32nd International Conference of Agricultural Economists
2-7 August 2024 I New Delhi I India

How Substituting Red Meat with Soybean Can Help China to Achieve Healthy and Environmental Goals?

Zhiming Yuan [1], Shenggen Fan[1,2], Yumei Zhang[1,2], Jingjing Wang[1], Ting Meng[1]

1:China Agriculture University, Beijing China 2:Academy of Global Food Economics and Policy

Corresponding author email: 15652805816@163.com

Abstract

In the current Chinese diets, merely 14% of residents adhere to the recent dietary guidelines. The excessive consumption of red meat presents significant health and environmental challenges, leading to increased pressure on protein feed imports. This study proposes a pragmatic solution wherein the entire population partially replaces red meat with soybeans in China, and evaluates the impacts. Employing meta-analysis and counterfactual analysis, we investigate the correlations between food intake and disease risk, calculating avoidable mortality and the associated disease burden. Consuming 50g/day of soybeans may prevent 1.2 million deaths annually, saving $250.74 million indirect costs and $3.52 billion in direct medical expenses. Through substituting, completely eliminating the population exceeding 100g daily red meat intake in China could preventing 0.28 million deaths, and saving $247.66 million indirect and $2.06 billion direct medical costs. Furthermore, utilizing a partial equilibrium model, we projected the regional impacts and costs of following the recommended soybean consumption on water use, land use, carbon, nitrogen, and phosphorus emissions. Through dynamic data validation, estimating a 19.6% reduction in carbon emissions, 5.4% less water use, 26.2% lower nitrogen footprint, and 24.6% less phosphorus footprint. These findings offer valuable evidence for improving agricultural economic policies and strategies in China.

JEL Codes:

Q180

Q510

I150

How Substituting Red Meat with Soybean Can Help China to Achieve Health and Environmental Goals?

1. Introduction

China is currently experiencing a significant shift in dietary patterns, characterized by an increased intake of red meat. The total meat consumption in China surged from 60 million tons (Mt) to 100 Mt between 2011 and 2021, marking a rapid increase of two-thirds (OECD/FAO, 2023). This rapid growth has had considerable health implications, leading to an increased risk of diseases such as obesity, hypertension, diabetes, and dyslipidemia. The Lancet Global Health Commission has established guidelines recommending the daily red meat consumption should not exceed 14g to mitigate health risks (Willett et al., Citation2019). However, China's per capita consumption of red meat has surpassed this threshold, with an average intake rising from 50g to over 70g per day over the last two decades. This excessive consumption pattern is corroborated by the "Report on Nutrition and Chronic Disease Conditions of Chinese Residents (2020)", which indicates a concurrent rise in the prevalence of cardiovascular diseases from 8% to 25% between 2010 and 2020.

The increase in red meat intake in China has necessitated a corresponding rise in large-scale livestock production, which heavily relies on soybean-based feed. Consequently,, China's soybeans import have significantly increased, a key component in the formulation of livestock feed. According to the National Bureau of Statistics, the demand for meat in China has surged from 12.05 to 92.27 Mt between 1980 and 2022. In 2021, the demand for soybeans reached approximately 90 million tons to meet the production needs of 450 million tons of total feed. This has led to a decline in China's soybean self-sufficiency rate to just 15% in 2021, resulting in increased soybean imports primarily from Brazil and the United States. This situation poses environmental challenges, as the increased production of soybeans for livestock feed contributes to higher carbon footprints, impacting global natural systems.

Recent cohort studies have investigated the associations between all-cause mortality and red meat intake, as well as the effects of substituting red meat with poultry or fish. However, the potential benefits of substituting red meat with direct soybean consumption by humans have been poorly explored. Soybean, through a nitrogen-fixing quality, enhances soil fertility, reduces water usage, and is less reliant on chemical fertilizers. Consequently, it would decrease in demand for chemical fertilizers and reduce energy consumption and emissions since the manufacturers would falter accordingly. Planting soybeans can bring environmental benefits, promoting biodiversity and fostering the growth of soil microbiota, as it helps reduce the adverse effects of pests and diseases. On the other hand, current meat consumption contributes heavily to climate change and causes a range of air pollution-related deaths (Liu et al.,2021). Substituting red meat with soybean could prevent 57,000 premature annual deaths linked to PM2.5 pollution (Guo et al.,2022).

Direct human consumption of soybeans results in considerably lower ecological footprints compared to using soybeans for livestock feed production. In 2021, China's soybean consumption reached 117 million tons, with 85% allocated to livestock feed and only 12.5% for human consumption. Nearly 70% of Chinese consumed less than 15 grams of soybean daily, and only 15% met the recommended intake according to dietary guidelines. Over half the Chinese population did not reach the recommended minimum daily intake of 25 grams of soybean and nut-based foods, with only West China adhering to the dietary recommendations.

In this study, we aims to examine the health and environmental impacts of partially substituting red meat with soybeans, while balancing environmental and economic objectives. We designed two dietary scenarios to evaluate the health and environmental effects of substituting red meat with soybeans, considering supply-demand dynamics and specific dietary habits in China from 2023 to 2030. These scenarios are meticulously derived from a robust meta-analysis and a thorough calculation of disease burden, with a particular emphasis on the unique dietary patterns prevalent in China. Through this multifaceted approach, our study seeks to contribute to the discourse on sustainable dietary practices and inform policy decisions that could lead to improved public health outcomes and a more environmentally sustainable food system.

2. RESULTS

Food Consumption in Different Regions under the Baseline Scenario

The baseline scenario for policy simulation uses historical consumption trends to predict future regional food demand and potential environmental impacts. From 2020 to 2030, total food consumption is expected to increase, accompanied by shifts in residents' food consumption patterns at both the national and regional levels. While direct consumption of grains is projected to decline, the consumption of meat, vegetables, and fruits is anticipated to rise, though at a slower pace. When examining per capita food consumption, the trends across different regions are observed to be increasingly converging (Figure 1). Specifically, per capita consumption of pork and eggs is projected to increase by approximately 10% compared to 2020 levels. The consumption of beef, mutton, and poultry is expected to grow even faster, exceeding 20%. Dairy and seafood consumption will exhibit the highest growth rates at around 25%, with an annual growth rate of approximately 2%. Furthermore, vegetable and fruit consumption will increase by 11% and 18%, respectively, with annual growth rates ranging from 1% to 2%.

Changes in total food consumption are expected to be relatively modest, closely aligning with per capita food consumption trends . Specifically, total direct grain consumption is expected to decline by 7.3% compared to 2020. Conversely, dairy and seafood consumption are expected to increase by 25%, while fruit and meat consumption rises by 17% and 15%, respectively. Vegetable and egg consumption are anticipated to grow by 10% and 8%. Additionally, potato and sugar consumption will see minor increases of around 2% (Figure 2).

This study also identifies notable regional disparities in consumption patterns across different areas. Generally, it is observed that the per capita consumption in the eastern regions (EC and CC) surpasses that of the central (NC and SC) and western (NW and SW) regions. Particularly, consumption of high-protein and nutritious foods such as seafood, meat, nuts, and fruits is notably higher in the eastern regions. Conversely, the central and western regions exhibit higher consumption proportions of staple crops like vegetables, edible oils, sugar, and potatoes. These regional disparities closely correlate with local economic development levels, industrial structures, and residents' consumption habits. From 2020 to 2030, consumption structures in various regions have undergone changes, with rapid growth observed in seafood and dairy consumption in the eastern regions, while significant increases in potato consumption are noted in the western regions.

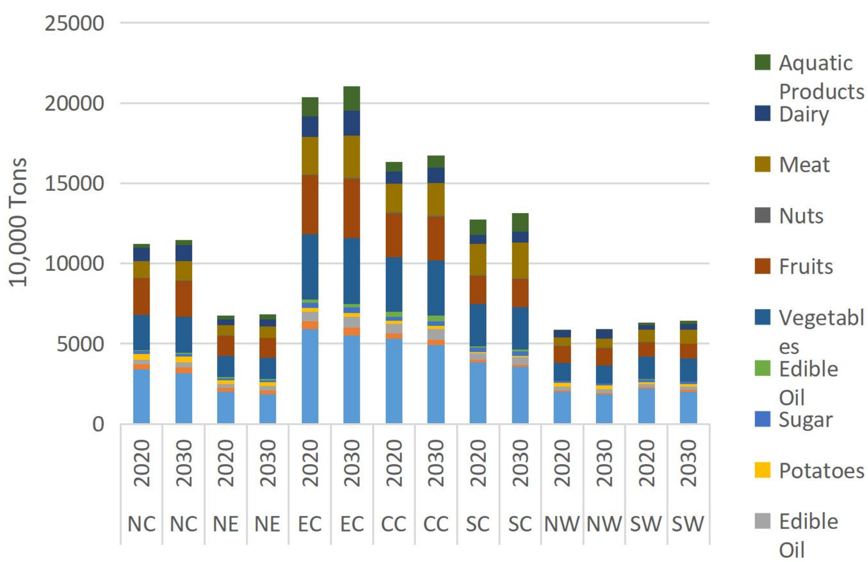

Figure 1 Projected Per capita Food Consumption by Region in China in 2020 and 2030

Note： NC=North China, NE=Northeast, EC=East China, CC=Central China, SC=South China, NW=Northwest, SW=Southwest

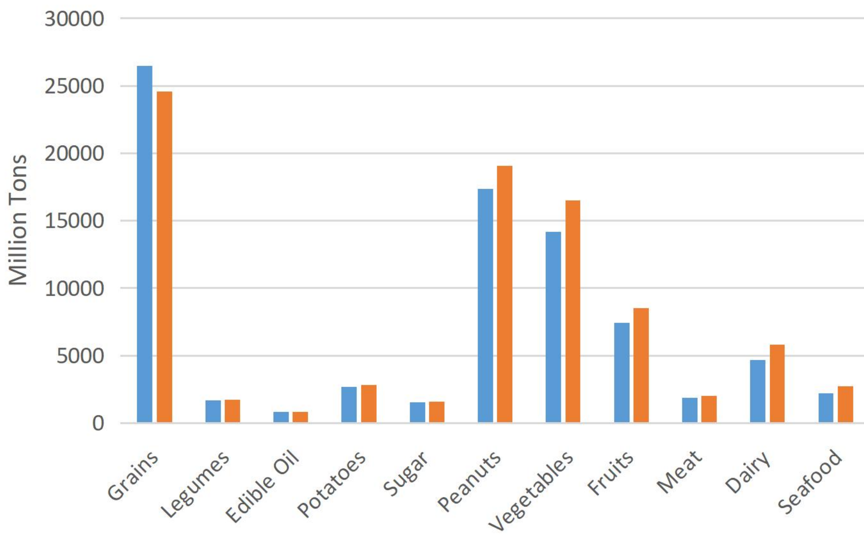

Figure 2 Total Food Consumption for National Residents in 2020 and 2030

Note: blue for 2020; orange for 2030

Environmental Impact of Food Consumption

The environmental impacts associated with food consumption, including carbon, water, nitrogen, and phosphorus emissions, were quantified based the emission factors of each food category and the amount of food consumption. The results are detailed below.

In the environmental module, carbon emissions from livestock products are calculated based on carbon emission coefficients per unit of livestock product. As illustrated in Figure3， In the base year of 2020, water usage per capita for the entire nation was 878 m^3/person. The northeastern region had the highest water usage per capita related to food consumption, reaching 971 m^3/person, exceeding the national average by ten percentage points. Across various regions, water usage in the Eastern, North, Northeast, Central, and Northwest accounted for approximately 21%-27% of the national total. However, meat consumption had the highest water footprint in the South and Southwest regions, oscillating between 34%-39%. The nitrogen emissions from food consumption were 13.2 kg/person, and the footprints from meat consumption dominated in all regions, making up 60%-80%, with the Northwest region exceeding 76% in 2020. The phosphorus emissions were 1.5 kg/person, with meat as the primary source. Regionally, the Northwest region had the highest phosphorus emissions per capita at nearly 2 kg/person. Meat also remains the primary source of phosphorus emissions in all regions, ranging from 52% to 75%, most prominently in the Northwest region, where it exceeded 74%.

In the same year, the total carbon emissions from food consumption nationwide reached 1.18 billion tons, accounting for approximately 10.4% of the country's total carbon emissions. When examining regional disparities, East China had the highest emissions, with food consumption comprising 270 million tons or 23.0% of the national total. The Central China region had approximately 220 million tons of emissions, accounting for 18.3%. In contrast, the Northwest and Northeast regions had the lowest food-related carbon emissions at around 90 million tons or 7.7%. Meat was the dominant source of carbon emissions across all regions, with footprints exceeding 40% in all areas and 57% in the Northwest region. Changes in residents' dietary habits and increases in consumption overall affected the environment. It is anticipated that by 2030, the food system will result in approximately 1.28 billion tons of carbon emissions and use about 13 trillion cubic meters of water, an increase of around 8%. The increase in gas emissions is particularly notable in the North China and East China regions, while water consumption shows significant growth in the Southwest and East China regions. In 2030, nitrogen and phosphorus emissions are estimated to reach 21.34 million tons and 2.49 million tons, with an increase of around 15%, respectively, and more significant increases in the East China and Central China regions.

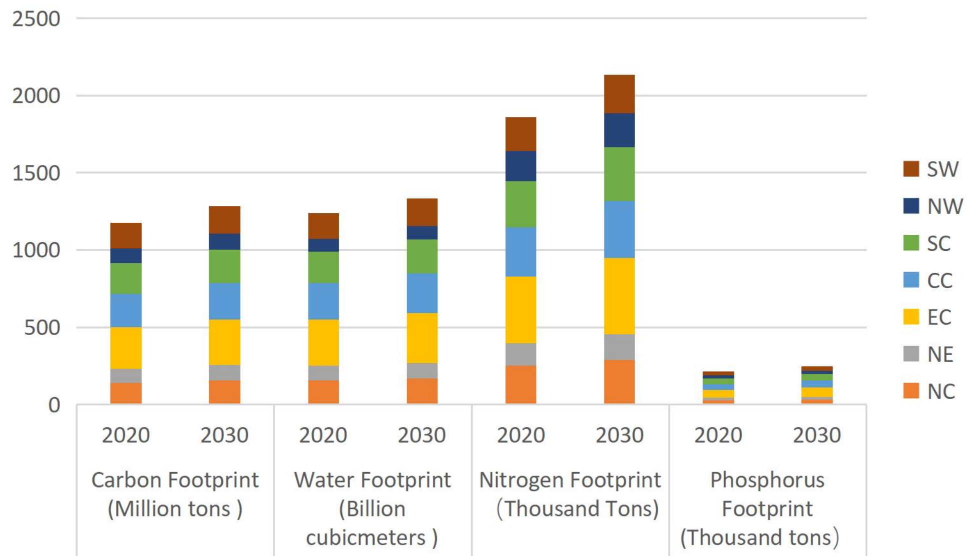

Figure 3 Environmental Impact of Food Consumption in Different Regions in 2020 and 2030

Note： NC=North China, NE=Northeast, EC=East China, CC=Central China, SC=South China, NW=Northwest, SW=Southwest

Environmental Impact of Food Consumption Under Different Scenarios

We have developed scenarios by considering substituting red meat by soybeans and evaluated the potential environmental benefits by 2030. Firstly, the "Red meat reduction" scenario (MEAT10), which targets a reduction of 5.3 million tons of red meat consumption, is expected to result in a 9.4% decrease in red meat intake. Conversely, soybean consumption may increase by 35%. Notably,, this shift does not significantly impact overall food consumption or the consumption of other food categories. In contrast, the "Increasing Soybean" scenario (SOYB35) aims to boost soybean consumption to replace pork, beef, and lamb consumption to alleviate environmental threats. In this scenario, soybean intake per capita increases from the current 15g per day to the recommended 50g per day, as suggested by The Lancet (Willett et al., Citation2019). This change is intended to replace an equivalent amount of pork, beef, and lamb by proportionally adjusting meat consumption to align with local dietary patterns. Reduced consumption of animal meat would lead to lower prices, decreased imports, and a reduced demand for feed grains, slightly decreasing the supply of staple grains. Under this scenario, grains for animal feed will be decreased by 10.22 million tons, equivalent to the land-saving area of 3.569 million acres based on crop yields from the 2019 Chinese Rural Statistical Yearbook.

The scenario MEAT10 aims to adjust the consumption structure of animal meat according to the food consumption characteristics of different regions, aligning per capita meat consumption within the recommended dietary guidelines. In this scenario, carbon emissions decrease by 6.2% compared to the baseline scenario, reducing from approximately 1.28 billion tons to approximately 1.207 billion tons. The Southwest region experiences the most substantial reduction, at 12.9%. The water footprint decreases from approximately 133 million m^3 to approximately 131 million m^3, representing a 1.3% reduction compared to the baseline scenario. Additionally, nitrogen and phosphorus footprints decrease significantly, with national averages declining by 9.3% and 8.2%, respectively.

The scenario SOYB35 aims to alleviate environmental pressures by replacing a portion of red meat consumption with soybeans. In terms of carbon emissions, this scenario results in a 19.6% reduction compare to the baseline scenario, decreasing from approximately 1.28 billion tons to approximately 1.07 billion tons. The Northwest region experiences the most substantial reduction at 83%, followed by the South China region with a 47.8% reduction. The water footprint decreases from approximately 133 million cubic meters to approximately 126 million cubic meters, representing a 5.4% reduction compared to the baseline scenario. Additionally, nitrogen and phosphorus footprints exhibit a national average decrease of 26.2% and 24.6%, respectively.

In summary, optimizing meat consumption structures based on regional food resources and substituting red meat with soybeans could mitigates environmental impacts by reducing emissions and water usage. This strategy effectively alleviates the strain on the environment and can be implemented into the current food system without significant effects on the supply and demand for other food commodities.

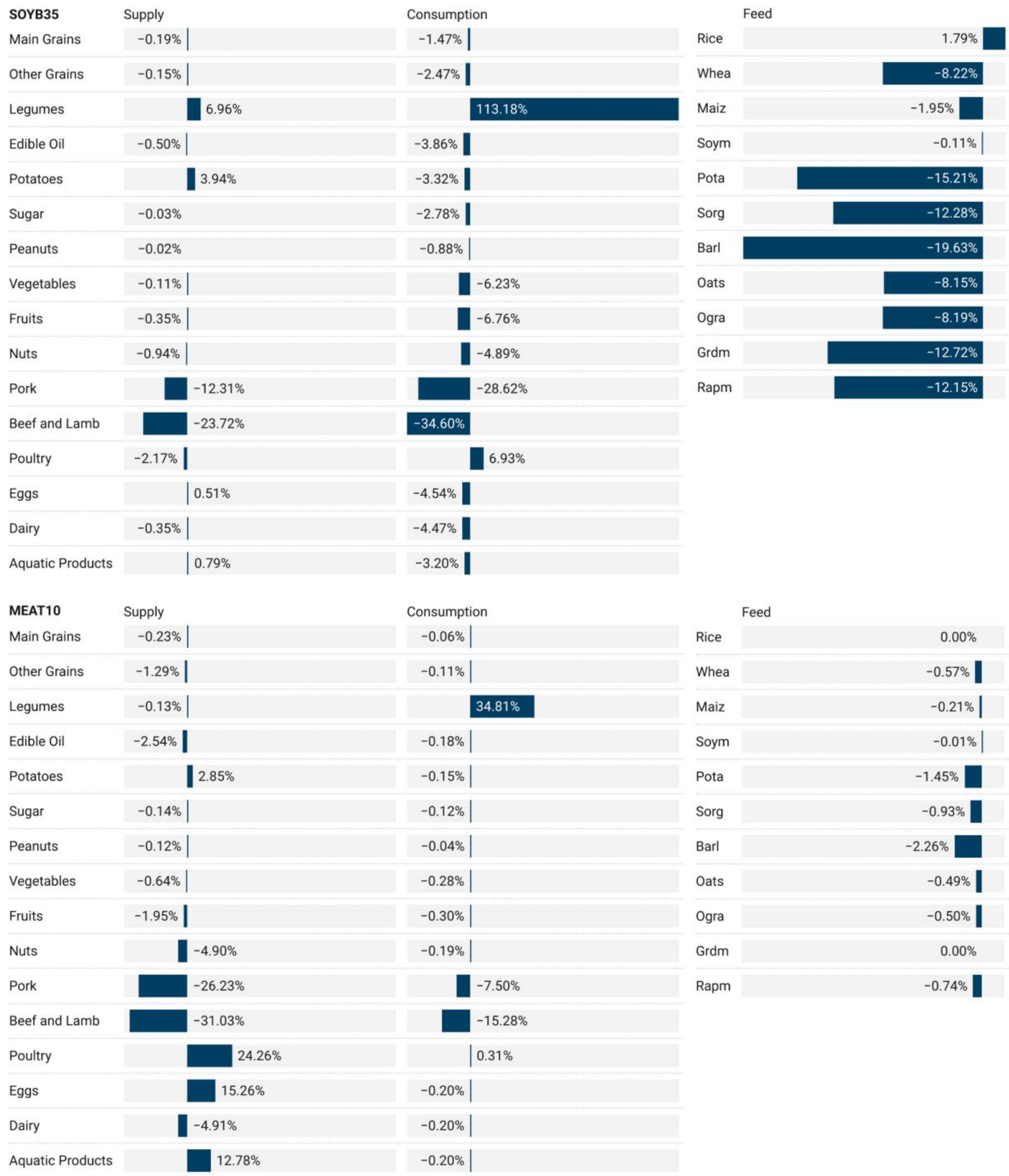

Figure 6 National Food Consumption, Supply and Feed Grain Demand in China Under Different Simulation Scenarios in 2030

Source: CAU-AFS Model Results

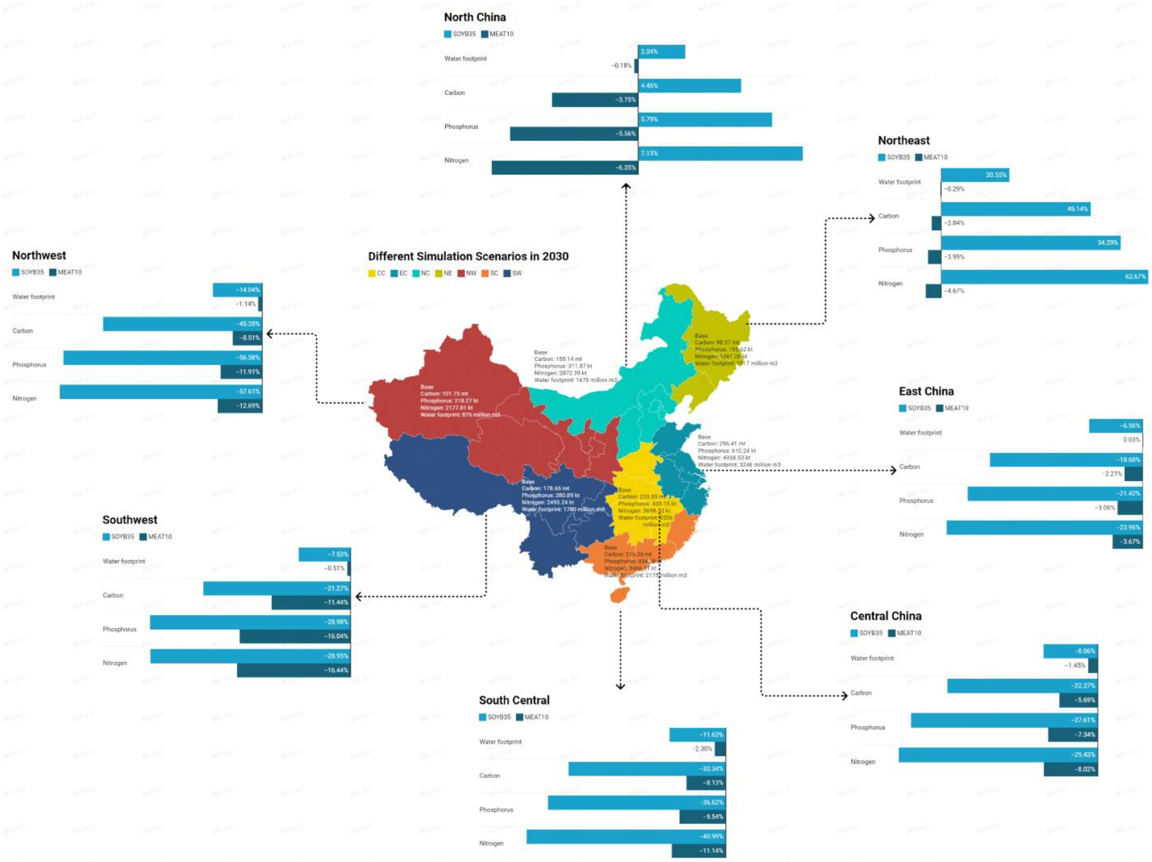

Figure 7 Total Environmental Impact by Regions in China Under Different Simulation Scenarios in 2030

Source: CAU-AFS Model Results

Meta Analysis Results for Health Impact

We conducted a systematic review and meta-analysis of published literature, presenting coefficients essential for calculating disease burden and offering insights into its association with health outcomes. Fifty-three articles published between 2011 and 2022 were selected for full-text review. Details of the literature review can be found in the Supplementary Information.

These studies demonstrate the significant health benefits associated with soybean consumption, including reduced risk of overall mortality (Schwingshackl L, et al., 2017), coronary heart disease

(Wangen K E et al.，2001；Huang et al., 2020; Zheng et al., 2012; Song et al., 2016; Budhathoki et al., 2019; Sina Naghshi et al., 2020; Bechthold et al., 2019; Guo Y et al., 2022), diabetes (Chang 2008; Li W et al., 2018), gastric cancer (Deng et al., 2013; Zhang et al., 2015; Thakur et al., 2014; Ni et al., 2018), breast cancer (LEE H P et al., 1991; LEE M M et al., 2005; LEE S A et al., 2009), and colorectal cancer (Thiagarajan et al., 1998; Yan L., 2010). Moreover, soybean consumption has been associated with improved glycemic control (Toyomura K, Kono S, 2002; Chang 2008; Minami Y et al., 2020; Li W et al., 2018; Toyomura K, Kono S, 2002; Chang 2008; Raquel et al., 2008; Tatsumi Y et al., 2013; Yan L., 2010), lower blood pressure (Zhou et al., 2022), and prevention of obesity (Bhathena SJ and Velasquez MT, 2002; Crujeiras et al. 2007; Trinidad et al. 2010; Gao M, Lv J, Yu C, et al. 2020; Abete et al., 2009), while also promoting enhanced bone health (Oxlund et al., 1995; Geil and Anderson, 1994; Civitelli et al., 1992; Ma et al., 2008; Liu et al., 2009; Lousuebsakul-Matthews et al., 2014).

Our meta-analysis results indicate that substituting total red meat with 50g soybean products per day is associated with a 46% reduction in the risk of stroke (SRR 0.54; 95% CI 0.34-0.87; Pheterogeneity = 0.001; I2 = 79.3%), a 14% reduction in coronary heart disease risk, and a 22%-25% reduction in gastric cancer risk (Soybean OR=0.75, 95% CI 0.66-0.85). Moreover, among Asian women, soybean consumption is linked to a 14% reduction in breast cancer risk (95% CI 0.78-0.94), and a 21% reduction in colon cancer risk (95% CI 0.65-0.97; P=0.026). Additionally, our analysis shows that a daily soybean protein intake of 100g is associated with a 23% lowers risk of ischemic heart disease (95% CI 0.65-0.90). Furthermore, compared to the lowest level of soybean intake, the highest recommended level of soybean intake can lower risk of type 2 diabetes by 35% among women and 27% among Asians (95% CI=0.66-0.91).

Our analysis underscores the adverse health effects associated with the consumption of red and processed meat, which are typically linked to heightened risks of coronary heart disease, stroke, type 2 diabetes, and cancer (Micha et al., 2010; Chen et al., 2013; Schwingshackl L et al.，2017). Specifically, the results indicate that a daily intake of 100g of red meat is associated with a relative risk of 1.25 for coronary heart disease (95% confidence interval 1.21-1.29; n=3), 1.12 for stroke (95% confidence interval 1.06-1.17; n=7), 1.12 for colon cancer (95% confidence interval 1.06-1.19; n=21), and 1.15 for type 2 diabetes (95% confidence interval 1.08-1.26; n=14). These findings emphasize the importance of incorporating soybean and plant-based proteins into dietary choices to maintain good health.

Table 1 Relative Risk Values for Food Intake and Disease Incidence

Food Intake	Population	Coronary Heart Disease	Ischemic Heart Disease	Stroke	Type 2 Diabetes	Colorectal Cancer	Gastric Cancer	Breast Cancer
Soybean (50g/day)	Female	N/A	N/A	N/A	0.65 (0.49–0.87)	N/A	N/A	N/A
	Male	N/A	N/A	N/A	0.73 (0.61–0.88)	N/A	N/A	N/A
	Overall	0.86 (0.78-0.94)	0.77 (0.9-0.65)	0.54 (0.82-0.44)	0.77 (0.66–0.91)	0.79 (0.65-0.97)	0.75 (0.66-0.85)	0.86 (0.78-0.94)
Red Meat (100g/day)	Overall	1.25 (1.21-1.29)	1.11 (1.06-1.16)	1.12 (1.06-1.17)	1.15 (1.08-1.26)	1.12 (1.06-1.19)	N/A	N/A

Source: Compiled by the authors using systematic meta-analysis.

Note: The data compilation prioritizes gender-stratified Asian datasets, with recourse to global data in instances where such specific datasets are unavailable. N/A: Lack of precise gender-segregated data.

Scenario Analysis Results for Health Impact

The relationship between food intake and disease risk is not linear. Therefore, we conducted a scenario analysis specifically for the SOYB35 scenario. We assumed that dietary modifications would be gradually implemented from 2023 to 2030 to meet the specified targets. Our calculations indicate that increasing soybean intake to 50g per day per capita, while reducing red meat consumption, would cost only 4 billion RMB. This change would result in the avoidance of 1.20 million people deaths, a reduction of 250.74 million USD (1.791 billion RMB) in indirect disease burden, and savings of 3.52 billion USD

(25.145billion RMB) in direct medical costs. Furthermore, this dietary transition would reduce carbon emissions by 19.6%, a 5.4% decrease in water footprints， a 26.2% reduction in the nitrogen footprint, and a 24.6% reduction in the phosphorus footprint.

Conversely, increasing red meat consumption beyond the recommended levels by 100g per day per capita would cost 41.46 billion RMB, leading to 0.28 million people deaths, an increase of 247.66 million USD (1.769 billion RMB) in indirect disease burden, and 2.06 billion USD (14.688billion RMB) in direct medical costs. These findings underscore the significant benefits of reducing red meat intake (Table 5).

Table 5 Simulation Results of Deaths and Diseases Burden

The number of deaths and disease burden avoided for per capita person in China intake 50g soybean daily(i)						
Disease type(x)	PIFi	DR(‰)	Population affected (10,000 people)	Δ Avoided Deaths (10,000 people)	Indirectly avoided disease burden (¥100 million)	Directly avoided medical expenses (¥100 million)
Type 2 Diabetes - Female	0.27	0.21	67200	3.81	1.15	28.18
Type 2 Diabetes - Male	0.21	0.21	71900	3.17	0.95	30.15
Stroke	0.37	1.41	139000	72.52	7.54	42.16
Ischaemic heart disease, IHD	0.17	1.23	139000	29.06	3.34	6.77
Stomach cancer	0.19	0.16	139000	4.23	1.69	1.11
Breast cancer-female	0.1	0.05	67200	0.34	0.27	0.79
coronary heart disease	0.03	1.35	139000	5.63	2.53	136.33
Colorectal cancer-female	0.16	0.15	67200	1.61	0.45	5.95

Total				120.37	17.91	251.45
The number of deaths and disease burden for per capita person in China intake more than 100g red meat daily(i)						
	PIFi	DR(‰)	Population affected (10,000 people)	Δ Deaths (10,000 people)	Indirect increasing disease burden (¥100 million)	Direct increase in medical expenses (¥100 million)
coronary heart disease	0.19	1.35	54071	13.87	13.90	100.76
Ischaemic heart disease, IHD	0.08	1.23	54071	5.32	1.36	2.11
Stroke / stroke	0.09	1.41	54071	6.86	1.59	14.76
colorectal cancer	0.09	0.15	54071	0.73	0.00	4.31
Type 2 diabetes	0.11	0.21	54071	1.25	0.84	24.94
Total				28.03	17.69	146.88

Additionally, this study highlights that red meat reduction intake by 10g per person per day, with a corresponding increase in soybean consumption to align with dietary recommendations, would yield several benefits. By 2030, this shift is expected to reduce carbon footprints by 6.2%, water usage by 1.3%, nitrogen outlet by 21.4% and phosphorus emissions by 8.2%. These results highlight the substantial of soybeans in terms of food security, nutritional health, climate change mitigation, and biodiversity conservation. Increasing soybean consumption can promote environmental sustainability and health while ensuring a balanced protein intake.

Sensitivity analysis

The sensitivity analysis was conducted to evaluate the robustness of our findings by varying key parameters. It identified crucial factors such as environmental coefficients and disease risk intervals, performing two sets of analyses.

The first set examines how changes in environmental coefficients impact various parameters related to food choices. The results show consistent proportional changes in carbon emissions, water footprint, nitrogen footprint, and phosphorus footprint.

The second set employs probabilistic sensitivity analysis to assess disease risk to evaluate the range of mortality rates and associated disease burden costs. Our findings suggest that a daily soybean consumption of 50 grams per capita in China could prevent 357,300 to 1,369,000 deaths, indirectly reducing disease burden by 2.2 billion to 8.337 billion RMB and directly lowering healthcare expenses by 79.8 billion to 344.3 billion RMB. Conversely, a daily red meat intake exceeding 100 grams per capita may lead to between 828,400 and 1,296,000 deaths, increased disease burden of \$4.2 billion to \$6.8 billion, and healthcare costs of \$84 billion to \$220 billion in China.

3. Discussion

Our study underscores the importance of a balanced dietary intake of soybean and meat proteins for both environmental and health benefits. However, previous research has several limitations that our study aims to address. Firstly, we noted a prevalent reliance on static historical data and national average to assess dietary intake in previous studies. This approach neglects the significant regional disparities in dietary habits and the prevalence of undernourishment, which are crucial factors to consider (Kaartinen et al., 2023; Gazan et al., 2021; Röös et al., 2020; Vasconcelos et al., 2020). Secondly, while some research has acknowledged the economic, cultural, and healthcare system differences among developed countries, there has been a notable omission of emerging economies, such as China. Thirdly, the majority of recent studies have focused on medical expenses associated with all-cause mortality, w with a relative scarcity of research that directly examines the health and environmental impacts of specific food groups. Our study aims to fill this research gap by conducting a detailed investigation into the health and environmental implications of specific food groups, particularly focusing on the balance between soybean and meat proteins.

A multitude of economic models have been employed by various research institutions to evaluate the potential impacts of policy changes. Prominent examples include the International Food Policy Research Institute's (IFPRI) IMPACT model and FAO in collaboration with OECD through their AGLINK-COSIMO model. However, the development of interdisciplinary economic models tailored to the specific conditions of China remains in its nascent stages. Existing Chinese economic models, such as CAPSiM and CHINAGRO, predominantly concentrate on national-level scenarios, often neglecting the broader implications of international market dynamics, natural resource limitations, and the effects of agricultural disasters. To address these limitations, our study employs an integrated economic model that incorporates essential components of agriculture, water resources, and crop production. This holistic approach allows for a comprehensive evaluation of the potential substitution of red meat with soybeans, taking into account the intricate interplay among policy interventions, constraints on natural resources, and external factors that may influence the agricultural sector. By integrating China-specific data and scenarios into our model, our research provides a more nuanced understanding of the health and environmental implications associated with dietary shifts within the context of an emerging economy.

Therefore, we add these additional measures to detect direct socioeconomic costs dynamically. Explicitly focusing on China while keeping its soybean production for direct human consumption, we aimed to estimate the impacts of 50g/day soybean intake on the outcomes of total mortality and deaths, and predict the future changes in diet by region. Our study overcomes the limitations of previous research through a comprehensive and rigorous approach. First, our methodology comprehensively accounted for an independent food group, soybeans, and its implications across genders, regions, and various parameters. Secondly, by incorporating regional variations in dietary patterns, socioeconomic conditions, and healthcare systems, our modeling provides a more nuanced and contextualized analysis. Thirdly, our study explicitly focuses on China while examining soybean production for direct human consumption, enabling us to estimate the impacts of soybean intake on mortality outcomes and predict future dietary changes at the regional level. Furthermore， We steer clear of potential reverse causation bias when examining the associations between disease risks and costs.Each food group could exert independent effects on specific disease types. Our study addresses a critical knowledge gap by investigating the associations between specific protein sources and their impacts on the disease burden attributable to dietary risk factors. The relative risk intervals for specific diseases were calculated based on prospective research from reputable global institutions, incorporating epidemiological health loss and economic loss methodologies, as well as pathological health risk assessment methods. Aligning with meta-analyses, the mean, maximum, and minimum values of the relevant risk factors were analyzed to derive the recommended risk intervals, thereby enhancing certainty. Finally, while acknowledging the statistical uncertainties in the evaluation results due to the need for further investigation of regional dietary habits, our study's timeliness and rigorous approach contribute to advancing the understanding of the complex interplay between dietary choices, health outcomes, and economic implications.

The soybean has been cultivated since Chinese agriculture began, and it has 5000 years of history. It is a staple food crop for the development of Chinese civilization, and soybean-based products become one of the most versatile foods in people's dining tables. China has had a rich and diverse soybean processing technology since ancient times, including non-fermented bean products (such as tofu, soybean milk, dried tofu, bean curd, etc.) and fermented bean products (such as fermented black beans, bean paste, fermented bean curd, etc.). However, Against the historical backdrop of resource scarcity in China, meat was perceived as a nutritious and scarce delicacy, due to its relative inaccessibility and high price compared to plant-based foods. Meat consumption has been imbued with cultural attributes closely associated with celebratory and familial social activities， leading to the marginalization of plant-based alternatives such as soybean. Even as health awareness has progressed, cultural factors continue to impede the widespread abandonment of meat-based diets among the Chinese populace. Concomitant with economic advancement and societal progression, we have deviated from our originally healthier dietary practices. Between 1989 and 2000, Chinese people's dietary structure was more in line with the 2022 Chinese Dietary Guidelines (CDGs) targets, mainly based on plant-based staples. However, the China Health and Nutrition Survey shows that the intake of soybeans and their products by Chinese residents has been declining since 2000; adult residents’ intake has dropped from 14.5 grams per day in 2000 to 12.8 grams per day in 2018.

Our study also highlights that the substitution of red meat with soybean-based protein sources can yield beneficial effects on the environmental sustainability.

The strategic augmentation of direct human consumption of soybeans as a partial replacement for red meat is essential for alleviating the concurrent issues of malnutrition and over-nutrition prevalent among both urban and rural populations in China. However, achieving this dietary shift may necessitate targeted policy interventions to reinforce the adherence to national dietary guidelines within the country. While China's policy aimed at revitalizing the soybean industry has successfully stimulated production, it has not thoroughly addressed the challenge of consumer acceptance. Future research should be directed towards identifying region-specific consumer preferences, which can inform the development of tailored soybean products that resonate with diverse demographic segments. Additionally, investigating the long-term health implications of sustained soybean consumption across diverse demographic groups could provide valuable insights into the long-term benefits and potential risks associated with this dietary change. Furthermore, a thorough cost-benefit analysis of various policy interventions and incentive structures could inform more effective strategies to encourage the cultivation and consumption of soybeans. Interdisciplinary collaborations that integrate expertise from fields such as agronomy, nutrition, consumer behavior, and public policy would facilitate a comprehensive understanding of the multifaceted aspects influencing the adoption of soy-based diets and their broader impact on health, the environment, and the economy.

It is important to acknowledge the limitations inherent in our study, which include potential biases within the coefficients utilized in our analyses. Specifically, when exploring the health impact of dietary change, constraints such as an inadequate sample size for statistical significance and a paucity of comprehensive data have limited our ability to fully delineate the population impact fractions across the spectrum of disease types. While the dietary risk factors were selected based on meta-analyses that provided convincing evidence of causal links to chronic diseases, the associations between specific foods and diseases are subjects of ongoing debate. The relative risk factors used in the health module calculations are based on previously published estimates of the statistical value of life from developed countries. These factors may not adequately account for regional disparities and may not be fully representative of the actual circumstances within China. Furthermore, our gender-based analysis implies that insights into soybean consumption may be more beneficial for targeting female consumers. The associated gender-specific risk variables may require further contextualization based on the origin of consumers and the delineation of age groups.

4. METHOD

Modeling

In this study, we established a baseline scenario that serves as the foundation for our recursive dynamic simulation, which extends to the year 2030. This scenario is predicated on a set of assumptions concerning key socio-economic indicators, namely population dynamics, urbanization rates, GDP growth, and technological advancements. Our demographic assumptions are grounded in the 2020 population data reported by the National Bureau of Statistics and are further informed by the population growth rates projected by the United Nations Population Division for China in 2022. We anticipate a stabilization in the national population, which is projected to decline to approximately 1.4 billion by 2030, concurrent with a gradual increase in the urbanization rate, expected to approach 70%. In the absence of detailed provincial population forecasts, we maintain the assumption that the population distribution across provinces will remain consistent throughout the simulation period. Economic growth is modeled using actual GDP growth rates observed from 2021 to 2022. These rates are then projected to gradually decline in the subsequent years, from 2023 to 2030, in accordance with historical GDP growth trends at the provincial level. We assume an average annual GDP growth rate that fluctuates within the range of 5% to 6%.We forecast an increase in income for both urban and rural residents, with a projection that rural incomes will grow at a marginally faster pace than their urban counterparts, thereby reducing the urban-rural income disparity. Technological progress in agriculture is assessed by examining the historical growth rates of crop yields and livestock body weights due to technological advancements. Finally, the model assumes that the total amount of arable land available for agricultural activities will remain relatively stable over the projection period.

Scenario Setting

The per capita daily protein consumption in China is reported to be 60.4 grams, with a slight variation between urban and rural demographics. Urban residents consume an average of 62.7 grams, while rural residents intake 58.7 grams. In urban areas, the protein intake is distributed across cereals (40.2%), soybeans (6.4%), and animal-based products (40.5%). Conversely, rural residents' protein consumption is more heavily reliant on cereals (51.5%), followed by animal-based foods (31.4%), with soybeans contributing a smaller proportion (5.6%) (China Residents' Nutrition and Chronic Diseases Report 2020). Soybeans, which contribute a relatively modest share to the overall protein intake, possess a direct absorption rate of approximately 60% (Baglieri A et al., 1994). This indicates that approximately 21 grams of protein per 100 grams of soybeans is readily by the human body, resulting in an effective soybean protein content of 21%. The digestibility of soybean protein can be further enhanced through processing, with various soy products demonstrating improved absorption rates. For instance, tofu achieves a protein digestion rate within the range of 92% to 96%, and soy milk exhibits a digestion rate of 84.9%. In comparison, the protein content in 100 grams of pork can vary by cut but averages to about 20 grams. Hence, our scenarios consider a 1:1 substitution ratio of soybeans for pork.

We recognizes a significant divergence between the self-reported soybean consumption data and actual intake levels. This discrepancy can be attributed to the presence of soybean-derived products in various processed foods, including baked goods, confectionery, dairy products, and beverages, which may not be accurately reflected in dietary surveys by respondents. Moreover, most dietary intake surveys rely on 24-hour recall method, which can lead to biases and may not accurately represent the true consumption. Taking into account the potential losses throughout the consumption-to-intake process of soybeans, we adopt the current per capita soybean intake figures derived from the Chinese Center for

Disease Control and Prevention survey. Specifically, we consider a baseline of 15 grams of soybeans and 85 grams of red meat per day for our simulations.

In Scenario 1 (MEAT 10), we implement a 10g/day reduction in red meat consumption per capita. This reduction is strategically offset by an equivalent increase in the intake of soybeans. Consequently, this adjustment results in a balance daily red meat consumption of 75g/day, while raising soybean intake by 10g/day. This increase in soybean intake aligns with the recommended minimum dietary guidelines, achieving a daily intake level of 25 grams (equivalent to 9.1kg annually).

In Scenario 2 (SOYB 35), we proposes a further increment in soybean intake by an additional 35 grams per day, replacing an equivalent amount of red meat, aligning more closely with international dietary standards. Importantly, this enhancement in soybean consumption is calibrated to maintain the recommended intake level of red meat at 50 grams per day.

Scenarios	Description of Simulation Scenarios	Reference for Setting
MEAT10	Reduce per capita daily pork, beef and lamb intake by 10g, simultaneously increase soybean intake by an equal amount.	Based on recommendations from "Chinese Dietary Guidelines (2022)" and disease burden calculations, adjusted red meat intake to 75g/day while ensuring soybean intake meets the minimum recommended level of 25g/day.
SOYB35	Increase per capita daily soybean intake by 35g, simultaneously reduce pork, beef and lamb intake by an equal amount.	Reference to recommendations by the World Health Organization and the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems (2019), raising soybean intake to 50g/day while Red meat reduction intake from 85g/day to 50g/day.

Table 2 Scenario Settings

Source: Authors' Setting

Note: The data presented here represent recommended intake levels; the model calculates food consumption based on the edible portion conversion.

Environment Module Coefficients Collection

This study is underpinned by a comprehensive dataset on the environmental impact factors, primarily from the China Product Life Cycle Greenhouse Gas Emission Coefficient Dataset (2022), the Barilla Center for Food & Nutrition Foundation, and relevant studies (Cai et al., 2022; Poore and Nemecek, 2018; Song et al., 2015; Xue et al., 2021). Water footprint parameters came from the Water Footprint Network database. Nitrogen and phosphorus footprint coefficients were primarily based on the work of Xue et al. (2021).

Soybeans emerge as a more environmentally sustainable dietary alternative to red meat, primarily due to the lower consumption of water and nonrenewable resources required for their production. . It is evident that the cultivation of soybeans results in significantly lower emissions of greenhouse gases compared to animal farming. Specifically, soybean production emits merely 0.4 kg of carbon dioxide per kg of product, which is a mere 2% of the emissions associated with animal farming. Furthermore, the nitrogen emissions from soybean cultivation are a fraction of those from beef production, at 13.66 grams per kg, representing a reduction of 57 times. In terms of water usage, soybean cultivation is markedly more efficient, with a consumption rate of 3016 cubic meters of water per ton, which is approximately one-third of the water required for beef production. Similarly, the phosphorus footprint of soybean production stands at 1.14 grams per kilogram, a reduction of 70 times when compared to the phosphorus emissions from beef production.

Table 6 The Environment Footprint of Food Consumption

Food type (kg)	Carbon Footprint(kg)				Water Footprint(m3/t)				Nitrogen Footprint (g)	Phosphate Footprint (g)
	Farm gate	Postpartum circulation	Household consumption	Total	Green water	Blue water	Gery water	Total		

Soybean	0.1	0.2	0.1	0.4	2549	249	218	3016	14	1
Pork	4.7	0.1	0.2	5	3686	286	473	4445	58	8
Beef	29.8	0.1	0.2	30.1	9085	350	282	9717	778	80
Mutton	24.4	0.1	0.2	24.7	3485	278	9	3772	892	79
Average Animal products	19.6	0.1	0.2	19.9	5419	304	255	5978	576	56
Average Animal products / soybean	163	1	3	50	2	1	1	2	42	49

Source: The carbon emission intensities of various food types at different stages along the food supply chain were calculated based on the China Productss Carbon Footprint Factors Database(2022), and other relevant reports(e.g., Cai et al.2022; Poore and Nemecek 2018;Song et al.2015; Xue et al.2021). The water footprint factors of different food types with green, blue,and gray WF parameters selected for each plant-based and animal-based product referred to Mekonnen, M. M. & Hoekstra, A. Y.(2011). The NF and PF coefficients referred to Xue (2021).

Health Module and Coefficients Collection

This study employs a systematic meta-analysis to elucidate the complex interplay between dietary patterns, specifically the consumption of soybeans and red meat, and their association with various diseases. A comprehensive search was conducted across multiple databases, including PubMed, Embase, and Google Scholar, utilizing three distinct sets of keywords: 'Soybean/Red meat,' 'disease name,' and 'disease burden.' The primary outcome of this meta-analysis is to synthesize evidence from studies examining the relationship between the consumption of soybeans and red meat and seven diseases with established dietary links. This includes an analysis of the economic implications of these diseases, encompassing both direct and indirect healthcare costs. To bolster our analysis, we have utilized data from three pivotal sources: the Global Burden of Disease Project (GBD2017), the China Cause of Death Surveillance Dataset, and the China Health and Wellness Statistical Yearbook (Yearbook). These sources have been pivotal in providing essential data on disease incidence, mortality, and disability-adjusted life years (DALY), with an emphasis on rates standardized to the Chinese population. Further information is provided by the China Health and Nutrition Survey, which reveals that only 30% of residents met dietary guidelines for soybean and soybean product consumption (25g). Additionally, findings from the 2015 Chinese adult nutrition transition study indicating that 49% of the adult population exceeded the recommended intake levels for poultry and meat, with 38.9% of individuals consuming more than 100g of meat per day.

Health Module Base Calculation

To evaluate the associated disease risks, we employ the attribution disease burden assessment method. This methodological framework is instrumental in quantifying disease risks across various dietary scenarios. Here we introduced Population Impact Fraction (PIF), which represents the proportionate change in disease cases that change when the exposure risk shifts from the baseline to a control situation. Two approaches, direct category analysis and counterfactual analysis, are utilized to calculate PIF., The first approach, direct category analysis, relies on empirical data to estimate disease risk through the computation of relative risks (RR). Utilizing the prevalence of the population (P(X)) and the RR of exposure factors derived from literature, we ascertain the attributable disease burden. The second approach, counterfactual analysis, operates on hypothetical scenarios to estimate the avoidable disease burden. This method juxtaposes the risks at varying levels of exposure to assess the potential reduction in disease burden. We calculate the relative risks for both the unexposed group (RRu) and the exposed group (RRa), employing these metrics to quantify the avoidable disease burden. This approach allows us to assess disease risks and compare burdens across different scenarios comprehensively. It provides a robust methodological foundation for understanding the potential health implications of shifting from red meat to soybean consumption. The attributable disease burden is calculated as follows.

$$\mathrm{PIF} = \frac{\int \mathrm{RR}(x)\mathrm{P}(x)dx - \int \mathrm{RR}(x)\mathrm{P}'(x)dx}{\int \mathrm{RR}(x)\mathrm{P}(x)dx}$$

The attributable mortality resulting from excessive red meat consumption, denoted as Δdeaths, can be quantified by a methodical calculation. This process involves multiplying the PIF of each disease by the disease-specific mortality (DR) and the size of population (P) that exceeds the recommended intake of red meat, which is more than 100 grams per day (38.9% of total). Conversely, the potential reduction in mortality that could be achieved through the daily consumption of 50 grams of soybeans is calculated by a similar method. This calculation involves (P).multiplying the disease-specific mortality (DR) and the total population (P):

$$\Delta deaths_i = PIFi * DR * P$$

The alteration in the burden of disease attributable to risk factors (i) such as soybean and red meat consumption, can be quantified using a structured formulaic approach. This method integrates the PIF for each disease, which represents the proportion of disease burden that can be attributed to a specific risk factor. The PIF is then multiplied by the per capita Gross Domestic Product of China (GDP), the specific disease of Disability-Adjusted Life Years (DALY). The resultant figure is divided by the per capita life expectancy China:

Indirect Cost of Disease = PIF * indirect cost = PIF * DALY (Disability-Adjusted Life Years) / average life expectancy * GDP (Gross Domestic Product) per capita

We used publicly available data sources to analyze comparative risk. Central to our analysis are the disability-adjusted life years (DALYs) reported in the 2019 all-sex, all-age Global Burden of Disease (GBD) study, encompassing all sexes and ages, and the World Health Organization's Global Health Estimates. In alignment with the strategic objectives outlined in China's "14th Five-Year Plan," the 2035 Long-Range Objectives, and the "Healthy China 2030" Outline, it is projected that the average life expectancy will surpass 79 years by the year 2030. According to the International Monetary Fund (IMF) World Economic Outlook report, China's Gross Domestic Product (GDP) is anticipated to reach 25,400 U.S. dollars by 2030. The Development Research Center of the State Council has provided a detailed demographic forecast for the year 2030, estimating the Chinese population to be 1.39 billion, with a gender ratio of 107 males for every 100 females, comprising 672 million females and 719 million males (Ma J, Li J, Zhang L, et al.,2022).

Then, we systematically calculated the treatment costs associated with various diseases by integrating three critical parameters: population numbers, disease incidence rates, and average medical expenses. The medical expense data is sourced from the "2021 China Health Statistics Yearbook", while the disease incidence data are derived from the National Cancer Center. We obtain the treatment costs by multiplying population numbers, disease incidence rates, and then by average medical expenses.

Direct Costs = Treatment Costs = Population * Disease Incidence Rate * Average Medical Expense

We have undertaken a meticulous calculation of the costs associated with food consumption, specifically focusing on the price comparison between soybeans and red meat. Our analysis is grounded in the reference retail prices obtained from the national agricultural products cost and benefit survey statistics compilation. The reference retail price for soybeans is recorded at 5.23 RMB per kilogram, while the corresponding price for red meat is noted to be 20.96 RMB per kilogram .

Table 3 Indirect costs and Direct costs of relevant diseases calculated from available data sources

Disease Type	Death Rate (‰)	Whole Chinese population Disability-Adjusted Life Years (DALYs, 2019)	Indirect Costs (Billions ¥)	Incidence Rate (‰)	The Average Medical Expense (¥)	Direct Costs (¥ Billion)
Colorectal Cancer	0.15	6,394,918	￥5.90	2.26	￥39,177.02	￥123.07
Cardiovascular Disease(coronary heart Heart Disease)	1.35	91,933,122	￥84.30	39	￥25,149.02	￥1,363.33

Stroke (Cerebrovascular Disease)	1.41	22,210,555	￥20.40	22.9	￥13,246.15	￥421.64
Type 2 Diabetes	0.21	9,579,860	￥8.80	53.1	￥7,896.73	￥582.85
Gastric Cancer	0.16	9,675,898	￥8.90	N/A	N/A	N/A
Breast Cancer	0.05	2,956,954	￥2.70	0.3	￥18,986.73	￥7.92
Ischemic Heart Disease (IHD)	1.23	21,393,857	￥19.60	3.34	￥14,591.15	￥67.74
Fractures (Falls)	0.09	7,020,888	￥6.40	N/A	N/A	N/A
Stomach Cancer	N/A	N/A	N/A	0.24	￥33,278.50	￥11.10

source： The mortality data for diseases are derived from the Annual Report on Causes of Death among Residents for the year 2021, specifically from the section titled "Main Disease Mortality Rates and Composition among Residents." ; The incidence rate data for diseases are sourced from the 2018 National Health Service Survey under the report titled "Prevalence of Chronic Diseases Among Residents in Surveyed Regions (per thousand)." This report encompasses data from 153 urban districts in 31 provinces nationwide and 378 counties or county-level cities in rural areas.Note: Discount the indirect costs to the present value by multiply discount rate.

Simulation of Resident Food Consumption and its Impact on Health and the Economy

As previously discussed, we computed the relative risk (RRi) and Population Impact Fraction (PIF) for soybean and red meat consumption concerning various diseases.

Indirectly avoided disease burden=PIFi * Indirect cost * The proportion of the risk(i) population

Directly avoided medical expenses= Direct cost * The proportion of the risk(i) population

P (x) is the number of people with risk factor level x in the population in real scenarios. According to the cohort study of the nutritional status of Chinese residents in 2015, 49.9 percent of adults in 15 provinces in China consumed livestock and poultry exceeded the recommended value of dietary guidelines, and 38.9% of adults exceeded the intake of 100 grams of meat per day. According to the China Health and Nutrition Survey, only 30 percent of Chinese residents met the dietary guidelines for soybean and soybean products in 2018 (25 grams/day). First, the PIF values between red meat intake and various diseases are calculated. We assume that all populations have adequate red meat intake; that is, 100% of people have standard red meat intake. By calculation, we found that red meat intake showed the strongest association with CHD, with a PIF value of 0.19. There were also some associations with stroke, colorectal cancer, and type 2 diabetes, with corresponding PIF values of 0.09,0.09, and 0.11, respectively. When considering the effect of soybean intake on disease risk, the association between soybean and type 2 diabetes, ischemic heart disease, gastric cancer, colorectal cancer, breast cancer, and coronary heart disease, corresponding to PIF values of 0.17,0.17,0.19,0.16,0.10 and 0.03 respectively, see the PIF calculation process in Table 4.

Table 4 Population Impact Fraction Calculation

Food Intake(i)	Disease type(x)	Relative value of disease onset risk RR (x)	The RR'in the counterfactual scenario	P(x)%	P'(x)% in the simulation protocol	(a) Actual Disease Failure Disease Risk: ∫RR (x) P (x) dx = RR * P (X) + RR'* (1-P (X))	(b) Disease Risk: ∫ RR (x) P'(x) dx	PIF=(a-b)/a
Red meat 100 g / day	Ischemic heart disease	1.11(1.06-1.16)	1.00	38.9	100	1.04	1	0.08
	Coronary heart disease	1.25 (1.21-1.29)	1.00	38.9	100	1.10	1	0.19
	Stroke	1.12 (1.06-1.17)	1.00	38.9	100	1.05	1	0.09
	Colorectal cancer	1.12 (1.06-1.19)	1.00	38.9	100	1.05	1	0.09
	Type 2 diabetes	1.15 (1.08-1.26)	1.00	38.9	100	1.06	1	0.11
Soybean 50g/ day	Coronary heart disease	0.86（0.78-0.94）	1.00	30	100	0.88	0.86	0.03
	Gastric cancer	0.75（0.66-0.85）	1.00	30	100	0.93	0.75	0.19
	Mammary cancer	0.86 （ 0. 78-0.	1.00	30	100	0.96	0.86	0.10

		94）						
	Ischemic heart disease	0.77 (0.9-0.65)	1.00	30	100	0.93	0.77	0.17
	Colorectal cancer	0.79（0.65-0.97）	1.00	30	100	0.94	0.79	0.16
	Type 2 diabetes mellitus -Female	0.65 (0.49–0.87)	1.00	30	100	0.90	0.65	0.27
	Type 2 diabetes mellitus- -Male	0.73 (0.61–0.88)	1	30	100	0.92	0.73	0.21
	Stroke	0.54(0.82-0.44)	1.00	30%	100%	0.86	0.54	0.37

REFERENCES

1．Abete I, Parra D, Martinez J A. Legume-, fish-, or high-protein-based hypocaloric diets: effects on weight loss and mitochondrial oxidation in obese men[J]. Journal of medicinal food, 2009, 12(1): 100-108.

2．Aleksandrowicz L, Green R, Joy E J M, et al. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review[J]. PloS one, 2016, 11(11): e0165797.

3．Aune, D. et al. Nut consumption and risk of cardiovascular disease, total cancer, all cause and cause-specific mortality: a systematic review and dose-response meta analysis of prospective studies. BMC Med. 14, 207 (2016).

4．Baglieri A, Mahe S, Zidi S, et al. Gastro-jejunal digestion of soya-bean-milk protein in humans[J]. British Journal of Nutrition, 1994, 72(4): 519-532.

5．Bechthold A, Boeing H, Schwedhelm C, Hoffmann G, Knüppel S, Iqbal K, et al. Food groups and risk of coronary heart disease, stroke and heart failure: A systematic review and dose-response meta-analysis of prospective studies. Critical Reviews in Food Science and Nutrition.2019;59:1071–90.

6．Bhathena SJ, Velasquez MT. Beneficial role of dietary phytoestrogens in obesity and diabetes. Am J Clin Nutr 2002;76(6):1191–201.

7．Budhathoki S, Sawada N, Iwasaki M , et al. Association of Animal and Plant Protein Intake With All-Cause and Cause-Specific Mortality in a Japanese Cohort[J]. JAMA Internal Medicine, 2019, 179(11):1509-.

8．Chang J H, Kim M S, Kim T W, et al. Effects of soybean supplementation on blood glucose, plasma lipid levels, and erythrocyte antioxidant enzyme activity in type 2 diabetes mellitus patients[J]. Nutrition research and practice, 2008, 2(3): 152-157.

9．Civitelli R, Villareal D T, Agnusdei D, et al. Dietary L-lysine and calcium metabolism in humans[J]. Nutrition (Burbank, Los Angeles County, Calif.), 1992, 8(6): 400-405.

10．Crujeiras, A. B., D. Parra, I. Abete, and J. A. Martinez. 2007. A hypocaloric diet enriched in legumes specifically mitigates lipid peroxidation in obese subjects. Free Radical Research 41 (4):498–506. doi: 10.1080/10715760601131935.

11．Deng, G.F.; Lin, X.; Xu, X.R.; Gao, L.L.; Xie, J.F.; Li, H.B. Antioxidant capacities and total phenolic contents of 56 vegetables. J. Funct. Food. 2013, 5, 260–266.

12．Food and Agriculture Organization of the United Nations. Food balance sheets: a handbook. (2001).

13．Gao M, Lv J, Yu C, et al. Metabolically healthy obesity, transition to unhealthy metabolic status, and vascular disease in Chinese adults: a cohort study[J]. PLoS Medicine, 2020, 17(10): e1003351.

14．Gazan, R, Maillot, M, Reboul, E et al. (2021) Pulses twice a week in replacement of meat modestly increases diet sustainability. Nutrients 13, 3059.

15．Geil P B, Anderson J W. Nutrition and health implications of dry beans: a review[J]. Journal of the American College of Nutrition, 1994, 13(6): 549-558.

16．Guo, Y., et al., (2022). “Environmental and human health trade-offs in potential Chinese dietary shifts”.One Earth 5, 268-282.

17．Huang J, Liao LM, Weinstein SJ, Sinha R, Graubard BI, Albanes D. Association Between Plant and Animal Protein Intake and Overall and Cause-Specific Mortality. JAMA Intern Med. 2020 Sep 1;180(9):1173-1184. doi: 10.1001/jamainternmed.2020.2790. PMID: 32658243; PMCID: PMC7358979.

18．Kaartinen N E, Tapanainen H, Maukonen M, et al. Partial replacement of red and processed meat with legumes: a modelling study of the impact on nutrient intakes and nutrient adequacy on the population level[J]. Public Health Nutrition, 2023, 26(2): 303-314.

19．LEE H P， GOURLEY L， DUFFY S W， et al． Dietary effects on breast-cancer risk in Singapore［J］． Lancet， 1991，337(8751) : 1197-1200．

20．LEE M M,CHANG I Y,HORNG C F,et al. Breast cancer and dietary factors in Taiwanese women [J]. Cancer Causes Control,2005,16(8) : 929-937.

21．LEE S A,SHU X O,LI H,et al. Adolescent and adult soy food intake and breast cancer risk results from the Shanghai Women’s Health Study[J]. Am J Clin Nutr, 2009(89) : 1920-1926.

22．Li W, Ruan W, Peng Y, et al. Soy and the risk of type 2 diabetes mellitus: A systematic review and meta-analysis of observational studies[J]. Diabetes research and clinical practice, 2018, 137: 190-199.

23．Liu J, Ho SC, Su YX, et al. Effect of long-term intervention of soy isoflavones on bone mineral density in women: a meta-analysis of randomized controlled trials[J]. Bone, 2009, 44(5): 948-953.

24．Liu X, Tai A P K, Chen Y, et al. Dietary shifts can reduce premature deaths related to particulate matter pollution in China[J]. Nature Food, 2021, 2(12): 997-1004.

25．Lou D, Li Y, Yan G, et al. Soy consumption with risk of coronary heart disease and stroke: a meta-analysis of observational studies[J]. Neuroepidemiology, 2016, 46(4): 242-252.

26．Lousuebsakul-Matthews V, Thorpe D L, Knutsen R, et al. Legumes and meat analogues consumption are associated with hip fracture risk independently of meat intake among Caucasian men and women: the Adventist Health Study-2[J]. Public health nutrition, 2014, 17(10): 2333-2343.

27．Ma D F, Qin L Q, Wang P Y, et al. Soy isoflavone intake inhibits bone resorption and stimulates bone formation in menopausal women: meta-analysis of randomized controlled trials[J]. European journal of clinical nutrition, 2008, 62(2): 155-161.

28．Ma J, Li J, Zhang L, et al. Understand the Basic Laws of Population Evolution and Promote the Longterm Balanced Development of China's Population[J]. J. Manag. World, 2022, 38: 1-19.

29．Mekonnen, M. M. & Hoekstra, A. Y. Te Green, Blue and Grey Water Footprint of Production and Consumption. Vol. 2: Appendices. Value of Water Research Report Series No. 50 (UNESCO-IHE Institute for Water Education, 2011); https://ris.utwente.nl/ws/portalfles/portal/5146139/Report50-NationalWaterFootprints-Vol2.pdf.pdf

30．Minami Y, Kanemura S, Oikawa T, et al. Associations of Japanese food intake with survival of stomach and colorectal cancer: A prospective patient cohort study[J]. Cancer science, 2020, 111(7): 2558-2569.

31．Naghshi S, Sadeghi O, Willett WC, Esmaillzadeh A. Dietary intake of total, animal, and plant proteins and risk of all cause, cardiovascular, and cancer mortality: systematic review and dose-response meta-analysis of prospective cohort studies. BMJ. 2020 Jul 22;370:m2412. doi: 10.1136/bmj.m2412. PMID: 32699048; PMCID: PMC7374797.

32．Nutrition and Chronic Diseases Status Report of Chinese Residents (2020) [J]. Acta Nutrimenta Sinica, 2020, 42(6), 521. ISTIC PKU CSCD CA, 2021.

33．Oxlund H, Barckman M, Ørtoft G, et al. Reduced concentrations of collagen cross-links are associated with reduced strength of bone[J]. Bone, 1995, 17(4): S365-S371.

34．Raquel Villegas and others, Legume and soy food intake and the incidence of type 2 diabetes in the Shanghai Women's Health Study, The American Journal of Clinical Nutrition, Volume 87, Issue 1, January 2008, Pages 162–167, https://doi.org/10.1093/ajcn/87.1.162

35．Röös, E, Carlsson, G, Ferawati, F et al. (2020) Less meat, more legumes: prospects and challenges in the transition toward sustainable diets in Sweden. Renewable Agric Food Syst 35, 192–205.

36．Schwingshackl L, Schwedhelm C, Hoffmann G, et al. Food groups and risk of all-cause mortality: a systematic review and meta-analysis of prospective studies[J]. The American journal of clinical nutrition, 2017, 105(6): 1462-1473.

37．Song M, Fung TT, Hu FB, Willett WC, Longo VD, Chan AT, Giovannucci EL. Association of Animal and Plant Protein Intake With All-Cause and Cause-Specific Mortality. JAMA Intern Med. 2016 Oct 1;176(10):1453-1463. doi: 10.1001/jamainternmed.2016.4182. Erratum in: JAMA Intern Med. 2016 Nov 1;176(11):1728. PMID: 27479196; PMCID: PMC5048552.

38．Springmann M, Spajic L, Clark M A, et al. The healthiness and sustainability of national and global food based dietary guidelines: modelling study[J]. bmj, 2020, 370.

39．Tatsumi Y, Morimoto A, Deura K, et al. Effects of soybean product intake on fasting and postload hyperglycemia and type 2 diabetes in J apanese men with high body mass index: The S aku S tudy[J]. Journal of diabetes investigation, 2013, 4(6): 626-633.

40．Thakur V S, Deb G, Babcook M A, et al. Plant phytochemicals as epigenetic modulators: role in cancer chemoprevention[J]. The AAPS journal, 2014, 16: 151-163.

41．Tharrey M, Mariotti F, Mashchak A, Barbillon P, Delattre M, Fraser GE. Patterns of plant and animal protein intake are strongly associated with cardiovascular mortality: the Adventist Health Study-2 cohort. Int J Epidemiol. 2018 Oct 1;47(5):1603-1612. doi: 10.1093/ije/dyy030. PMID: 29618018; PMCID: PMC6658814.

42．Thiagarajan D G, Bennink M R, Bourquin L D, Kavas F A (1998). Prevention of precancerous colonic lesions in rats by soy flakes, soy flour, genistein, and calcium. Am J Clin Nutr, 68(suppl), 1394S-9S.

43．Toyomura K, Kono S. Soybeans, soy foods, isoflavones and risk of colorectal cancer: a review of experimental and epidemiological data[J]. Asian Pac J Cancer Prev, 2002, 3(2): 125-132.

44．Trinidad, T. P., A. C Mallillin, A. S. Loyola, R. S. Sagum, and R. R. Encabo. 2010. The potential health benefits of legumes as a good source of dietary fibre. British Journal of Nutrition 103 (4):569–74. doi: 10.1017/S0007114509992157.

45．Vasconcelos M W, Gomes A M, Pinto E, et al. The push, pull, and enabling capacities necessary for legume grain inclusion into sustainable agri-food systems and healthy diets[J]. Hidden Hunger and the Transformation of Food Systems, 2020, 121: 193-211.

46．Wangen K E, Duncan A M, Xu X, et al. Soy isoflavones improve plasma lipids in normocholesterolemic and mildly hypercholesterolemic postmenopausal women[J]. The American journal of clinical nutrition, 2001, 73(2): 225-231.

47．Willett, Walter, Johan Rockström, Brent Loken, Marco Springmann, Tim Lang, Sonja Vermeulen, Tara Garnett, David Tilman, Fabrice DeClerck, Amanda Wood., et al. 2019. Food in the anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393 (10170):447–92. doi: 10.1016/S0140-6736(18)31788-4.

48．Xue L, Liu X, Lu S, et al. China’s food loss and waste embodies increasing environmental impacts[J]. Nature Food, 2021, 2(7): 519-528.

49．Yan L, Spitznagel E L, Bosland M C. Soy consumption and colorectal cancer risk in humans: a meta-analysis[J]. Cancer epidemiology, biomarkers & prevention, 2010, 19(1): 148-158.

50．Yan L, Spitznagel EL, Bosland MC. Soy consumption and colorectal cancer risk in humans: a meta-analysis. Cancer epidemiology, biomarkers & prevention: a publication of the American Association for Cancer Research, cosponsored by the American Society of Preventive Oncology. 2010;19(1):148–58. pmid:20056634.

51．Zhang Y J, Gan R Y, Li S, et al. Antioxidant phytochemicals for the prevention and treatment of chronic diseases[J]. Molecules, 2015, 20(12): 21138-21156.

52．Zheng J, Huang T, Yu Y, et al. Fish consumption and CHD mortality: an updated meta-analysis of seventeen cohort studies［J］. Public Health Nutrition, 2012, 15(4): 725-737

Zhou C, Wu Q, Ye Z, et al. Inverse Association Between Variety of Proteins With Appropriate Quantity From Different Food Sources and New-Onset Hypertension[J]. Hypertension, 2022, 79(5): 1017-1027.

53．Springmann M, Spajic L, Clark M A, et al. The healthiness and sustainability of national and global food based dietary guidelines: modelling study[J]. bmj, 2020, 370.