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Chinese Food Consumption Adaptation and Sustainability Under Climate Warming

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Abstract

Changes in food consumption are closely related to food production, loss, and waste. Few studies focused on people's adaptation to climate warming through changes in food consumption quantity. This study examined how climate warming in the current year and the preceding year affects the per capita consumption quantity of 14 food items, identifying both passive and active adaptations. The study employed a dynamic panel data regression model based on annual average daily temperatures from 1985 to 2022 in 30 provinces of China. We found that Chinese residents actively adapted to climate warming by increasing their consumption of pork, mutton, eggs, and beef while decreasing their intake of dairy products, aquatic products, vegetable oil, beans and tubers, and animal fats. They passively adapted to climate warming by increasing their consumption of dried and fresh fruits, aquatic products, vegetable oil, animal fats, poultry, and beans and tubers while decreasing their consumption of grains, pork, dairy products, and beef. Moreover, climate warming drove region and income specific dietary shifts through active and passive adaptations that raise pork eggs grains and oils while cutting beef poultry beans and tubers across South/North and rich/poor areas. These findings will help policymakers achieve the goal of sustainable food consumption by aligning climate, nutrition, and equity targets for resilient food-system transitions.

Keywords: climate warming; food consumption; climate adaptation; sustainable consumption

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1. Introduction

Global warming remains a pressing concern. According to the World Meteorological Organization's State of the Global Climate 2024, the global mean temperature in 2024 reached a new high, exceeding the pre-industrial levels (1850–1900) by 1.55 ± 0.13 °C. It marked the warmest year since the inception of instrumental records. The extreme temperatures in 2024 were driven by the combined effects of the El Niño phenomenon and record-high concentrations of greenhouse gases [1]. China is also experiencing significant climate warming. According to the China Climate Change Blue Book (2024), the country's annual mean surface temperature in 2023 was 0.84 °C above the long-term average, marking it the warmest year since 1901 [2].

With the rapid economic development and accelerated urbanization in China, the food consumption structure of residents has undergone significant changes. According to the China Statistical Yearbook, per capita grain consumption in China declined from 1981 to 2023, while the consumption of vegetables, fruits, meat, eggs, milk, and aquatic

products increased markedly. Food consumption is highly susceptible to climate warming, which could be manifested in two aspects. Firstly, climate warming can affect national food consumption through changes in the food supply. As reported in The State of Food Security and Nutrition in the World 2018: Building Climate Resilience for Food Security and Nutrition [3] climate warming has substantially reduced agricultural production in many Asian and African countries, resulting in food shortages that are likely to lead to price increases, thereby reducing the affordability of certain products, particularly fresh foods, which ultimately limits people's access to sufficient energy and essential nutrients. Secondly, climate warming can influence food consumption by altering dietary habits. Specifically, climate warming affected food consumption by reducing agricultural productivity and nutritional quality, which drove up food prices and altered affordability, thereby shifting dietary patterns towards less nutritious options [4].

The concept of climate change adaptation was first introduced by the Intergovernmental Panel on Climate Change (IPCC), calling for societies to implement various measures and actions to mitigate the adverse impacts of climate change [5]. In 2001, the IPCC expanded the definition of climate change adaptation, emphasizing that it is a process by which the social system changes itself in response to actual or expected climate change [5]. Examining how people adapt to climate warming by changing their food consumption quantities is likely to enhance the understanding of the causes and trends of changes in dietary habits.

Some scholars have explored differences in food consumption across diverse populations [6,7] but these studies focused more on environmental issues and organic food behaviors rather than climate adaptation. It should be noted that existing studies have examined the influence of climate change on residents' dietary diversity from the perspective of agricultural production. These studies argued that extreme drought reduced the availability of grain and key agricultural products, thereby reducing food consumption diversity [4] and quantity [8]. Conversely, increased precipitation has been reported to increase food yields and dietary diversity [9]. A few studies have explored the correlation between climate change and food consumption, revealing that climate warming decreased the consumption of unprocessed foods while increasing the consumption of ultra-processed foods because higher temperatures shorten fresh-food shelf life and raise kitchen labor costs, pushing households toward shelf-stable, ready-to-eat products [10] and household dietary diversity since warming expands the cultivable range of high-latitude crops and tropical fruits and lengthens maritime shipping windows, enabling cross-seasonal and cross-continental food flows [11]. Regarding food consumption as a climate change mitigation strategy, some studies explored the impact of reduced food consumption through literature reviews, case studies, and quantitative analyses [12,13]; others examined how reducing food waste [14] and choosing sustainably certified foods [15] could reduce greenhouse gas emissions and conserve water and soil resources. When food consumption changing was considered a climate change adaptation strategy, several studies examined how smallholder farmers in South Africa altered their dietary habits to adapt to extreme droughts. These studies found that farmers experiencing livestock feed shortages due to droughts tended to reduce their meat consumption and increase their intake of drought-resistant vegetables and legumes [16]. However, most studies focused on the effects of farmers' active adaptation to climate change on agricultural production, such as the use of agrochemicals [17], crop diversification [18], irrigation technologies [19,20], and climate-resilient crop varieties [21]. In short, limited scholarly attention was paid to how diverse populations adjusted their food consumption habits in response to climate change. To fill this gap, our study innovatively divided residents' food-consumption adaptation to climate change into active and passive adaptation, and specified that active adaptation emphasizes

residents' conscious efforts to adjust their habits in response to climate change, whereas passive adaptation involves involuntary adjustments driven by the immediate pressure from climate change.

This study aimed to gain a better understanding of how Chinese residents changed their food consumption quantities as active and passive adaptations to climate warming. A dynamic panel data regression model was employed to investigate the potential relationship between climate warming in the current or preceding year and per capita consumption quantities of 14 food items. Given the significant geographical and dietary differences between South and North China [22] and the disparities in industrial structure and consumption capacity between low- and high-income area [23,24], this study identified the regional characteristics of food consumption quantities for active and passive adaptations to climate warming. The findings will help policymakers achieve the sustainable food consumption goal of increasing green supply and reducing food waste.

2. Theoretical Analysis Framework and Hypotheses

We constructed a theoretical framework for analyzing how residents adapted to climate warming by changing their food consumption quantities based on dual-systems theory, availability heuristic theory, heat stress response theory and stimulus–organism-response theory. As illustrated in Figure 1, residents' food consumption quantities can vary along with active and passive adaptations to climate warming, provided that all other conditions remain unchanged. Dual-systems theory posits that individual decision-making relies on the intuitive system 1 (e.g., experience dependence) and the rational system 2 (e.g., prospective planning) [25]. Grounded in the availability heuristic theory [26], individuals tend to assess current risks and adjust their behaviors based on easily recalled past experiences, such as extreme heat events from the previous year. Therefore, if residents lack accurate cognition of current climate warming, they are more likely to rely on the previous year's climatic experiences to predict and adjust current food consumption, which can be regarded as a forward-looking adaptation, a form of active adaptation. Thus, Hypothesis 1 is proposed below.

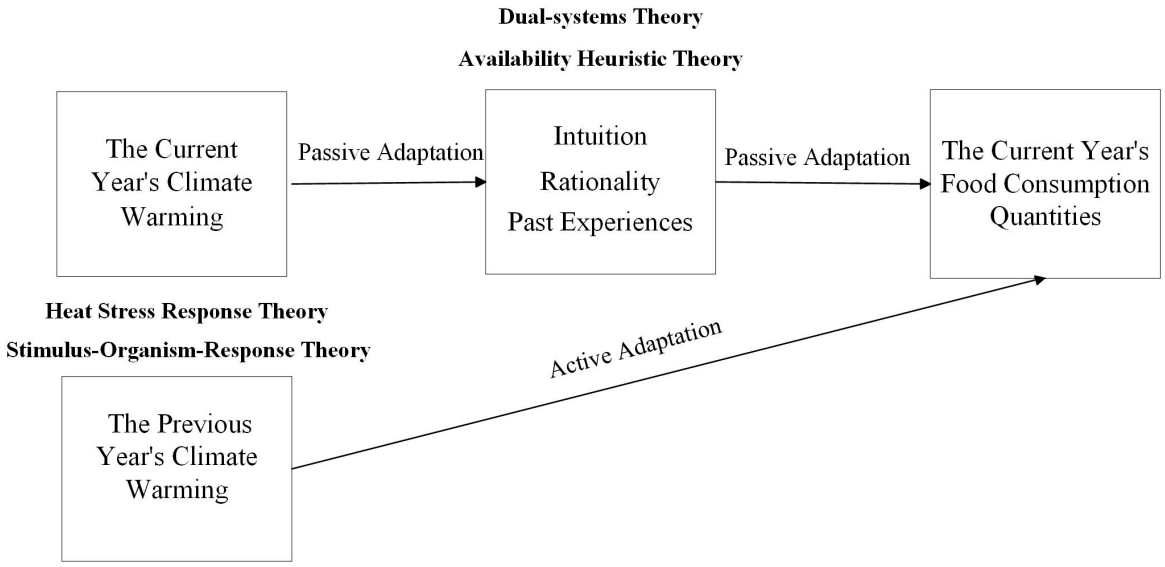


Figure 1. Theoretical Framework of Residents' Food consumption Quantities Change for Active and Passive Adaptions to Climate Warming. Source: The author's own work.

H1: *Climate warming in the previous year significantly affects residents' food consumption quantities in the current year.*

As heat stress response theory [27] indicated, high-temperature environments directly trigger physiological appetite changes and shifts in food preferences. The stimulus–organism-response (S-O-R) theory [28] suggests that changes in the external environment, such as rising temperatures, act as a stimulus that subconsciously guides individuals (organism) to adjust consumption decisions (response), resulting in passive adaptation. Thus, current climate warming may compel residents to adjust their dietary intake within the same year by altering their physiological states and psychological preferences, constituting a mechanism of passive adaptation. Hypothesis 2 is proposed below.

H2: *Climate warming in the current year significantly affects residents' food consumption quantities in the same year.*

3. Materials and Methods

3.1. Data Collection

Our study focused on 30 provinces (excluding Tibet) in China, utilizing data from China Statistical Yearbook and China Animal Husbandry and Veterinary Yearbook which provided authoritative, systematic, and verifiable high-quality data through uniform indicators, rigorous standards, and continuous publication. Limited by the sparse official data, the variables sourced from China Statistical Yearbook (2015–2022) include per capita consumption quantities of grain, beans and tubers, vegetable oil, animal fats, sugars, vegetables and mushrooms, dried and fresh fruits, pork, beef, mutton, poultry, eggs, dairy products, and aquatic products which are the most commonly consumed food groups in China [29]. It should be noted that all food items covered in the Yearbook are reported in their unprocessed forms. Additional variables include per capita GDP, disposable income, social security and employment expenditure, the proportion of the population aged 65 and above, the proportion of individuals with a college degree or higher, the retail price index of livestock meat, the retail price index of meat, poultry, and their products, the consumer price index, and the GDP index. The average market prices of pork, beef, mutton, and chicken were obtained from China Animal Husbandry and Veterinary Yearbook (2015–2022).

Climate warming in a given year is defined as the annual average daily temperature exceeding the average daily temperature of the preceding 30 years [30]. To assess climate warming from 2015 to 2022, we utilized the annual average daily temperature data from China Statistical Yearbook (1985–2022). Similarly, climate warming in the preceding year was defined based on the comparison of the preceding year's average daily temperature with the preceding 30-year average. The same method was applied to calculate precipitation changes from 2015 to 2022.

For missing data on temperature and precipitation in Hainan (1984–1987), Chongqing (1984–1986), and 30 provinces (1990–1991), the ARMA method [31] was employed for interpolation, leveraging its embedded autocovariance structure, to perform optimal linear prediction interpolation for missing temperature and precipitation observations in Hainan, Chongqing and 30 provinces under the criterion of minimum mean square error. Due to the limited availability of poultry market prices, chicken market price was used as a proxy. To adjust for inflation, the market prices of pork, beef, and mutton were deflated using the livestock meat retail price index, and the chicken market price was deflated using the retail price index of meat, poultry, and their products. Disposable income of residents, social security, and employment expenditure were deflated using the consumer price index,

while per capita GDP was deflated using the GDP index. Provinces with a per capita GDP exceeding the national average from 2015 to 2022 were classified as high-income areas; otherwise, they were classified as low-income areas.

3.2. Method

Our study employed ANOVA (Analysis of Variance) and the Kruskal–Wallis test to determine whether there were significant differences in per capita food consumption quantities due to climate warming. ANOVA is a parametric test designed to compare the means of multiple groups by examining the ratio of between-group variance to within-group variance. It is applicable when the data follow a normal distribution [32]. In contrast, the Kruskal–Wallis test is a non-parametric method that assesses whether there are significant differences in the medians of multiple groups by comparing the ranks of the data, making it suitable for data that do not follow a normal distribution or contain outliers [33].

We set up a dynamic panel data linear regression model based on demand theory to quantify the changes in residents' food consumption quantities as active and passive adaptations to climate warming. Empirical and theoretical studies confirmed that the current food consumption behavior of residents was significantly influenced by past consumption habits [34]; therefore, it is necessary to include food consumption habits, specifically the quantities consumed in the preceding year, as an explanatory variable. The dynamic panel data linear regression model integrates the structure of panel data with the characteristics of dynamic time series, making it a suitable econometric model for analyzing the impact of lagged values of the dependent variable on its current value [35]. The specific model expression is as follows:

$$Y_{it} = \alpha_0 + \alpha_1 Y_{it-1} + \alpha_2 difftemp_{it} + \alpha_3 difftemp_{it-1} + Control_{it} * \beta + \lambda_i + \upsilon_t + \varepsilon_{it} \quad (1)$$

In Equation, i denotes the province in China, and t denotes the year. Y_{it} represents the per capita consumption quantities of grain, beans and tubers, vegetable oil, animal fats, sugars, vegetables and mushrooms, dried and fresh fruits, pork, beef, mutton, poultry, eggs, dairy products, and aquatic products in the province i in year t. Y_{it-1} indicates the per capita food consumption quantities in province i in year $t-1$. $difftemp_{it}$ represents the difference between the average temperature in province i in year t and the average temperature of the preceding 30 years. $difftemp_{it-1}$ indicates the difference between the average temperature in province i in year $t-1$ and the average temperature of the preceding 30 years. $Control_{it}$ denotes other variables that affect the per capita food consumption quantities in province i in year t, including long-term precipitation changes in the current year, long-term precipitation changes in the preceding year, disposable income per capita, the retail price of meat, social security and employment expenditure per capita, the proportion of the population aged 65 and above, and proportion of individuals with a college degree or higher. α_0 is the constant term. α_1 is the coefficient representing the impact of per capita food consumption quantities Y_{it-1} in province i in year $t-1$ on per capita food consumption quantities Y_{it} in year t. α_2 is the coefficient representing the impact of the temperature difference $difftemp_{it}$ in province i in year t on per capita food consumption quantities Y_{it}, which indicates the changes in per capita food consumption for each 1 °C increase in the average daily temperature above the preceding 30-year average, namely the food consumption quantities change for passive adaptation to climate warming. α_3 is the coefficient representing the impact of the temperature difference $difftemp_{it-1}$ in province i in year $t-1$ on per capita food consumption quantity Y_{it}, which indicates the change in per capita food consumption for each 1 °C increase in the average daily temperature above the preceding 30-year average, namely the food consumption quantities change due to

active adaptation to climate warming. β represents the vector of coefficients for the impact of other variables on per capita food consumption quantities Y_{it} in province i in year t. λ_i is the province fixed effect, υ_t is the year fixed effect, and ε_{it} is the random disturbance term.

Based on the regression analyses on the per capita consumption quantities of 14 food items as active and passive adaptations to climate warming, as well as further analyses for regional differences between South and North China and between high- and low-income areas, 70 regression models were estimated. We then presented the marginal consumption quantities of 14 food items through visualized coefficient plots of the regression models.

4. Results

Stata (version 18.0, StataCorp LLC, College Station, TX, USA) [36] was used for descriptive statistics, ANOVA, the Kruskal–Wallis Test, and dynamic panel data linear regression analysis.

4.1. Descriptive Statistics

The statistical characteristics of the variables are presented in Table 1. Overall, the figure depicts a "plant-based dominant, animal-protein supplementary" pattern of per capita food consumption in China. Among the food items consumed by residents in 30 provinces from 2015 to 2022, per capita consumption of grain was the highest at 118.99 kg/year, followed by vegetable and mushroom (100.68 kg/year), dried and fresh fruits (54.40 kg/year), pork (20.28 kg/year), dairy products (13.92 kg/year), aquatic products (11.98 kg/year), vegetable oil (9.58 kg/year), poultry (9.52 kg/year), beef (2.55 kg/year), mutton (1.99 kg/year), sugars (1.30 kg/year), and animal fats (0.56 kg/year). The average daily temperatures in 30 provinces for the current year and the preceding year were 0.45 and 0.44 °C higher than the average during the preceding 30 years, respectively. Regarding other variables, the annual precipitation in the current year and the preceding year were 57.63 and 65.78 mm higher than the average during the 30 preceding years, respectively. The average market prices of pork, beef, mutton, and chicken were 31.22, 80.67, 78.01, and 35.02 CNY/kg, respectively. The disposable income of residents was 24,800 CNY/year·person, the social security and employment expenditure was 1769 CNY/year·person, the proportion of the population aged 65 and above was 16.86%, and the proportion of individuals with a college degree or higher was 21.34%. The sample sizes for North China and South China were 120 each, comprising 63 samples from high-income areas and 177 from low-income areas.

Table 1. Statistical characteristics of variables.

Variables	Variables Definition and Unit	Mean	Standard Deviation	Obs.
grain consumption quantities	kg/year·person	118.99	18.01	240
bean and tuber consumption quantities	kg/year·person	11.46	3.45	240
vegetable oil consumption quantities	kg/year·person	9.58	2.26	240
animal fat quantities	kg/year·person	0.56	0.63	240
sugar consumption quantities	kg/year·person	1.30	0.37	240
vegetable and mushroom consumption quantities	kg/year·person	100.68	16.25	240
dried and fresh fruit consumption quantities	kg/year·person	54.40	15.52	240

Table 1. *Cont.*

Variables	Variables Definition and Unit	Mean	Standard Deviation	Obs.
pork consumption quantities	kg/year·person	20.28	8.27	240
beef consumption quantities	kg/year·person	2.55	1.55	240
mutton consumption quantities	kg/year·person	1.99	2.67	240
poultry consumption quantities	kg/year·person	9.52	5.67	240
egg consumption quantities	kg/year·person	10.59	4.31	240
dairy product consumption quantities	kg/year·person	13.92	5.74	240
aquatic product consumption quantities	kg/year·person	11.98	8.29	240
temperature difference (current year)	difference between current year's average daily temperature and the preceding 30-year average (°C)	0.45	0.56	240
temperature difference (previous year)	difference between previous year's average daily temperature and the preceding 30-year average (°C)	0.44	0.56	210
precipitation difference (current year)	difference between current year's precipitation and the preceding 30-year average (mm)	57.63	293.51	240
precipitation difference (previous year)	difference between previous year's precipitation and the preceding 30-year average (mm)	65.78	311.58	210
pork retail price	CNY/kg	31.22	6.65	240
beef retail price	CNY/kg	80.67	21.21	240
mutton retail price	CNY/kg	78.01	22.36	240
poultry retail price	CNY/kg	35.02	6.38	240
disposable income of residents	ten thousand CNY/year·person	2.48	1.02	240
social security and employment expenditure	hundred CNY/year·person	17.69	7.73	240
proportion of population aged 65 and above	%	16.86	44.79	240
proportion of individuals with college degree or higher	%	21.34	60.12	240
North China	Yes	—	—	120
	No	—	—	120
High-income areas	Yes	—	—	63
	No	—	—	177

Source: The author's own illustration.

4.2. Food Consumption Quantities in the Presence of Climate Warming

The results of the ANOVA and Kruskal–Wallis test are presented in Table 2. The per capita consumption quantities of grain, animal fats, dried and fresh fruits, pork, eggs, and dairy products showed *p*-values less than 0.1, indicating significant differences in climate warming in the current year. The per capita consumption quantities of animal fats, sugars, pork, eggs, and dairy products showed *p*-values less than 0.1, indicating significant differences in climate warming in the preceding year.

Table 2. Per capita food consumption quantities in the presence of climate warming.

Food Items	Climate Warming in Current Year			Climate Warming in Previous Year		
	Yes	**No**	***p*-Value**	**Yes**	**No**	***p*-Value**
grain	117.96	123.11	0.077	118.10	123.32	0.091
beans and tubers	11.47	11.40	0.972	11.38	11.81	0.419
vegetable oil	9.60	9.51	0.888	9.61	9.46	0.994
animal fats	0.53	0.72	0.081	0.53	0.75	0.035
sugars	1.28	1.35	0.121	1.28	1.36	0.082
vegetable and mushroom	101.12	98.90	0.399	100.85	99.86	0.723
dried and fresh fruits	55.34	50.63	0.060	54.86	52.15	0.309
pork	19.68	22.67	0.025	19.80	22.61	0.048
beef	2.58	2.45	0.703	2.56	2.50	0.942
mutton	1.98	2.04	0.362	1.99	2.01	0.323
poultry	9.38	10.07	0.708	9.43	9.96	0.577
eggs	11.04	8.81	0.001	10.96	8.77	0.005
dairy products	14.38	12.08	0.002	14.26	12.23	0.007
aquatic products	12.27	10.80	0.319	12.25	10.64	0.275

Source: The author's own illustration.

4.3. Marginal Food Consumption Quantities for Active and Passive Adaptations

The correlation test and multicollinearity test were performed before conducting the regression analysis. A significant correlation was found between the independent and dependent variables, and the variance inflation factor (VIF) of each independent variable was less than 10, indicating that multicollinearity was not a serious problem. Our study employed a relatively liberal significance level ($p < 0.1$) to reduce the risk of Type II errors and avoid overlooking potential relationships that may exist but exhibit weaker effects. To control for potential false discoveries arising from multiple comparisons, the Bonferroni correction method was applied to maintain the family-wise error rate at an acceptable level ($p < 0.1$), thereby identifying statistically significant associations. Furthermore, the robustness checks were conducted including winsorizing continuous variables at the 1st and 99th percentiles, incorporating province-by-year interaction fixed effects, and excluding observations during the African swine fever epidemic (2018–2020) and the COVID-19 pandemic (2020–2022). The results demonstrated that the baseline regression findings remained statistically significant across all these alternative specifications, indicating that the conclusions of this study were robust.

Figure 2 shows the marginal food consumption quantities if the temperature of the current year and the preceding year was 1 °C higher than the preceding 30-year average. As shown in Panel a, climate warming in the preceding year had a statistically significant impact on the per capita consumption quantities of beans and tubers, vegetable oil, animal fats, pork, beef, mutton, eggs, dairy products, and aquatic products in the current year. It indicated that residents in China changed their consumption quantities of these food items as an active adaptation to climate warming. Specifically, if the average daily temperature in the preceding year was 1 °C higher than the preceding 30-year average, the per capita consumption quantities of pork, mutton, eggs, and beef in the current year increased by 4.302, 0.497, 0.261, and 0.129 kg, respectively, whereas that of dairy products, aquatic products, vegetable oil, beans and tubers, and animal fats decreased by 2.275, 0.664, 0.623, 0.456, and 0.123 kg, respectively. Among these, pork consumption exhibited the greatest increase, while dairy product consumption showed the most significant decrease.

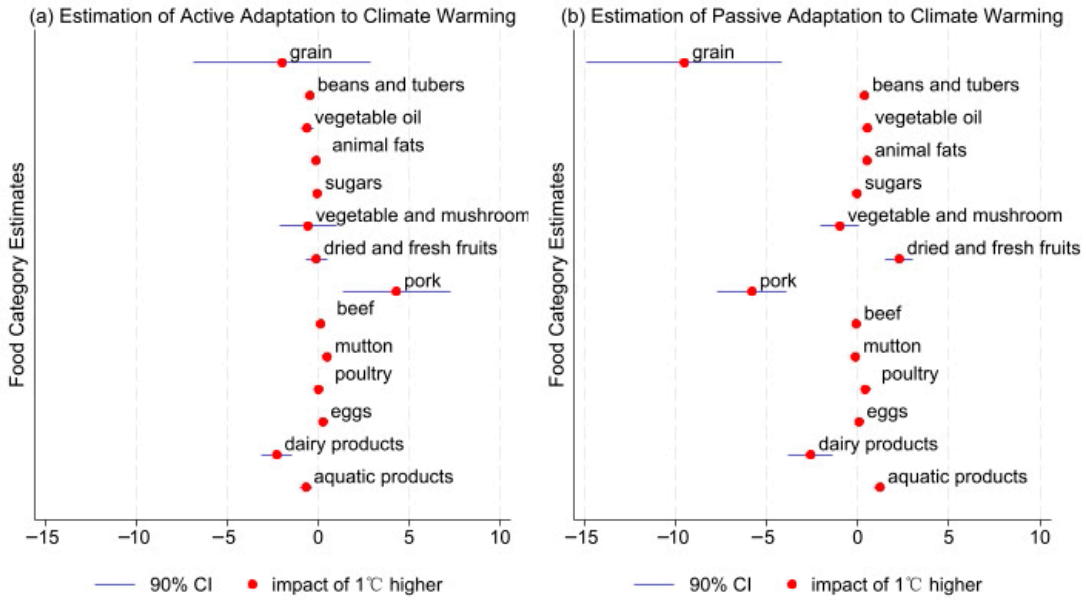


Figure 2. Marginal food consumption quantities for active and passive adaptations to climate warming in China. Source: The author's own illustration.

As shown in Panel b, climate warming in the current year had a statistically significant impact on the per capita consumption quantities of grain, beans and tubers, vegetable oil, animal fats, dried and fresh fruits, pork, beef, poultry, dairy products, and aquatic products. It indicated that residents in China passively changed their consumption quantities of these food items as a passive adaptation to climate warming. Specifically, if the average daily temperature in the current year was 1 °C higher than the preceding 30-year average, the per capita consumption quantities of dried and fresh fruits, aquatic products, vegetable oil, animal fats, poultry, beans and tubers increased by 2.286, 1.230, 0.531, 0.518, 0.411, and 0.377 kg, respectively, while that of grain, pork, dairy products, and beef decreased by 9.501, 5.798, 2.573, and 0.075 kg, respectively. Among these, dried and fresh fruits experienced the highest increase in consumption, while grains exhibited the most significant decrease in consumption.

4.4. Marginal Food Consumption Quantities for Active and Passive Adaptations in North China and South China

Figure 3 shows the marginal food consumption quantities if the temperature of the current year and the preceding year was 1 °C higher than the preceding 30-year average in North China and South China. As shown in Panels c and e, residents in South China increased their consumption of pork and beef while decreasing their consumption of vegetable oil and poultry as active adaptations to climate warming. In contrast, residents in North China increased their consumption of eggs while decreasing their consumption of grain and sugars. Specifically, if the average daily temperature in the preceding year was 1 °C higher than the preceding 30-year average, the per capita consumption of pork and beef in South China increased by 3.634 and 0.263 kg, respectively, while the consumption of poultry and vegetable oil decreased by 2.921 and 1.088 kg, respectively. In North China, the per capita consumption of eggs increased by 1.770 kg, while the consumption of grain and sugars decreased by 9.686 and 0.079 kg, respectively.

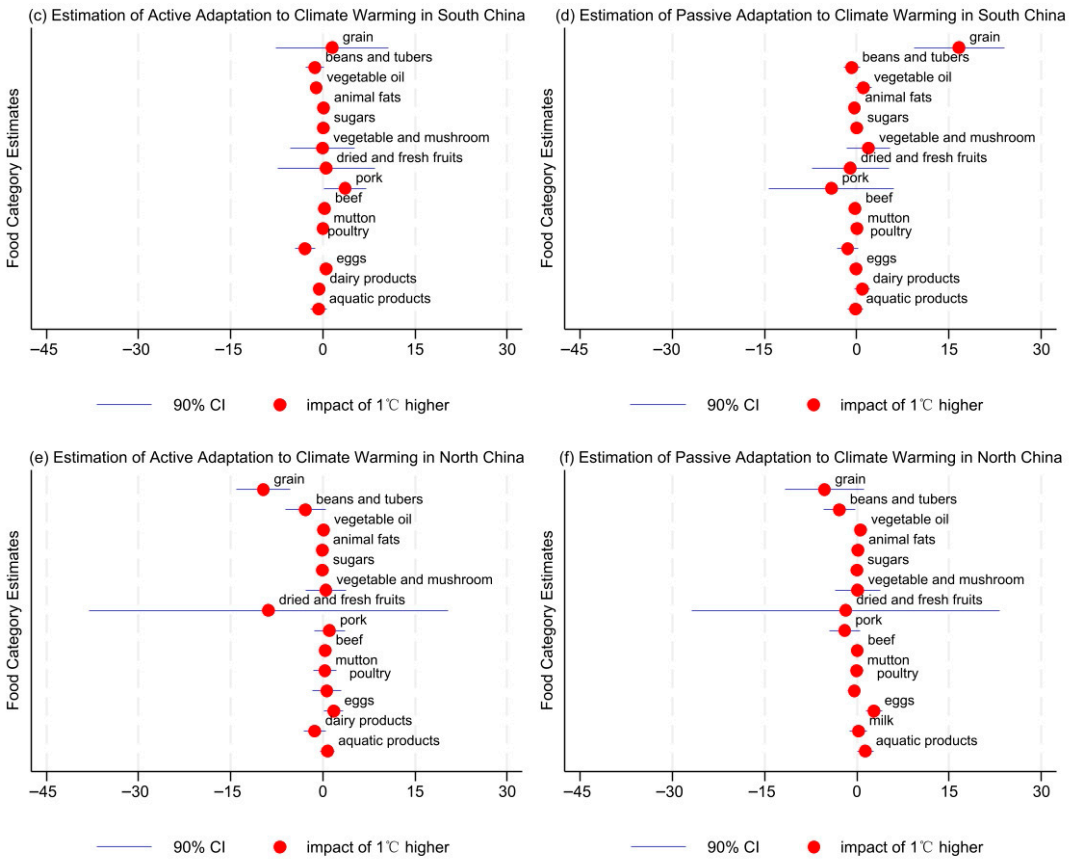


Figure 3. Marginal food consumption quantities for active and passive adaptations to climate warming in South China and North China. Source: The author's own illustration.

As shown in Panels d and f, residents in South China increased their grain consumption while decreasing their beef consumption as passive adaptations to climate warming. In contrast, residents in North China increased their consumption of vegetable oil, animal fats, eggs, and aquatic products while decreasing their consumption of beans and tubers. Specifically, if the average daily temperature in the current year was 1 °C higher than the preceding 30-year average, the per capita consumption of grain in South China increased by 16.612 kg, while the consumption of beef decreased by 0.283 kg. In North China, the per capita consumption of eggs, aquatic products, vegetable oil, and animal fats increased by 2.777, 1.381, 0.596, and 0.183 kg, respectively, while the consumption of beans and tubers decreased by 2.839 kg.

4.5. Marginal Food Consumption Quantities for Active and Passive Adaptations in High- and Low-Income Areas

Figure 4 shows the marginal food consumption quantities if the temperature of the current year and the preceding year was 1 °C higher than the preceding 30-year average in high- and low-income areas. As shown in Panels g and i, residents in high-income areas increased their egg consumption while decreasing their poultry consumption as active adaptations. In contrast, residents in low-income areas increased their consumption of vegetable and mushroom, beef, and mutton while decreasing their consumption of beans and tubers, animal fats, dried and fresh fruits, poultry, and dairy products. Specifically, in high-income areas, the per capita consumption of eggs increased by 1.281 kg, while that of poultry decreased by 2.973 kg. In low-income areas, the per capita consumption of vegetable and mushroom, mutton, and beef increased by 7.075, 0.597, and 0.233 kg,

respectively, while the consumption of dried and fresh fruits, poultry, dairy products, beans and tubers, and animal fats decreased by 5.891, 1.351, 0.845, 0.487, and 0.288 kg, respectively.

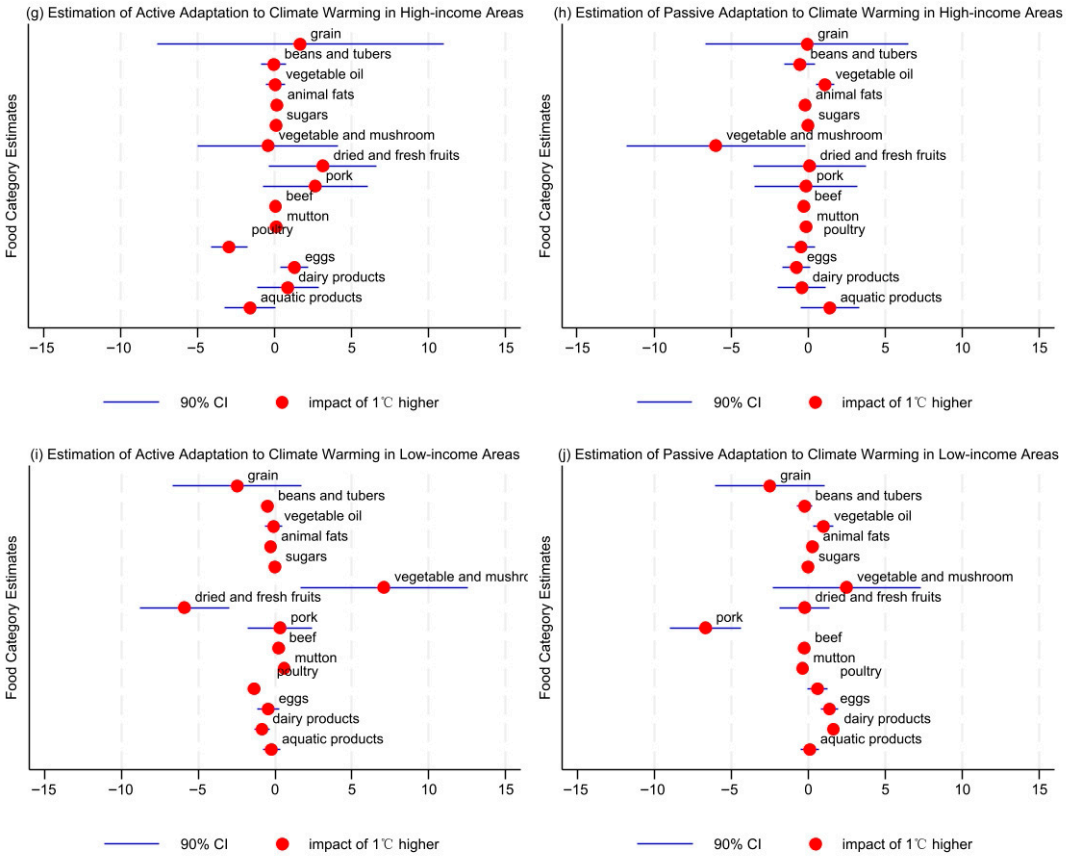


Figure 4. Marginal food consumption quantities for active and passive adaptations to climate warming in high- and low-income areas. Source: The author's own illustration.

As shown in Panels h and j, residents in high-income areas increased their grain consumption while decreasing their beef consumption as passive adaptations. In contrast, residents in low-income areas increased their consumption of vegetable oil, animal fats, eggs, and aquatic products while decreasing their consumption of beans and tubers. Specifically, if the average daily temperature in the current year was 1 °C higher than the preceding 30-year average, in high-income areas, the per capita consumption of vegetable and mushroom decreased by 5.991 kg, and the beef consumption decreased by 0.281 kg; in low-income areas, the per capita consumption of dairy products, eggs, and vegetable oil increased by 1.626, 1.371, and 0.976 kg, respectively, while the consumption of pork, mutton, and beef decreased by 6.677, 0.372, and 0.263 kg, respectively.

5. Discussion

Our study constructed and verified a theoretical framework for analyzing how residents adapt to climate warming by changing their food consumption quantities. We enhanced the theoretical explanation of the variation characteristics in residents' food consumption habits in the context of climate warming and summarized regional differentiation. The findings offer actionable insights into optimizing food supply structures, enhancing dietary guidance strategies, and promoting food security.

5.1. Discussion on Food Consumption Quantities in the Presence of Climate Warming

The per capita consumption of animal fats and pork was lower if the temperature of the current year and the preceding year was higher than the preceding 30-year average, while the per capita consumption of eggs and dairy products was higher. This is most likely due to the increasing attention to climate warming and healthy eating among residents in China. Residents may prefer low-carbon and healthy dietary patterns, reducing their consumption of high-fat and high-calorie meats in favor of lighter and healthier options, such as eggs and dairy products.

5.2. Discussion on Marginal Food Consumption Change for Active and Passive Adaptations to Climate Warming

Hypotheses 1 and 2 were supported, suggesting that Chinese residents changed consumption quantities of some food items as active and passive adaptations to climate warming. Additionally, both active and passive adaptations led to a significant decrease in dairy consumption. This may be due to changes in dietary preferences caused by climate warming, similar to consumers' preference for cool beverages over traditional dairy drinks in hot weather [37]. Residents in China increased their consumption of pork and beef but decreased their consumption of vegetable oil, beans and tubers, and animal fats as active adaptations to climate warming. Passive adaptation to the climate was exactly the opposite. This may be because pork and beef have long been regarded in Chinese dietary culture as high-value foods that enhance physical strength. As household incomes rise and urban-rural dietary patterns converge, consumers are likely to prioritize maintaining or even increasing their intake of these high-quality animal proteins—even under climatic stress—to uphold nutritional adequacy and dietary satisfaction, thereby exhibiting a path dependence on traditional food culture. However, residents who opt for passive adaptation may focus more on healthy eating, reducing their intake of high-fat and high-carbohydrate foods to alleviate discomfort in hot weather.

5.3. Discussion on Marginal Food Consumption Change for Active and Passive Adaptations to Climate Warming in South China and North China

For active adaptation, residents in South China changed the consumption quantity of more food items, mainly meat, while those in North China changed the consumption quantity of more plant-based foods. This may be due to the traditional dietary culture in South China, where meat has long been an integral part of the diet. Even under climate warming, residents in South China tend to choose high-protein, high-energy meats, such as pork, mutton, and beef, to meet their nutritional needs [38]. In contrast, residents in North China experienced cold and dry winters, and the demand for high-calorie foods decreased with climate warming [39]. For passive adaptation, residents in North China changed their consumption quantity of more food items, including beans and tubers, vegetable oil, eggs, and aquatic products, while residents in South China primarily changed their consumption quantity of grain and beef. This divergence in passive adaptation patterns reflects the foundational differences in dietary structures and culinary traditions between North and South China, as established in their respective active adaptation behaviors.

5.4. Discussion on Marginal Food Consumption Change for Active and Passive Adaptations to Climate Warming in High- and Low-Income Areas

Residents in high- and low-income areas exhibited differences in food consumption quantities in response to climate warming, reflecting underlying disparities shaped by long-standing dietary habits and regional agricultural practices.

For active adaptation, low-income areas experienced changes in the consumption of a wider range of food items, including beans and tubers, vegetable oil, fruits and

vegetables, pork, mutton, beef, and dairy products. This broader adjustment can be attributed not only to limited economic capacity and higher consumption elasticity but also to dietary patterns rooted in traditional agricultural systems. In many low-income regions, diets have historically relied on staple crops such as beans and tubers, which remain affordable and culturally familiar sources of nutrition [40]. In contrast, high-income areas witnessed changes primarily in eggs and poultry. The more pronounced reduction in poultry consumption in these areas may reflect a greater emphasis on dietary diversification and health-conscious adjustment [41], supported by greater access to alternative protein sources and modern food supply chains.

For passive adaptation, residents in low-income areas again altered a broader set of food categories, including vegetable oil, pork, mutton, beef, dairy products, and eggs. This pattern underscores their heightened vulnerability to climate-induced market fluctuations and their reliance on a narrow set of locally available and historically consumed staples [42]. By comparison, high-income areas adjusted consumption mainly for vegetables and beef, with a more significant reduction in beef. This selective adaptation aligns with both the higher baseline consumption of beef in wealthier diets and a greater capacity to shift toward more diversified, plant-based, or alternative food sources in response to climatic stressors.

5.5. Limitations

Several limitations need to be noted. Firstly, climate warming was measured solely by the difference between the current year's average daily temperature and its long-term average, neglecting the multifaceted nature of climate warming. This limitation was primarily due to data constraints in provincial statistical yearbooks, which only provided annual average temperature data without daily maximum/minimum temperature or precipitation records, resulting in a narrow range of meteorological dimensions. This simplified operationalization, while practical for broad-scale analysis, failed to capture critical dimensions of climate change that may more directly influence consumption behavior. Specifically, it omitted the increasing frequency and intensity of extreme weather events such as heatwaves that directly suppress appetite and alter food preferences, droughts that threatened agricultural productivity and increased food price, and heavy rainfall that disrupted food supply chains. These discrete shocks served as more salient triggers for behavioral adaptation than gradual temperature shifts. Future research would be strengthened by incorporating such indicators. For instance, the number of extreme heat days, drought indices, or precipitation anomalies, to better capture the complex pathways through which climate change affected household-level decisions. Secondly, the use of provincial-level panel data constrained the precise reflection of differences among areas.

Regional classification classifying areas solely based on per capita GDP and location in North or South China oversimplified China's economic and geographic diversity. Due to the limited granularity of provincial-level data, the analysis did not fully capture structural variations within different areas. Future research would incorporate sub-provincial microdata and adopt more refined classifications such as urban versus rural and coastal versus inland areas to enable a more nuanced analysis of regional heterogeneity in dietary adaptation strategies. Thirdly, although provincial-level demographic variables (e.g., income, education) are included as controls, their aggregated nature poses a limitation. This approach fails to capture the intra-provincial variation in socioeconomic status, potentially leading to ecological fallacy and biased estimates. The relationship observed at the group level may not hold at the individual household level, and the true effect of a factor like income could be confounded. Therefore, future work should prioritize the use of household-level microdata to directly model how individual and household characteristics

shape adaptation strategies. This would not only validate the present findings but also uncover the precise micro-level mechanisms that aggregate data cannot reveal.

6. Conclusions

Our study quantifies the change in residents' consumption quantities of 14 food items as active and passive adaptations to climate warming using panel data from China. We arrived at the following findings. First, the per capita consumption quantities of animal fats, pork, eggs, and dairy products showed significant differences between climate warming and non-warming conditions. Second, the consumption of pork, mutton, eggs, and beef increased, while that of dairy products, aquatic products, vegetable oil, beans and tubers, and animal fats decreased to facilitate active adaptation. Third, the consumption of dried and fresh fruits, aquatic products, vegetable oil, animal fats, poultry, and beans and tubers increased, while that of grains, pork, dairy products, and beef decreased as a result of passive adaptations. Fourth, for active adaptation, pork consumption increased in South China while poultry consumption decreased, and egg consumption increased in North China, alongside a decrease in grain consumption. Fifth, for passive adaptation, grain consumption increased while beef consumption decreased in South China, and egg consumption increased while bean and tuber consumption decreased in North China. Sixth, for active adaptation, egg consumption increased while poultry consumption decreased in high-income areas, and vegetable and mushroom consumption increased while dried and fresh fruit consumption decreased in low-income areas. Lastly, in high-income areas, grain consumption increased while beef consumption decreased because of passive adaptation. In low-income areas, the consumption of vegetable oil, animal fats, eggs, and aquatic products increased, while bean and tuber consumption decreased.

The following policy recommendations are proposed to address the dietary impacts of climate warming, integrating both supply- and demand-side interventions: First, on the supply side, given the increased consumption of certain food items such as fruits and pork, efforts should be made to expand cultivation areas and livestock farming systems to improve yield and quality, while also diversifying and securing import channels. Second, from a consumer guidance perspective, in light of potential nutrient deficiencies—such as in vitamin D, calcium, and iron—due to reduced consumption of grains and dairy products, it is essential to update national dietary guidelines to incorporate climate-adaptive nutrition advice. These guidelines should be disseminated through public education campaigns that help consumers make informed, health-conscious food choices under changing climate conditions. Third, to address regional disparities, grains, beef, and eggs should be strategically allocated between South and North China to ensure adequate supply, reflecting divergent regional preferences for animal- and plant-based foods. Targeted pricing policies, such as subsidies for nutritious staple foods, could also help shift consumption patterns toward more sustainable and regionally appropriate diets. Fourth, regarding distribution and access, channels for eggs and other key commodities should be expanded—sourcing both from low-income regions within China and internationally—to meet demand in high-income areas. Simultaneously, oilseed cultivation should be encouraged to boost vegetable oil production, improving affordability for low-income residents. Consumer education on the nutritional value of these foods, combined with subsidized pricing schemes, can further promote their uptake. Finally, from a sustainability perspective, it is critical to promote the production and consumption of plant-based proteins and drought-resilient crops. Such initiatives not only reduce the environmental footprint of the food system but also enhance its resilience to climate-related shocks, ensuring long-term food security and ecological balance.

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