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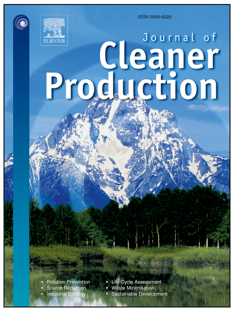

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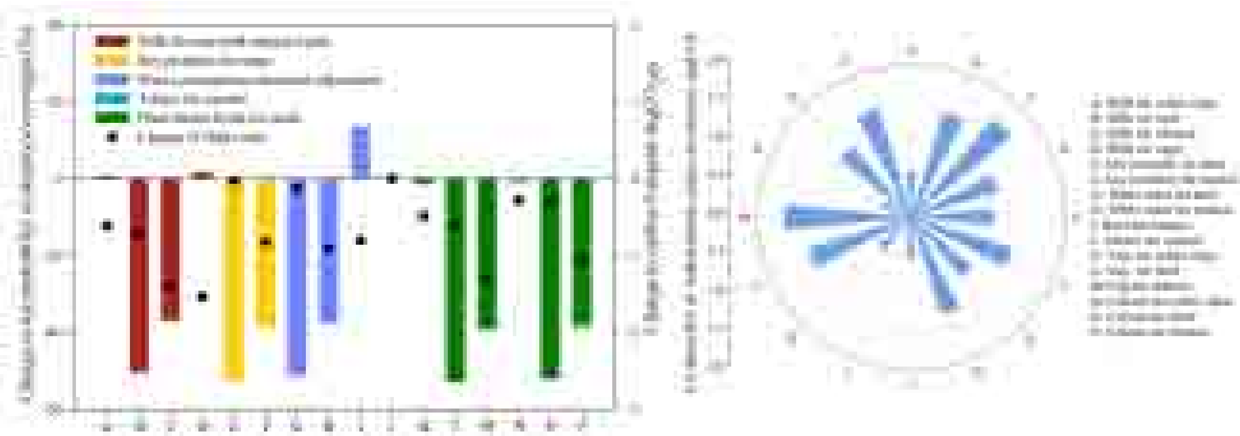

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Abstract

Dietary adjustment through food group substitutions is an adaptive strategy for obesity management in human populations and action on climate change. However, specific dietary adjustment scenarios (DASs) are underexplored in the current research. This study applied logistic regression to establish an association between the probability of obesity/overweight (O/O) and eleven food groups. The findings suggest that consumption of greater amounts of vegetables (odds ratios (OR) =0.964) and milk (OR=0.946) is associated with a less likelihood of O/O, while greater amounts of eggs (OR=1.367), white meat (OR=1.078), cereal (OR=1.037), beef (OR=1.105), and mutton (OR=1.317) is associated with a greater likelihood of O/O. With a 100g replacement, the scenario of substituting milk for eggs is related to a 31% reduction in the probability of O/O (P_O); substituting vegetables for beef would produce a 2.65 kg CO_2e reduction in individual CF per year; substituting milk for mutton is related to the highest co-benefits with P_O and CF reduced by 28% and 1.85 kg CO_2e per year, respectively. Moreover, making a 50g replacement, the scenario of substitution of red meat with milk, soy products, and white meat produces a 9.1 Mt, 6.5 Mt, and 3.4 Mt CO_2e annual CF reduction in China under an assumption that half of the population adopt the dietary substitution twice a week. Similarly, the scenario of substituting cereals with tubers would cut the national CF by 0.3 Mt CO_2e per year. On nutritional effects, almost DASs produce slight disturbance on protein, fat, and calorie and the change ratio is within 5%. Dietary adjustment measures focus on increasing plant-based food consumption, re-orienting the mix of meat products consumption

(via substituting red meat with white meat and introducing meat alternatives, especially soy products), publicizing the benefits of dietary adjustment to consumers, and emphasizing the changes in nutrition, especially in situations of substitution of animal-based foods with plant-based foods, but the influence on protein and fat deserves attention.

Keywords: dietary adjustment, Body Mass Index, obesity/overweight, carbon footprint, sustainable diet

1 Introduction

Balancing the relationship between human health and greenhouse gas (GHG) emissions agrees with the UN Sustainable Development Goals (SDGs) for human well-being and climate action. Moreover, most of the world is undergoing a dietary transition towards higher consumption of refined sugars, refined fats, oils and meats as a consequence of urbanization and changing income levels (Tilman and Clark, 2014), which is increasing the prevalence of obesity and adding to carbon footprint of the global food system, which now emits about 19-29% of total anthropogenic GHG (Vermeulen et al., 2012). Increasing the carbon emission is main cause of global climate change (Wamsler et al., 2014) and has posed a dramatic threat to planetary systems and human wellbeing (Chen et al., 2013; IPCC 2007). According to the fifth IPCC Assessment Report, the global average temperature will rise by 0.3-4.8□, the sea level will rise by 0.26-0.82m by the end of this century, which will likely cause frequent severe weather events, such as heatwaves and rainstorms (IPCC 2014).

Moreover, climate change has deteriorated biodiversity conservation, linked to global ecosystem services (Essl et al., 2017; Cameron et al., 2019).

At the same time, more than 6.7 hundred million people suffered from obesity in 2017, with one-in-eight adults in the world being classified as obese (FAO, 2018). Obesity often coexists with other chronic diseases including, hypertension, Type II diabetes, cardiovascular disease (CVD), coronary heart disease, and reproductive diseases (Fallah-Fini et al., 2017), which are influenced by genetic and environmental factors, among the latter of which, diet is primary (Canales Holzeis et al., 2019). In places like China, where the economy has rapidly developed and the income of residents has grown in a short space of time, food consumption patterns have shifted to higher sugar, higher fat, and higher processed food intake. The total number of obese people in China has now surpassed the number in the United States of America (NCD, 2017), foreshadowing an era of obesity (Chen et al., 2015). During 2002-2012, the percentage of overweight and obese adults dramatically increased in China, increasing from 22.8% to 30.1% and from 7.1% to 11.9%, respectively (NHFPC, 2015). Simultaneously, food system is the source of more than a quarter of GHG emissions in China, up to 17 % of which are associated with agricultural production (Dong et al., 2008). Annual carbon emissions from food production surged from 500 to 900 million tones (Mt) CO_2e during 1981-2015 (Zhang et al., 2018). Tackling the obesity/overweight (O/O) epidemic and the associated increasing carbon footprint (CF) through dietary adjustment is critical for realizing sustainable dietary policies in China and other rapidly urbanizing economies.

Many recent studies have investigated aspects of the link between human health and the environment. One group of studies has explored the association between food consumption and obesity thoroughly, including red meat and white meat (Rouhani et al., 2015), fatty meat and lean meat (Wang et al., 2014), ultra-processed meat (Mendonca et al., 2016), vegetables and fruit (Charlton et al., 2014), whole grain, and refined grain (Cho et al., 2013) consumption and so on. Among them, the positive association between meat consumption and obesity (Wang et al., 2009) as well as the negative relation between vegetables and obesity have almost been reached consensus (Charlton et al., 2014; Yu et al., 2018). In terms of method, logistic regression (Charlton et al., 2014; Wang et al., 2009), multilevel mixed-effect regression models (Wang et al., 2014), and cox proportional hazards models (Mendonca et al., 2016) were applied to establish the link between food consumption and obesity. Moreover, systematic review and meta-analysis also summarized the relation (Tohill et al., 2004; Schlesinger et al., 2019). Previous research provided a firm foundation for the current study. One group of studies has estimated the potential consequences of dietary adjustment, primarily focusing on reducing meat, substituting red meat with white meat, and increasing vegetable and fruit consumption (Scarborough et al., 2012; Alexander et al., 2017). Dietary adjustment practices also seek to substitute traditional animal-based meats with artificial meats, such as cultured meats, *in vitro* produced meats, lab-grown meats, and insect meats (Bonny et al., 2017). However, given the various food types in daily diets, existing food substitution choices may be limited. Health effects have focused on nutrition from food intake, type II diabetes, cancer, coronary heart disease, and life expectancy (Wilson et al., 2013; Tilman and Clark 2014; Springmann et al., 2016). For instance, Scarborough et al. (2012) observed in a study of the UK population that a 50% reduction in meat and dairy consumption with replacement by fruit, vegetables, and cereals, could result in a 19% reduction in GHG emissions and 36,910 deaths delayed or averted per year. The second group of studies have modeled the benefits of current diets shifting to recommended or specific diets, such as the WHO nutritional recommendation (Milner et al., 2015), the Vegetarian diet (White and Hall, 2017), the UK dietary recommendation (Horgan et al., 2016), the Mediterranean diet (Castañé and Antón, 2017), and the Chinese dietary guidelines (Song et al., 2019). The third group of studies has performed optimization analysis to identify healthy and environment-friendly dietary patterns after taking nutrition, food price, environmental cost, and feasibility into consideration (Wilson et al., 2013). Indices used to reflect the effect of dietary shifts on health focusing on nutritional impacts such as energy, saturated fatty acids, protein, minerals, and fiber intake (Heller et al., 2013). In China, some studies have evaluated the effects of shifting current food consumption to meet dietary guidelines on environment and nutrition at country and city scales (He et al., 2019; Xiong et al., 2020; Wang et al., 2020). After taking food intake, environment, nutrition, and culture into consideration, linear programming has been applied to optimization of the current diets (Yin, et al., 2020; Song et al., 2017). Song et al. (2019) estimates the carbon, ecological, and water footprint from food consumption by obese and non-obese groups and put forward age-gender specific optimal diets. The idea that dietary adjustment can be an effective solution to the dual health-environment dilemma is growing in support. Generally, overweight and obesity are one of the outcomes of food over-consumption, which is associated with substantial health costs and unnecessary carbon emission. Research linking obesity and CF is essential for sustainable development in China and consequentially for the whole world, given China's population size and position as a reference for rapidly urbanizing countries. In the study, we aim to explore the following questions in China: (1) what kind of dietary adjustment scenarios (DASs) are capable of balancing the relationship between obesity and carbon footprint? (2) What are feasible dietary adjustment choices for residents?

Our study focuses on providing comprehensive DASs to reduce the simultaneous risks of O/O and CF. The framework for our research is to establish the link between dietary factors and O/O using logistic regression and calculation of the initial probability of O/O (P_O) faced by individuals. Based on this, we put forward various DASs and assess the effects on O/O. Due to the different carbon intensities of various food types, the effects on CF are concomitantly evaluated. We then estimate the change in calories, protein, and fat intake to reflect the influence of dietary adjustment on nutrition. Finally, we examine the overall effects of O/O and CF and select the DASs that produce significant impacts.

2 Methodology and data

2.1 Data sources and study population

We extracted dietary and socio-economic and obesity status data from the China Health and Nutrition Survey (CHNS, https://www.cpc.unc.edu/projects/china). The survey uses a multi-stage, random cluster process to draw a sample to account for geography, economic status, and other background factors. Detailed information from the survey has been presented in previous research (Popkin et al., 2010). The CHNS has updated in 2019, but the individual food consumption data only updated to 2011 which are a main part in the current study. Therefore, we used six waves of survey data (1997, 2000, 2004, 2006, 2009 & 2011). Dietary data based on three consecutive 24-h dietary recall surveys from the *Nutrition Survey* in the CHNS, including recalls for two weekdays and one weekend day. Socio-economic and obesity status data were derived from the *Adult Survey* in the CHNS. Lastly, we matched the three parts data through individual IDs. The study included participants aged 18-75 and collected complete information on dietary, anthropometric, demographic, socioeconomic, and other lifestyle factors in the same wave. Individuals who were pregnant, lactating or suffering from cancer, hypertension, diabetes, or cardiovascular disease were excluded because the physical conditions may affect energy intake. Moreover, those with implausible energy intake (<800kcal per day or >6000kcal for males and <600kcal per day or >4000kcal for females), unrealistic height, weight, or Body Mass Index (BMI) were also not considered in the analysis. After exclusion, 38,070 participants were eligible for the study from the six waves, including 19,045 males and 19,025 females.

The CF of the food production system was calculated using the IPCC method, multiplying the emission factors (EF) by the activity data. The main GHGs emitted were CO_2, CH_4, and N_2O. The CF components in plant-based food production include direct energy use, CH_4 from rice paddies, and N_2O from fertilizer applications; and in the animal-derived foods they include direct energy use, CH_4 and N_2O from manure management, and CH_4 from enteric fermentation (Gao, 2007; Lin et al., 2015). Source contributions to the CF from the industrial and service sectors include fuel combustion, energy supplies, and industrial emissions (cement manufacture). We cite the CF data of different food types from our research (Lin et al., 2015), which can be seen in Table S1.

2.2 Dietary and socio-economic factors as well as overweight/obesity index

We extracted 2,020 food names from food codes used in the original *Nutrition Survey* by matching food types in the China Food Composition Tables (CFCT) (Yang et al., 2002; Yang et al., 2004). The 2,020 food items were further classified into 22 different types (Table S2), including 14 kinds of plant-based foods and 8 kinds of animal-derived foods. The 14 plant-based foods were as follows: cereals, tubers, vegetables, soy products, salted vegetables, fruit, nuts and seeds, dessert, sugar, beans, oils, alcohol, soft beverages, and others (medicinal materials, condiments). The 8 animal-derived foods included pork, beef, mutton, poultry, seafood, eggs, milk, and other animal-based foods. Amongst them, we defined pork, beef, and mutton as red meat, and poultry and seafood as white meat. First, we matched the food ID with the food name in the China Food Composition Tables (CFCT) and determined food consumption for each item; then, we summed the consumption of each food item after classification to determine the food consumption of each type. Amounts included three days of food consumption. We used this amount to divide the person-days to get the per capita daily food consumption of each food type. During the calculation, we unified the types of food. For instance, we converted the dairy products to liquid milk, converted dehydrated vegetables to fresh vegetables, and converted soybean to soy products. According to the amount of protein contained in every 100g edible part and a rehydration ratio, we converted dairy products into liquid milk using a factor of 6.6 (CFCT) and converted dehydrated vegetables to fresh vegetables using a factor of 3.5 (Zhao et al., 2013). In the study, individual oil intake was calculated based on the proportion of each household member's total food intake in total household consumption. Ultimately, cereals, tubers, vegetables, fruit, soy products, pork, beef, mutton, white meat, eggs, and milk were considered to account for more than 94% of the total food amount. We treated food factors as continuous variables. Socio-economic data were considered as confounding variables in the model, including urban residency, age, the highest degree of education, employment status, drinking (alcohol) status, smoking status, income, and work intensity. A detailed description and classification of socio-economic data are available in Table S3.

We took the widely approved criterion BMI to judge whether the individual was obese or not. Based on the criteria recommended by the Working Group on Obesity in China (WGOC, 2004), BMI was divided into four categories, underweight: BMI < 18.5 kg · m^{-2}; normal: BMI: 18.5-23.9 kg · m^{-2}; overweight: BMI 24.0-27.9 kg · m^{-2}; and general obesity: BMI ≥ 28.0 kg · m^{-2}. The underweight and normal types were treated as not being obese (obesity=0), and those who were overweight or obese were included as overweight (overweight/obesity=1). The classification of obesity was treated as the dependent variable.

In order to estimate the adjustment in macro-nutrition, we evaluated the changes in calories, protein, and fat for each individual to reflect the effects of dietary adjustment on nutrition and took the change ratio in the range of 0 to10% as the line of nutritional disturbance with a 50g dietary substitution. Overall, the proportion of the population falling in the range was used to measure the impact of that adjustment scenario on macro-nutrition. Detailed data on the calories, protein, and fat content in different food types per 100g are presented in Table S4.

2.3 Statistical analysis

Logistic regression (LR) analysis is most frequently used to examine the risk of relationships between disease and exposure. In previous research, both linear and logistic regression were used extensively to classify and diagnose obesity and identify the risk factors (Tripepi et al., 2011; Hatami et al., 2014). In terms of prediction, the method models the chance of an outcome based on individual characteristics, which has previously been applied to predict overweight/obesity (Beyerlein et al., 2008; Heydari et al., 2012). Until recently, few studies have explicitly examined the effects of increasing the amount of different foods consumed on obesity. In this study, LR was applied to establish the link between obesity and dietary patterns as well as food intake and model the probability of obesity based on socio-economic characteristics and dietary factors, which has been used in other research (McCarthy et al., 2006; Zhang et al., 2009; Cho et al., 2011). According to the utilization and scope of applying the method mentioned above, we applied logistic regression to evaluate the probability of obesity based on individual socio-economic characteristics and food intake. The probability of obesity is modeled by:

$$P = \frac{\exp(\beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)}{1 + \exp(\beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)} \quad (1)$$

In order to simulate the regression coefficient β_k, the Logit transformation, denoted as Logit (P), is given as follows:

$$\text{Logit (P)} = \ln\left(\frac{P}{1-P}\right) = \beta + \beta_1 x_{1} + \cdots + \beta_k x_k \quad (2)$$

where p is the probability that the O/O event occurs and β_0 is a constant terms. β_i is the regression coefficient for the independent variable x_k while exp (β_k) is equal to the Odds Ratio (OR). It means that the odds of the event increase (OR greater than 1) or decrease (OR less than 1) when x_k increase by 1 unit, with all other factors remaining unchanged. The cross-sectional nature of the data means that the results should be interpreted carefully, and we followed the scientific norm of explanation, which has been applied in similar studies (McCarthy et al., 2006; Bonnie et al., 2015; Zhang et al., 2016). For instance, McCarthy et al. (2006) pointed out that consumption of greater amounts of food per serving is significantly associated with a greater likelihood of being obese. And the number of nights a family eats (OR=0.83, 95% CI 0.72-0.96) together provides a protective factor for obesity with about a 16% reduction for every extra night the family eats together (Zhang et al., 2016). In the study, the model controlled for age, urban location, employment status, income level, education, smoking status, work intensity, and dietary factors, such as vegetables, fruit, beef, white meat, and eggs to estimate the adjusted OR with 95% confidence intervals [CI] for O/O. Additionally, both the variance inflation factor (VIF) and the condition index were used to test multicollinearity. We established the initial P_0 and treated it as a reference value. Eq. (3)

$$P_0 = \frac{\exp(\beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)}{1 + \exp(\beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)} \quad (3)$$

Then, we substituted one food type for another and kept other factors unchanged, which can obtain the adjusted P_1. Eq. (4)

$$P_1 = \frac{\exp(\beta_o + \beta_1 x_1^{'} + \beta_2 x_2^{'} + \ldots + \beta_k x_k)}{1 + \exp(\beta_o + \beta_1 x_1^{'} + \beta_2 x_2^{'} + \ldots + \beta_k x_k)} \quad (4)$$

Last, the change ratio (P_c) between initial P_0 and adjusted P_1 was used to reflect the change in P_O of DASs. Eq. (5)

$$P_c = \frac{P_1 - P_0}{P_0} \quad (5)$$

We replaced the former food type with the alternative one gradually under the equal quantity principle, starting with one serving (equal to 100g) and taking each additional substituted serving as a step. Based on the two considerations, we put forward the principle. First, the study emphasized the DASs within the similar nutritional contents, for example, structural adjustment of meat consumption (replacement within protein) and substituting cereals with tubers (replacement within carbohydrate). Specifically, substituting 1 unit potatoes with staple food. Second, our data present that, under 25g substituting amount, the variation range of carbohydrates, energy, and protein is about 5%, so that these DASs hardly disturb the nutritional status of the individual (Table S5). The adjustment process is shown in Figure 1, where T_i is food type *i*. The eight food types on the left are the alternatives, successively substituted for the others in the same row so that there are eight dietary adjustment sets. The effect of dietary adjustment on carbon is refers to the substitution amount multiplied by the difference of carbon footprint between food A minus food B. Using this procedure, we derived the adjusted P_1 for each individual. We applied P_c and the change in CF to reflect the impacts of dietary adjustment. All analyses were performed in SPSS 19.0 (IBM SPSS Inc., USA), and P-values less than 0.05 were considered significant.

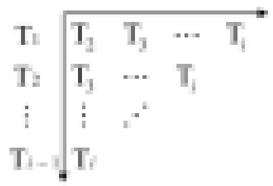

Figure 1. Sketch of the dietary adjustment process

We normalized the two indexes and summed the two values recording the sum as W_i to reflect the effects of all DASs. The larger W_i, the higher the co-benefits of the scenario$_i$. Given the circumstance where the two values were negative, the normalization of the two indicators was calculated as:

$$X = \frac{X_{obs} - X_{Max}}{X_{Min} - X_{Max}} \quad (2)$$

where X_{obs} is the observed value of variable X, and X_{Max} and X_{Min} are calculated from the P_c or changes in CF. The value of X ranges from 0 to 1.

2.4 Essential dietary adjustment scenarios

Putting the focus on DASs with similar nutritional and policy preference may enhance the residents' identification and acceptance of adjustment. Here, we focus on the following five types of adjustment (A-E). A: Substituting meat with soy products. Meat consumption is far higher than the dietary guidelines and continues to increase in China, likely producing severe health issues. Plant protein contained in soy products is similar to that in animal-derived meat, while fats and saturated fatty acids are significantly lower than in meat (Yang et al., 2004). Moreover, the carbon footprint of soy production is less than that for meat (Lin et al., 2015). B: Substituting milk for non-milk animal-derived foods. In terms of nutrition, milk can offset the loss of protein due to reduced meat consumption. The gap between current milk consumption and the recommended amount, and excessive meat intake ensures the feasibility of the scenario. The government has promoted a series of policies to guarantee the development of the milk production base and market, emphasize the role of milk in a healthy diet, and promote milk consumption, e.g. the school milk policy (MOE and MOA, 2002; GOSC, 2018). Besides, with rising incomes and an awareness of healthy diet promotion, high-quality diets, which include milk consumption, may be more readily accepted. C: Structural adjustment of meat consumption. Red meat (pork, beef, and mutton) consumption is about 40% higher than white meat (poultry and seafood) consumption in China. The excessive consumption of the former is strongly indicated in the rise in obesity and carbon footprint. Furthermore, there is a chance for dietary adjustment away from meat with a trend toward diversified meat consumption. Increasing the component of white meat in total consumption may enhance the resilience of the meat supply chain, especially when it is facing disturbances such as African swine fever (Roth, 2020). The ADC has been carried out as a result of the re-regulation of the meat production structure in Guizhou, China (PGGP, 2010). D: Substituting cereals with tubers. Tubers can provide energy, vitamins, and minerals. Under the principle that nutrition guides consumption and consumption guides production, the Chinese government has promoted potatoes as a staple food (PSF) since 2015 to guide potato consumption (MOA, 2017) and set a target that staple food consumption accounts for 30% of total potato consumption by 2020 (MOA, 2016). Potatoes are a prominent alternative crop in agricultural structural adjustment because they use less water, land, and fertilizer than cereal crops. E: Substituting meat with plant-based foods. Increasing meat consumption has caused serious health and environmental issues. A recent UN report has pointed out that reducing meat consumption could substantially relieve climate change (IPCC, 2019). Meanwhile, the consumption of plant-based foods remains below the Chinese dietary guidelines recommendations, especially consumption of fruit, which has reached only about half of the recommended amount. The effects of this scenario have been discussed widely (Scarborough et al., 2012; Alexander et al., 2017). With the enhancement in health and environmental awareness, many more people may accept recommendations for substituting meat with plant-based foods.

3 Results

3.1 Changes in dietary pattern, obesity/overweight and CF

During 1997-2011, dietary patterns in China changed substantially (Figure 2). The consumption of milk and fruit had increased to 34 and 58 g day^{-1} by 2011. Cereal consumption had reduced by 81 g day^{-1}. Vegetable consumption had declined by 8 g day^{-1}. Meat consumption had increased continuously, and red meat consumption accounted for almost 70% of the total amount. In addition, the total prevalence of ‘overweight’ and ‘obese’ individuals had increased from 26% to 44% during this period. At the same time, the CF of food production and distribution had also increased apart from a sharp decrease in 2009, which was probably due to a decrease in daily beef consumption of 2g per capita, and the price of pork as a beef alternative continuing to decline until 2009 (Hu et al., 2017). The carbon footprint intensity of beef is almost 14 times higher than that of pork. The dietary changes resulted in a daily CF reduction of 0.07 kg CO_2e per capita. Per capita daily food consumption is shown in Table S6. The correlation coefficient between the rate of O/O and CF is 0.92 ($p<0.05$), reflecting that food consumption plays a role in O/O and CF and offering a potential avenue for balancing O/O and a low-carbon diet. We find that the rate of overweight/obesity and CF both increase a lot, which deserve more attention. It is necessary to slow down the double high speed increment in obesity and CF through dietary adjustment.

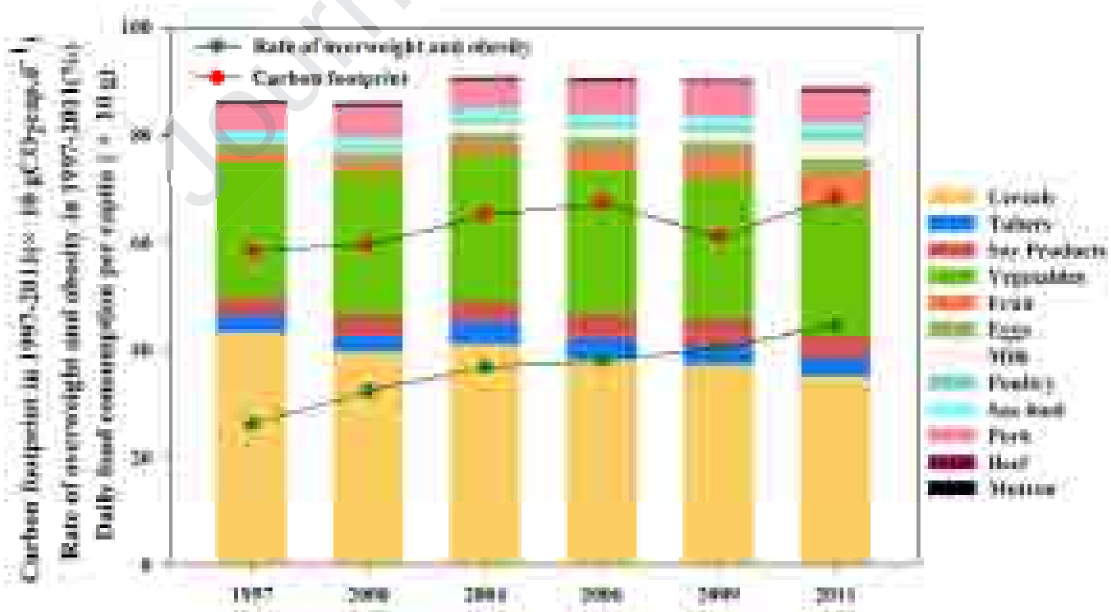

Figure 2. Rate of obesity/overweight and carbon footprint between 1997 and 2011

3.2 Roles of dietary and socio-economic factors in obesity/overweight and CF

The results show that the maximal Variance Inflation Factor (VIF) and Condition

Index of the model are 1.12 and 8.27, respectively, which means the multicollinearity between variables is weak or non-existent. All of the dietary factors and other covariates can be used in the logistic regression. The significance value of the Likelihood ratio test is 0.00 (less than 0.05), which means the model is significant overall. The impacts of socio-economic and dietary factors on O/O are shown in Table 1. Milk (OR=0.946, 95% CI: 0.907 - 0.986) and vegetables (OR=0.973, 95% CI: 0.959 - 0.987) consumption had a positive effect on weight loss, while other food types, such as beef (OR=1.105, 95% CI: 0.984-1.242), mutton (OR= 1.317, 95% CI: 1.144-1.517), white meat, and eggs (OR=1.367, 95% CI: 1.278-1.462) played a negative role. There was no observed association between pork intake and O/O. Consumption of larger amounts of soy products is associated with greater odds (OR=1.098 95% CI: 1.064-1.133) of being obese. Fruit intake was also positive for weight gain, and 1 unit increment of fruit is related to a greater increment likelihood on P_O. Lastly, we listed all food types based on OR, which is a pre-condition for the subsequent food substitution (Table 1):

Table 1. Role of dietary and socio-economic factors in obesity/overweight among Chinese adults, CHNS[a] 1997-2011

	Coefficient		95%CI			Coefficient		95%CI	
Variable	（β）	OR	Lower	Upper	Variable	（β）	OR	Lower	Upper
Constant	-1.391	0.249			Age	0.016	1.016***	1.014	1.018
Urban	0.028	1.029	0.978	1.082	Income	0.146	1.157***	1.133	1.183
Education	0.012	1.012	0.979	1.045	Work	-0.121	0.886***	0.886	0.906
Smoking	-0.101	0.904***	0.882	0.926	Employment	-0.203	0.816***	0.768	0.867
Cereals	0.036	1.037***	1.024	1.051	Eggs	0.313	1.367***	1.278	1.462
Soy products	0.094	1.098***	1.064	1.133	White meat	0.075	1.078***	1.029	1.129

Fruit	0.038	1.039***	1.011	1.067	Milk	-0.056	0.946***	0.907	0.986
Tubers	0.036	1.037***	1.011	1.064	Mutton	0.276	1.317***	1.144	1.517
Vegetables	-0.028	0.973***	0.959	0.987	Beef	0.100	1.105*	0.984	1.242
Pork	-0.019	0.981	0.947	1.017					

p < 0.01***, p < 0.05**, p < 0.1*

[a] Model adjusted for Urban, Age, Smoking status, Income level, Employment status, Education, Work intensity, Eggs, Soy products, Milk, Cereals, Beef, Mutton, Fruit, Pork, Tubers, White meat, Vegetables.

When the CF is considered, there is consistency between the carbon footprints and OR of food types (Figure 3). Animal-derived foods contribute more to both the P_O and CF than plant-based foods. For instance, the OR of beef and mutton are 1.317 and 1.105, while the carbon footprint intensities are the highest at 26.59 kg CO_2e /kg and 19.77 kg CO_2e/kg, respectively. The OR (and carbon footprint intensities) of vegetables and cereals are 0.973 (0.11 kg CO_2e /kg) and 1.037 (0.5 kg CO_2e /kg), respectively. The carbon footprint intensity of beef is about 53-fold that of cereals. From the perspective of comprehensive effects, vegetables are an optimal choice, followed by tubers, cereals, and fruit. Mutton and beef are the least optimal choices.

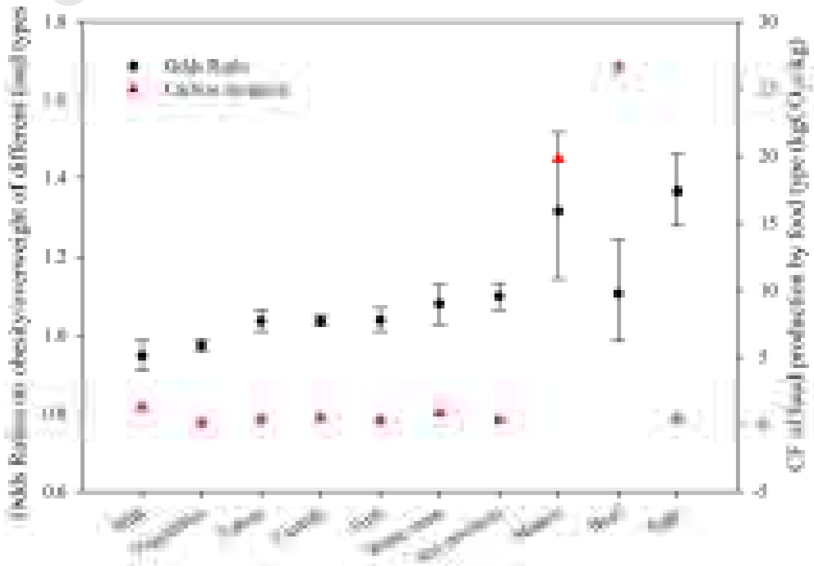

Figure 3. Impacts of food groups on obesity and carbon footprint

3.3 Impact of dietary adjustment on obesity/overweight and CF

We assessed the dual effects of 45 DASs on CF and O/O under 1-serving substitution (Figure 4). Trends in the consequences of food adjustment for O/O are non-linear, while those of CF are linear. That because in logistic regression, the relationship between the probability of obesity and independent variables is non-linear as Eq. (3) shows. Therefore, when we substituted one food type for another and kept other variables unchanged, the change ratio (Pc) between initial P_0 and adjusted P_1 is non-linear with the substitution increase (Fig.S1). In the study, food adjustment is under the equal quantity principle, so with the increase in substitution quantity, the change in carbon footprint is linear. And as the substitution amount increases, the differences become more distinct (Fig.S1). In Figure 4, if the bar and points in a DAS are both below the X-axis, it means that the DAS produces dual benefits. Otherwise, the scenario is unsatisfactorily biased towards benefits for either O/O or CF reduction. The results indicate that all scenarios provide benefits in reducing the P_O, and the effects of replacement of mutton and eggs with other foods are better than other scenarios. However, only one-third of scenarios benefit CF reduction, including the substitution of mutton (~ 2.0 kg CO_2e reduction) and beef (~2.5 kg CO_2e reduction) with other foods. Scenarios with dual benefits account for 60% of all DASs. The scenario of substituting other foods (besides beef and mutton) with milk inducing a 0.12 kg CO_2e increase in CF, driven by the replacement of plant-based foods, such as vegetables, fruit, and cereals. Conversely, on the scenario of substituting other foods with vegetables and fruit produces benefits. Among all DASs, the most desirable effect on O/O is the scenario of substituting eggs with milk and vegetables with an accompanying 31% and 29% reduction in the P_O. The substitution of beef with vegetables produced most massive benefit on CF with a 2.65 kg CO_2e reduction. Followed by the substitution of beef with fruit and CF reduced by 2.63 kg CO_2e.

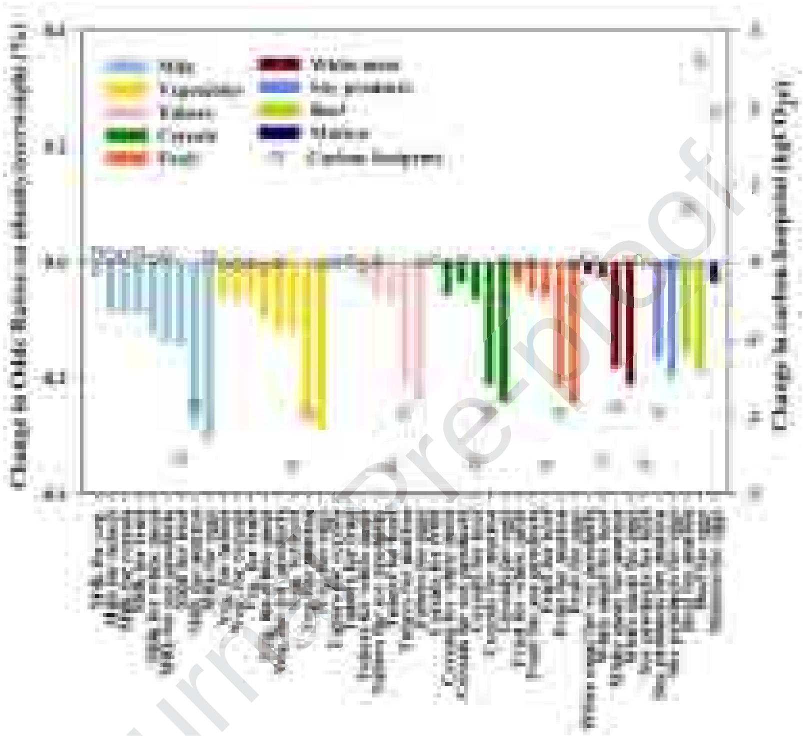

Figure 4. Effects of dietary adjustment scenarios on obesity/overweight and carbon footprint

Overall, many DASs produce co-benefits for O/O and CF reduction. However, given the rationale of the scenarios and their acceptability to consumers, not all scenarios are feasible. For example, the scenario of substituting fruit with milk, substituting soy products with fruit, and substituting eggs with tubers are not easily adopted in most diets. Consequently, we have focused on 5 types of DASs as mentioned above (Figure 5).

A: Substituting meat with soy products. The substitution has a significant effect on reducing CF and P_O. On the scenario of substituting beef with soy products, the P_O

almost unchanged, but CF was reduced by 2.60 kg CO_2e. Moreover, the scenario of substituting mutton with soy products, the P_O reduced by 17%, and CF reduced by 1.90 kg CO_2e. These results indicate benefits from substituting animal protein with plant protein, which is consistent with a growing interest in the consumption of artificial meats. B: Substituting non-milk animal foods with milk. Four scenarios are included in the group. Among them, the benefits of substituting red meat with milk are higher than for substitutions of white meat or eggs, with the P_c ranged from -14% to -28% and the CF reduced by 1.85-2.53 kg CO_2e. However, when substituting white meat, the CF slightly increased by 0.04 kg CO_2e and the P_O was reduced by 13%. C: Meat consumption structural adjustment. On the scenario of substitution of red meat with white meat produced co-benefits. In the scenario of substituting beef with white meat, the P_O would reduce by 3%, and the CF was reduced by 2.6 kg CO_2e. And on the scenario of substituting mutton with white meat, the P_O was reduced by 18%, and the CF was reduced by 1.9 kg CO_2e. Although the P_O reduced by 16% on the scenario of substituting mutton with beef, the CF increased by 0.68 kg CO_2e. Overall, the adjustment of meat type is associated with obvious benefits, especially when substituting red meat with white meat. D: Substituting cereals with tubers. This scenario had limited effects except for a slight reduction in CF of 0.01kg CO_2e. E: Substitution of meat with plant-based foods. On the scenario of substituting red meat with vegetables or cereals, the largest reduction in CF was 2.61kg CO_2e, and the most significant P_c was -26%. However, when substituting white meat with plant-based foods, the most striking effect was a 10% reduction in the P_O and a reduction of 0.08

kg CO_2e in CF. On the whole, substituting meat, especially red meat, with plant-based foods produces significant benefits for both CF and obesity/overweight.

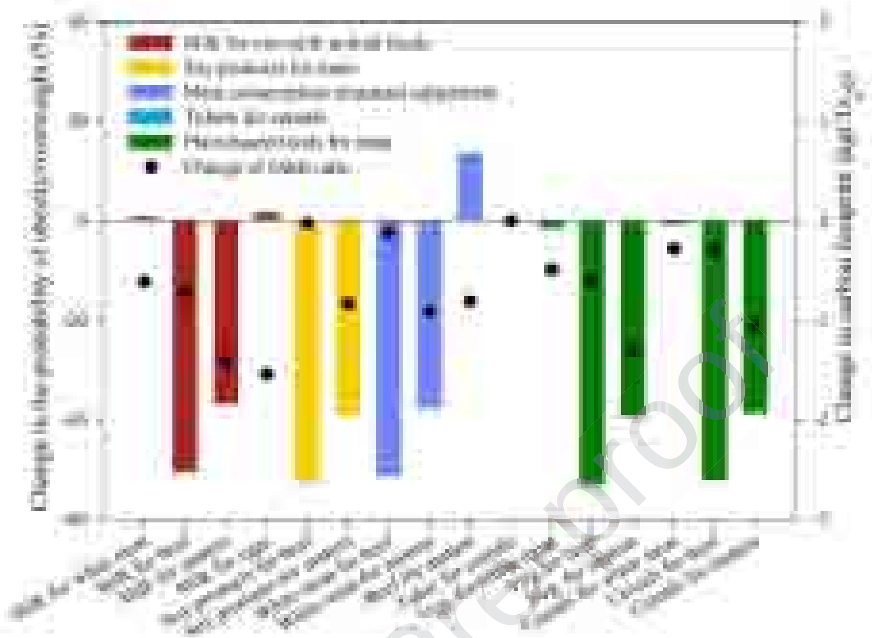

Figure 5. Effects of mutual substitutions between animal-based foods and plant-based foods both on obesity/overweight and carbon footprint

The impacts of various dietary scenarios on macro-nutrition are different (Table 2). Except for the scenario of substituting beef with white meat, the change ratios for calories of 90% of all the samples are within 10%. For 50% of the samples, the change ratios for calories are within 10% on the scenario of substituting beef with white meat, and if we adjusted the change ratio from 10% to 20%, the percentage of samples falling within this band would increase to 94%. The corresponding proportion for protein and fat would increase to 30% and 90%, respectively (for a 20% bandwidth). In scenarios of substitution of meat with cereals, vegetables, and tubers, the change ratios for the protein of 50% of the samples are within 10%, and deserving of attention for dietary adjustment policy design. The effects of substitutions on fat consumption are noticeable when substituting milk for other foods. Twenty percent of the sample had a change ratio within 10% for fat. In addition, the change ratios for calories, protein, and fat of substituting soy products for eggs and meat are all within 10%, showing the likely feasibility of these substations from a macro-nutritional perspective. In scenarios of meat substitution, the change ratios for the three macro-nutrients are all within 10%. Greater change exist in protein and fat on the scenario of substituting animal-based foods with plant-based foods.

Table 2 Effects of dietary adjustment on calories, protein, and fat (%)

Scenario	Calories	Protein	Fat	Scenario	Calories	Protein	Fat
Milk to Veg.	0.82	0.99	0.01	Beef to Mutton	1.00	1.00	0.99
Milk to White meat	1.00	0.97	0.17	Tuber to Cereal	0.91	0.95	0.98
Milk to Beef	0.99	0.90	0.07	Tuber to White Meat	1.00	0.59	0.33
Milk to Mutton	0.99	0.95	0.14	Tuber to Beef	1.00	0.48	0.87
Milk to Egg	1.00	1.00	0.20	Tuber to Mutton	1.00	0.55	0.50
White meat to Beef	0.49	0.08	0.15	Veg. to White Meat	1.00	0.67	0.35
White meat to Mutton	1.00	1.00	1.00	Veg. to Beef	1.00	0.53	0.89
White meat to Egg	1.00	1.00	1.00	Veg. to Mutton	1.00	0.64	0.53
Soy prod. to Egg	1.00	1.00	1.00	Cereal to White Meat	1.00	0.99	0.51
Soy prod. to Mutton	1.00	1.00	1.00	Cereal to Mutton	0.99	0.97	0.72
Soy prod. to Beef	1.00	1.00	0.99	Cereal to Beef	0.99	0.96	0.98

Note: Soy prod. refers to Soy product. Veg. refers to vegetables. The value refers to the sample proportion with a change ratio for the macro-nutrient within 10% for each dietary adjustment scenario. For instance, 0.97 means that for protein substitution when substituting milk for white meat, the proportion of samples with a change ratio within 10% to the total sample set is 97%.

3.4 The co-benefits of dietary adjustment scenarios

The effects on O/O and CF (a) and the comprehensive effects (b) of the 16 DASs after standardization are shown in Figure 6. For instance, the benefits of scenario A (milk for white meat) for CF are 0.19 and 0.39 for CF and O/O, respectively. The co-benefits of scenario A is 0.58. The better scenarios are the substitution of mutton with milk, vegetables, and cereals. Among these three, although the co-benefits of substituting mutton with milk is 1.67, and substituting mutton with vegetables is 1.64, they are very similar. The latter scenario may be more optimal from the perspective of CF reduction. At the other end of the spectrum, the co-benefits of substituting cereals with tubers is 0.21, substituting white meat with cereals is 0.40, and substituting mutton with beef is 0.52, producing the least desirable quantity of total co-benefits. Additionally, the distribution of points of the same color is a scatter, indicating that within the same substitution type, the co-benefits of each scenario can be quite different. For instance, within the meat consumption structural adjustment substitution type, the co-benefits of substituting red meat with white meat (G and H) are higher than from the substitution of mutton with beef (I). Similarly, within the substitutions of milk for non-milk animal-derived foods, the benefits of substituting milk for white meat (A) and eggs (D) are lower than for substitutions of milk for beef (B) and mutton (C).

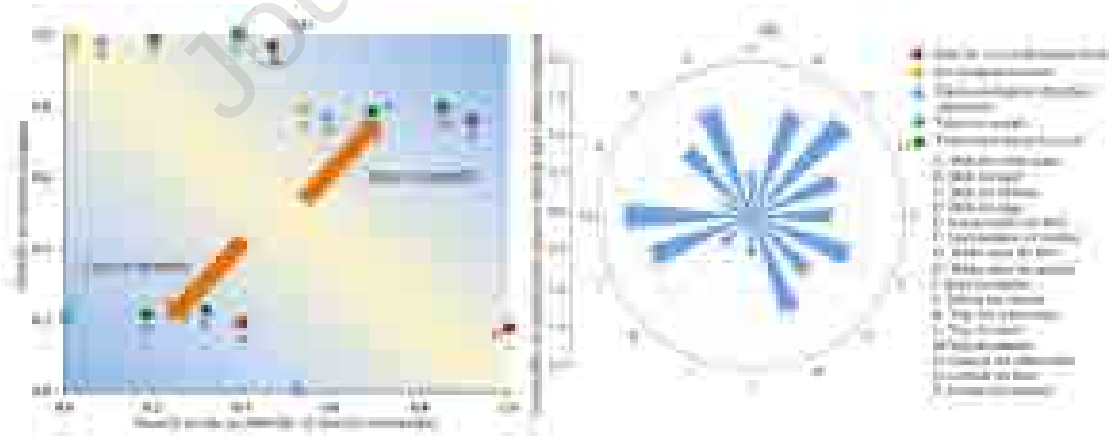

Figure 6. The co-benefits of 16 types of dietary adjustment scenarios. Points with the same color in the quadrant map (a) on the left reflect substitution of the same food types. The graph (b) on the right presents the co-benefits of the dietary adjustment scenarios.

4 Discussion

4.1 Effects of dietary factors on obesity

After adjusting for socioeconomic variables, milk and vegetables were protective factors against O/O, while other foods represent risk factors. The role of milk in obesity is consistent with results from epidemiological studies and health interventions (Pereira et al., 2002; Rosell et al., 2006). Rosell et al. (2006) estimated that women with a constant daily intake of more than one serving of milk per day had a significantly lower risk of gaining weight. Besides, an increase in dairy food intake produces significant and substantial suppression of the oxidative and inflammatory stress associated with being overweight or obese (Zemel et al., 2010). Additionally, dietary calcium contained in milk has been suggested to play a crucial role in the regulation of energy metabolism by down-regulating the concentrations of circulating parathyroid hormone and calcitriol, and there is also an increment of calcium in adipocytes, which in turn stimulates lipolysis and inhibits fatty acid synthesis (Zemel and Miller, 2004). Dietary fiber may be related to body weight regulation by inducing greater satiety among individuals consuming self-selected diets, meaning vegetable consumption can play a role in weight regulation (Pereira et al., 2001). But for fruit, fructose intake may be related to a higher risk of weight gain with increased consumption. Field et al. (2003) indicated that a diet rich in fruit might lead to substantial gains in weight. In our study, consumption of cereals is correlated with O/O, which is in line with research on Chinese university students (Field et al., 2003). There was a significantly higher prevalence of overweight and obesity for people who consumed potatoes more than once a week (Heidari-Beni et al., 2015), which might be because of the consumption of higher fat and energy intake (Dabbagh-Moghadam et al., 2017). However, several studies support the view that potato consumption is a protective factor against weight gain (Khosravi-Boroujeni et al., 2012). When it comes to soy product consumption, our results are contrary to previous studies (Velasquez and Bhathena, 2007). The latest research reports that no significant body weight reductions are associated with soy protein food intake (Speaker et al., 2018). Research on the effects of egg consumption on obesity is limited and has not reached consensus. Our results support the positive effect of egg consumption on weight gain (Song et al., 2012).

Previous research has summarized the evidence of a prospective association between the intake of foods and the risk of general overweight/obesity (Schlesinger et al., 2019). According to the results, we can know that with each increase in egg intake of 50g/d, the OR was 1.24, and the OR for weight gain was 1.16 in high per a 100g/d increase in red meat consistent with our result. The study indicated that egg intake was associated with an increased risk of weight gain. The RR for high egg intake compared with low intake was 1.54 (95% CI: 1.00, 2.37), and with each increase in egg intake of 50 g/d, the OR was 1.24 (95% CI: 1.00, 1.54). However, high-quality and standardized randomized controlled trials or cohort studies are necessary to explore the relationship. Meat consumption is positively correlated with O/O, which may be related to food energy density altering appetite control signals (Vergnaud et al., 2009). However, different results suggest these links are not yet shown conclusively

(Leslie et al., 2002; Wagemakers et al., 2009), and partly due to differences in the definitions of red meat and obesity in the different surveys and the statistical methods used for analysis. Lastly, pork consumption had no correlation with O/O in our study and deserved to be further studied.

4.2 Benefits of dietary adjustment for human health and the environment

This study provides a relatively comprehensive DASs and evaluates the effects on obesity and CF. In terms of the effect on nutrition, there are big disparities between plant-based foods and animal-derived foods, so it is necessary to supplement with other foods to make up nutrition loss. For instance, soy products are rich in protein but lack certain micronutrients that are necessary for growth, especially for children. Our results indicate that the scenario of substituting milk for non-milk animal foods (especially red meat) can produce significant benefits on obesity and CF. Currently, milk consumption is lower than the Chinese dietary guidelines, while meat intake has exceeded the upper level of the recommendation and continues increasing. Under an assumption that half of the population participate in the dietary substitution twice a week in China, then in the scenario of substituting red meat with milk (50g substitutions), a total of 9.1Mt CO_2e in emissions would be saved per year, which equates to 12% of GHG emissions from New Zealand agriculture (Leslie et al., 2008). In terms of cost, milk is cheaper than meat, and the time spent on cooking meat can be reallocated to other activities. However, although milk can substitute for the protein contained in meat, other nutrition such as amino acids, iron, and zinc are challenging to compensate for and would need to be obtained from other foods or additives. If half of the population participates in substituting meat with soy products twice a week in China, there would be a 6.5Mt CO_2e reduction per year, which is equal to 1.5% of emissions due to plant-based food production in China. Daily intake of 47g soy protein is associated with a fall in total cholesterol of 9.3%, a fall in low-density lipoprotein (LDL)-cholesterol of 12.9%, a fall in triglycerides of 10.5%, and an increase (non-significant) in high-density lipoprotein (HDL)-cholesterol of 2.4%, with associated benefits for prevention of other diseases, such as CHD, cancer, and diabetes (Anderson et al., 1995). However, there is oxalic acid in soy products, which may impede the absorption of minerals, such as iron, calcium, and zinc (Liu et al., 2004). Apart from soy products, other meat alternatives are currently very topical as meat alternatives, such as cultured meat and *in vitro* meat. In a life-cycle analysis, *in vitro* meat has the potential to reduce land usage by 99%, water usage by 90%, and energy consumption by 40%, compared with conventional meat production under specific production conditions (Tuomisto and Mattos, 2011). The environmental cost of soy-based meat is lower than traditional meat and other kinds of artificial meat (Smetana et al., 2015). However, some challenges still exist for new meat alternatives. Conventional meat products are well established in the market and have a significant advantage over novel products (Bonny et al., 2017). Furthermore, the technology to produce *in vitro* meat on a large industrial scale remains theoretical at current stage. Importantly, meat alternatives currently hold a small market share, and only 43% of people are willing to try *in vitro* meat (Bonny et al., 2017). Overall, the meat alternatives market is promising, such as soy-based meat.

Among the scenarios of meat structural adjustment, reduced CF by about 2.0 kg CO_2e and the P_c was up to -18%. Under the assumptions mentioned above, substituting red meat with white meat would produce a reduction of 3.4Mt CO_2e of footprint per year. Restructuring meat variety consumption is a promising way to produce dual benefits for the environment and human health (Gu et al., 2019). In light of low seafood consumption in China, it may be desirable to substitute red meat with seafood. The evidence reflects that an increase of 50 g/d in processed meat and red meat intake has been positively associated with CVD mortality (Abete et al., 2014). The scenario of substituting tubers with cereals results in no apparent benefits at the individual level. However, given the population size of China, the scenario would produce a reduction of 0.3Mt CO_2e of CF per year under the assumption mentioned above. A policy of consuming potatoes as a staple food (PSF) could result in CF reductions equal to 1.1-9.0% of CO_2e as a result of reduced emissions associated with CH_4 and N_2O emitted from the Chinese agroecosystems in 2005, and this change would also result in reduced use of N fertilizer and irrigation-water (Gao et al., 2019). Potatoes contain various nutrients essential to the human body, including higher lysine content than wheat or rice (Yang et al., 2004). Promoting the value of tubers in nutrition and health helps promote the environmental benefits of this scenario. Similar to previous studies, our study enhanced the benefits of substituting meat with plant-based foods. Michaelowa and Dransfeld (2008) assumed that a 25% consumption reduction in livestock products in Organization for Economic Co-operation and Development (OECD) populations could reduce obesity risk and result in a 17% reduction in GHG emissions. In an extreme scenario with complete substitution of animal-derived foods, the estimated agricultural GHG emissions could decrease by 28% but maybe create new nutritional problems (White and Hall, 2017). In global terms, human mortality rates could be reduced by 6%-10%, and food-related GHG emissions reduced by 29%-70%, compared with a reference scenario in 2050 (Springmann et al., 2016). But Vieux et al. (2012) found that substituting meat with fruit and vegetables resulted in no or even increased diet-associated GHG emission changes. This result is not in line with our findings, probably because of the principle of iso-caloric substitution, which means needing many more vegetables or fruit to compensate for the energy contained in meat. Overall, these results suggest that replacing red meat with other foods such as vegetables, cereals, and poultry could produce positive benefits for human health and the environment. Dietary adjustment is a promising way to balance human health and the environment if plant-based dietary consumption patterns are widely adopted.

4.3 Limitation and outlook

The study comprehensively explored the effects of DASs on obesity and carbon footprint. We establish the statistical relationship between dietary factors and P_O, which is a correlation, not causality. In the model, not all related risk factors for O/O were considered, including nutritional value, price, and food availability. Additionally, more environmental indices should be examined, including water and energy consumption, land use, reactive nitrogen, and phosphorus use, not just CF. Given the complexity of obesity and its risk factors, introducing a machine learning method, such as artificial neural nets, maybe a helpful avenue for future research. Also, dietary habits are hard to change in the short term, so understanding practices to modify food consumption behaviors is needed. In responding to the current dietary shift in places like China, total food demand and supply should also be considered.

5 Conclusions

This study couples obesity/overweight and carbon footprint through the dietary adjustment to balance the synergies between healthy diet choices and environmental impacts. We found that most DASs had a significant effect on weight loss and CF. Consumption of vegetables, cereals, and fruit produce more optimal co-benefits than consumption of mutton and beef. In all of the DASs, the most benefit refers to the 30% reduction in P_O, and CF changes ranged between -2.65 kg CO_2e and 2.61 kg CO_2e. The scenario of substituting mutton with vegetables produced the most co-benefits. Moreover, we should also focus attention on the effect of dietary adjustment on nutrition, especially protein consumption. The study highlights the view that dietary transition is effective for addressing the human health – environment dilemma. What a person chooses to eat does make a difference.

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Supporting Information

The supporting information includes six tables and one figure.

Table S1 Carbon footprint intensity of different food types (kgCO_2e/kg)

Table S2. Food Classification

Table S3. Overweight/obesity proportions of subjects with different characteristics in the CHNS (1997-2011)

Table S4 Calorie, protein, and fat content in different type foods per 100g

Table S5 Changes of dietary adjustment on calories, protein, and fat

Table S6 Per capita daily consumptions of different food type during 1997-2011

Table S6. Association between socioeconomic factors and obesity/overweight among Chinese adults, CHNS[a] 1997-2011 (n=38070)

Fig. S1 Consequences of different dietary adjustment scenarios both on obesity/overweight and CF

Table S1 Carbon footprint intensity of different food types ($kgCO_2e/kg$)

Milk	1.30	White meat	0.89
Vegetables	0.11	Soy products	0.32
Tubers	0.40	Mutton	19.77
Cereals	0.50	Beef	26.59
Fruit	0.24	Eggs	0.46

Table S2. Food Classification

Food group	Food items
Cereals	Corn, millet, wheat, oatmeal, buckwheat, black rice, rye, sorghum, barley, rhubarb, glutinous rice, bread, japonica rice, noodles, etc.
Tubers	Potato, taro, sweet potato, areca taro, yam, etc.
Vegetables	Amaranth, eggplant, laver, bamboo shoot, celery, rapeseed, bean, cabbage, leek, onion, radish, mustard, mushroom, dragon's horn, tomato, squash, lettuce, pea, baby cabbage, beet, green lettuce, bitter gourd, water spinach, etc.
Salted vegetables	Eight dishes, artichokes, co-Jin dishes, dog sprouts, sauce packet melon, garlic sauce, radish, pickled chives, mustard, pickled cucumber, etc.
Nuts and seeds	Ginkgo, walnuts, peanuts, chestnuts, sunflower seeds, pine nuts, hazelnuts, etc.
Dessert	Cake, pineapple cake, Jiangmi strip, mung bean cake, red bean cake, biscuit, smashing, rice cake, peach cake, moon cake, wife cake, ect.
Sugar	White sugar, rock sugar, honey, brown sugar, gum candy, sugar candy, marshmallow, toffee, chocolate, crisp sugar, etc.
Beans	Lentils, mung beans, red beans, kidney beans, peas, cowpeas, peas, etc.
Alcohol	White wine, red wine, beer, wheat wine, yellow wine, etc.
Soft beverage	Cola, red juice, orange juice, chocolate soy milk, soda, sour plum soup, joy, almond dew, etc.
Fruit	Pears, grapes, apples, kiwifruit, oranges, dates, coconut, carambola, plum, apricot, watermelon, longan, peach, fig, grapefruit, banana, persimmon, mangosteen, mulberry, soft pear, pomegranate, syzygy jumbos, loquat, lemon, papaya, citrus, litchi, strawberry, dragon fruit, orange, sour thorn, etc.
Soy products	Tofu pudding, tofu, dried bean curd, soybean milk, vegetarian chicken, soybean skin, soybean, soybean meal, tofu skin, dried brine, soybean powder, etc.
Oil	Lard, sesame oil, corn oil, fish oil, sheep oil, salad oil, butter, cottonseed oil, peanut oil, soybean oil, tea oil, rapeseed oil, etc.
Other plant-based foods	medicinal materials, condiments, chicken legs crisp, jelly, cool skin, etc.
Pork	Pork, pork ribs, pork fillet, pork liver, pork ears, ham, pork chops, pork belly, pork liver, pork large intestine, pig's trotters, pig's toggles, etc.
Beef	Beef, beef tendon, beef jerky, tripe, bovine lung, cattle brain, beef

	tendon, cattle heart, cow blood, cattle kidney, etc.
Mutton	Mutton, mutton string, Sheep brain, sheep tongue, sheep kidney, sheep heart, sheep liver, sheep lung, sheep large intestine, etc.
Poultry	Pheasant, duck, duck wings, native chicken, frog, chicken, dove, goose, etc.
Seafood	Mackerel, turtle, shrimp, octopus, caviar, squid, sardines, tuna, bighead, whitebait, skate, grass carp, small yellow croaker, scallop, snails, oyster, black carp, loach, cuttlefish, prawn, silver carp, carp, oral fish, flower, yellow croaker, mussel, sea cucumber, hardtail, razor clam, etc.
Eggs	Duck eggs, eggs, turtle eggs, goose eggs, quail eggs, etc.
Milk	Yoghurt, cow milk, goat milk, milk powder, cow milk powder, goat milk powder, milk tablets, calcium milk, etc.
Other animal foods	Horse meat, donkey meat, morel, rabbit meat, dog meat, horse heart, camel palm, camel, etc.

Table S3. Overweight/obesity proportions of subjects with different characteristics in the CHNS (1997-2011)

Variable	Total	Obesity	Overweight	Variable	Total	Obesity	Overweight
Sample size (%)	38070	3044(8.0)	10856(28.5)	Smoking status (%)			
Town (%)				Never	25307	2133(8.4)	7414(29.3)
Yes	12814	1158(9.0)	4011(31.3)	Before	1062	114(10.7)	380(35.8)
No	25256	1886(7.5)	6847(27.1)	Current	11701	797(6.8)	3064(26.2)
Drinking status (%)				Employment status (%)			
Yes	14230	1878(7.9)	6659(27.9)	Yes	29735	2121(7.1)	7917(26.6)
No	23834	1166(8.2)	4199(29.5)	No	8335	923(11.1)	2941(35.3)
Income status (%)				Work intensity (%)			
In debt	598	43(7.2)	145(24.2)	Extremely light	8298	888 (10.7)	2940(35.4)
<5000	11544	736(6.4)	2741(23.7)	Light	7588	699(9.2)	2335(30.8)
5000 <x<10000	8764	657(7.5)	2458(28.0)	Moderate	5835	484(8.3)	1722(29.5)
10000 < x< 20000	9857	887(9.0)	3000(30.4)	Heavy	15894	925(5.8)	3736(23.5)
>20000	7307	721(9.9)	2514(34.4)	Very heavy	251	21(8.4)	59(23.5)
Marriage status (%)				No working ability	202	27(13.4)	64(31.7)
Yes	35279	2936(15.2)	10434(29.6)	Education level			
No	2791	108(3.9)	424(8.3)	Low	27563	2204(8.0)	7499(27.2)
				Middle	7798	609(7.8)	2529(32.4)
				High	2709	231(8.5)	830(30.6)

Table S4 Calorie, protein, and fat content in different type foods per 100g

	White meat	Beef	Mutton	Pork	Milk	Eggs	Soy Product	Cereal	Tuber	Fruit	Vegetable
Calorie	187.8	158.9	171.8	285.9	340.3	171.5	189.6	349.2	95.0	54.5	41.1
Protein	17.7	21.4	19.1	16.3	8.0	13.1	19.3	9.4	1.5	0.9	2.4
Fat	11.1	5.9	9.3	21.2	25.0	11.6	9.2	2.2	0.2	0.2	0.5

Journal Pre-proof

Table S5 Changes of dietary adjustment on calories, protein, and fat

Scenario	Calories	Protein	Fat	Scenario	Calories	Protein	Fat
Milk to Veg.	0.04	0.02	0.21	Beef to Mutton	0.001	0.006	0.02
Milk to White meat	0.01	0.01	0.04	Tuber to Cereal	0.03	0.03	0.02
Milk to Beef	0.02	0.03	0.11	Tuber to White Meat	0.01	0.05	0.06
Milk to Mutton	0.02	0.03	0.09	Tuber to Beef	0.01	0.05	0.0.3
Milk to Egg	0.02	0.01	0.08	Tuber to Mutton	0.01	0.05	0.05
White meat to Beef	0.05	0.17	0.07	Veg. to White Meat	0.02	0.04	0.06
White meat to Mutton	0.002	0.004	0.01	Veg. to Beef	0.01	0.05	0.03
White meat to Egg	0.02	0.01	0.003	Veg. to Mutton	0.01	0.05	0.05
Soy prod. to Egg	0.002	0.02	0.01	Cereal to White Meat	0.02	0.02	0.05
Soy prod. to Mutton	0.002	0.0008	0.001	Cereal to Mutton	0.02	0.03	0.02
Soy prod. to Beef	0.003	0.005	0.02	Cereal to Beef	0.02	0.02	0.04

Table S6 Per capita daily consumptions of different food type during 1997-2011

	Cereal	Tuber	Soy Product	Vegetable	Fruit	Egg	Milk	Poultry	Seafood	Pork	Beef
1997	431.0	30.3	34.6	252.3	14.0	19.4	3.0	7.7	14.8	48.0	2.1
2000	396.2	27.8	39.4	265.7	12.8	21.8	7.9	8.4	15.1	55.7	2.1
2004	410.9	37.3	40.1	273.5	19.2	22.3	17.6	8.9	17.0	53.1	6.1
2006	382.5	37.6	44.1	267.4	37.6	25.4	17.4	8.7	18.5	57.9	6.4
2009	371.5	34.8	48.9	262.5	41.9	26.7	17.6	11.1	19.8	61.9	5.2
2011	350.0	31.1	43.5	244.5	58.0	27.0	34.2	13.5	19.8	57.5	6.8

Data source:

Yang, Y.X., Wang, G.Y., Pan, X.C., 2002. China Food Composition Tables. Beijing, Peking University Medical Press.

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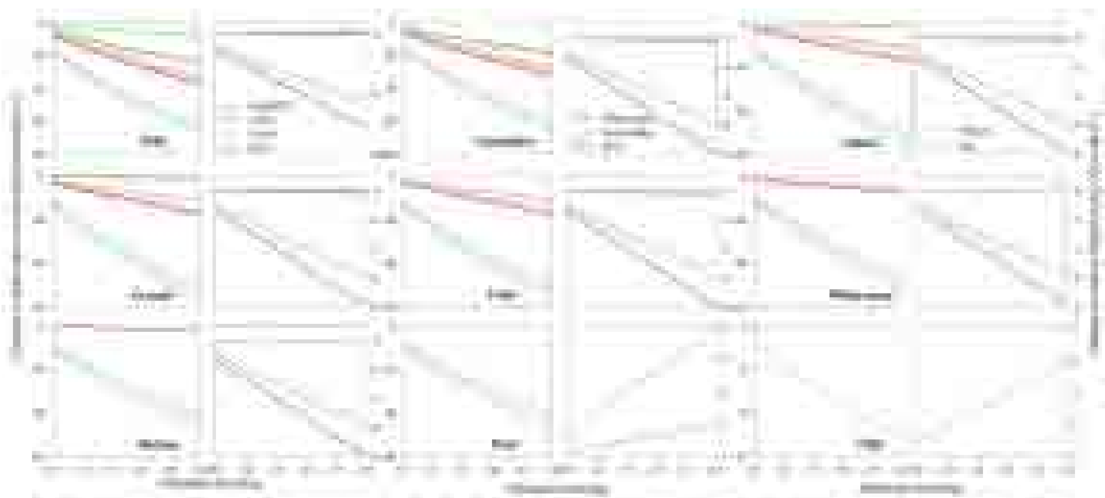

Fig. S1. Consequences of different dietary adjustment scenarios both on obesity/overweight (left) and CF (right)

Highlight:

- Impacts of 11 foods on overweight/obesity and carbon footprint (CF) are evaluated
- The effects of 16 scenario on overweight/obesity and CF are mainly estimated.
- Substituting mutton with milk produced the best co-benefits.
- Scenario of meat structure adjustment could produce the largest CF benefit
- Substituting meat with soy products is promising for obesity-CF delimma

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: