The potential benefits of dietary shift in China: synergies among acceptability, health, and environmental sustainability

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Abstract: The transition to a healthier diet recommended by national dietary guidelines in China may not achieve sufficient environmental benefits. This study assesses China's potential of transforming into a sustainable diet and the trade-offs among reducing food-related environmental impacts, improving nutritional quality and respecting eating habits. We used multi-objective optimization to build optimized scenarios, with the lowest environmental footprint and minimum departure from the currently observed diet as optimization goals, and adequate macro- and micronutrient intake levels as constraints. In doing so, we assessed the actual benefits and synergies of reducing carbon footprint (CF), water footprint (WF), and ecological footprint (EF) and improving health and respecting dietary acceptance under the corresponding scenarios. The results show that CF, WF and EF can be reduced by 19%, 15% and 30% respectively, while satisfying nutritional constraints and achieving the minimum deviation from the current food combination. The greatest synergistic benefits for CF, WF and EF are achieved when the minimum CF is the optimization goal; the maximum synergistic benefits for the environment, health and acceptability are achieved when the CF is reduced by 10%. Our findings identify the trade-offs and synergies dietary changes considering nutritional benefits, environmental sustainability and acceptability, and reveal the challenges and opportunities for achieving such synergies.

Keywords: Diet optimization; Environmental footprint; Sustainable diet; Synergy and trade-offs; Environmental-health-acceptability nexus; Integrative benefits

1. Introduction

The food system driven by consumption accounts for 19–29% of anthropogenic greenhouse gas emissions (GHGEs), 70% of total fresh water withdrawals, and 38% of total land occupation (Foley et al., 2011; Vermeulen et al., 2012). If current trends continue, due to population growth and the consequent increase in demand for emission-intensive products such as meat and dairy products, the environmental pressure of the food system will intensify, and humanity may soon approach the planetary boundary for global freshwater and land use (Marco Springmann and Fabrice Declerck, 2018). The global consumption transition from basic products (grains, fruits and vegetables) to protein and highly processed foods (e.g., refined sugars, fats or oils) has resulted in problems such as overweight or obesity in 2.1 billion people (Ng et al., 2014; Popkin, 2012). Those dietary changes and the resulting increase in body mass index (BMI) are associated with the increase in the global incidence of chronic noncommunicable diseases (especially type 2 diabetes, coronary heart disease and certain cancers) (Tilman and Clark, 2014). Meanwhile, micronutrient deficiencies ("hidden hunger") affect more than 2 billion people worldwide, leading to impaired immune function, hindered physical and cognitive development, and increased risk of noncommunicable diseases (Chaudhary and Krishna, 2019). Diet-related diseases have become the leading cause of death and disability in humans around the world (Horton, 2012).

China's rapid urbanization and increase in wealth have promoted significant changes in the dietary structure. Between 1980 and 2009, the consumption of pork, beef, poultry and milk by Chinese residents increased by 3 times, 10 times, 11 times and 20 times, respectively (Song et al., 2017). Such a significant change brings increasing challenges on China's environmental sustainability. Food-related GHGEs (including ammonia) increased by 24% in 2010 compared to 1996, the water footprint in 2003 tripled compared with 1961, and agricultural land occupation in 2014 increased by 50% compared to 1961 (He et al., 2018). In addition, the prevalence of obesity and diet-related noncommunicable diseases has become a growing burden on public health (Song et al., 2017). China has surpassed the United States to become the absolute leader in the number of obese people (Bai and Zhu, 2019). Hypertension, diabetes and stroke affect 226 million, 110 million, and 11 million Chinese adults, respectively (Song et al., 2019). At the same time, the lack of micronutrients has gradually become a hidden danger to public health, and calcium deficiency is particularly prominent in China. According to the "Nutrition and Chronic Disease Status of Chinese Residents" (2015) report, the calcium intake of Chinese residents is less than half of the recommend nutrient intake (RNI) (800 g/d) and has shown a downward trend in the past ten years (Gu, 2016). The risks of zinc, iron, vitamin A, vitamin B1 and vitamin B2 deficiency are 35.6%, 11.5%, 77.0%, 77.8% and 90.2%, respectively (Yu et al., 2018). Inadequate intake of micronutrients in the diet can further complicate the food-related environmental problems, because adopting environmentally friendly dietary strategies (mainly by reducing animal-based foods) may exacerbate micronutrient deficiencies (such as vitamin B12, selenium and calcium deficiency) (Chaudhary and Krishna, 2019). Therefore, the trade-off between nutrition and environmental benefits has become a challenge of dietary shift in China.

Food choices have a profound impact on the environment and human health. Existing research shows that there is a clear synergy between choosing a healthier diet and a more sustainable diet (Behrens et al., 2017; Green et al., 2015; Irz et al., 2016; Tukker et al., 2011), despite that some researchers argued that a healthier diet is not necessarily a diet that is more sustainable (Macdiarmid et al., 2012; Masset et al., 2014; Perignon et al., 2016; Seves et al., 2017). It is also known that dietary guidelines that promote healthy nutrition usually have a positive impact on the environment (Arrieta and González, 2018; Biesbroek et al., 2017), and reducing meat consumption and shifting to plant-based diets will have a beneficial impact on the environment and health (Berners-Lee et al., 2012; de Ruiter et al., 2017; Nijdam et al., 2012; Pradhan et al., 2013). However, those conclusions are mainly based on diet studies in developed countries, but Chinese people have significantly different dietary structures comparing with western countries. It remains to be explored whether they can achieve synergy between the environment and health through dietary changes.

When it comes to environmental impacts of food consumption, many studies have focused on diet-related GHGEs (He et al., 2019; Horgan et al., 2016; Payne et al., 2016; Song et al., 2017). But diet-related environmental impacts are diverse: among the 169 targets of the Sustainable Development Goals, water deprivation and land degradation are also identified as areas of environmental concern that need to be addressed (Perignon et al., 2019), and looking at each indicator in isolation can lead to inconsistent policies, inefficient use of resources, or short-sighted estimates of costs and benefits (He et al., 2019). There are some differences in dietary structure under different environmental mitigation goals, and eating patterns that promote a decrease in one environmental impact may inadvertently increase another environmental impact (Chaudhary and Krishna, 2019; Gephart et al., 2016). For example, Marco Springmann and colleagues (2018) found that replacing animal-derived foods with plant foods helps to mitigate GHGEs but increases the use of some resources, such as freshwater, cropland and phosphorus. Additionally, Chaudhary and Krishna (2019) predicted that in East Asia and the Pacific, the carbon footprint (CF), water footprint (WF), nitrogen footprint (NF) and phosphorus footprint (PF) can decrease 10%-20% in an optimized dietary structure scenario, but the ecological footprint (EF) will increase by 15% from the current level. Therefore, tradeoffs occur when the dietary composition changes from one given minimum environmental footprint to another (Gephart et al., 2016), and it is necessary to use a method involving synergies and tradeoffs to analyze the compatibility of different environmental mitigation scenarios when proposing an ideal sustainable diet.

In addition, existing studies on dietary optimization in China generally consider only the dual benefits regarding the environment and health (He et al., 2019; He et al., 2018; Song et al., 2019; Song et al., 2017) and ignore acceptability, which may weaken the practicality of a dietary shift (Yin et al., 2020). Therefore, this study attempts to answer three questions: 1) What is the potential for

China’s dietary shift that reduces diet-related CF, WF and EF, without impeding nutritional adequacy and dietary habits? 2) In an optimized dietary structure in China, how will the practical benefits of the three dimensions of environment, health and acceptability change? 3) To what extent can synergies be achieved between different environmental impact dimensions (i.e., CF, WF, and EF) and dietary benefit dimensions (i.e., the environment, health, and acceptability) under optimized scenarios? To answer those questions, we adopt a multi-objective optimization method in which the lowest environmental footprint and greatest acceptability are the optimization goals, and adequate macro- and micronutrient intake are the constraints. We quantify the practical environmental footprint mitigation benefits under each optimized scenario, as well as the corresponding changes in nutritional benefits, acceptability benefits, and food composition. In addition, we measure the synergies among the environmental impact dimensions and dietary benefit dimensions under each optimized scenario, and we combine the practical benefits together as a measure to evaluate the comprehensive benefits of each optimized diet scenario.

2. Material and methods

2.1 Food composition data

Food consumption is calculated based on national statistical information (National Bureau of Statistics of China (NBSC), http://www.stats.gov.cn/tjsj/) and the ratio of eating at home to eating out (Table A.1, Table A.2 in the Appendix). The database provides the per capita consumption of 17 food items at home, which are cereals, tubers, vegetables, fruits, legumes, nuts, edible vegetable oil, animal oil, pork, beef, mutton, poultry, eggs, dairy products, aquatic products, sugar and salt. In order to facilitate the comparison with the balanced diet structure proposed in the dietary guidelines, we regrouped the 17 food items into 7 food groups: Grain, V&F, L&N, Edible oil, Meat, High quality protein foods, and Seasonings (Table A.3).

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2.2 Dietary nutrients

For a more comprehensive assessment of dietary nutrition levels, we refer to the China Food Composition Table (Yang, 2019a, b) and calculate the total energy contents as well as the intake of 21 nutrients, including macronutrients and micronutrients. We incorporate both salt and sodium nutrients into the analysis framework mainly because Chinese households not only obtain sodium from edible salt, but also from foods such as bacon, pickles, and soybean paste; thus, a single choice of salt or sodium nutrient intake is insufficient to characterize the dietary health status (Li et al., 2020).

To facilitate the comprehensive assessment of nutritional quality under various dietary patterns, this paper draws on the definition of the mean adequacy ratio (MAR) proposed by Vieux et al. (Perignon et al., 2016). That is, the RNIs for 16 major beneficial nutrients are used as the reference standard to measure the difference between the intake level of each nutrient and the reference standard. The formula is as follows:

$$MAR = \frac{1}{16}\sum_{n=1}^{16}\frac{Q_{bn}}{RNI_{bn}}\times 100 \qquad (1)$$

where Q_{bn} denotes the daily intake of each beneficial nutrient and RNI_{bn} is the corresponding recommended quantity for this nutrient. Each ratio ($Q_{bn}/RNI_{bn} > 1$) is set to 1 so that a high intake of one nutrient cannot compensate for a low intake of another, thus affecting the accuracy of nutrition evaluation (Perignon et al., 2016).

The mean excess ratio (MER) is calculated for each diet with reference to the recommended tolerable upper intake level (UL) of 5 nutrients: fats, saturated fatty acid (SFA), cholesterol, Na and free sugars. The formula is as follows:

$$MER = \left(\frac{1}{5} \sum_{n=1}^{5} \frac{Q_{rn}}{UL_{rn}} \times 100 \right) - 100 \qquad (2)$$

where Q_{rn} is the restricted-intake nutrient (rn) and UL_{rn} is the corresponding recommended maximum intake value, Each ratio $(Q_{rn}/UL_{rn}) < 1$ is set to 1, so that a low intake of one harmful nutrient cannot compensate for the high intake of another (Perignon et al., 2016).

Both the RNIs for the 16 beneficial nutrients and ULs for the 5 restricted nutrients are given in Table 1.

2.3 Environmental impacts of food consumption

An environmentally friendly diet has multiple dimensions but this paper considers 3 aspects, i.e., the CF, WF and EF, based on the data available. The CF is used to measure the total GHGEs caused by direct or indirect activities during the product life cycle (Bastianoni et al., 2004). In this study, the CF refers to the GHGE (including CO_2, N_2O and CH_4) produced in the entire food supply chain (including crop cultivation, breeding, industrial processes, transportation and storage). The WF is the cumulative virtual water content that all products and services need to consume in a certain area (Hoekstra, 2003). The EF is the biological production area occupied by human economic activities, which mainly includes productive land that provides six key ecosystem services, namely cropland, grazing land, fishing grounds, forest, carbon uptake land and built-up area (Galli et al., 2012). To avoid overlapping with the carbon footprint accounting account, the EF discussed in this article only includes the production area occupied by the production of food for human consumption, namely cropland, grazing land and fishing grounds.

The CF, WF and EF produced by each food consumption are calculated by multiplying the consumption by its corresponding footprint coefficient (formula 3-5). The CF and WF coefficient referred to the research of (Song et al., 2015), who obtained based on the global life cycle assessment (LCA) literature database at the Barilla Center for Food & Nutrition. These detailed coefficient and uncertainties for each food category were available in Table A.2 of the Appendix. The EF coefficient referred to (Cao and Xie, 2016; Cao et al., 2014), who used the input-output method to analyze the input material flow in the life cycle of each unit of food in China, and then converted the material flow into the "global hectare" land use area needed to support its production based on global production and equilibrium factors..

$$CF_i = cf_i \times x_i \tag{3}$$

$$WF_i = wf_i \times x_i \tag{4}$$

$$EF_i = ef_i \times x_i \tag{5}$$

where CF_i, WF_i, EF_i are the carbon footprint, water footprint and ecological footprint of food i, and cf_i, wf_i, ef_i are the coefficients for food i; x_i (g d^{-1}) is a variable representing the daily consumption of food i.

2.4 Dietary acceptability

We think that a diet similar to the current diet structure is culturally acceptable, while a diet with a larger deviation from current diet is less acceptable (Perignon et al., 2016; Yin et al., 2020). To avoid unrealistic dietary shift, we include dietary acceptability as one of the key factors to consider when optimizing the diet, and take deviation from the food items and food groups in OBS as a proxy of acceptability. The formula is as follows:

$$f(DA)=\frac{1}{17}\sum_{i=1}^{17}ABS(\frac{Q_i-Q_{obs,i}}{Q_{obs,i}})+\frac{1}{7}\sum_{j=1}^{7}ABS(\frac{Q_j-Q_{obs,j}}{Q_{obs,j}}) \tag{6}$$

where $f(DA)$ denotes the function of dietary acceptability, Q_i and Q_j represent the quantities of food item i and food group j in the optimized diet, respectively, $Q_{obs,i}$ and $Q_{obs,j}$ are the corresponding consumption in the OBS.

2.5 Diet modeling through multi-objective optimization

Multi-objective optimization is used to find one or more solutions that correspond to minimizing (or maximizing) several specified objectives and satisfying all constraints. In this study, we use the nondominated sorting genetic algorithm version II (NSGA-II) (DebK et al., 2002) performed by Matlab 9.0 as our multi-objective optimization method, to find the optimal food combination with low environmental impacts, sufficient nutrition, and high acceptability. Each simulation is repeated 100 times to increase the probability of finding the overall optimal solution instead of the local optimal.

Objective function setting

To ensure the acceptability of the optimized diet by achieving the minimum deviation from each food item and food group consumed in the OBS, the optimized objective function is set as follows: :

$$\min imize f(1) = f(DA) \tag{7}$$

To ensure that the optimized diet is environmentally friendly, we set CF, WF and EF minimization as the optimization goal, and the objective formula is as follows:

$$\min imize f(2) = \sum_{i=1}^{17} CF_i / WF_i / EF_i \tag{8}$$

Constraint setting

The energy intake under the OBS is 2434 kcal. Thus, we restricted the total energy at 2400 kcal, and proteins, fats and carbohydrates are constrained as 15%-20%, 20%-30% and 50%-75% of total energy, respectively. In the simulation process, we found that the simulations could not identify a combination of foods that respected all the conventional RNIs (see Column 2 in Table 1), had a low level of departure from the OBS, and reduced environmental footprints. Therefore, we adjusted the beneficial nutrient limits appropriately (see Column 3 in Table 1) by setting the intake in the OBS as the lower limit for nutrients for which it is difficult to reach the conventional RNI (such as Ca, fiber, riboflavin, and Se); the remaining nutrient limits still refer to the conventional RNIs. By doing so, we ensure that the nutrient quality in the optimized diets is higher than in the OBS. In addition, the present study set constraints on the total food quantity to limit the deviation from the current diet, with the upper and lower limits being 120% and 80% of the total weight of the OBS, respectively.

In order to set up dietary optimization scenarios, we firstly define the minimum mitigation scenario as a 5% reduction of each dietary impact footprint. We then set up a series of scenarios in which each of the target footprint has an in-step increment of 5%, until it reaches the maximum reduction possibility, i.e., the maximum mitigation scenario. In the end, twelve optimized scenarios are obtained, which are characterized as follows: $\mathbf{S_{opt\text{-}WF}}$, a series of scenarios in which WF is reduced by 5% ($\mathbf{S_{opt\text{-}WF\text{-}5\%}}$) , by 10% ($\mathbf{S_{opt\text{-}WF\text{-}10\%}}$) and maximum reduction ($\mathbf{S_{opt\text{-}WF\text{-}min}}$); $\mathbf{S_{opt\text{-}CF}}$, a series of scenarios in which CF is reduced by 5% ($\mathbf{S_{opt\text{-}CF\text{-}5\%}}$), by 10% ($\mathbf{S_{opt\text{-}CF\text{-}10\%}}$), by 15%($\mathbf{S_{opt\text{-}CF\text{-}15\%}}$) and maximum reduction ($\mathbf{S_{opt\text{-}CF\text{-}min}}$); $\mathbf{S_{opt\text{-}EF}}$, a series of scenarios in which EF is reduced by 5% ($\mathbf{S_{opt\text{-}EF\text{-}5\%}}$), 10% ($\mathbf{S_{opt\text{-}EF\text{-}10\%}}$), 15% ($\mathbf{S_{opt\text{-}EF\text{-}15\%}}$), 20% ($\mathbf{S_{opt\text{-}EF\text{-}20\%}}$) and maximum reduction ($\mathbf{S_{opt\text{-}EF\text{-}min}}$).

Table 1 Nutritional constraints implemented in the diet optimization models

Nutritional constraint type	**RNI**	**Constraints in optimization**
Total energy(kcal)	2400(=OBS)	applied
Proteins(%E)	15-20	applied
Total fats(%E)	20-30	applied
Carbohydrates(%E)	50-75	applied
Fibers(g/d)	≥25	adjusted(> 12.2)
Saturated fatty acid(%E)	< 10	applied
Cholesterol(mg/d)	< 300	applied
Thiamin(mg/d)	≥1.4/1.2(male/female)	applied
Riboflavin(mg/d)	≥1.4/1.2(male/female)	adjusted (> 0.8)
Niacin(mg/d)	≥12-15	applied
Folic acid(ug/d)	≥400	applied
Vitamin C(mg/d)	≥100	applied
Vitamin E(mg/d)	≥14	applied

Ca(mg/d)	≥800	adjusted (> 380)
P(mg/d)	≥720	applied
K(mg/d)	≥2000	applied
Na(mg/d)	< 2759/2365(male/female)	applied
Mg(mg/d)	≥330	applied
Fe(mg/d)	≥12/20(male/female)	applied
Zn(mg/d)	≥12.5/7.5(male/female)	applied
Se(mg/d)	≥60	adjusted (> 55)
Cu(mg/d)	≥0.8	applied
Iodine(ug/d)	≥120	applied
Added sugars(%E)	<10	applied

Notes: the RNI of proteins, carbohydrates, cholesterol and Na refer to M Perignon's paper (Perignon et al., 2016), and total fats, SFA, fibers, vitamins, minerals (except for Na) and added sugar refer to the recommendations for age 18 and older in the China Food Composition Tables (Yang, 2019b).

2.6 Assessment of practical benefits and synergies

In this paper, the benefits of diet optimization are decomposed into practical benefits and synergies. The practical benefits are the extent to which the optimized diet mitigates environmental impacts and improves the nutritional level, as well as the degree of deviation from the current diet (a negative indicator) relative to the OBS. The synergistic benefits are the degree of deviation between the actual benefits with regard to the environment, nutrition and acceptability in the optimized scenario and the optimal value in all optimized scenarios. The smaller the degree of deviation is, the higher the synergistic benefits will be.

3. Results

3.1 Analysis of the practical benefits of the diet optimization scenarios

In addition to the observed diet scenario and optimized scenarios, we also set the nutritional diet scenario as a proxy of healthy diet. The nutritional diet scenario consists of five diets, from a low calorie recommended diet ($RD_{1600kcal}$) to a high calorie recommended diet ($RD_{2400kcal}$) recommended by Chinese dietary guidelines (CNS, 2016) (Table A4 in Appendix). Comparisons of environmental impacts, the nutritional level and acceptability under various scenarios are shown in Fig. 1.

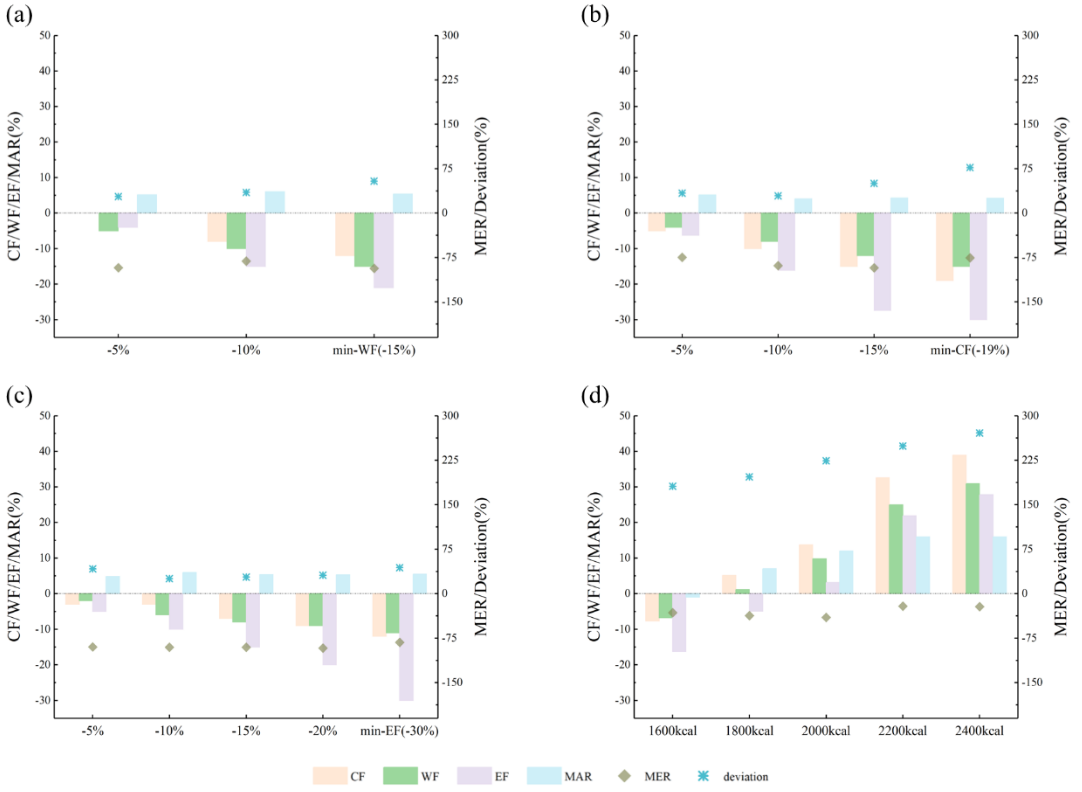

Fig. 1. The environmental impacts, nutrient quality and acceptability of different dietary scenarios compared to the OBS. (a), (b) and (c) are optimized scenarios $S_{opt\text{-}WF}$, $S_{opt\text{-}CF}$, and $S_{opt\text{-}EF}$, respectively, and (d) is the balanced diet structure recommended by Chinese dietary guidelines. The positive bars indicate an increase in the environmental footprints and nutritional level (MAR), and the negative bars indicate a decrease compared to the OBS; the positive dots indicate a decrease in acceptability (deviation) and the nutritional level (MER), and the negative dots indicate an increase.

3.1.1 Analysis of practical benefits for the environment

In optimized scenarios $S_{opt\text{-}WF}$, $S_{opt\text{-}CF}$ and $S_{opt\text{-}EF}$, the maximum reduction in the WF, CF and EF can be achieved by 15%, 19% and 30%, respectively (Fig. 1(a)–(c)). Comparing the environmental footprints under different degrees of mitigation in $S_{opt\text{-}WF}$, $S_{opt\text{-}CF}$ and $S_{opt\text{-}EF}$, we find that the EF has the largest reduction in each scenario, followed by the target environmental footprint (e.g., the target environmental footprint is the WF in $S_{opt\text{-}WF}$). The main reason is that the livestock meat consumption significantly decreases in each scenario, and its large EF coefficient leads to a significant decrease in the EF. Vegetable oil and beef contribute the most to the reduction in the WF, CF and EF, while cereals, dairy products and eggs, with significant increasing consumption, contribute the most to offsetting the mitigation of environmental impacts (Fig.A.1 in the Appendix).

The combined environmental footprint is the sum of the reduced proportions of the CF, WF and EF. In the $S_{opt\text{-}WF}$, $S_{opt\text{-}CF}$ and $S_{opt\text{-}EF}$, when the target footprint reaches the maximum reduction, the combined environmental footprints is minimized by 48%, 64% and 53%, respectively. Notably, the maximum reduction occurs in the series of scenarios with CF as the optimization target when comparing the combined footprint reduction under the same mitigation levels. Particularly, when the CF reaches the maximum reduction rate of 19%, the WF and EF both achieve the maximum reduction rate of 15% and 30%, respectively. The reason for this can be explained by the correlation coefficient. The Pearson correlation coefficient of CF-WF ($r=0.6287$, $p<0.001$) and CF-EF ($r=0.8071$, $p<0.001$) for food consumption is higher than that of WF-EF ($r=0.5027$, $p<0.001$), so the diet model with the CF reduction as the optimization goal can also achieve a large reduction in the

WF and EF. In the nutritional diet scenarios (Fig. 1(d)), with an increase in energy intake, the environmental impacts relative to the OBS first decrease and then increase significantly, with the CF increasing the most (from -8% to 40%), followed by the EF (from -16% to 29%) and the WF (from -6% to 32%). Among the dietary patterns at all energy levels, the CF also increased more than the other two footprints, indicating that in the recommended dietary patterns, the CF is the greatest environmental impact to be reduced. Therefore, the relevant environmental impacts in the dietary guidelines should be further considered in future revisions.

3.1.2 Analysis of practical benefits for nutrition

The MAR and MER are used to represent comprehensive nutritional levels. As shown in Fig. 1, the higher the positive bar representing the MAR and the lower the negative dot representing the MER, the higher the nutritional level is compared with the OBS. As a proxy for healthy eating, the nutritional level of the balanced diets is significantly higher than that of the optimized scenario: The increment in the MAR increases with the increase in calorie levels, changing from a decrease of 1% in $RD_{1600kcal}$ to an increase of 16% in $RD_{2400kcal}$. The reason is that with the increase in caloric intake, the amount of food consumed increases, and the nutrient intake becomes more abundant. In particular, the fiber, calcium and folic acid contents in the OBS, which have not yet reached 55% of the RNIs, significantly increase, which greatly improves nutritional quality. The negative decrease range of the MER shows a trend of first increasing and then decreasing, indicating that under the nutritional scenarios, the overintake level of restrictive nutrients in all dietary patterns is lower than that of the OBS. In this regard, the excess rate is the lowest in $RD_{2000kcal}$ and the highest in $RD_{2200kcal}$. In the optimized scenarios, the MAR improves less and does not change significantly with the progressive reduction in environmental footprints (Fig. 1(a)-(c)), mainly because fibers, riboflavin and Ca, for which the RNIs are more difficult to meet are all set higher than the OBS intake level as constraints during optimization. The MER under the optimized scenarios is much lower than that of the OBS, mainly due to a significant reduction in the intake of salt and fats from meat and cooking oils.

3.1.3 Analysis of practical benefits for acceptability

Acceptability is characterized by comparing the deviation in food items and food groups from the OBS. The dietary deviation under the nutritional dietary scenarios (Fig. 1(d)) is significantly larger than that under the optimized scenarios (Fig. 1(a)-(c)), indicating that the dietary patterns recommended by Chinese dietary guidelines are less acceptable despite being healthier. Under optimization, $S_{\text{opt-EF}}$ has the lowest average deviation (34%), followed by $S_{\text{opt-WF}}$ (39%), and $S_{\text{opt-CF}}$ has the largest average deviation (48%). Comparing the deviation at different mitigation levels under the same optimized scenario, we find that the deviation increases with the increment in environmental impact reduction, mainly because to realize a continuous decrease in the CF, WF and EF, livestock and poultry meat are significantly reduced while cereals, dairy products, and eggs increase as nutritional substitutes, leading to a growing deviation from the current food consumption structure.

3.2 Analysis of diet-related synergies

Under different optimized scenarios, the benefits of the three dimensions of the diet-related environment, nutrition and acceptability are different. To avoid sacrificing the benefits of one dimension to achieve the optimal benefits of another dimension in the optimized scenario, we evaluate the synergies of the environment, nutrition and acceptability in each scenario. In the S_{opt-CF} series (Fig. 2), the WF, CF and EF have the greatest synergetic benefit (the color in the first row has the largest diamond overlapping area). In particular, in $S_{opt-CF-min}$, the reduction in the WF, CF and EF reach the optimal values of 15%, 19% and 30%, respectively. However, although the maximum synergies of the three footprints can be achieved under this scenario, nutritional quality and acceptability deviate greatly from the optimal value, which means that nutrition and acceptability are partly sacrificed to obtain environmental benefits in $S_{opt-CF-min}$. As we set strict restrictions on beneficial and restrictive nutrients during the optimization process, the MAR and MER, which serve as nutrient proxies, have fewer tradeoffs, while more tradeoffs occur in regard to acceptability. To identify the “waxing and waning” relationship of the benefits of various indicators, it is necessary to evaluate the integrated benefits in each scenario, including the practical benefits and synergies.

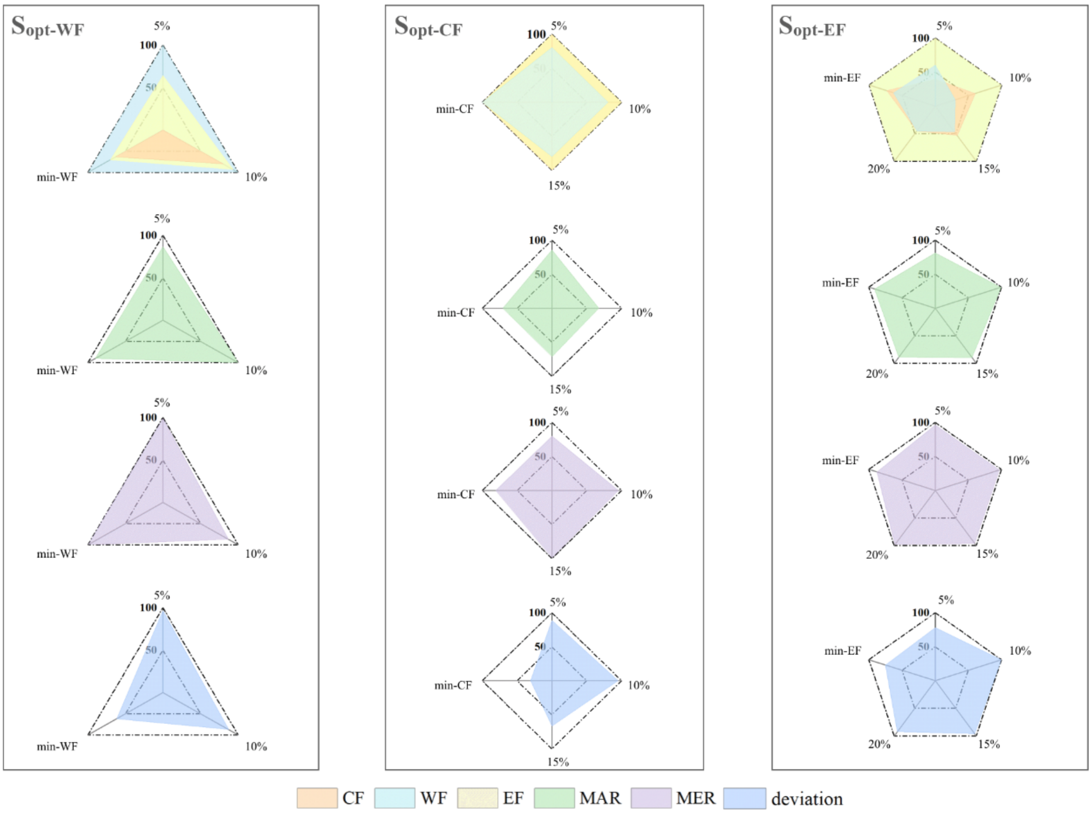

Fig. 2. Comparison of diet-related synergies. The degree of fitting between the environmental benefits, nutritional benefits and acceptable benefits in each scenario and the optimal value of the corresponding index (set as 100%) is regarded as a synergistic benefit. A high degree of fitting indicates good synergy, which is represented as a large overlapping area (line 1) or as vertices close to the graph (line 2, line 3 and line 4).

3.3 Analysis of integrative benefits with regard to the environment, health and acceptability under various optimized scenarios

Fig. 3 illustrates the integrative benefits of various optimized scenarios. Among them, the practical benefits include the combined footprints reduction (the sum of the reductions in the CF, WF, and EF relative to the OBS), the health benefits (the difference between the MAR and MER), and acceptability, which are shown as the dark column above the X-axis in the figure; the higher the column is, the greater the practical benefit of this indicator will be. To distinguish synergies from practical benefits, the synergies in the figure are shown below the X-axis, indicating the proportion of each indicator being weighed in the process of obtaining the practical benefits. The smaller the proportion (the shorter the column under the X-axis or the higher the column above the X-axis) is, the less the tradeoffs or the greater the synergies.

As shown in the figure, the integrated benefits in the series scenarios of $S_{opt\text{-}CF}$, $S_{opt\text{-}WF}$ and $S_{opt\text{-}EF}$ generally present an inverted U-shaped curve. That is, when the mitigation amplitude of the CF, WF and EF are the minimum and maximum, the actual benefits and synergies are small, while in other mitigation scenarios, the actual benefits and synergies are large. The reason is that changes in integrated benefits are mostly driven by environmental benefits and acceptability benefits: In $S_{opt\text{-}WF\text{-}5\%}$, $S_{opt\text{-}CF\text{-}5\%}$ and $S_{opt\text{-}EF\text{-}5\%}$, the integrated benefits are relatively small because the combined footprint is much smaller than that in other scenarios. In $S_{opt\text{-}WF\text{-}min}$, $S_{opt\text{-}CF\text{-}min}$ and $S_{opt\text{-}EF\text{-}min}$, although the combined footprints are the largest compared to other scenarios, the large deviation in food composition from the OBS results in a smaller acceptability benefit; thus, the overall practical benefits are low. Comparing the composition structure of the integrative benefits under each scenario, we find that the practical environmental benefit under the $S_{opt\text{-}CF\text{-}min}$ is the largest (the combined footprint reduction is 64%), and the synergistic benefit for acceptability is the smallest (-69%), indicating that the improvement in environmental benefits has come at the cost of acceptability benefits to a certain extent. In $S_{opt\text{-}EF\text{-}10\%}$ and $S_{opt\text{-}WF\text{-}min}$, the actual acceptability benefit (52%) and the nutritional benefit (99%) are achieved by weighing the environmental benefit (-37%) as well as the acceptability and environmental benefit (-38%, -25%), respectively. When the practical benefits and synergistic benefits are combined to analyze the integrative benefits brought by diet optimization, the integrative benefit in $S_{\text{opt-CF-10\%}}$ is the largest, although the sum of the practical benefits with regard to the environment, nutrition, and acceptability (174 %) is lower than that in $S_{\text{opt-CF-15\%}}$ (177%), $S_{\text{opt-EF-15\%}}$ (175%) and $S_{\text{opt-EF-20\%}}$ (181%). However, the sum of the synergistic benefits in $S_{\text{opt-CF-10\%}}$ is only positive (2%) and higher than the other scenarios, indicating that when reducing the CF is the optimization goal and the CF is reduced by 10%, the synergy of the environment, health and acceptability can be achieved. The results also reflect the role of synergistic in evaluating the comprehensive benefits of a dietary shift.

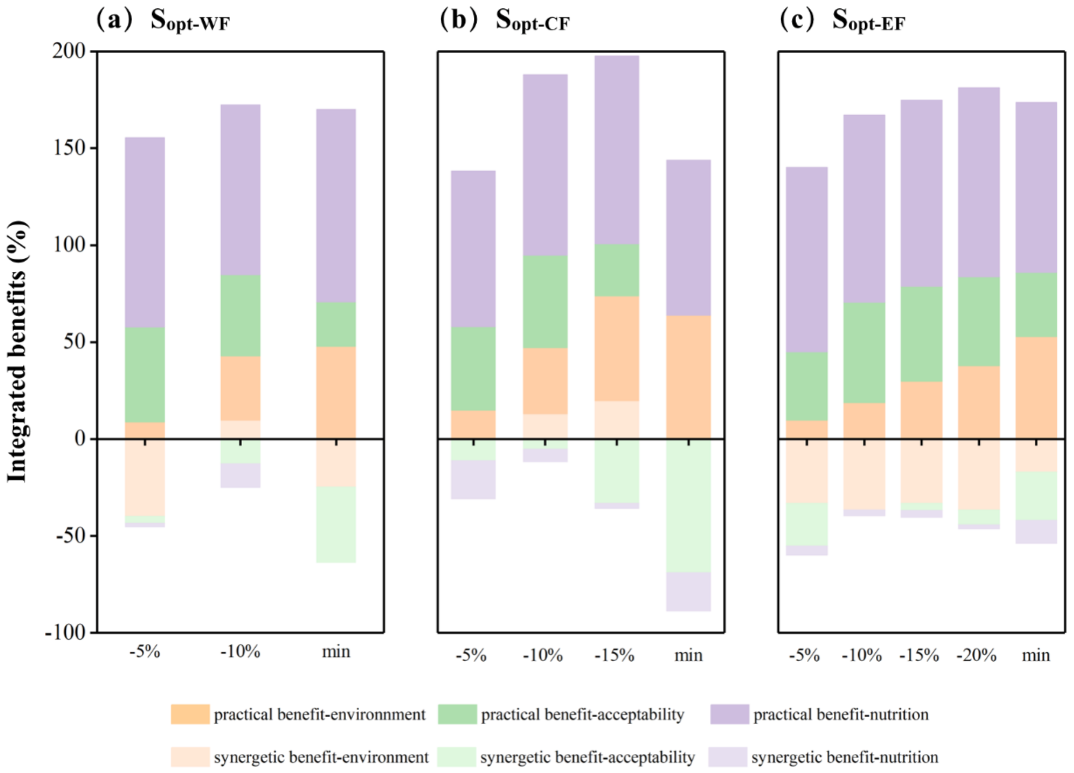

Fig. 3. Decomposition of integrated benefits by practical benefits and synergistic benefits. The positive bars indicate an increase in integrative benefits, and negative bars indicate a decrease, with different colors denoting the composition of the environmental dimension, nutrition dimension and acceptability dimension.

4. Discussion

4.1 The dilemma of the Chinese dietary shift

This study shows that the food consumption-related WF, CF, and EF can be reduced by up to 15%, 19%, and 30%, respectively, when nutritional constraints are satisfied and food item consumption (diet)deviate slightly from the OBS. The reductions in environmental footprints are smaller than those of high-income countries, such as the United Kingdom (Berners-Lee et al., 2012; Green et al., 2015; Macdiarmid et al., 2012; Reynolds et al., 2019), France (Perignon et al., 2016; Vieux et al., 2018), the Netherlands (Kramer et al., 2017), Austria (Vanham, 2013), Italy (Corrado, et al., 2019), Finland and Sweden (Vieux et al., 2018). It is known that 60%-80% of daily protein intake in America and Europe is obtained from meat, eggs and dairy products, but Chinese households consume only half from those foods (Gu et al., 2019). Due to the differences in the current dietary baseline, when western countries shift towards a diet with fewer animal-based food, specifically the reduction of red and processed meats, they generate a lot more environmental-health synergy benefits(Aleksandrowicz et al., 2016; Creutzig et al., 2016; Emstoff et al., 2017; Springmann et al., 2016; Tilman and Clark, 2014). Meanwhile, “hidden hunger” is a major nutritional problem faced by Chinese people. Achieving mitigation results that are similar to those of high-income countries would require significant reductions in animal-based foods, which would aggravate the deficiencies in certain micronutrients. Therefore, due to the irreconcilable characters of nutrition, environment and eating habits, it is currently difficult for China to draw some research conclusions similar to researches of dietary changes in high-income countries, that is, through a dietary shift, huge benefits have been achieved in terms of environmental friendliness, nutritional health and cultural acceptability.

4.2 Trade-offs among health, environment and acceptability

During the optimization process, we conducted hundreds of simulations and found that minimizing the environmental footprint and deviation from the current diet under strict nutritional constraints based on RNIs was impossible. Therefore, we finally decided to relax the constraints on individual micronutrients in the optimization algorithm; that is, Ca, Se, fiber and riboflavin are only required to be greater than the intake of OBS instead of RNIs. Similar considerations were also adopted in Song's research. When he found that it was impossible to minimize CF, WF and EF simultaneously under strict constraints, he chose to reduce CF to the maximum without increasing WF or EF instead of realizing a "synergy reduction" in CF, WF and EF (Song et al., 2019). Compared with his choice to relax environmental constraints, we chose to relax nutritional constraints, although doing so reduced nutritional quality to a certain extent and caused some food items to be lower than the recommended dietary intake (in particular, the intake of dairy products was less than the recommended 300 g/d). An optimized diet that reduced environmental impacts, had lower deviation from the OBS and did not impair the current nutritional level is considered a compromise choice for the dietary shift.

To prove this conclusion, we compared the environmental costs caused by the intake of various nutrients under the optimized scenario and the balanced diet recommended by the dietary guidelines (Table A5 in Appendix). The results showed that in most optimization scenarios, with the exception of Ca and vitamin C, the environmental cost per unit intake of other nutrients is lower than that of the balanced diet, indicating that the environmental benefits of diet optimization are greater than the nutritional benefits. Given that its nutritional benefits are higher than that under the current diet, it is feasible to shift to the optimized diet under a sustainable framework. The relatively high environmental cost of calcium and vitamin C under the optimized diet is mainly due to the low intake of dairy products, fruits and vegetables, as they are the main sources of these two nutrients. Although the vitamin C intake and fruit and vegetable intake under the optimized scenario are lower than the dietary recommended intake (300 g/d and 500 g/d-850 g/d, respectively), they meet the intake recommended by the Chinese Nutrition Society of 100 mg/d for vitamin C (Yang, 2019b), and by the World Health Organization of 400 g/d for fruits and vegetables (WHO, 2015). The milk intake of Chinese people has been insufficient for a long time (He et al., 2018; Wang et al., 2020; Zhang et al., 2017). From 1997 to 2011, the average daily consumption of dairy products by urban residents only increased by 1.2 grams per year (He et al., 2018), and the daily consumption growth of rural residents was even slower (Zhang et al., 2017). The low consumption elasticity of dairy products reflects the fact that the public is reluctant to substantially increase their consumption of dairy products. Our study demonstrated that the environmental costs of calcium needs to be reduced in order to achieve a sustainable dietary transition. Thus, while maintaining the current level of milk intake, increase the intake of other calcium-rich foods (such as green leafy vegetables, soy products) or advocate for the use of nutritional supplements, such as calcium tablets, may be feasible, desirable and relatively easy solutions.

4.3 Strengths and limitations

To the best of our knowledge, this study is the first to evaluate the integrative benefits of a dietary shift from the perspective of synergies and tradeoffs. There is a general consensus that dietary change across the globe can have multiple health and environmental benefits. Our analysis confirms this view and takes a step forward in providing better estimates of the magnitude of the possible benefits by decomposing them into practical benefits and synergies. In this study, it is concluded that dietary changes with the CF as the optimization goal can achieve the greatest synergistic benefits with regard to WF, CF and EF, and the diet scenario that reduces the CF by 10% can achieve the greatest integrative benefits. However, this conclusion is based on Chinese dietary data. Whether or not the conclusion is universal needs to be verified by relevant studies in other countries. Certainly, this optimized scenario is not intended to be a nationwide realizable dietary outcome, but to explore the interweaving of diet-related environments, health and acceptability influences. In addition, this research builds on the previous discussion of the win-win benefits of dietary shifts, adds consideration of dietary habits, and attempts to explore a dietary shift that achieve the triple benefits of environment, health, and acceptability. Although the method of quantifying acceptability still needs further discussion, it is also a useful attempt to study the Chinese dietary shift.

This study has some limitations. One limitation is that the CF and WF coefficients are not specific to the Chinese food system; instead, they refer to the coefficients aggregated from the global life cycle analysis (LCA) literature, as described by Song (Song et al., 2019; Song et al., 2015), which make them insufficient to reflect the efficiency of the Chinese food system. However, considering that the purpose of this study is not to compare the CF and WF produced by diets in different countries, but to evaluate the mitigation potential of the diet in the same countrsy, that is, the indicator framework is the same, so the uncertainty of the indicator value has less impact on the main results. Secondly, due to the lack of tracking survey data reflecting human health, when assessing the health benefits of dietary changes, we directly use nutritional evaluation indicators

(MAR and MER) to characterize health instead of using more scientific indicators such as all-cause, cardiovascular disease, and cancer mortality. Although existing research shows that a diet that reflects the core principles of healthy eating can reduce the risk of death (Biesbroek et al., 2017; Reedy et al., 2014), it is unclear whether it can reduce the risk of other diseases. Thirdly, we set the nutritional constraints to satisfy the minimum recommended requirements for optimization based on the simple assumption that "there is no interaction in nutritional intake between foods"; however, this assumption is not sufficiently rigorous, because the presence of one food will affect the availability of nutrients in another food (Gephart et al., 2016; Chaudhary and Krishna, 2019; Hunt, 1996). Therefore, even if the nutrients of the optimized diet exceed the RNIs, there is still a risk of micronutrient deficiency.Additionally, Food waste places a burden on the environment and represents an inefficient food system（Corrado et al., 2019a). Reducing food waste is an important part of the UN Sustainable Development Goal (SDG) 12.3, and it is also the easiest way to reduce the environmental impact of the "food basket"（Corrado et al., 2019b). However, because there is no available food waste data, this article does not consider food waste, which may lead to underestimation of the environmental impact of current food consumption and overestimation of nutritional intake levels.

4.4 Strategies for dietary transition

National dietary guidelines are developed to facilitate the attainment of nutrient recommendations (Maillot et al., 2010), but in the context of sustainable development, dietary guidelines should also take the responsibility of defining "healthier" for both consumers and the environment. The Dutch Health Council proposed in 2011 that 'guidelines for a healthy diet' are not only good for human health but also planetary health, and issued an advisory report ‘Guidelines for a healthy diet: the ecological perspective’, which takes a critical step in guiding people to choose a sustainable diet (van Dooren et al., 2014). The Chinese dietary guidelines are based on the single goal of health, and some studies have shown that the recommended dietary patterns increase environmental burdens (He et al., 2019; Song et al., 2019). Regrettably, in the revised content of the Chinese Dietary Guidelines released in June 2020 (CNS, 2020), the environmental impact of diet is still not included. Acceptability are also factors that must be considered when formulating dietary guidelines, but dietary guidelines seldom consider the public’s actual consumption willingness, although the purpose is to improve the nutritional quality. A typical example is that the consumption of dairy products in China increased from 15 g in 1992 to 25 g in 2010-2012 (Zhang et al., 2017), while the recommended intake in the Chinese dietary guidelines increased from 100 g (1997 version) to 300 g (2007 version and 2016 version), despite the low acceptance of dairy products. To summarize, the formulation of dietary guidelines should be based on considerations including sustainability issues and household welfare, and should form more inclusive guidelines for consumers to allow them to make sustainable dietary choices.

Our study demonstrates that the further reduction of environmental impacts needs to be at the expense of acceptability. Therefore, improving the public’s acceptance of a sustainable diet is the key to the future dietary shift. Some studies reveal that consumers are generally less likely to compromise taste to a great extent for health (Irz et al., 2016; Verbeke, 2006) or environmental benefits (Tobler et al., 2011). Nonetheless, they are willing to change their eating habits if they are presented with clear information about the impact of their diets (Hunter and Roos, 2016; Popkin, 2012). Therefore, while formulating and implementing guidelines for sustainable and healthy eating, it is necessary to accompany them with awareness raising campaigns and outreach programs to ensure that the principles of healthy eating are fully understood and to avoid unintended rebound effects (Arrieta and González, 2018). In the National Nutrition Plan (2017-2030), the Chinese government proposed that the public awareness rate about nutrition and health knowledge will continue to increase by 10% based on 2020 (General Office, CCCPC, 2017), which ignores propaganda about the diet-related environmental impacts. Therefore, available policy tools can be used when formulating sustainable diet-related strategies, such as increasing the promotion of sustainable diets and providing environmental information about food, to enhance the public's willingness to transition to a sustainable diet.

5. Conclusion

This study shows that it is difficult in China to achieve a sustainable diet with all micronutrients satisfying the RNIs, significant environmental impact mitigation and little deviation from the OBS, which can be achieved in Western countries through a dietary shift. However, when the nutritional constraints are appropriately relaxed, small food deviations can be achieved and the CF, WF and EF can be reduced by up to 19%, 15% and 30%, respectively. Our diet optimization scenarios show that in the three dimensions of the environment, health, and acceptability, achieving the maximum practical benefit of one dimension will weigh the benefits for the remaining one or two dimensions to the greatest extent. In the diet scenarios with minimization of the CF as the optimization goal, the greatest synergistic benefits on the simultaneous reduction of the CF, WF and EF are achieved, and when the CF is reduced by 10%, the greatest synergistic benefits for the environment, health and acceptability are achieved. The perspective of synergies and trade-offs is used in this article to study the dilemma of China's dietary shift. We hope that the ideas and methods of this study can provide a good starting point for the choice of sustainable dietary patterns.

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Conflict of interest declaration

None.

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