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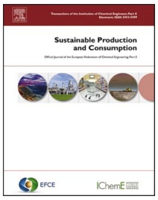

# Transition towards sustainable diets: Multi-objective optimization of dietary pattern in China

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ABSTRACT

Global diversity in food cultures has led to a variety of dietary patterns, the evolution of which can significantly impact greenhouse gas (GHG) emissions. To address the dual challenge of climate change and malnutrition, we need to examine feasible pathways towards sustainable diets that balance nutritional adequacy, environmental impact, and cultural acceptability. We propose an optimized dietary transition pathway in China, which aligns with the nation's dietary guidelines (DGs) while aiming to reduce diet-associated GHG emissions and maintain the cultural food preferences. We also examine how the current dietary patterns will change under three different scenarios: 1) meeting nutritional needs (N), minimizing GHG emissions while maintaining nutritional standards (NE), and sustaining cultural acceptance and maintain GHG emissions at a low level while ensuring standard nutrient intake (NEC). We analyze data from 31 provinces in China between 2000 and 2020 to explore sustainable dietary patterns. In this period, plant-based food consumption has experienced a substantial 12 % decrease, in contrast to the 68 % increase in animal-sourced food intake. Meanwhile, diet-associated GHG emissions in China have increased by 17 %. However, dietary nutrition remains below national standards. The diet-associated GHG emission under NEC is 63.43% lower than N and is 7.04% higher than NE, while NEC in cultural unacceptability is 28.39% lower than NE. Our optimized dietary patterns demonstrate the potential to achieve the national nutrition standard, significantly cut GHG emissions, and retain higher cultural acceptability. Acknowledging the regional disparities in sustainable dietary pathways, we propose the implementation of customized provincial directives aimed at fostering compliance with these favorable trends. Our study offers critical policy implications towards achieving a sustainable diet in China, which contributes to managing the complex trade-offs among nutrition, cultural preferences, and environmental impact.

## 1. Introduction

Sustainable diets extend beyond fulfilling nutritional needs. They encompass the imperative of minimizing environmental impact and respecting cultural acceptability, providing actionable guidelines instead of remaining as theoretical ideals (Chaudhary et al., 2018; Gazan et al., 2018; Perignon et al., 2017). The significant contrast between the rising prevalence of overnutrition-induced diseases in high-income countries and the persistent issue of malnutrition in low-income ones highlights the global challenge of improving dietary nutrition (Willett et al., 2019). Meanwhile, the food system, contributing over a third of global greenhouse gas (GHG) emissions with a 1 % annual increase, ranks as the second-largest emitter worldwide, following only industrial activities (Crippa et al., 2021). In a scenario where unchecked dietary evolution, coupled with heightened nutritional quality, leads to significant environmental impacts, causing intensification of malnutrition and environmental degradation as production capacity increases (Doro and Réquillart, 2020; Garnett, 2014; Liao et al., 2021; Roos et al., 2015).

Food culture profoundly influences daily lives of communities, reflecting unique regional nuances and characteristics (Dengerink et al., 2021; Ibarrola-Rivas and Nonhebel, 2022). This cultural inertia, which upholds existing dietary patterns, can pose challenges when trying to adopt globally recognized nutritional diet such as the Lancet diet, the Mediterranean diet, or China's national dietary guidelines (DGs). This challenge is particularly pronounced in regions where dietary habits are intertwined with cultural traditions and practices (Broaddus-Shea et al., 2020). Therefore, acknowledging and accommodating food

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### Nomenclature

| | |
|---|---|
| $a_{(j,k)}$ | the proportion of nutrient $k$ in the $j^{th}$ food group; k refers to the macronutrients, which include protein, fat and, carbohydrate |
| $CF_j$ | the carbon footprint of the $j^{th}$ food group |
| $CUA_j$ | the gap of the food group $j$ between the status and optimized dietary patterns |
| $FC_{j_{bau}}$ | the consumption of the $j^{th}$ food group in 2020 |
| $FC_{j_{lower}}$ and $FC_{j_{upper}}$ | the recommended lower and upper limit of food intake respectively |
| $FC_{j_{opt}}$ | the consumption of the $j^{th}$ food group in optimized dietary patterns |
| $FC^t_{i,j}$ | the consumption of the $j^{th}$ food group by residents of area $i$ in year $t$ |
| $N_{k_{lower}}$ and $N_{k_{upper}}$ | the recommended lower and upper limit of nutrient $k$ respectively |
| $N^t_{i,k}$ | the intake of nutrient $k$ by residents of area $i$ in year $t$ |

acceptability are crucial for facilitating the transition towards sustainable diets that harmonize nutritional, environmental, and cultural factors, which is a pivotal global endeavor (Rohmer et al., 2018).

As a rapidly developing nation with a large population, China has witnessed significant shifts in its dietary patterns over the past few decades (Gazan et al., 2018). Propelled by modernization, the nation's food system is struggling with considerable sustainability challenges, presenting a complex dual problem for the Chinese government (Gazan et al., 2018). On the one hand, there are lingering issues of malnutrition; on the other hand, the increasing prevalence of over nutrition is burdening the healthcare system (Bai et al., 2022). In response to these nutritional challenges, the government has launched a series of initiatives, including the "Outline of the Healthy China 2030 Plan", "The National Nutrition Plan (2017-2030)", "Healthy China Action Plan (2019-2030)" (Wang et al., 2022). However, some analyses of China's dietary patterns have overlooked sustainability, focusing solely on individual components (Yue et al., 2022b). It is, therefore, essential to recognize that the modernization of dietary patterns, coupled with population growth, implies not only an elevation in nutritional demand but also an increase in GHG emissions from the food system. This necessitates a delicate balance between nutritional needs and environmental impact (He et al., 2019; Li et al., 2016; Tian and Yu, 2015). Existing research often confines itself to specific regions of China (Ding et al., 2022; Li et al., 2020; Yin et al., 2020) or distinguishes research areas based on urban or rural divisions according to household registration (Dou and Liu, 2023; Wang et al., 2020; Wu et al., 2022). This approach is likely to miss the vast regional variations in food habits across China's diverse geographic and cultural landscapes. Given the rich diversity of food habits across different provinces, developing a uniform dietary pattern for the entire country is a challenging endeavor (Zhu et al., 2013). The intricate mosaic of food habits suggests that a standardized dietary approach may not suffice for China.

To address the above mentioned issues, we propose a multi-objective optimization approach that navigates the complex interplay between nutrition, environment, and culture. This approach empowers us to deliver province-specific policy recommendations, uniquely tailored to address the distinct needs of each region in China. The optimized dietary patterns we identify aim not only to fulfill nutritional requirements but also reduce diet-associated GHG emissions. Furthermore, they strive to enhance cultural acceptability, thus forming a robust foundation for effective dietary guidance policy. In doing so, we contribute valuable insights to the ongoing global discourse on sustainable diets. The remainder of the paper is organized as follows: Section 2 offers a review of relevant literature. Section 3 outlines the primary methodology and data employed in our research. Section 4 presents the findings on dietary patterns, nutrient intake, GHG emissions, and the multi-objective optimization of dietary patterns. Section 5 presents the discussion, and Section 6 provides the conclusions of the paper.

## 2. Literature review

Over the past decade, the primary driver of increase in global food demand has shifted from population growth to changes in dietary patterns (Bajzelj et al., 2014). This shift has led to numerous studies aimed at optimizing dietary patterns. However, the focus on nutritional adequacy often results in an escalation of environmental stress associated with these patterns, thereby compromising their sustainability (Ambikapathi et al., 2022; Gill et al., 2015). To address this challenge, various studies have incorporated environmental impact assessments, exploring strategies to mitigate these effects, such as reducing diet-associated GHG emissions across the entire life cycle (Esteve-Llorens et al., 2020; Geyik et al., 2023). Nevertheless, the application of Life Cycle Assessment (LCA) with a cradle-to-gate system boundary often neglects GHG emissions linked to food utilization and consumption (Esteve-Llorens et al., 2019; Usva et al., 2023), because a cradle-to-gate LCA model represents only a fraction of the whole life-cycle. Consequently, reported GHG emissions underrepresented the actual figures, resulting in underestimated environmental impacts (Hallstrom et al., 2015; Vidergar et al., 2021).

When studies aim to optimize dietary patterns while considering cultural dimensions, they often employ the degree of change or the ratio between current and optimized dietary patterns as an indicator of food culture acceptability (Perignon et al., 2016; van Dooren et al., 2014). This approach often neglects the inherent evolution of dietary patterns, which can include changes that consumers find culturally unacceptable. For instance, some authors introduced the acceptability constraint as a range (Biesbroek et al., 2014; Macdiarmid et al., 2012; Yip et al., 2013). Similarly, others presented the concept of "consumption inertia" for specific agricultural and food products (Arnade et al., 2008; Karagiannis et al., 2000; Karagiannis and Velentzas, 1997; Stanton, 2007), which follows a rational that the consumption of highly consumed goods tends to continuously increase over time. Therefore, it is critical to holistically integrate nutritional, environmental, and cultural dimensions in the optimization of dietary patterns and extend GHG emissions analysis from the farm gate stage to the trajectory of dietary changes.

We applied optimization models to identify the tradeoffs in diets across the nutritional, environmental, cultural dimensions. The linear programming models considering a desirable single goal or multi-goals were used to optimize diets pattern. In terms of algorithm for adaptive dietary patterns, optimal dietary goals such as GHG mitigation were selected as the objectives, and nutritional requirements were chosen as constraints (Chungchunlam et al., 2020; Larrea-Gallegos and Vázquez-Rowe, 2020; van Dooren et al., 2015). In recent years, non-linear heuristic optimization algorithms have been proven effective in addressing diet optimization due to the nonlinear effects of socio-economic indicators on food demand (Chaudhary and Krishna, 2019). Some studies have used non-linear programming such as particle swarm optimization (PSO) (Yin et al., 2020) and non-dominated sorting genetic algorithm II (NSGA-II) (Yue et al., 2022b) to perform dietary pattern optimization. Especially, NSGA-II, known for its diverse solutions and fast non dominant sorting, addressing the subjectivity of weight allocation in multi-objective research (Rahman and Szabo, 2021), has been wildly introduced to addressing diet pattern optimization (Yin et al., 2020).

Our research bridges several knowledge gaps. First, it recognizes the dynamic interplay among nutrition, environment, and culture, emphasizing how a shift in one can affect the others, and explores a sustainable diet that is nutritionally adequate, environmentally sustainable, and culturally acceptable. Second, it incorporates a comprehensive analysis of the food product life cycle, covering GHG emissions from production

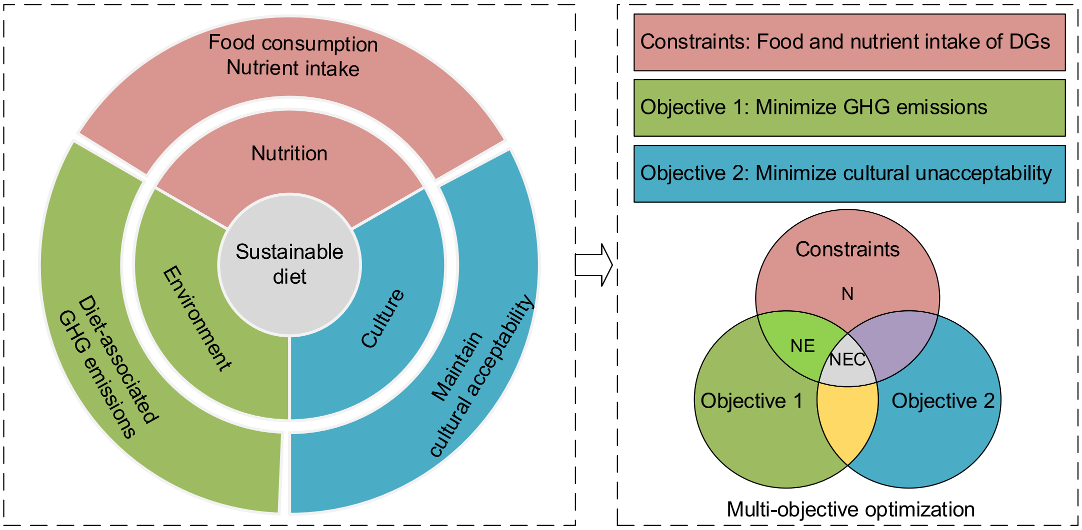

**Fig. 1.** Research conceptual framework. The left panel reveals the three dimensions of sustainable diet. The right panel illustrates the multiple objectives and how their overlaps lead to our three scenarios. N = Nutrition scenario; NE = Nutrition-Environment scenario; NEC = Nutrition-Environment-Culture scenario.

to disposal, thereby enhancing our understanding of the environmental impact of dietary choices. Third, it defines "unacceptability" when the modeled diet deviates from observed food trends, accounting for emerging dietary patterns alongside traditional food habits. As such, it is especially relevant for regions undergoing significant dietary shifts, such as China.

## 3. Methods

### 3.1. Conceptual framework

We propose a comprehensive framework of a sustainable diet which encapsulates the complex interplay among nutrition, environment, and culture (Fig. 1). The advantage of this framework is that it incorporates multifaceted dimensions in dietary pattern. Specifically, while the primary goal of this dietary pattern is to provide the body with necessary nutrients for survival, it respects cultural acceptability of different foods among people with various dietary preferences and restrictions stemmed from their unique tastes, beliefs, or religious obligations (the left panel). Meanwhile, this framework also considers the environmental impacts of dietary patterns and can minimize GHG emissions through comparing GHG emissions under three scenarios and shifting towards sustainable diets that emit less GHG.

Although organically synthesized into a comprehensive framework, there may be trade-off between the three dimensions (Gazan et al., 2018). For instance, a dietary pattern that meets nutritional requirements may pose challenges to the environmental and/or food preference (Brouwer et al., 2021). Similarly, reducing environmental impacts by limiting consumptions of high-GHG emission food may result in insufficient nutrient intake (Ambikapathi et al., 2022). Additionally, while some traditional dishes carry cultural significance, they may also give rise to health concerns or result in elevated environmental impacts (Poppy et al., 2022).

We aim to increase food diversity and nutrient intake while respecting local food preferences and traditions and minimizing GHG-emission through transiting towards optimal dietary patterns. To achieve the goal, we first compare different dietary patterns and their associated nutrient intake and GHG emission. We then employ multi-objective optimization method to optimize dietary patterns through shifting to food consumption that complies with local food preferences and food intake range recommended by China's DGs, and explore GHG emission under the transition to sustainable dietary patterns. We also construct three scenarios using 2020 as a baseline to examine to that extent the current dietary patterns should be changed under different scenarios. The first scenario (Nutrition, or N scenario) is centered on meeting nutritional needs. The second scenario (Nutrition-Environment, or NE scenario) aims to minimize GHG emissions while maintaining nutritional standards. The third scenario (Nutrition-Environment-Culture, or NEC scenario) aspires to sustain cultural acceptance and maintain GHG emissions at a low level while ensuring standard nutrient intake.

### 3.2. Measuring dietary patterns and nutritional status

Referring to the existing literature (Ding et al., 2022; Wang et al., 2021; Wu et al., 2022; Zhen et al., 2010), we use a comprehensive set of eleven food groups, comprising grains, vegetables, fruits, pork, beef, mutton, poultry, aquatic products, eggs, dairy products, and edible oil to delineate the dietary patterns, which are aggregated into food groups that mostly match the DGs' food patterns components used for dietary recommendations for a healthy diet based on the nutritional values of different foods. The analyses of dietary patterns align with the recommended food intake range provided by the "Food Guide Pagoda" for Chinese Residents (see Appendix 1). This guide serves as the DGs proposed by the Chinese Nutrition Society (Chinese Nutrition Society, 2022).

The analyses of nutrient intake levels adhere to the recommended nutrient intake range (see Appendix 2). Existing research consistently shows that the study of macronutrients is primarily focused on the field of food nutrition (Jiang et al., 2021; Springmann et al., 2018; Yin et al., 2020; Yu and Du, 2022). Drawing on this body of work, we chose to focus on three specific nutrients, namely carbohydrate, fat and protein, alongside energy. The consumption of each food group is converted into the intake of energy and three important macronutrients that are obtained through each food group:

$$\mathrm{N}_{\mathrm{i,k}}^{\mathrm{t}} = \sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{FC}_{\mathrm{i,j}}^{\mathrm{t}} \cdot \mathrm{a}_{\mathrm{j},k} \tag{1}$$

where $i$ is an index for the cross-sectional dimension (spatial units), with $i = 1, 2, 3, \dots, P$; $t$ is an index for the time dimension (time periods), with $t = 1, 2, 3, \dots, T$; $j$ is an index for the types of the food groups, with $j = 1, 2, 3, \dots, n$, and $k$ is an index for the types of nutrients, with $k = 1, 2, 3, \dots, K$. $N_{i,k}^{t}$ is the intake of macronutrient $k$ by residents of area $i$ in year $t$; $FC_{i,j}^{t}$ is the consumption of the $j^{th}$ food group by residents of area $i$ in year $t$; $a_{j,k}$ is the proportion of nutrient $k$ in the $j^{th}$ food group. $i$ is 31 provinces in

China; *t* is 2000, 2005, 2010, 2015, and 2020; *j* is eleven food groups, comprising grains, vegetables, fruits, pork, beef, mutton, poultry, aquatic products, eggs, dairy products, and edible oil; *k* is protein, fat, and carbohydrate from diet.

The dietary pattern data of each province are assessed for the years 2000, 2005, 2010, 2015, and 2020. We employ distinct procedures to process the data as they come from different sources across years. For 2000, 2005 and 2010, the data is first divided into urban and rural areas. For urban residents, the dietary pattern data of dairy products is directly collected from the table "output of livestock products and major farm products" in China Dairy Statistical Yearbook, and others are collected from provincial statistical yearbooks. As for missing data, we derived them from various consumption expenditures (from the China Statistical Yearbook) and corresponding prices (from the China Yearbook of Agricultural Price Survey) of each food group by considering the grain conversion factors (0.85) (Yu and Du, 2022). For rural residents, the dietary pattern data is directly collected from the table "output of livestock products and major farm products" in China Statistical Yearbook. In the case of 2015 and 2020, the data is directly collected from the China Statistical Yearbook. Energy and macronutrient intakes are derived from these dietary patterns and corresponding conversion factors. The conversion coefficients between food groups and their nutrient contents are obtained from the Chinese Food Composition Table.

### 3.3. *Quantifying diet-associated GHG emissions*

To quantify diet-associated GHG emissions, we employ the Life Cycle Assessment (LCA) method. Considering that the carbon footprints of each food group at different times are difficult to obtain, we use a uniform carbon footprint to measure diet-associated GHG emissions. This methodology accounts for the entire process as system boundary including raw food material acquisition, production, processing, storage, transportation, consumption, and recycling (Jones et al., 2016) (see appendix 3). To maintain the consistency of the system boundary, we select the carbon footprints of food groups that align with this boundary, as per the China Products Carbon Footprint Factors Database (CPCD) (China City Greenhouse Gas Working Group, 2020).

In the CPCD database, there are numerous carbon footprint data from different regions, time periods, and measurements. According to the technical reporting guidelines of the Intergovernmental Panel on Climate Change (IPCC), in order to reduce the influence of these factors, we set the food carbon footprint parameters to follow a triangular distribution with the minimum, mean and maximum values of the triangular distribution respectively (see Appendix 4). Monte Carlo method was used to solve the uncertainty of the food carbon footprint parameters (Hu et al., 2020). We further improve the accuracy of food carbon footprint calculation by randomly sampling subsets of the database. When the numbers of sampling instances is sufficiently large, the distribution of the output carbon footprint parameters will closely approximate the true probability distribution. Therefore, this study uses Oracle Crystal Ball software to conduct 10,000 random sampling for each of the carbon footprint parameters of the food products. Accordingly, 10,000 random data sets are generated for each category, based on which we determine the probability distribution of each food carbon footprint parameter (Li, 2020).

### 3.4. *Optimizing multi-objective dietary patterns*

We developed optimization models to investigate dietary patterns under the three scenarios mentioned above. We set constraints and objectives to facilitate this investigation. The constraints align with the recommended food intake according to the "Food Guide Pagoda" for Chinese Residents. One of our objectives explores GHG emissions of different dietary patterns and approaches to minimize GHG emissions. The other objective seeks to maintain cultural acceptability.

Correspondingly, under the N scenario, we aim to reach the average value of DG's as dietary pattern since it is unrealistic to accomplish maximum values given the high diversity of dietary patterns and food cultures across China. We consider the Euclidean distance between optimized diet and the average value of DG as the objective function to achieve the dietary pattern. Under the NE scenario, we also choose the single goal linear programming models with minimized diet-associated GHG emissions as objectives, and the DG's range as constraints to achieve the dietary pattern.

We then employ a multi-objective optimization method to investigate dietary patterns that can potentially minimize diet-associated GHG emissions, comply with DGs, and mitigate disruptions to traditional food culture. Under the NEC scenario we select minimized diet-associated GHG emissions and minimized cultural unacceptability as objectives, and the DG's range as constraints. In terms of algorithm for adaptive dietary patterns, the non-dominated sorting genetic algorithm (NSGA-II) (Pan et al., 2023; Yin et al., 2020) is used to estimate the production-possibility frontier of optimal dietary with respect to the dimensional objectives function and constraints. We employ the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), a comprehensive evaluation method, to obtain the optimal solution that best reconciles the potential conflict between nutritional demand, environmental impact and cultural acceptability. The specific implementation of the objective functions and the determination of the optimal solution using TOPSIS are described below.

#### 3.4.1. *Meeting nutrition needs*

If dietary pattern falls within DG's range, the dietary pattern is considered nutrition adequate. To ensure that the optimized dietary patterns meet the nutritional demands, we set constraints to ensure that the consumption of eleven food groups and the intake of four essential nutrient fall within the recommended intake range:

$$\mathrm{FC}_{\mathrm{j}_{\mathrm{lower}}} \leq \mathrm{FC}_{\mathrm{j}_{\mathrm{opt}}} \leq \mathrm{FC}_{\mathrm{j}_{\mathrm{upper}}} \tag{2}$$

$$\mathrm{N}_{\mathrm{k}_{\mathrm{lower}}} \leq \mathrm{N}_{\mathrm{k}} \leq \mathrm{N}_{\mathrm{k}_{\mathrm{upper}}} \tag{3}$$

where *j* is an index for the types of the food groups, with $j = 1, 2, 3, \ldots, 11$, and *k* is an index for the types of nutrients, with $k = 1, 2, 3, \ldots, \mathrm{K}$. $FC_{j_{opt}}$ is the consumption of the $j^{th}$ food group in optimized dietary patterns; $FC_{j_{lower}}$ and $FC_{j_{upper}}$ are the recommended lower and upper limit of food intake respectively; $N_k$ is the intake of nutrient *k* from diet; $N_{k_{lower}}$ and $N_{k_{upper}}$ is the recommended lower and upper limit of nutrient *k* respectively; *j* is eleven food groups, comprising grains, vegetables, fruits, pork, beef, mutton, poultry, aquatic products, eggs, dairy products, and edible oil; *k* is protein, fat, and carbohydrate from diet.

#### 3.4.2. *Minimization of diet-associated GHG emissions*

To make the optimized dietary patterns environmentally sustainable, we aim to minimize the environmental impact of food consumption. Accordingly, we set with the objective function, $\mathrm{F_E}$, to achieve the lowest possible diet-associated GHG emissions:

$$\mathrm{F_E} : minf_{\mathrm{GHG}} = \sum_{\mathrm{j=1}}^{11} \mathrm{FC}_{\mathrm{j}_{\mathrm{opt}}} * \mathrm{CF}_{\mathrm{j}} \tag{4}$$

where $CF_j$ is the carbon footprint of the $j^{th}$ food group.

#### 3.4.3. *Maximization of food cultural acceptability*

In ensuring that the optimized dietary patterns are consistent with the existing dietary habits of residents, we aim to minimize cultural unacceptability. We know factors such as tastes, beliefs, religious obligations, age, and other factors are some of the main direct causes of regional dietary cultural differences. However, it is challenging to directly quantify regional dietary cultural differences using these factors. Since dietary culture has a historical inheritance, incongruity between the trends in changes of optimized dietary patterns and the

**Table 1**
Definition of unacceptability of food culture.

| | | Actual food consumption trends | |
|---|---|---|---|
| | | Increasing | Decreasing |
| Optimized food consumption trends | Increasing | Consistent | Inconsistent |
| | Decreasing | Inconsistent | Consistent |

existing habits could indirectly represent intricate mosaic of food habits. If there is any incongruity between the trends in changes of optimized dietary patterns and the actual trends, we consider this as the degree of unacceptability ($CUA_j$). Therefore, minimizing this degree of inconsistency forms our objective function, $\mathrm{F_{cul}}$:

$$\mathrm{F}_{cul} : minf_{\mathrm{uncul}} = \sqrt{\sum_{\mathrm{j=1}}^{11} \mathrm{CUA}_{\mathrm{j}}^{2}} \tag{5}$$

$$\mathrm{CUA_j} = \mathrm{FC}_{\mathrm{j_{opt}}} - \mathrm{FC}_{\mathrm{j_{bau}}} \tag{6}$$

where $CUA_j$ is the gap of the food group $j$ between the status and optimized dietary patterns; $FC_{j_{opt}}$ is the modeled consumption of the $j^{th}$ food group; $FC_{j_{bau}}$ is the consumption of the $j^{th}$ food group in 2020.

The cultural unacceptability is determined as detailed in Table 1 and illustrated in Fig. 2. Specifically, the degree of unacceptability ($CUA_j$) is calculated as the Euclidean distance representing the gap between the optimized dietary patterns and the 2020 dietary status. If the optimized consumption trends deviates from the actual consumption trend, the unacceptability degree of the $j^{th}$ food group will be recorded as $FC_{j_{opt}} -$

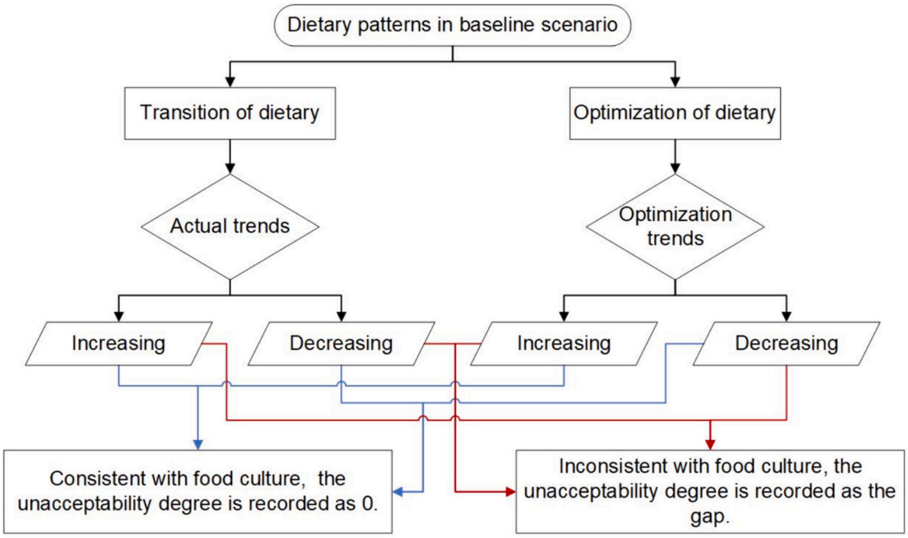

**Fig. 2.** Illustration of determining the cultural unacceptability of food.

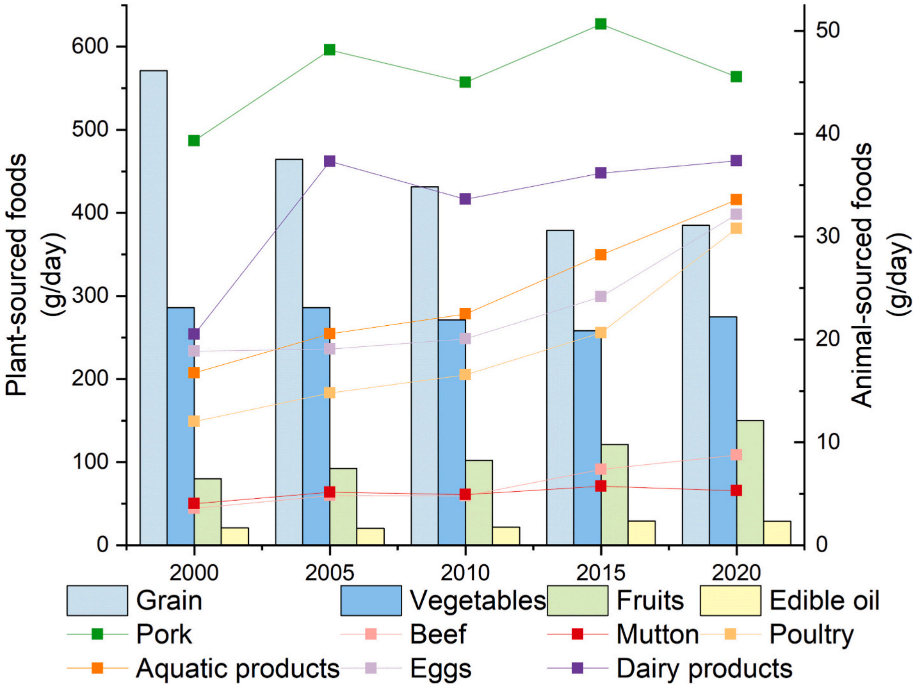

**Fig. 3.** The per-capita dietary pattern of China from 2000 to 2020. The left axis applies to bars, and right axis applies to lines in the plot.

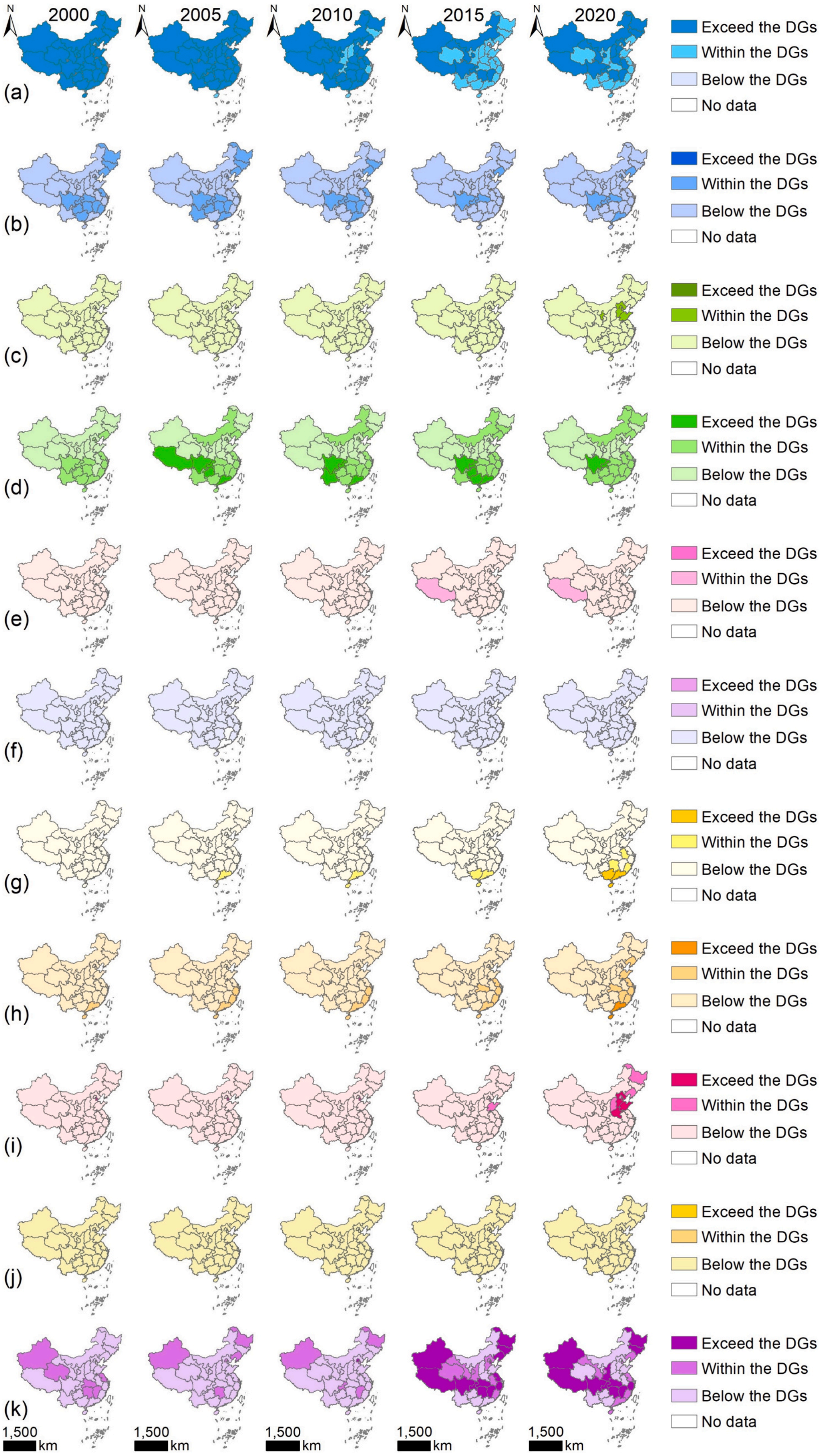

**Fig. 4.** The per-capita dietary pattern across provinces in China from 2000 to 2020. (a) -(k) indicate the intake of grain (a), vegetables (b), fruits (c), pork (d), beef (e), mutton (f), poultry (g), aquatic products (h), eggs (i), daily products (j), and edible oil (k) respectively.

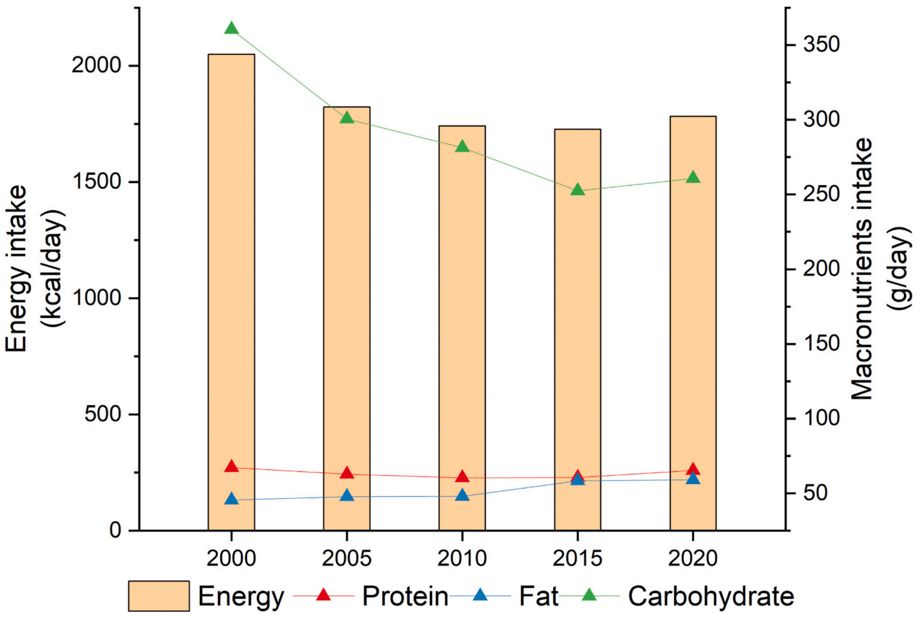

**Fig. 5.** The average nutrient intake of China from 2000 to 2020. The left axis applies to bars, and right axis applies to lines in the plot.

$FC_{j_{bau}}$. For example, the actual consumption trend of grain decreased from 2000 to 2020. If optimized trend suggests an increase in grain consumption, the unacceptability degree for grain is recorded as the difference between the optimized and baseline consumption levels $FC_{j_{opt}} - FC_{j_{bau}}$.

### 3.4.4. *Determining the solution of multi-objective optimization with TOPSIS*

Since the NSGA-II algorithm will identify a set of Pareto Optimal Solutions that fulfill nutritional requirements, minimize diet-associated GHG emissions, and minimize cultural unacceptability, it is essential to evaluate these solutions and determine the optimal one. Following the existing research (Li et al., 2023), we use TOPSIS methods to obtain the optimal solution that best mediates the conflict between reducing GHG emissions and preserving food culture. As a multi-objective decision-making method, TOPSIS ranks each solution based on its Euclidean distance from the positive ideal solution under different optimization objectives (Li et al., 2023). The solution with the shortest distance is considered to perform the best, indicating it achieves the optimal balance across the nutritional, environmental, and cultural dimensions (Sheikh et al., 2021).

## 4. Results

### 4.1. *Dietary patterns, nutrient intake and GHG emissions*

### 4.1.1. *Dietary patterns*

The evolution of China's average dietary patterns from 2000 to 2020 demonstrates a clear divergence in the consumption trends of plant-based and animal-sourced foods (Fig. 3). Over these two decades, plant-based food consumption has experienced a substantial 12.44 % decrease (from 349.56 g/day to 306.07 g/day), in contrast to the 68.10 % increase (from 42.01 g/day to 70.63 g/day) in animal-sourced food intake. Grain consumption has a significant drop of 32.57 % (from 208.42 g/day to 140.54 g/day), and shifts to align with the recommended intake range in 2015. Both vegetable and fruit intake remain below the necessary levels, albeit following contrasting trends: vegetable consumption witnesses a marginal decrease of 3.85 % (from 104.32 g/day to 100.31 g/day), while fruit consumption increases by 87.43 % (from 29.19 g/day to 54.71 g/day). Furthermore, the consumption of edible oil shifts from a state of inadequacy to a moderate level in 2015. Regarding animal-sourced food, all categories have seen a consistent increase in consumption over the study period. The consumption of meat (including pork, beef, mutton and poultry) surpasses recommended levels in 2015, while the intake of aquatic products, eggs, and dairy products remains below adequate levels.

The evolution of average dietary patterns across provinces from 2000 to 2020 generally mirrors the national trend for each food group, with remarkable regional variations highlighting the influence of local food cultures (Fig. 4). For example, grain consumption from 2000 to 2015 is significantly lower than national average in Beijing and Shanghai but remarkably higher in Tibet. By 2020, 14 provinces still exhibit excessive grain consumption. Contrarily, the intake of vegetables is consistently insufficient across the nation. The provinces with moderate vegetables consumption decrease from 13 in 2000 to just 7 in 2020, with Liaoning, Hubei and Chongqing persistently reflecting moderate consumption levels. The insufficient fruits consumption is a universal trend in all provinces in 2000, but by 2020, it evolves to moderate levels in Beijing, Tianjin, Hebei, Shandong, and Ningxia. The geographical disparity is especially pronounced in edible oil consumption: initially inadequate in 24 provinces in 2000, it becomes excessive in 11 provinces by 2020. Regarding meat consumption, the number of provinces categorized as inadequate, moderate, and excessive in 2000 is 5, 20, and 6, respectively. These numbers notably shift by 2020 to 0, 11, and 20. While many provinces show inadequate consumption of aquatic products, eggs and dairy products, long-term improvements are evident. For instance, in 2000, Shanghai, Guangdong, and Hainan consume moderate amounts of aquatic products, but by 2020, Guangdong and Hainan exceed the moderate level. Similarly, eggs consumption is moderate in Tianjin in 2000, but it escalates to excessive levels in Tianjin, Hebei, Shandong and Henan in 2020. However, dairy product consumption remains inadequate across all provinces.

### 4.1.2. *Nutrient intake*

The average nutrient intake in China from 2000 to 2020 reveals a trend towards healthier dietary patterns (Fig. 5). Throughout this period, energy and protein intake consistently remain within the recommended range. By 2015, fat intake has transitioned from inadequate to moderate levels, while carbohydrate intake reduces from excessive to moderate in 2005. Despite a long-term decrease (from 2000 to 2020) in average intake of energy (from 2049.30 kcal/day to 1782.36 kcal/day), protein (from 67.30 g/day to 65.39 g/day) and carbohydrates (from 360.38 g/day to 260.65 g/day), these trends have shown a slight

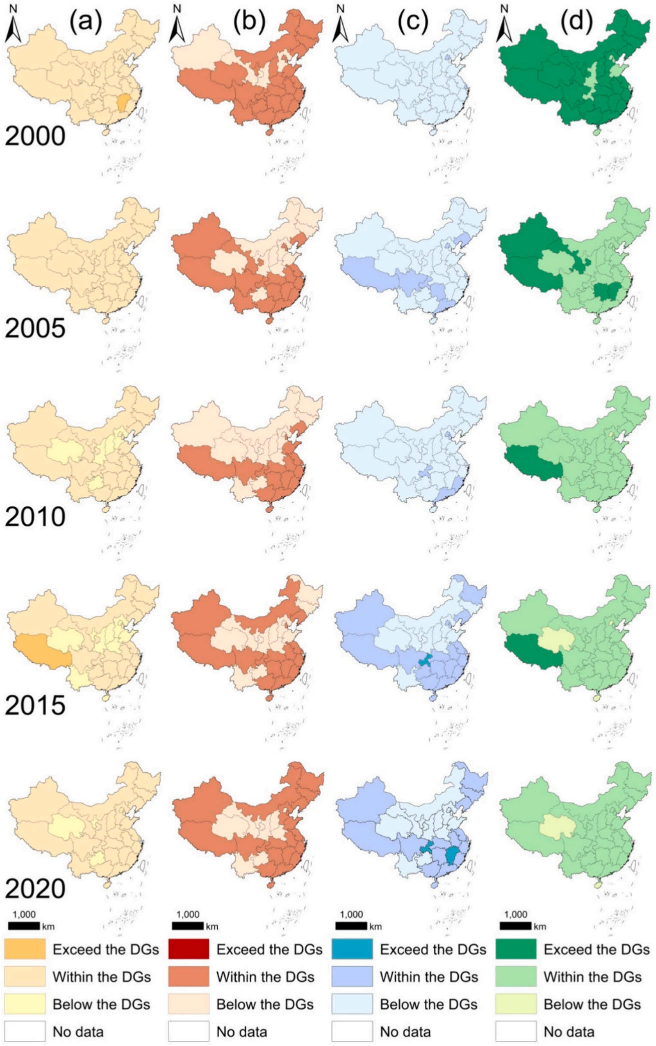

**Fig. 6.** The average nutrient intake across provinces in China from 2000 to 2020. Note: (a) to (d) indicate the intake of energy (a), protein (b), fat (c), and carbohydrate (d) respectively.

rebound in recent years. Meanwhile, fat intake has seen a steady increase of 29.76 % (from 45.57 g/day to 59.14 g/day). The decline in grain consumption in recent years has led to a slower reduction in energy, protein, and carbohydrate intake (see Fig. 3). Additionally, the increasing consumption of pork, poultry, and edible oil has consistently driven an increase in fat intake.

Provincial dietary patterns across China from 2000 to 2020 reveal significant disparities in nutrient intake, despite a national trend towards more balanced diets (Fig. 6). Specifically, energy intake is generally moderate in most provinces; however, as of 2020, 4 provinces are not reaching the recommended levels. Similarly, the number of provinces with inadequacy protein intake have increased from 4 in 2000 to 9 in 2020, with provinces such as Shaanxi consistently falling short in protein intake. The intake of carbohydrates is on the decline, leading to inadequacy in Shanghai, Hainan, Guizhou, and Qinghai in 2020. Furthermore, fat intake, previously inadequate in all provinces except Beijing and Shanghai in 2000, still shows 13 provinces falling short in 2020, while Jiangxi and Chongqing are marked by excessive intake.

### *4.1.3. GHG emissions*

Diet-associated GHG emissions in China have seen a 16.56 % increase (from 2610.31 g/day to 3042.53 g/day) from 2000 to 2020, with a minor dip between 2005 and 2010 attributable to the decrease in emissions from grains and some animal-sourced foods such as pork and dairy products (Fig. 7, Fig. 3). Emissions from plant-sourced foods decrease by 16.17 % (from 1667.57 g/day to 1397.87 g/day), whereas those from animal-based foods increase by 74.56 % (from 942.74 g/day to 1644.67 g/day) over the past two decades. By 2020, animal-sourced foods account for 54.06 % of diet-related GHG emissions, surpassing plant-based foods. Despite a 32.56 % decrease (from 1065.19 g/day to 718.28 g/day), grain-related emissions remain a significant proportion of total GHG emissions. It is worth noting that all categories of animal-sourced foods have witnessed a remarkable rise in associated GHG emissions.

From 2000 to 2020, most provinces in China experience a fluctuating yet generally increasing trend in average diet-associated GHG emissions (Fig. 8). Interestingly, Guizhou and Qinghai are exceptions, recording decreases in emissions by 356.49 g/day and 348.94 g/day. And there is peculiarity in diet-associated GHG emissions in Tibet. Tibet is located on the highest plateau in the world and known as the “roof of the world”. Natural disasters such as droughts and floods have a significant impact on agricultural and animal husbandry production. Meanwhile, the climate in Tibet is highly variable, and crop yields are also unstable. Therefore, changes in diet associated GHS does not follow a pattern and the change is abrupt from year to year. Although the disparity in GHG emissions from plant-sourced food consumption has diminished over the period, the variations in emissions from animal-sourced foods remain significant. Notably, there is considerable regional heterogeneity in GHG emissions from beef, mutton and dairy products. The proportion of emissions from animal-sourced foods exceeds 50 % in an increasing number of provinces, starting from 5 provinces in 2000 and rising sharply to 23 provinces in 2020. By 2020, the primary contributors to GHG emissions from animal-sourced foods are pork (averaging 327.92 g/day) and poultry (averaging 313.35 g/day). A regional examination reveals that Chongqing and Guangdong have the highest GHG emissions from pork (590.08 g/day) and poultry (867.10 g/day), respectively. Conversely, Xinjiang and Tibet record the lowest GHG emissions from pork (67.10 g/day) and poultry (33.46 g/day), respectively.

## *4.2. Multi-objective optimization of dietary patterns*

### *4.2.1. Pareto optimal solution for multi-objective optimization*

Fig. 9 shows the Pareto optimal solutions for multi-objective optimization in each province in China. This collection presents solutions that simultaneously achieve the lowest possible diet-associated GHG emissions and food culture unacceptability while maintaining nutritional adequacy. The red, blue, and green points represent the lowest GHG emission solution, the lowest cultural unacceptability solution, and the most balanced solution between GHG emission reduction and local food preference, respectively. The GHG emissions are primarily distributed between 5200 and 5800 g/day, with the exception of Qinghai, Tibet and Xinjiang, while cultural unacceptability is less than 100 g/day for all provinces except Qinghai and Tibet.

### *4.2.2. Multi-objective optimization results*

Fig. 10 compares diet-associated GHG emissions and cultural unacceptability of dietary shift under different scenarios, using the status of 2020 as the baseline scenario. To meet the nutritional needs, the diet-associated GHG emissions will increase in all scenarios. Compared to the baseline scenario, the GHG emission will increase 142.15 % (increase 4325.05 g/day) in N scenario when only nutrition is considered, the GHG emission will increase 71.57 % (increase 2177.67 g/day) in NE scenario when the environmental impacts are added into consideration, and the GHG emission will increase 78.69 % (increase 2391.86 g/day) in NEC scenario when food habits are taken into consideration. In terms of GHG emission, NEC scenario will have only 7.04 % more GHG emissions than NE scenario that pursuit lowest GHG emissions within nutrition constrain. Regarding the acceptability level, the N scenario is the most contrary to the existing trend of food habits of residents, and the NEC

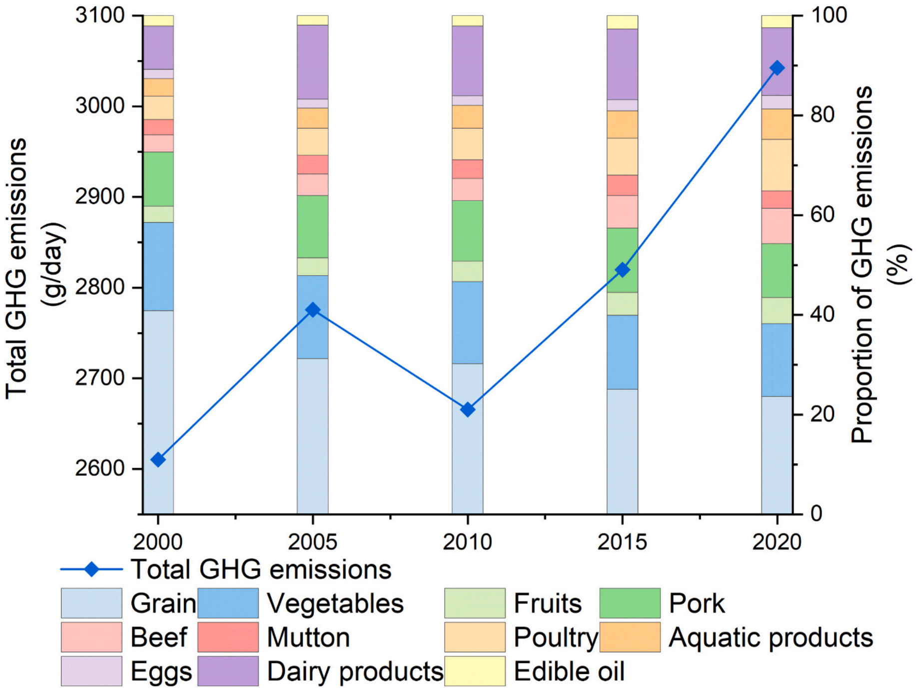

**Fig. 7.** The average diet-associated greenhouse gas emissions of China from 2000 to 2020. The left axis applies to line, and right axis applies to bars in the plot. The uncertainty (%) of diet-associated GHG emissions in the food groups are indicated in Appendix 5.

scenario that takes food habits into consideration demonstrates better performance than others. In general, the N scenario has the highest GHG emissions and unacceptability, while taking culture dimension into account (NEC scenario) has slightly higher GHG emissions but is optimized to a large extent in terms of acceptability to the population.

Optimized dietary patterns for the provinces, which consider nutrition, environment, and culture simultaneously, present a significant departure from the 2020 status (Fig. 11). The primary changes involve a decrease in grain consumption, with an average reduction of 103.23 g/day, aligning with the existing trend. Vegetables and edible oil intake exhibit noticeable variations across provinces. Although most provinces are expected to observe an increase in fruit intake, a slight decline in consumption is projected for Hebei, Shandong and Ningxia. Furthermore, livestock and poultry consumption are predicted to decrease, with different regions showing varying reductions. Aquatic product intake, with the exception of Anhui, will experience a considerable increase, particularly in Shanxi, Guizhou, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang, while a decrease is expected in Guangdong. An overall increase in egg consumption is anticipated, except for a few provinces in the north, and all provinces are expected to experience a significant rise in dairy product consumption.

The disparities between diet-associated GHG emissions across provinces under varying scenarios are substantial (Fig. 12). This increase from dairy consumption offers an abundance of high-quality protein to residents but also significantly elevates GHG emissions (see Fig. 11). The N scenario shows the most substantial rise in emissions, followed by the NEC scenario, and then the NE scenario. The NE and NEC scenarios, oriented towards minimizing GHG emissions, demonstrate comparatively lower GHG emissions than the nutrition-focused N scenario, mainly because of the decreased consumption of animal-sourced foods. The NEC scenario witnesses diverse changes in dietary patterns across provinces, but the GHG emissions increase stays within the range of 1900-2800 g/day. Among all provinces, Guizhou is expected to experience the highest increase in GHG emissions across all scenarios. The lowest increase in the N and NE scenarios will be in Guangdong, while Inner Mongolia will experience the least growth in the NEC scenario.

Cultural acceptability of dietary changes varies across provinces and scenarios (Fig. 13). The least accepted scenario is N (average unacceptability of 135.16 g/day), followed by NE (average of 60.82 g/day), and finally NEC (average of 47.37 g/day), which aligns best with current food habits. In the N scenario, resistance to increased vegetable consumption and decreased livestock and poultry consumption leads to higher unacceptability (see Fig. 11). The NEC scenario, favoring higher livestock and poultry consumption causes a decrease in unacceptability, particularly in Beijing, Tianjin, Hebei, Shanghai, Guangdong, Guangxi, Hainan, and Xinjiang.

### *4.2.3. Regional variation in diet transition*

The transition towards optimal dietary patterns shows both regional similarities and variations across different provinces in China. There is a general consistency between observed and optimal trends for decreased grain intake and increased consumption of fruits, aquatic products, eggs, and dairy products, indicating a shift towards healthier and more sustainable diets. However, inconsistency arise for vegetables, livestock, poultry, and edible oil where the observed trend does not match the optimal trend favoring decreased consumption of livestock, poultry, and edible oil, and increased vegetables intake.

Across provinces, there is a consistent optimal trend for grain, livestock, poultry, and dairy products intake. However, variation is remarkable in the optimal trends for vegetables, fruits, aquatic products, eggs, and edible oil. For instance, the optimal trend for vegetable intake indicates an increase in 24 provinces, except Beijing, Tianjin, Liaoning, Hubei, Guangdong, Chongqing, and Sichuan. Fruit consumption shows an optimal increase in 28 provinces, with slight decreases observed in Hebei, Shandong, and Ningxia. Aquatic product intake is anticipated to increase in 20 provinces, with the exception of a few, such as Tianjin and Guangdong. The majority of provinces (23 out of 31 provinces) also show an increase in optimal egg consumption, while a decrease observed in provinces such as Beijing, and Henan. Edible oil demonstrates a decrease in optimal consumption in 19 provinces, excluding provinces like Beijing, Hebei, and Ningxia, among others. In summary, these patterns underscore the regional nuances in the endeavor towards sustainable diets.

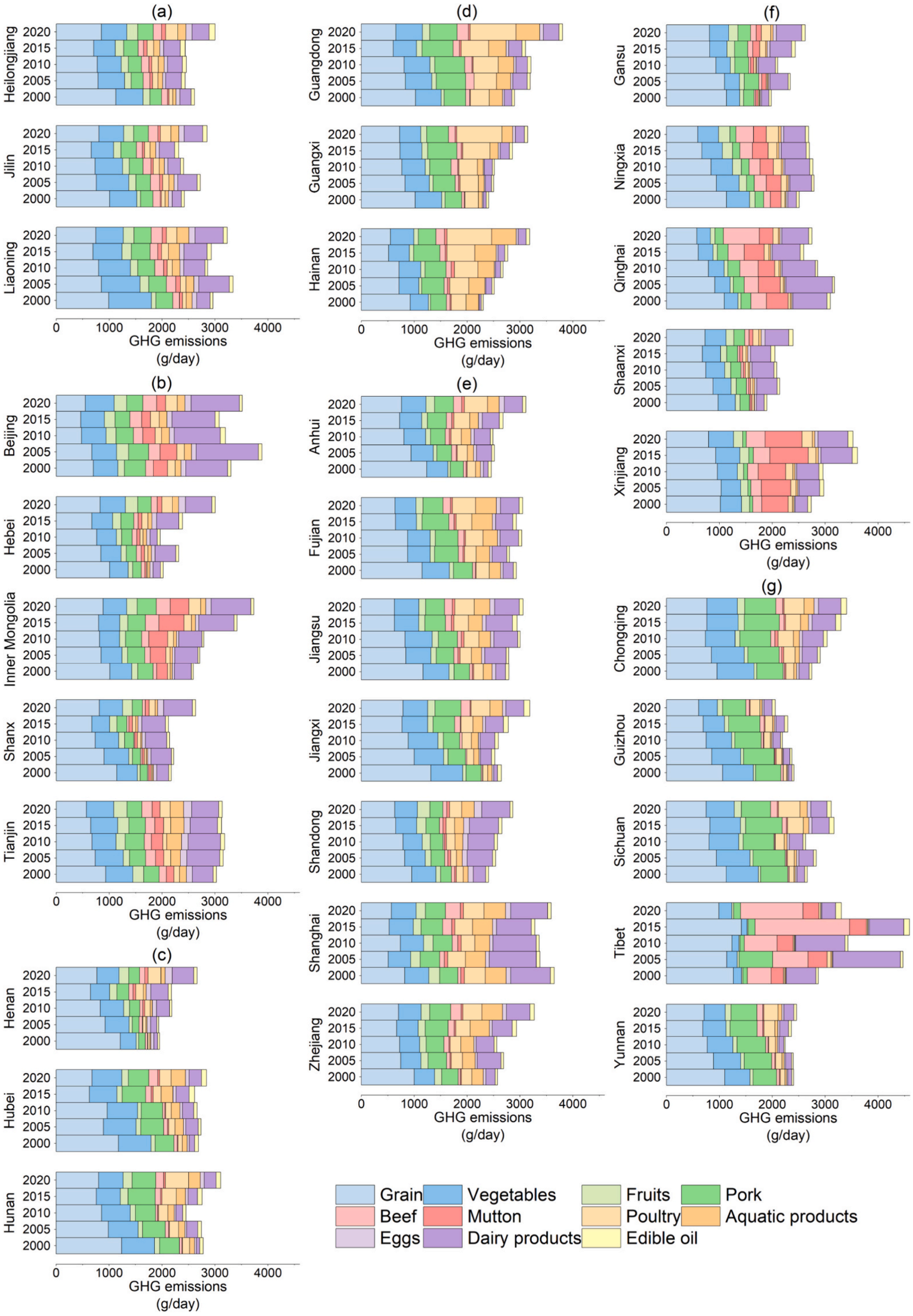

**Fig. 8.** The average associated greenhouse gas emissions across provinces in China from 2000 to 2020. (a)-(g) indicate Northeast China (a), North China (b), Central China (c), South China (d), East China (e), Northwest China (f), and Southwest China (g) respectively. **The uncertainty (%)** in Diet-associated GHG emissions of each province are indicated in Appendix 6.

## 5. Discussion

Our study contributes to the existing research on sustainable diets addressing the complex trade-offs among nutritional requirements, environmental impact, and cultural acceptability. Our findings reveal that both nutritional quality and diet-associated GHG emissions have been increasing between 2000 and 2020. This trajectory mirrors dietary patterns evolution in certain Asian countries such as Japan and South Korea (Yang et al., 2013). The decrease of grain consumption and the increase of animal-sourced foods may be due to the pursuit of quality foods during economic development (Zhang and Xu, 2022), which leads to a rapid surge in animal-sourced dietary pattern, particularly livestock and poultry (Hou et al., 2021). The carbon emissions from animal-source foods primarily originate from raw material acquisition, as well as production and processing activities. In contrast, the carbon emissions of plant-based foods are largely attributed to their production and

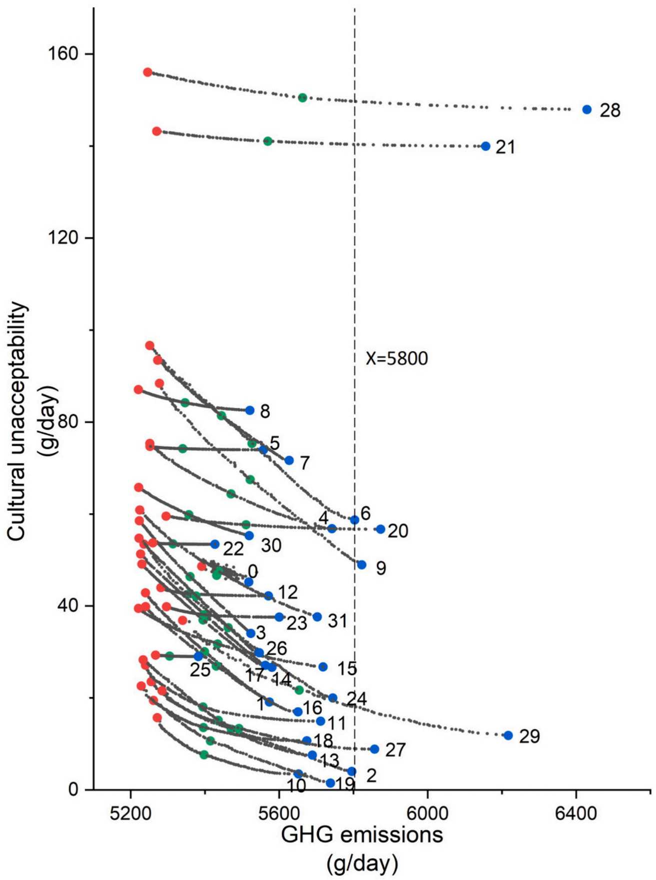

**Fig. 9.** Pareto optimal solution sets for multi-objective optimization for China (0) and across province in China. The solution sets marked by numbers from 1 to 31 represent the Pareto optimal solution set of each province, according to alphabetical order of these provinces including Anhui (1), Beijing (2), Chongqing (3), Fujian (4), Gansu (5), Guangdong (6), Guangxi (7), Guizhou (8), Hainan (9), Hebei (10), Heilongjiang (11), Henan (12), Hubei (13), Hunan (14), Inner Mongolia (15), Jiangsu (16), Jiangxi (17), Jilin (18), Liaoning (19), Ningxia (20), Qinghai (21), Shaanxi (22), Shandong (23), Shanghai (24), Shanxi (25), Sichuan (26), Tianjin (27), Tibet (28), Xinjiang (29), Yunnan (30), and Zhejiang (31).

processing phases, including the storage and transportation of fruits and vegetables. This observation is consistent with findings from existing research (Peters et al., 2010; Sim et al., 2007; Weber and Matthews, 2008). Factors such as economic levels and food production predominantly influence regional variations in local food consumption (Affret et al., 2017; Yue et al., 2022a). The decline in household nutrient intake may be attributed to an increasing trend of eating out and snacking (Fjellström, 2004). In line with previous research (Han et al., 2020), our study finds that diet-associated GHG emissions are on an upward trajectory, with forecasts indicating a continued increase. The increasing GHG emission is predominantly driven by the consumption of foods with superior taste and nutritional quality such as animal-sourced foods (Errickson et al., 2021; Hayek et al., 2021; van Bussel et al., 2019; Xu et al., 2021).

Our analysis of GHG emissions across different dietary scenarios reveals that maintaining the recommended food intake range will lead to increased emissions. This finding is consistent with existing studies (He et al., 2021; Huang and Xie, 2022), suggesting that GHG emission from increasing food consumption (particularly animal-sourced food) among Chinese residents is on the rise. Even a slight increase in animal-sourced food consumption can contribute to significant shifts in dietary-related GHG emissions. Compared to scenario N, both scenario NE and scenario NEC have halted the increase in animal food consumption, resulting in relatively low dietary carbon emissions.

While existing research attributes the rise in GHG emissions mainly to increased meat consumption (Sun et al., 2022), our study suggests dairy products as the major contributor of GHG emission in China in the future, due to the current state of dietary practices in the country, with dairy consumption being critically low and meat consumption excessive in certain provinces. This is because the current livestock production conditions in China limit the development of dairy farming and production of dairy products in most regions. The consumption of dairy products by Chinese people is far below the recommended values in dietary guidelines. With increasing international trade in dairy products and the continuous promotion of dairy production technology, the consumption of dairy products in China will continue to increase. Therefore, the increase in dairy products will be the main source of GHS emissions in China. The recommended reduction of livestock and poultry in optimized diets is in line with existing dietary research (Jiang et al., 2021).

Considering cultural acceptability is essential in dietary patterns optimization, a fact underscored by various studies (Berning et al., 2023; Erlich, 2004). However, dramatic changes aimed at reducing GHG emissions can often compromise the nutritional quality and cultural acceptability of diets (Perignon et al., 2016). Consequently, we suggest careful evaluation of shifts in food consumption for potential cultural acceptability, particularly in regions undergoing significant dietary shifts. For example, under optimized dietary patterns, we observe a decrease in grain consumption and an increase in dairy product intake, which is consistent with observed dietary trends (Wang et al., 2010; Yang et al., 2013). Accordingly, we treat these consumption shifts as culturally acceptable in our study. However, resistance arises mainly from recommendations to increase vegetable consumption and reduce intake of livestock, poultry, and edible oil. Despite potential pushback, these recommendations are well-founded and consistent with current research, underscoring the reasonable and necessary balance between dietary optimization and cultural preferences (Hou et al., 2021). It is also a fact that GHG emissions would be higher with more sustainable diets and be exacerbated with the increased population. We advocate promoting low-carbon technologies in agricultural production and food processing to reduce carbon emissions due to the higher GHG emissions in the agricultural production and processing. We also encourage residents to dine at home and reduce consumption of poultry and animal meat to reduce carbon emissions from dietary structure.

As we delve deeper into the geographical context of China, with its vast territory and diverse food culture (Erlich, 2004), it becomes evident that these optimal dietary transition trends are not uniform across the country. For instance, regions witnessing a decrease in vegetable consumption are mainly located in the plains and the Sichuan Basin, while provinces showing reduced aquatic product intake are primarily near the Yangtze River basin and Hainan Island, despite a minor decrease in overall fruit consumption. Meanwhile, the northern regions show a trend towards increased egg consumption, whereas the southern mountainous areas and the northwest region are experiencing a rise in edible oil consumption. Addressing these regional disparities requires targeted, innovative strategies. We recommend the development and implementation of policies that encourage dietary changes that diverge from current consumption trends. For instance, food policies should promote a reduction in grain consumption and an increase in the intake of fruits, aquatic products, eggs, and dairy products, along with encouraging greater vegetable consumption, minimizing the consumption of livestock, poultry, and edible oil, and reflecting local conditions and food preferences.

Our research presents a novel exploration into striking a balance between minimizing GHG emissions and respecting food habits while meeting nutritional needs, a task undertaken through an examination of dietary patterns and their evolution in each province in China. Despite these advances, some limitation persists in our research. We recognize the importance of micronutrients in dietary patterns and that future

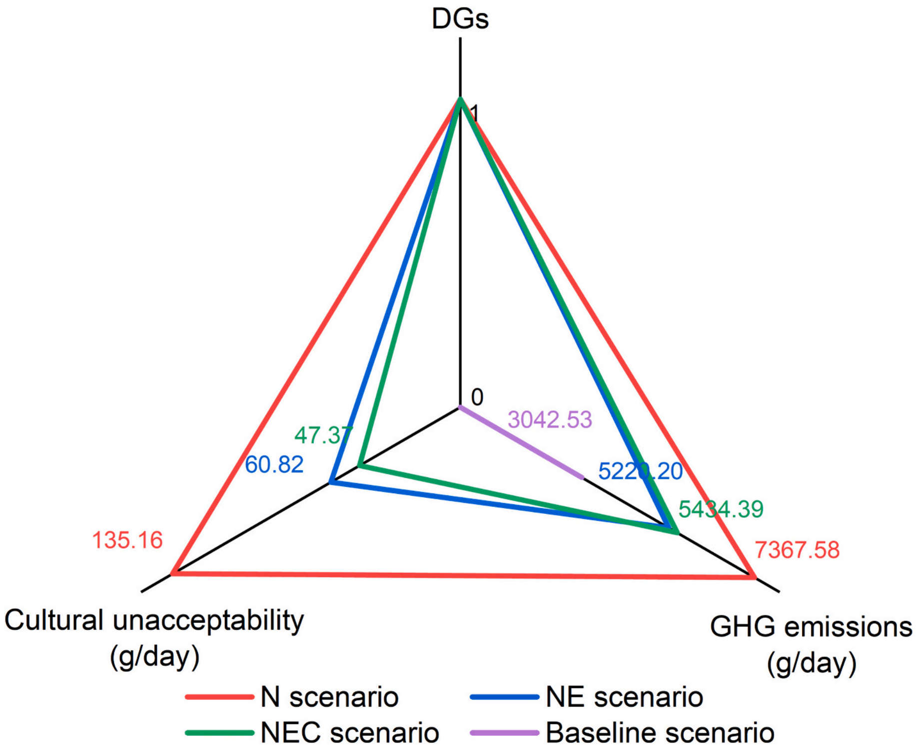

**Fig. 10.** Different scenarios versus 2020 in China. On the dietary guidelines (DGs) axis, 0 represents consumptions of some food groups in types of food groups do not meet the recommended levels of DGs, while 1 represents consumptions of 11 types of food groups are in the range of DGs.

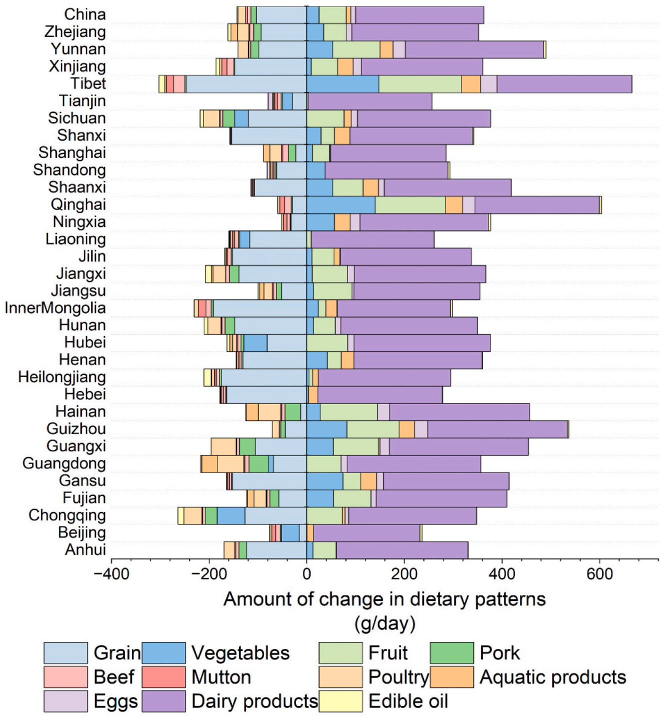

**Fig. 11.** The multi-objectives optimized dietary patterns (NEC scenario) relative to 2020 across provinces in China.

research needs to incorporate them into the nutritional dimension to enhance the comprehensiveness and accuracy of data analysis. We acknowledge one limitation in our research: the uncertainty of GHG emissions data. To mitigate this, we used Monte Carlo simulations to adjust the GHG emissions data, thereby reflecting emissions generated by different food products throughout their life cycle to avoid carbon leakage. We anticipate this uncertainty will diminish with future improvements in data accuracy, rendering our findings increasingly practical. We also acknowledge that a more granular consideration of various food types and considering carbon footprint over time of food groups would enhance the precision of carbon emission calculations and dietary pattern optimization models. However, an overly detailed classification of food could complicate the optimization process and pose significant challenges in operational management strategies. Given the challenge in accessing carbon footprint data for more specific food categories, we opted for a generalized set of food group carbon footprints to assess diet-associated GHG emissions. We suggest that the accuracy of estimating diet-associated GHG emissions could be improved if more detailed food carbon footprints were available. In addition, economic factors significantly influence dietary pattern and nutrition, yet they were not addressed in our research. Incorporating economic factors into the optimization of dietary pattern will be a crucial area for further research.

## 6. Conclusions

This study employs a novel multi-objective optimization algorithm, accounting for factors such as GHG emissions, food culture, and nutritional guidelines to explore dietary patterns and their associated GHG emissions under different scenarios. This approach allows us to quantify GHG emissions in the food system and construct a method for measuring cultural unacceptability. Using dietary data from 31 provinces in China, we uniquely optimize dietary patterns for each province and highlight the varied pathways towards sustainable diets. Our findings thus provide insights into developing dietary strategies across China.

Our study illuminates key policy implications, primarily emphasizing the regional variations when devising strategies for the transition towards sustainable diets. Because of such diversity, it becomes apparent that a one-size-fits-all policy would not suffice due to the nuanced regional variations in dietary patterns and habits. Thus, we

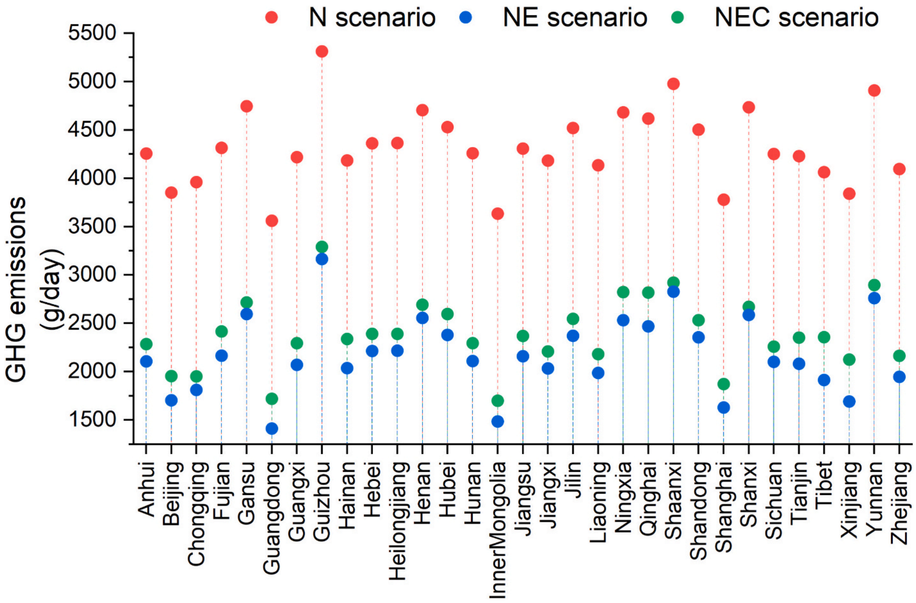

**Fig. 12.** The diet-associated greenhouse gas emissions relative to 2020 under different scenarios across provinces in China.

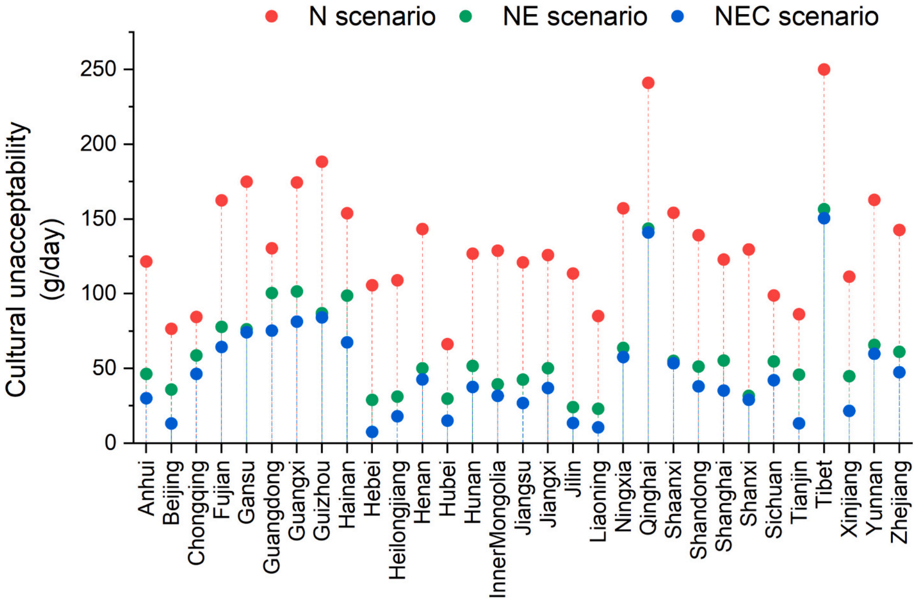

**Fig. 13.** The unacceptability level of food under different scenarios across provinces in China.

suggest developing place-specific dietary guidelines that acknowledge these subtleties and promote dietary shifts aligned with optimal trends for future policy-making.

Our research pinpoints optimal dietary trends on a national scale, indicating a need to decrease consumption of grains, livestock, poultry, and edible oils, while simultaneously advocating for increased consumption of vegetables, fruits, aquatic products, eggs, and dairy products. These findings can aid in shaping policy formulation by continuously evaluating shifts in consumption patterns, especially those that significantly diverge from existing trends. Our research also identifies these optimal dietary trends at provincial level, demonstrating consistency with the national level in grain, livestock, poultry, and dairy products intake, but revealing substantial variation in vegetables, fruits, aquatic products, eggs, and edible oil intake. These distinct regional patterns underscore the necessity for policymakers to focus their efforts on specific food groups. In summary, our findings call for the development of place-specific dietary guidelines that reflect these regional variations, offering a critical roadmap to achieve both nutritional security and carbon emission mitigation targets.

Addressing these regional disparities requires targeted, innovative strategies. We recommend the development and implementation of policies that encourage dietary changes that diverge from current consumption trends. Our study highlights the need for a balanced policy approach that aligns nutritional adequacy, environmental sustainability, and cultural acceptance. This multi-faceted strategy forms a comprehensive and robust framework for sustainable diet policy development, serving as a starting point for policymakers to turn research insights into actionable policy interventions.

## CRediT authorship contribution statement

**Haiyue Fu:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis, Conceptualization. **Yating Li:** Writing – original draft, Visualization, Formal analysis, Data curation. **Penghui Jiang:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Shuai Zhou:** Writing – review & editing, Writing – original draft. **Chuan Liao:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.04.029.

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