboptimal choice, given that no official 'sustainable diet' has been defined.

Previous studies have focused on solving this dilemma, but some questions remain. For example, what are the actual resource utilization and environmental costs of current and recommended diets? Specifically, what will happen to environmental footprints when current food consumption shift to the recommended diet? Besides, to achieve the recommended diet, how will the food supply need to be adjusted and what about the changes in the corresponding environmental footprints? Moreover, it is imbalanced about research of the topic around the world, with existing studies mostly concentrating on developed countries, such as the US, UK, France, and New Zealand, and few studies focused on developing countries including China, which has the largest population and is experiencing very rapid economic development and unprecedented urbanization. China also has the most massive N fertilizer production as well consumption (Zhang et al., 2013), and is the most substantial emissions of CO_2 in the world (Chakravartya et al., 2009). Among the researches in China, the carbon footprint of different food types was cited from European and American database rather than the domestic parameter, which is insufficient to reflect the real efficiency of food system in China (Song et al., 2017).

Therefore, our study aimed to assess the changes in environmental footprints when the current diet shift to a sustainability-oriented diet, namely the recommended diet in China. First, the disparities between current food consumption patterns and dietary guidelines at the individual level were assessed in both urban and rural areas. Second, we explored the relationships between total food supply and food demand at the recommended level, in 1990,2000,2010,and 2015, based on the ratios of different food supplies and consumptions. Third, we evaluated the environmental impacts of current and recommended diets by using the nitrogen footprint (NF), phosphorus footprint (PF), carbon footprint (CF), and water footprint (WF) indicators, and proposed some measures to realize the recommended diet in China. Findings will provide useful information to facilitate shifting to a sustainability-oriented diet.

2. Data and methodology

2.1. Current food consumption

Generally, the uses of crop products include food, feed, seed, loss in stock and food processing, and other uses. In this study, only the food part was taken into consideration, including cereal, tubers, pulses, vegetables, fruit, eggs, pork, beef, mutton, poultry, fish, and milk. We separately calculated food consumption in both urban and rural households from 1990 to 2015 by per capita food consumption at home and the ratios of eating out in different years (Table S1 and S2). Urban and rural residents' food consumption and the division between rural and urban households were based on national statistical information (NBSC, http://www.stats.gov.cn/tjsj/). The database provides the per capita food consumptions of urban and rural resident. Total food consumption amount was calculated by individual food consumption multiplied the population in urban and rural, respectively. Urban residents' cereal consumption was directly reported in the national statistical information after 2013, but it was reported as processed grain from 1990 to 2012; we transferred it to raw grains according to the conversion coefficients, such as rice (Liu, 2012). The function can be written as follows:

$$C_{i,f} = P_{i,Urban} * (1 + r_{out-Urban}) * V_{f,Urban} + P_{i,Rural} * (1 + r_{out-Rural}) * V_{f,Rural}$$

where $C_{i,f}$ represents the total consumption (unit/Mt) of food f in year i; $P_{i,Urban}$ and $P_{i,Rural}$ represent urban and rural populations (in millions of persons) in year i; $V_{f,Urban}$ and $V_{f,Rural}$ represent per capita food consumption at home (unit/kg) in urban and rural households; and $r_{out-Urban}$ and $r_{out-Rural}$ represent the ratios of eating out in urban and rural areas, respectively.

The average per capita food consumption at the national level was based on the total consumption divided by the total population.

2.2. Food supply

Food supply refers to the total domestic supply. According to the FAO food balance sheet (http://www.fao.org/faostat/en/#data/FBS), food supply refers to balance national food production, imports, exports, and stock variation. Due to loss and waste, food supply is much more than food consumption. In the study, the waste ratio is food supply divided by food consumption, which is used to calculate the actual food demand. For instance, we assume that the ratio of one kind food is a, and if consume one unit, 1*a units food demand are needed in the perspective of food supply. Food production data were collected from the China Statistical Yearbook (NBSC, 1991–2016) and included 12 types of food as mentioned above. The production amount of meat were obtained by taking the production volume of animal carcass multiplied by the meat-bone ratios, as cited in Table S3. The import and export quantities of cereals, fruit, vegetables, pulses, and fish were collected from national statistical information (NBSC, 1991–2016), while the quantities of pork, beef, mutton, poultry, eggs, and milk were based on China's customs statistics yearbook (1990–2011) and the UN Comtrade database (2012–2015). Stock variations of food were sourced from the Food Balance Sheet (FBS) in the FAO statistical database. The function can be written as follows:

$$S_{i,f} = (P_{i,f} + I_{i,f} - E_{i,f} + S_{i,f}) * r_{f,food}$$

where $S_{i,f}$ represents the supply quantity of food f in year i;

$P_{i,f}$ represents the production of food f in year i;
$I_{i,f}$ and $E_{i,f}$ represent the import and export quantities of food f in year I, respectively;

$S_{i,f}$ represents the stock variation of food f in year i;
$r_{f,\ food}$ represents the proportion attributable to food in the total supply quantity; it was calculated based on the FBS in FAOSTAT (Table S4).

2.2. Recommended diet and food demand at the recommended level

In this study, the recommended diet was described in the Chinese Dietary Guidelines 2016 (Table S5), which was formulated from the perspective of human health and fully considered nutrition requirements. To match food types with the guidelines, cereals, tubers, pulses, vegetables, fruit, eggs, milk, fish, and meat (including poultry, pork, beef, and mutton) were included. We first calculated each food demand based on the recommended minimum and maximum levels and the total population. Given the gaps between food supply and consumption, the actual food demands of different foods were calculated by multiplying the recommended level by the total population and the ratios between supplies and consumptions (Table S6). Specifically, we analyzed the actual food demand amount when meet with the requirement of recommended diet in the perspective of food supply. For example, the ratio between meat supply and consumption is 1.3, and the average daily meat recommended amount in dietary guidelines is 58 g. Therefore, the daily actual meat demand for one person is 75 g.

2.3. Changes in environmental footprints when the current diet shifts to the recommended diet

We calculated the NF, PF, CF, and WF of different food types to evaluate the environmental impacts of food consumption adjustments. First, the sources of the reactive nitrogen, carbon, and phosphorus emission were crop, livestock, poultry, and aquacultural production. Second, we collected and estimated the data of activity level (including production amount, planting area, number of animal heads, and aquaculture area), agriculture input rate (e.g. crop nitrogen input per unit area), emission factors (e.g. methane emission per unit area of paddy field). Then, we evaluated the material input of each process, including yield, material reuse, emission, and the total emissions from all food types. These emissions sources mainly include chemical and organic (straw and manure) fertilizer application, seed, biological nitrogen fixation, nitrogen deposition, pesticide use, direct energy use, irrigation for crop production, rice paddies, enteric fermentation, feed, fertilizer input in aquaculture, and animal manure management in livestock breeding,. The difference is P accumulation in soil also takes into account. The detail information of emission sources, dataset, parameters, and relevant reference can be seen in our previous research (Cui et al., 2013, 2015; Hu et al., 2018; Lin et al., 2015). Water footprint includes blue water footprint, green water footprint, and gray water footprint (GWF). The first two part equal to the accumulation of daily evaporate and emission during the growth period. The evaluation of GWF is based on quality standard for water and the pollution discharged to the water body in food production. The parameters are collected from Hoekstra et al. (2011) and reports (WFN, 2010). The food production data are from China statistical yearbook, China rural statistical yearbook, China agricultural yearbook as well as FAOSTATA.

Considering the huge difficulties in modifying the consumption behavior of residents in the short term (Zhu et al., 2013), we simulated the relative changes of NF, PF, CF, and WF by designing different degrees of implementation: 20%, 40%, 60%, 80%, and 100% when current food consumption shifts to the recommended level and is compared with 2015 (Fig. S3). We take a mean effect (50%) to indicate the impact (Fig. 4). Meanwhile, four scenarios (S1-S4) were designed to assess the corresponding changes of four footprints. S1 and S2 represent food consumption in 2015 transitioned to the minimum and maximum levels of the recommended diet, respectively. There is, however, a large difference between food supply and consumption (Table S6). Therefore, we assessed the changes of environmental footprints when the food supply matched the actual food demand at the recommended level after considering the gaps, and took the changes at minimum and maximum levels as S3 and S4, respectively.

2.4. Uncertainty analysis

The data employed in the analysis had multiple sources with various uncertainties. Monte Carlo (MC) was performed to test the impacts from the parameters of the meat-bone ratio and the eating-out ratio, and the delivery of input uncertainty and variability to the results. We provided the ranges of parameters and defined the average of the two boundary values as the most likely value. Parameters were provided with triangular and uniform distributions (Table S7). The uncertainties of activity data from the national statistical information were set at 5% (Zhang et al., 2018). We took ± 10 percentage as the uncertainty range when a parameter was a single value rather than has a range. Ten thousand time trials were run for the measurements of uncertainty, including the mean and 95% confidence intervals. The results can be seen in Table S8.

3. Results

3.1. Historical changes in per capita food consumption and disparities with the recommended diet

The results clearly show that current food consumption is deviated from the recommended diet (Fig. 1). Current cereal and meat consumptions exceeded the maximum recommended level (Max_RL). Cereal consumption decreased at a rate of 1.6% annual, but it was still higher than the Max_RL by 24% and 47% in urban and rural households in 2015, respectively. At the same time, meat consumption has doubled and the consumptions of urban and rural residents were 1.2 and 1.6 times the Max_RL, respectively. The consumptions of vegetables, pulse, and fish have reached the minimum recommended level took China as a whole (Min_RL), but substantial differences remained between urban and rural areas. Per capita vegetables, pulse, and fish consumptions were higher (56, 9, and 5 g d^{-1}) in urban areas and lower (40, 12, and 16 g d^{-1}) in rural areas compared with the Min_RL. Daily tuber, fruit, egg, and milk consumptions were clearly less than the Min_RL. Milk consumption, especially, came to only 10% of the recommended level in China. Tuber consumption nearly stagnant in recent years. Egg and fruit consumptions have been steadily increasing. The results showed that current Chinese food consumption patterns had distinct disparities with the recommended diet, whether in urban or rural areas.

On the other hand, the structure of meat product consumption has changed. The ratio of red meat consumption declined from 71% to 55% during 1990–2015 in whole China (Fig. S1). Specifically, pork consumption was still popular in China, and the proportion decreased to 48% in 2015, while the percentage of poultry increased from 10% to 19% in 2015. Beef and mutton consumption almost unchanged.

3.2. Environmental footprints of food supply and consumption and of the recommended diet

Results indicated that the environmental footprints of food consumption, food supply, and the recommended diet differed greatly (Fig. 2). The consumptions of meat and cereal led the food groups in NF (and CF): 3.45 and 24.99 g N (0.20 and 1.12 kg CO_2e), respectively. For PF (and WF), fish, fruit, and vegetables took the top three positions after meat: 1.17, 0.86, and 0.96 g P (0.16, 0.12, and 0.11m^3), respectively. However, the environmental footprints of tubers, pulses, and milk consumption were small. The CFs of these three foods were 0.01, 0.01, and 0.05 kg CO_2e, respectively. In terms of the recommended diet (including lower and upper level), meat (9.05–16.97 gN), fish (3.22–6.04 gN), and milk (4.42 gN) were the main NF contributors, and their CF values were similar. For PF, the top three were meat

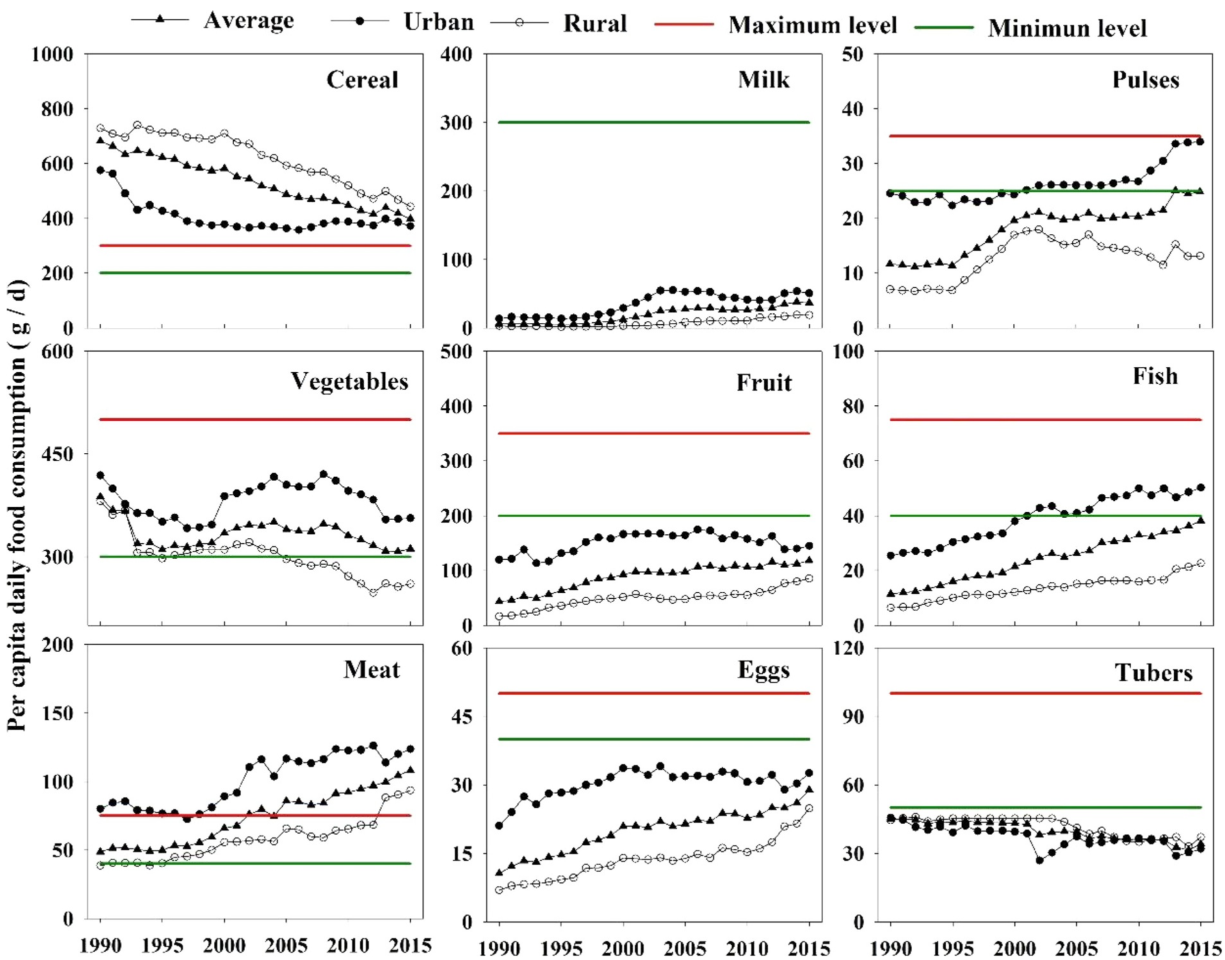

Fig. 1. Disparities of per capita food consumption between current and recommended diets.

(1.65–3.09 gP), fruit (1.45–2.53 gP), and vegetables (0.92–1.53 gP). For WF, milk, fruit, and grains were the three major contributors. In the recommended diet, animal foods took up about 80% of the NF, PF, and CF. Moreover, the total environmental footprints of food consumption were higher than the recommended diet. As for the gaps between food consumption and supply, the most considerable differences were 5.3 and 7.2 g N cap.$^{-1}$ d^{-1} (0.3 and 0.3 g CO_2e cap.$^{-1}$ d^{-1}) for cereals and meat for NF (and CF), respectively. For PF, fruit and vegetables had the largest differences between supply and consumption: 3.1 and 2.6 g P cap.$^{-1}$ d^{-1}. For WF, cereal had the largest difference about 0.5 m^3cap.$^{-1}$ d^{-1}, followed by vegetables and fruit about 0.4 m^3cap.$^{-1}$ d^{-1}, then fish and meat, about 0.1 m^3 cap.$^{-1}$ d^{-1}. Overall, the gaps for animal foods were smaller than for plant foods, and the gap for eggs was the smallest. The larger differences between different foods' supplies and consumptions meant significant food waste existed. The discrepancies among the three parities mean that the environmental footprints of foods will be changed through improving the efficiencies of the food supply and food consumption, and by accelerating the current food consumption transition toward the recommended diet.

3.3. Gaps among food supply, consumption and food demand of recommended diet

There was an apparent positive correlation between food supplies and consumptions from 1990 to 2015 (Table S9). Results clarified a notable mismatch among food supply, consumption, and demand of the recommended diet. The gaps of the three parts in 1990, 2000, 2010, and 2015 were major, especially the ratios of supply to consumption (Fig. 3). The food demands at the recommended level without considering gaps among the three parts were shown in Fig S2. For instance, we assumed that the current fruit consumption is 100 g and the recommended amount is 200 g, so the fruit demand is 200 g without considering the gaps between consumption and supply. However, if take the gaps into consideration and assume the ratio is 2, the actual fruit demand is 400 g when meet with the recommended level. The ratios of plant-based foods grew larger in recent years, particularly for cereals, fruit, and vegetables. In detail, these increased from 1.3, 1.8, and 1.1 in 1990 to 2.6, 4.1, and 4.3 in 2015, respectively. In other words, 1 unit of cereal, fruit, and vegetable consumption required 2.6, 4.1 and 4.2 units in the food supply chain, respectively. Tubers were also slightly wasted and the ratio was 1.54 in 2015. Waste of animal-derived foods experienced slight increases compared to plant-based foods, during 1990 and 2015: from 1.7 to 2.0, 1.5 to 1.8,1.4 to 1.6, and 1.1 to 1.3 for milk, fish, eggs, and meat, respectively. The increased disparities between food supply and consumption led to much more serious food waste.

Based on the trilateral relationships, the nine kinds of food could be classified into three groups: (i) Meat and cereal: China's meat supplies increased by more than two folds and consumptions simultaneously doubled over the past two decades. Meanwhile, cereal supplies increased by 40%, and consumption decreased by 30%. In 2015, the supplies of cereals and meat had exceeded the demand at the Max_RL levels by about 34% and 47%, respectively. (ii) Vegetables supply had increased by about three folds by 2015, which was higher than the demand at the Min_RL level, but total vegetables consumption decreased slightly by 3% in 2015 compared to 1990. The supply needs to be further increased to meet the recommended vegetables consumption if the current efficiency unchanged. (iii) For the remaining food types,

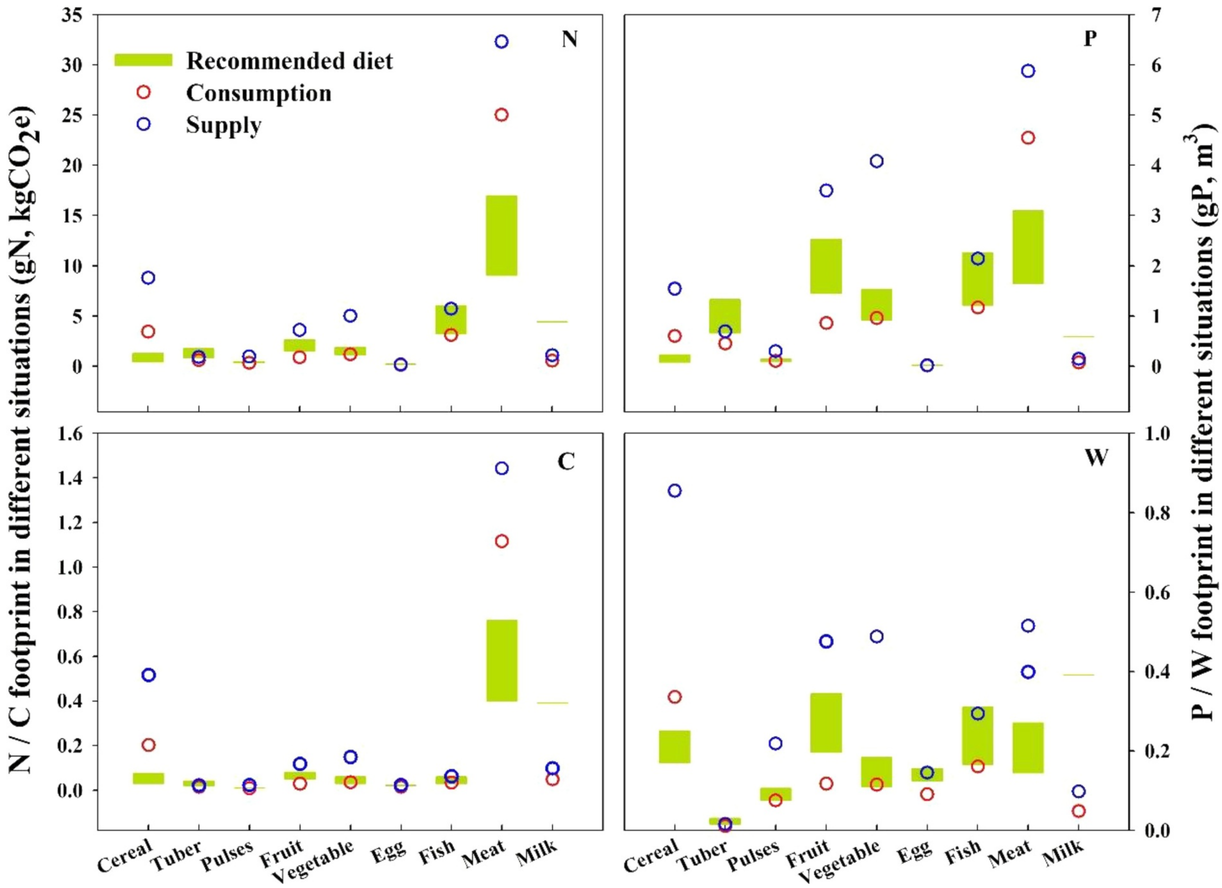

Fig. 2. Environmental impact intensities of all food types under different situations. Light green bars represent the reactive nitrogen footprint (NF), phosphorous footprint (PF), carbon footprint (CF), and water footprint (WF) of different food types at the recommended level. Blue and red points represent the NF, PF, CF, and WF of per capita daily food supply and consumption of each food type, respectively. .

the supplies of tubers, pulses, fruit, eggs, milk, and fish were less than the demands at the Min_RL. Milk and fish accounted to only 12% and 60% of the Min_RL demands. As for fruit, the supply was 60% lower than the actual recommended demand, and a 40-Mt gap existed between current food consumption and dietary guidelines. Dietary adjustment measures are needed to balance food supply and food demand, particularly for meat, cereals, fruit, and milk.

3.4. The environmental footprints of dietary adjustments

With various increment in the implementation of the recommended diet, we observed obvious changes in the environmental effects when the implementation is 50% (Fig. 4). Under the four scenarios, changes in the environmental footprints relied on different foods. For instance, meat took up 80% of the total cut in the NF, PF, and CF: about 22.8 Mt N, 0.9 Mt P, and 230.7 Mt CO_2e, respectively; while cereals took a dominant place in WF reduction, with a $1.1 \times 10^{11} m^3$ decrease under S3. Most of the food adjustments toward the recommended diet led to an increase in environmental footprints. Milk and fruit played an overwhelming role: almost took up 90% of the total increase. The former resulted in an apparent increase of 173.8 Mt CO_2e and the latter produced the most remarkable effect on the P footprint increased by 0.6 Mt P under S3. Apart from the two types, fish and vegetables also contributed to the increment. Under S4, the environmental footprint increases caused by fish and vegetable adjustments were 214.9 Mt N,1.1 Mt P, 36.2 Mt CO_2e, and $1.4 \times 10^{11} m^3$, which amounted to 34%, 32%, 12%, and 23% of the total increases, respectively. In short, the major contributors to the changes of environmental effects were the adjustments on cereals, meat, milk, and fruit.

The net effects of current diets transitioned to the recommended diet on NF, PF, CF, and WF under different implement degrees in four scenarios were compared to the environmental footprints of food consumption and supply in 2015 (Fig. 5). The NF, PF, CF, and WF of total food consumption were 17.7 Mt N, 4.4 Mt P, 751.7 Mt CO_2e, and $6.78 \times 10^{11} m^3$, respectively. The corresponding four footprints were 29.4 Mt N, 9.2 Mt P, 1227.3 Mt CO_2e, and $15.6 \times 10^{11} m^3$ for the food supply. The environmental impacts of dietary adjustment on food consumption and food supply can be seen in Fig. S3. On the whole, WF increased by $0.19 \times 10^{11} m^3$ (3% footprint of food consumption), while NF, PF, and CF were reduced by 36%, 22%, and 29% under S1 relative to food consumption in 2015, if the gaps between food supply and consumption are neglected. As mentioned above, the reduction on the three footprints were mainly attributable to the decrease in cereal and meat consumptions when current diet were transitioned to the recommended diet. NF, PF, and CF showed different extended reductions under S3, relative to Scenario S1, when we considered the ratios of different foods' supplies and consumptions (Table S6). But if current consumptions shifted to the Max_RL (Scenario S2), the four footprints would increase by 0.86 Mt N, 1.59Mt P, 40.34 Mt CO_2e, and $3.46 \times 10^{11} m^3$, amounting to 5%, 36%, 5%, and 51% increment relative to food consumption in 2015, respectively. And if the food supply met the demands at the Max_RL diet and take the gaps between food supply and food consumption into consideration, the four footprints would increase by 6.51 Mt N, 5.76 Mt P, 270.46 Mt CO_2e, and $10.16 \times 10^{11} m^3$, which equaled 22%, 63%, 22%, and 65% of the footprint of food supply in 2015, respectively. The results implied that the Min_RL diet would reduce NF, PF, and CF from both food supply and consumption perspectives, but would trigger a relatively small increase in WF. When

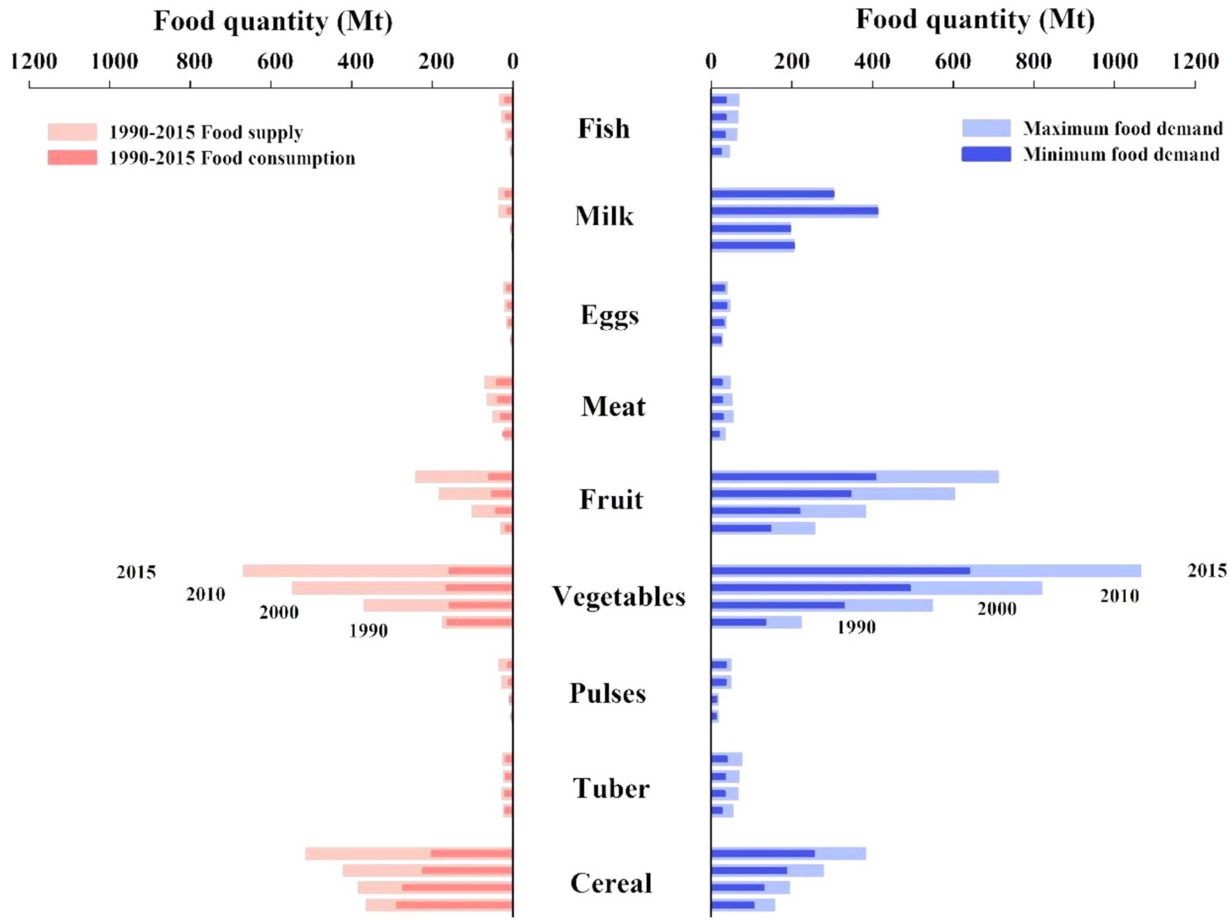

Fig. 3. Comparisons of food supplies, consumptions, and actual food demands at the recommended minimum and maximum levels in selected years. Light pink (pink) indicates food supplies (consumptions) of different food types in 1990, 2000, 2010, and 2015. Light blue (blue) represents the actual food demands at the maximum (minimum) level for different food types in 1990, 2000, 2010, and 2015.

meeting the requirement of the Max_RL diet, much higher N, P, C, and W footprints would be produced, especially the W footprint under S4. Moreover, all of these were significantly increased as the implementation degrees approached the Max_RL.

4. Discussion

4.1. Disparities between current food consumption and the recommended diet

With the improvement of living standards, the need to define healthy and environmental friendly diets has attracted the attention of both the general population and academic communities (Tilman and Clark, 2014; Afshin et al., 2019). However, current dietary transitions in many countries go against the sustainable diet toward higher meat, higher fat, and lower fiber consumptions. Previous research has determined that apart from grains, meat, and oil, the consumption of other foods is less than the amounts recommended by the China Health and Nutrition Survey in 2011 (He et al., 2018). Our results suggested that over the past two decades, food consumption patterns of urban and rural residents have experienced striking shifts, but still show large disparities comparing with dietary guidelines, especially for meat—the findings are consistent with Gao et al. (2019). Meat consumption continued to increase with the rise in income and improvement of living standards (Tilman and Clark, 2014), but the good news was that cereal consumption dropped steadily toward the recommended level. It was estimated that meat consumption for the lowest-income group in China's rural region has exceeded 100% above the dietary guidelines of 2011, and this figure was 300% in the high-income urban group (He et al., 2018). However, this appear be overestimated and was far from both our results and another finding (Wang et al., 2015). Per capita milk, fruit, and egg consumptions have increased in the past two decades, but they were still below the Min_RL, especially milk, which only reached about 10% of the recommended level. Per capita vegetables consumption decreased to 311 g d^{-1} in 2015. Additionally, the relationships between food consumptions and the recommended diet in 2009 were assessed, and results suggested that the consumptions of milk, fish, fruit, and pulses were below the Min_RL, except for the pulse supply, which was consistent with our results (Zhou et al., 2011). It may be that the total pulse data reflected the part was consumed directly, and neglected other uses, such as processed food and feed so that its supply as the food was overestimated. Our estimation of pulse consumption was in accordance with He et al. (2018). Tuber consumption both in urban and rural areas are less than the recommended level, although these might increase in the future because the Chinese government has advocated treating potatoes as one of the staple foods for healthy and sustainable diets. The consumptions of pulses, vegetables, and fish differed between urban and rural areas (Gao et al., 2018), but all of them were below the Max_RL. The disparities in food consumption between urban and rural households may be much greater than the disparities in urban development, income, health consciousness, or population structure (Gao et al., 2019). On the other hand, Miller et al. (2015) emphasized the need for continual monitoring of the quality of the food supply and applied the Healthy Eating Index to estimate the food consumption quality in the USA during 1970 to 2010. Consumptions of fruit, total vegetables, greens and beans, whole grains,

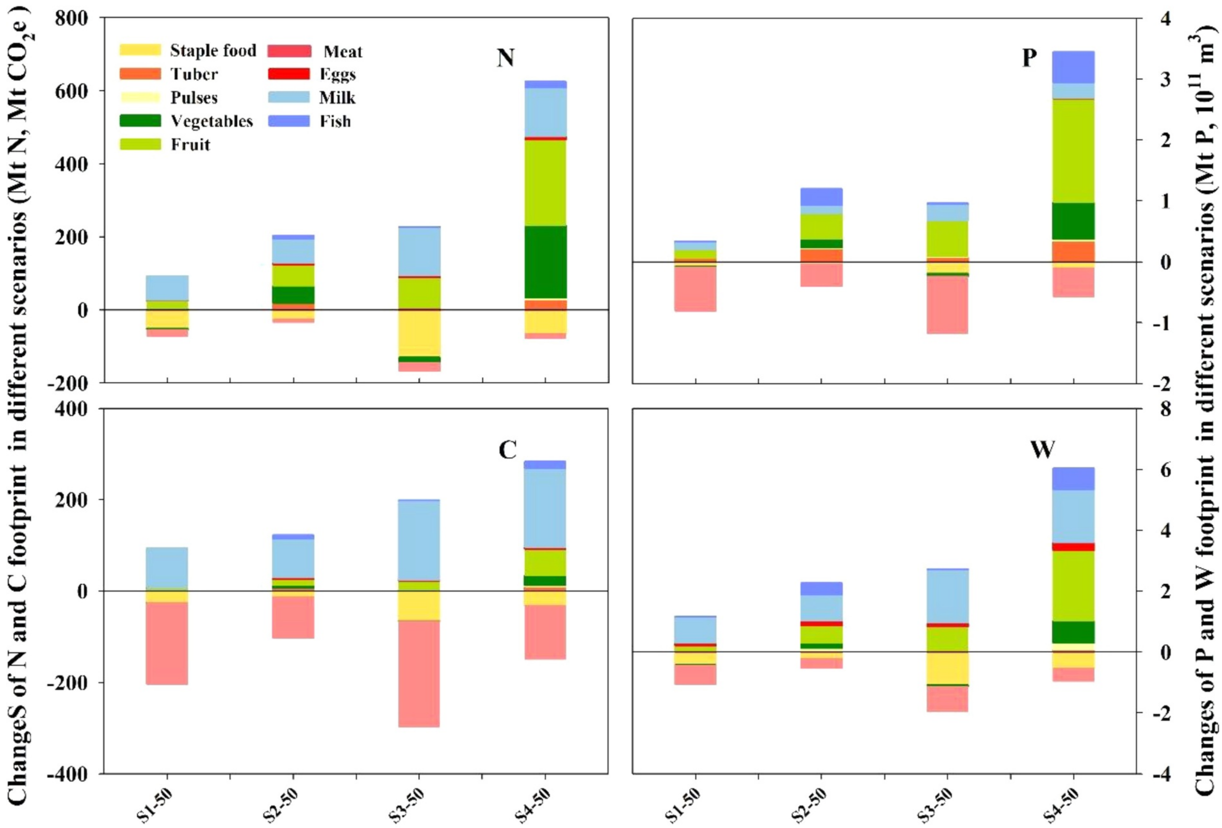

Fig. 4. Environmental effects of all foods under four scenarios with 50% implementation degrees. S1and S2 represent current food consumption transitioned to the dietary guidelines at the minimum and maximum levels, respectively; S3 and S4 represent the changes of actual food demands at the minimum and maximum levels, respectively, considering the ratio of supply and consumption. .

and dairy products remained around or even below half the optimal consumptions. In the UK, assessments of dietary intake have shown that in all age groups intake of saturated fatty acid and non-milk extrinsic sugar are above the recommended levels and have led to a lower micronutrient intake in younger adults (NDNS, 2011). In India, severe gaps would exist in vegetables, fruit, and poultry consumption in the next two decades (Kumar et al., 2016). Throughout the world, discrepancies still exist between food consumption and recommended diet, and it is widely understood that overcoming these discrepancies is the key to effective dietary adjustments for food security. Implementation of dietary adjustments requires re-regulation of dietary pattern in urban areas and bringing food consumption quantities up to the recommended values in rural areas. China has a long way to go in transition current diets to the recommended ones, especially in rural areas.

4.2. Gaps between food supply and food consumption

Most of the previous research focus on the environmental effects of food production, food consumption, and dietary adjustments (Meier and Christen, 2013; Zhang et al., 2019). Land use, NH_3 emission, P use, and blue water use would drop by 17%, 28%, 14%, and 27%, respectively, if current diets shift to the recommended diets in Germany (Meier and Christen, 2013). CF would decline by 9–15% if food consumption meet with the National Food-Nutrition Plan (NPFN) in China (Song et al., 2017). This figure was lower 34% than our result, possibly because of the different benchmarks for dietary guidelines and system boundaries in carbon footprint calculation. For instance, the daily recommended amounts of meat and fruit consumption were 80 g and 165 g in 2020 NPFN, respectively (SC, 2014), while the corresponding figures were 58 g and 275 g in the Chinese dietary guidelines (CNS, 2016). There were distinct differences between foods supplies and consumptions (Fig. 3). We found that the ratios of vegetables and fruit consumptions and supplies were about 1 to 4 and 1 to 2.6, and meat was 1 to 1.3. Other results indicated that the food loss rates of grains in the entire supply chain were 19%, 20–30%, and 5–15% for vegetables, fruit, and eggs, respectively (Liu et al., 2013). The loss ratio in China as a whole was 13.3–35.2% from 1990 to 2009 (Cui et al., 2016). In Japan, about 14% of vegetables and fruit production—approximately 2.3 million tones, which required 497,000 ha of land—-were discarded in the field without being delivered to the market (Wakiyama et al., 2019). Hence, considering the actual food demand rather than just limiting the analysis to food consumption transition to the recommended diet could accurately reflect the environmental effects of dietary adjustment. Many studies, for example, have used virtual N and P inputs and virtual N use efficiency as indicators to evaluate the actual environmental effects of food consumption at nation, region, and city level (Cui et al., 2016; Gao et al., 2019). On average, a 38% decrease in food waste can reduce the climate impacts by 41% and biodiversity by 30% (Beretta et al., 2019). When we transferred per capita differences between actual food supply and consumption into NF, PF, CF, and WF, the size of the difference depended on the food type (Fig. 2), because the four footprints evidently varied for different kinds of food. Taking CF as an example, red meat led all the meat products on carbon emission factors and ranged from 2.9 to 90.2 kg CO_2eq kg^{-1}; cereal and milk values were 0.5 and 13 kg CO_2eq kg^{-1} (Lin et al., 2015). We can conclude that when the current diet shifts to the recommended diet, obvious benefits on NF, PF, CF, and WF would be generated.

4.3. Effects of transitioning current diets to recommended diets

We found that the adoption of the Min_RL diet would result in NF,

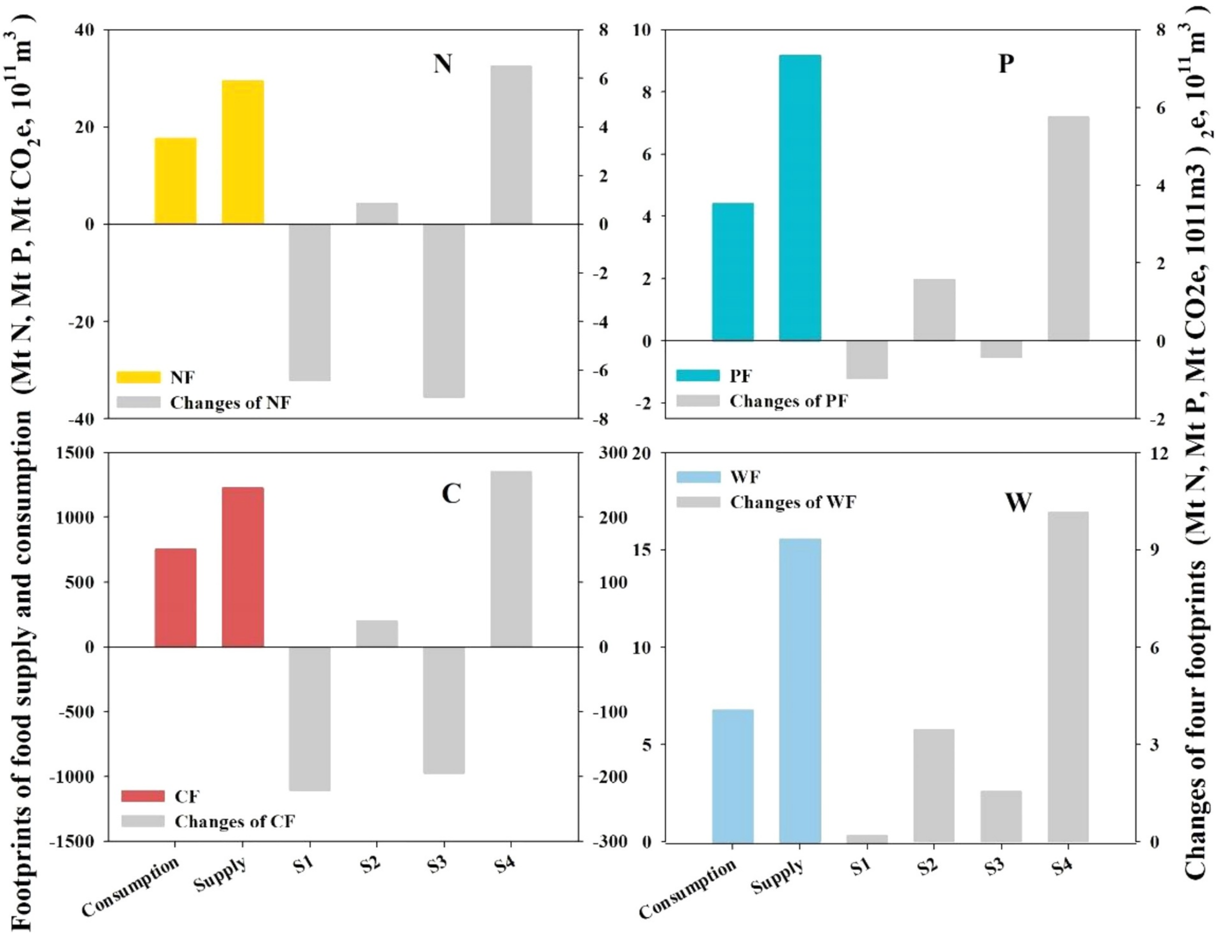

Fig. 5. Relative changes of different environmental footprints under different implementation degrees in four scenarios compared with the effects in 2015. The first two bars in each sub-graph represent the total environmental footprints of food consumption and food supply. The gray bars represent the changes in environmental footprints under different scenarios. .

PF, and CF reductions from food supply and consumption sides, except for a relatively small increase in WF caused by an obvious increment in milk consumption (Fig. 4). Moreover, the reductions of CF and PF would be overestimated by 12% and 3%, respectively, when the current diet transitions to the Min_RL diet, if the ratio between food supply and consumption were neglected. There was a 195Mt CO_2e reduction, equal to 51% of the GHG from agriculture in India when food consumption shift to the dietary guidelines in S3 (Nelson et al., 2009). In Organization for Economic Co-operation and Development (OECD), a 25% consumption reduction in livestock products could result in a 17% reduction in GHG emissions (Michaelowa and Dransfeld, 2008). A shift to universal recommended diet suggested that reducing red meat consumption contributes to a 25% reduction in the overall environmental impacts in Europe (Tukker et al., 2011). In an extreme scenario with complete substitution of animal-derived foods, agricultural GHG emissions could decrease by 28% in the US but would create new nutritional problems (White and Hall, 2017). A suitable method of comprehensively evaluation the environmental effects of food consumption adjustments is needed in the future. Meeting the Max_RL would cost much higher amounts of N, P, C, and W resources, especially in water resource. Under S4, NF, PF, CF, and WF would be underestimated by 32%, 95%, 31%, and 99%, respectively. Hence, the gaps between food consumption and supply should be treated seriously. Moreover, the environmental footprints in this study just referred to the process of food production, excluding transportation, storage, and food waste (Hu, 2018). Therefore, the environmental effects of food consumption might be underestimated.

Much more attention should be paid to improving the resources use efficiencies and reducing environmental effects in food production. Milk consumption is far less than the recommended amount at present. GHG emissions and land use for cow feed production and N losses would increase if milk consumption were adjusted to close to the recommended diet. In order to meet the milk demand in a business-as-usual scenario in 2050, the global dairy-related GHG emissions would increase by 35%, and land use for dairy feed production would increase by 32% compared to 2010. While N losses from the dairy sector would increase by 48% and aggravate the scarcity of water resources in China (Bai et al., 2017; Bai et al., 2018a). The actual demand for fruit at the Min_RL is far higher than the supply, and the environmental pollution of fruit production will be exacerbated if current resource use efficiencies remain unchanged. Hence, more attention should be paid to improving food consumption efficiencies and reducing the environmental impacts in production processes. Mitigating the environmental effects of food consumption can accelerate the achievement of the combined goals of improved human health and environmental sustainability.

4.4. Strategies for transitioning to a more sustainable diet

Modification of food consumption behaviors, such as by propagating information about the environment and nutrition (Zhu et al., 2013) and enhancing food labeling (Leach et al., 2016) is necessary. Recently, specific practices, for example, reducing meat consumption have been advocated and encouraged from the perspectives of environmental protection, human health, and animal welfare (Westhoek et al., 2014; De Backer and Hudders, 2015). In the past few decades, food requirement has risen along with incomes, and the preference for meat has been stimulated by economic growth, especially those in poverty. We also propose some further suggestions from the food supply perspective, where the government can play a dominant role. In China, per capita cereal consumption declined gradually toward the recommended level in both urban and rural areas, and total cereal consumption decreased because the dietary change effect exceeded the population growth effect (Gao et al., 2018). In addition, cutting down the cereal supply appropriately and improving food storage technology are the main approaches to rational cereal supply.

The rapid increasing meat consumption, not only in China but also in the whole world, is affecting human health and the environment profoundly. It has been estimated that overconsumption of red meat induces serious chronic diseases (McAfee et al., 2010). Given the mismatch in quantity and structure of meat products in China, our study suggests that reforming meat-product consumption patterns has the potential for achieving the dual benefits of the environmental-human nexus which was identified by Gu et al. (2019). In light of the lower fish consumption in China, it may be desirable to replace meat products with fish in the Chinese diet. Concrete measures include withdrawing the meat subsidies to slow down red-meat production and raising the product price to curb consumption, given that income and price appear to be the pivotal factors in meat consumption (Wang et al., 2015). Even though the effect of every 1% increase in the price of pork and poultry could be offset by a 1% increase in income, a price policy for meat demand is effective because of the large elasticity in this approach (Shimokawa, 2015). To meet the recommended fish consumption will promote the development of aquaculture and accelerate the serious water-pollution problem, unless significant improvements are made in aquaculture technology. Milk consumption is closely related to household characteristics, such as education, age, gender, advertising, income, food preference, distance to market, and the foundation of the milk industry in China (He et al., 2016; Wu et al., 2018). Apart from the concern for quantity, milk quality is attracting extensive attention since some scandals were exposed in 2008. On considering the burden on the environment and resource inputs, substituting soy milk for animal milk is advocated, as the nutritional values are similar (Yang et al., 2004).The government should promote higher efficiency in meat production, through favorable subsidies, policy on the right of production, free market price policy, and the Vegetable Basket Program (Bai et al., 2018b).

The increasing demand for fastidiousness and the consequent rejection of lower-quality food with the improvement in living standards exacerbates the food-waste problem (Ma et al., 2012). Reducing food loss and waste is an alternative strategy for relieving the food-demand pressure when diet shift the recommended level. Altogether, measures for reducing food waste encompass three aspects: values (addressing values and perceptions—such as saving money—that drive behavior), skills (enabling people to change their behaviors: e.g., by providing training on how to prevent food waste), and logistics (Thyberg et al., 2016).

5. Conclusions

Taking into account the loss between food supply and consumption, we systematically analyzed the relationships among food consumption, food supply, and the recommended diet, as well as the relative changes in environmental footprints that would occur if current diet shift to the recommended diet. Several major conclusions can be drawn. The disparities between current diet and the recommended diet are remarkable, particularly for cereal, meat, milk, and fruit. Moreover, large gaps exist between food supply and food consumption, and much higher levels of resource utilization would be required, in order to meet the requirements of the recommended diet, even at the minimum level, let alone at the maximum level. In light of the continually increasing population and dietary transitions, the impacts on environmental resources would be severe. Hence, incentives focus on improving the efficiency of food production, especially meat products. At the same time, narrowing the gaps between supply and consumption and to improve the efficiency of the food supply chain, especially for fruits and vegetables, which are the major contributors to the increase in W and P footprints. Such improvements are critical for the development of a sustainable diet. In the whole, the transition to a sustainability-oriented diet can produce overt benefits on the environment, at least at the minimum recommended level .

CRediT authorship contribution statement

Lan Wang: Conceptualization, Project administration, Methodology, Formal analysis, Writing - review & editing. **Bing Gao:** Conceptualization, Project administration, Formal analysis, Writing - review & editing. **Yuanchao Hu:** Data curation, Visualization, Methodology. **Wei Huang:** Data curation, Visualization. **Shenghui Cui:** Conceptualization, Project administration, Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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