The evolving individual protein intake and environmental footprint in China

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Abstract

China's shift from plant-based to animal-based protein has raised concerns over its health and environmental consequences. Drawing dietary data from nine provinces (1997-2011), this study quantifies the environmental impacts of changing protein consumption and highlights trade-offs between improved diet quality and environmental sustainability. Notable disparities emerge across regions and socioeconomic groups: high-income, male, and well-educated individuals tend to overconsume protein, while older adults, low-income groups, and people with obesity often face protein deficits. Scenario analysis suggests that curbing overconsumption could offset the environmental costs of addressing deficiencies. While adopting the Chinese Dietary Guidelines may increase environmental pressures, these can be mitigated by replacing red meat with poultry or plant-based protein. Our findings call for integrated dietary policies that align health and environmental objectives. Future guidelines should account for regional dietary cultures and the nutritional needs of vulnerable groups to promote more sustainable and equitable food system.

Keywords: protein transition, environmental impact, health-environment nexus, socio-economic disparities, dietary scenario analysis

1. Introduction

Dietary protein consumption connects human health with planetary health. As the main source of amino acids, protein is fundamental for human health (Moughan, 2021; Willett et al., 2019). Adequate protein intake, particularly high-quality protein, is essential for the physical and cognitive development of all age groups (El Bilali et al., 2019). However, the global transition in protein consumption patterns is highly uneven and shaped by socio-economic disparities.

Global protein consumption patterns are diverging. In many developing countries, including China, rapid economic growth and urbanization have driven a shift from traditional, plant-based staples toward increased consumption of animal-sourced foods (El Bilali et al., 2019; Guo et al., 2022; Willett et al., 2019). In contrast, many developed countries, especially European countries are undergoing a reverse transition towards plant-based diets and alternative proteins (Aiking and de Boer, 2020; Duluins and Baret, 2024). These divergent trajectories underscore that the “protein transition” is not a simple one-to-one food substitution, but rather a broader food-system transformation requiring careful attention to implementation pathways and potential unintended consequences (Jenkins et al., 2024).

Protein-energy malnutrition contributes significantly to the diet-related health burden globally (Blakstad et al., 2021; Han et al., 2022; Moughan, 2021). In developed countries, excessive protein consumption—particularly from red and processed meats—poses a significant health challenge (Aiking and de Boer, 2020; He et al., 2019; Wu et al., 2014). Average protein intake in many Western nations exceeds recommended levels by 50-100% (Aiking and de Boer, 2020). Protein overconsumption is associated with greater health risks of chronic non-communicable diseases, including cardiovascular diseases, stroke, hypertension, and diabetes (Clark et al., 2019; Guo et al., 2022; Tilman and Clark, 2014; Willett et al., 2019). Meanwhile, many developing countries are experiencing a dual burden of malnutrition with the coexistence of undernutrition and obesity (Behrens et al., 2017; Blakstad et al., 2021; He et al., 2019). Protein deficiency remains a key driver of undernutrition in many developing countries, especially among children under five years old (Aiking and de Boer, 2020; Wang et al., 2023).

The global protein transition also carries significant environmental consequences. Intensive production of animal-sourced protein, particularly red meat, requires substantially more resources and generates higher environmental impacts than plant-based alternatives (Aiking and de Boer, 2020; Henchion et al., 2017; Tilman and Clark, 2014; Willett et al., 2019). For instance, greenhouse gas (GHG) emissions per gram of protein from ruminant meat are approximately 250 times higher than those from legumes (Tilman and Clark, 2014). Environmental impacts also vary within animal-based foods: pork, poultry, eggs, dairy, and fish typically have much lower emissions per gram of protein than ruminant meats (Ambikapathi et al., 2022; Poore and Nemecek, 2018; Tilman and Clark, 2014). With the global population projected to reach nearly 10 billion by 2050, current dietary trajectories are likely to intensify pressures on both human health and planetary boundaries (Clark et al., 2019; Duluins and Baret, 2024; Henchion et al., 2017; Wu et al., 2014).

Yet the environmental implications of protein transition remain under-explored in developing countries. Cross-country evidence suggests that the health–environment efficiency of diets follows a nonlinear trajectory: it often deteriorates during the phase of rising animal-source food consumption before improving in later stages of development (He et al., 2024). China is currently in this critical middle phase, making it an important case for understanding how dietary shifts can be steered toward more sustainable pathways.

In this study, we investigate the nutrition-environment nexus from the perspective of protein consumption in China between 1997 and 2011—a period marked by rapid dietary transition. Using the latest available data from the China Health and Nutrition Survey (CHNS), we estimate individual-level daily protein intake and quantify associated environmental footprints, including GHG emissions, land use, acidification, eutrophication, and freshwater consumption, based on life cycle assessment (LCA). We develop four alternative healthy diet scenarios and compare their environmental impacts to assess the synergies and trade-offs of dietary changes, particularly in addressing the dual burden of protein malnutrition across different population subgroups. Our findings offer practical insights into healthy and sustainable dietary interventions for diverse subpopulations in China and other developing countries undergoing similar protein transition trajectories distinct from those in Western nations.

2. Literature Review

Recent studies addressing the diet–environment–health trilemma have largely focused on developed countries, where shifting diets away from animal-based foods—especially red meat—towards more plant-based options can yield both human health and environmental benefits (Ambikapathi et al., 2022; Clark et al., 2019; Duluins and Baret, 2024; Humpenöder et al., 2022; Rubio et al., 2020; Tilman and Clark, 2014). However, these synergies do not apply universally. Behrens et al. (2017) found that nationally recommended diets could substantially reduce GHG emissions, eutrophication, and land use in high-income nations, but increase environmental impacts in lower-middle-income countries. Similarly, Blakstad et al. (2021) showed that while plant-source foods yield greater health and environmental benefits for adults, animal-source foods remain essential for children's development in contexts such as urban Ethiopia. Recent global projections further indicate that emerging and developing economies may face higher trade-offs—particularly for water use and food affordability—during the initial phases of dietary transitions toward healthier patterns (Deng et al., 2025).

The EAT-Lancet Commission proposed a global reference diet emphasizing plant-source foods with limited red and processed meat (Willett et al., 2019). Although useful for advocacy, such global benchmarks often lack sensitivity to local food cultures and consumption patterns, limiting their effectiveness in guiding national and regional dietary transitions (Blakstad et al., 2021; Miller et al., 2022b). Given that dietary patterns are shaped by regional and socioeconomic contexts (Clark et al., 2019; Miller et al., 2022b; Tilman and Clark, 2014), few countries met the EAT-Lancet targets as of 2018 (Miller et al., 2022a).

China has experienced rapid dietary transition characterized by declining intake of staple grains and increasing consumption of animal products, fruits and vegetables (Han et al., 2022; He et al., 2019; He et al., 2018; He et al., 2021; Wang, X.X. et al., 2022; Zhang et al., 2022). Between 1982 and 2012, average per capita calorie intake decreased by 12.9%, primarily due to reduced physical labor, while nutritional status improved significantly—the undernourishment rate dropped from 15% in 2002 to 11.4% in 2012 (Han et al., 2022; He et al., 2019; He et al., 2021). However, excessive intake of red meat, fats and added sugar has led to rising rates of overweight and obesity (Du et al., 2004; Su et al., 2015; Wang, L. et al., 2021; Wang, L. et al., 2022; Wang, X.X. et al., 2022).

China currently faces a dual burden of malnutrition. On one hand, the adult obesity rate increased from 7.1% to 11.9% between 2002 and 2012, with household consumption of grains, meat, and cooking oil exceeding nutritional requirements (Cai et al., 2024; He et al., 2018; Wang, L. et al., 2022). On the other hand, intake of dairy, eggs, seafood, fruits, vegetables, soybeans, and nuts remains insufficient, and protein contributes only 13.2% of daily energy—below the recommended 15–16% (Cai et al., 2024; Jiang et al., 2021). Vulnerable groups such as children under five and adults over 70 continued to experience protein deficiency as of 2015 (Han et al., 2022).

Alongside nutritional shifts, diet-related environmental burdens in China have increased across all demographic groups (He et al., 2018; Song et al., 2015). He et al. (2021) found that while reduced calorie intake lowered diet-related GHG emissions by 21%, increased consumption of animal-source foods led to a 25% increase in emissions. Shifting toward healthier diets may thus generate complex environmental synergies and trade-offs (Guo et al., 2022; He et al., 2021; Wu et al., 2022), and the specific types of animal products consumed can make a substantial difference (Cai et al., 2024).

Despite these advances, existing nexus studies of China's dietary change have focused primarily on calorie intake rather than protein consumption (Cai et al., 2024; He et al., 2018; Song et al., 2015). This gap is notable because protein sources are commonly used to classify dietary patterns and carry distinct environmental footprints (Willett et al., 2019). Recent modeling studies indicate that healthy and sustainable diets in China can generate substantial long-term co-benefits, but outcomes depend on feasibility constraints and on bundling measures across consumption and production domains (Cai et al., 2025; Wang, X. et al., 2025). Policy analyses further emphasize that dietary guidelines should integrate sustainability with affordability and cultural acceptability to be actionable (Zhang et al., 2025).

Socio-demographic and socioeconomic factors play a critical role in shaping dietary patterns and associated environmental impacts in China (Cai et al., 2024; He et al., 2018; He et al., 2021). Urban, high-income, and highly educated populations generally exhibit better dietary quality but higher environmental burdens (Cai et al., 2024). Greater affordability among high-income groups enables increased consumption of resource-intensive foods such as meat and dairy, exacerbating inequalities in environmental impacts across income groups (Kou et al., 2024). Geographic, climatic, and cultural differences also significantly influence household food choices and related environmental impacts (Xiong et al., 2022). However, current nutrition-environment nexus studies often overlook these heterogeneous contexts, limiting their relevance for targeted policy interventions. A thorough understanding of the linkage between protein consumption and environmental outcomes at the sub-national level remains missing, particularly for developing countries.

In light of these gaps, we examine the nutrition-environmental nexus through the lens of protein transition in China. Specifically, we compare nutritional quality and related environmental impacts across socio-economic and demographic groups at the sub-national level, focusing on East, Central, West and Northeast China. We then develop four healthy diet scenarios based on the latest Chinese Dietary Guidelines and historical protein consumption patterns to ensure practical relevance. By leveraging micro-level data, this study captures the implications of protein transitions across subgroups and regions over time.

3. Methods

3.1 Quantifying Individual Protein Intake Status

Individual protein intake was calculated based on dietary data from the China Health and Nutrition Survey (CHNS), an ongoing longitudinal cohort study jointly conducted by the University of North Carolina at Chapel Hill and the Chinese Center for Disease Control and Prevention. Six waves of surveys were conducted during our study period (1997, 2000, 2004, 2006, 2009 and 2011)[1]. The survey covers nine

[1] Although CHNS surveys were also conducted in 2015 and 2019, detailed dietary intake data beyond 2011 are not publicly available, making 2011 the most recent wave accessible for this analysis.

provinces representing four major regions of mainland China: East China (Shandong and Jiangsu), Central China (Henan, Hubei, and Hunan), West China (Guizhou and Guangxi) and Northeast China (Heilongjiang and Liaoning)[2].

The nine CHNS provinces account for 41.4% of mainland China's population (2010 census) and encompass diverse socioeconomic, demographic, and cultural contexts across regions (Cai et al., 2024; He et al., 2021). CHNS offers several key advantages for studying the nutrition-environment nexus in China. First, its longitudinal design enables tracking of dietary transitions over an extended period. Second, its detailed individual-level socioeconomic data—including income, education, and urbanization—allow for granular subgroup analyses that most dietary surveys cannot support. Third, CHNS has been widely used in prior studies examining regional protein consumption patterns in China, providing a consistent basis for comparison (He et al., 2018; He et al., 2021; Cai et al., 2024).

To improve the representativeness of the sample, we stratified individuals into 352 subgroups based on region, age, gender, and urbanization level, and reweighted them using distributions from the closest Chinese Population Census, following He et al. (2021). We validated this approach by comparing the reweighted 2011 per capita daily protein intake (64.9 g) with the 2012 national benchmark (65.9 g) from *the Scientific Research Report on Dietary Guidelines for Chinese Residents* (Chinese Society of Nutrition, 2021), showing close alignment. Detailed procedures are provided in the Supporting Information.

Despite these strengths, certain limitations should be noted. The CHNS does not include megacities such as Beijing and Shanghai, where higher incomes, greater dietary diversity, and more food-away-from-home consumption may be associated with higher intake of animal-source foods and dairy. As a result, our estimates may understate protein intake among high-income urban residents in the most developed metropolitan areas. Nevertheless, the data remain informative for understanding dietary transitions and subgroup disparities across the four broad regions covered by the survey.

[2] Although CHNS expanded its coverage to include three additional megacities after 2011, we retained the original nine provinces in our analysis to ensure temporal consistency over our study period.

CHNS records household dietary data over three consecutive days using a weighting method, alongside individual intake data collected via 24-hour recall. Following Du et al. (2004), we triangulated more accurate individual daily food intake by combining household weighing and individual self-reported data (see the SI for details). All food items were coded using the *Chinese Food Composition Tables* (Yang, 2004) and categorized into 14 main protein source groups: beef, lamb, pork, eggs, poultry, fish, milk, seafood, other animal sources, grains, legumes, nuts, other plant-based foods, and other foods. Consistent with He et al. (2018), individuals with intake levels exceeding four standard deviations above the group mean were treated as outliers.

Individual protein intake was calculated by multiplying food intake by protein density, based on data from the *Chinese Food Composition Tables* (Yang, 2004). Recommended Nutrient Intake (RNI) values vary by age, gender, body weight and physical activity status. We computed each individual's recommended daily protein intake according to China's *Dietary Reference Intakes Guidelines*. Details are provided in the Supporting Information. To evaluate protein intake adequacy, we developed a protein deviation index for each individual:

$$Protein\ deviation_i = \frac{Protein\ intake_i - Protein\ RNI_i}{Protein\ RNI_i} \quad (1)$$

where $Protein\ deviation_i$ indicates how much each individual's protein intake level deviates from the RNI; $Protein\ intake_i$ is the actual protein intake of individual i, and $Protein\ RNI_i$ is the recommended protein intake for individual i. A positive value indicates adequate or excessive intake, while a negative value suggests protein deficiency.

3.2 Assessing Dietary Environmental Impacts

Life Cycle Assessment (LCA) coefficients were drawn primarily from the harmonized meta-analysis by Poore and Nemecek (2018), supplemented by Clark et al. (2019) for a small number of food categories where needed (see details in Table S7 in the SI). Poore and Nemecek (2018) compiled product-specific impacts across five indicators using a globally reconciled LCA database and reported impacts along the supply chain. This LCA dataset has been widely used to assess the sustainability of various diets globally (Bianchi et al., 2022; Green et al., 2021; Jung et al., 2024).

In this study, dietary environmental footprints are estimated using a cradle-to-retail boundary, which captures upstream production and supply-chain stages up to retail, including agricultural inputs and on-farm processes (e.g., fertilizer use and irrigation), as well as post-farm stages including processing, packaging, transport, and retail. This boundary also incorporates transportation-related processes and losses occurring before retail.

However, the boundary does not include consumer-stage activities after purchase—such as household cooking, food preparation, and post-purchase food waste—because these stages are not covered in the underlying meta-analytic coefficients. For the few food categories supplemented from Clark et al. (2019), the coefficients represent impacts of production, including the manufacture and use of agricultural inputs and equipment, but exclude transport, processing, retail, and food preparation. We therefore treat these coefficients as production-stage estimates and acknowledge that any remaining boundary mismatch may render our cradle-to-retail estimates slightly conservative for those items.

To integrate the datasets, we aggregated CHNS food items into 47 LCA food categories based on weight equivalence (see details in the SI). We focus on five types of dietary environmental footprints: greenhouse gas (GHG) emissions, land use, freshwater use, acidification, and eutrophication. The calculation formula is:

$$X_i = \sum_{m=1}^{n} (standard\ weight_m \times f_m) \tag{2}$$

where X_i is the environmental impact of individual i's diet; $standard\ weight_m$ is the adjusted weight of food item m; f_m is the corresponding environmental impact coefficient.

We further conducted correlation analyses to examine how socioeconomic and physical characteristics influence individual-level protein malnutrition and dietary environmental impacts.

3.3 Potential Healthy Dietary Scenarios

To explore the synergies and trade-offs of the nutrition-environment nexus, we constructed four practical healthy dietary scenarios based on China's Dietary Guidelines (CDG) and observed protein consumption patterns across subpopulations. The 2022 CDG provides recommended intake ranges for major broad food groups (e.g., cereals, tubers, fruits, vegetables, animal foods, beans and nuts, and milk and dairy products) and specifies balanced dietary patterns by energy requirement levels (see Table S6) (Chinese Society of Nutrition, 2023).

Based on the CDG, we estimated each individual's energy needs by age and gender and derived a corresponding recommended dietary pattern and protein intake structure (see details in the SI). However, the CDG does not differentiate among types of animal foods, despite their wide variation in environmental impacts (Cai et al., 2024). To address this, we developed four dietary scenarios incorporating adjustments within and between food groups to evaluate the environmental synergies and trade-offs of meeting each individual's protein RNI.

- **Scenario 1 (S1): Meeting RNI with current diet structure.**

S1 assumes that individuals meet their recommended nutrient intake (RNI) for protein while maintaining their original protein intake structure across food groups. This scenario is designed to illustrate the environmental impacts of achieving adequate protein intake without altering existing dietary habits.

- **Scenario 2 (S2): Meeting RNI with balanced diet.**

In S2, we assume that each individual's diet meets both the protein RNI and the balanced dietary pattern recommended by the CDG. To reflect typical eating habits, we maintain each individual's original protein distribution within food groups. Comparing S2 with S1 highlights the environmental implications of transitioning to more nutritionally balanced diets.

- **Scenario 3 (S3): Partial red meat substitution with poultry.**

Building on S2, S3 adjusts the composition of animal protein by replacing red meat with poultry—up to 50% of an individual's total meat-based protein—unless their existing poultry intake already exceeds this level. Poultry provides high-quality protein and typically has substantially lower environmental impacts than ruminant meat (Tilman and Clark, 2014). Comparing S3 with S2 isolates the mitigation potential of within-animal substitution while holding overall diet balance constant.

The 50% replacement rate is designed as a policy-relevant, moderate-intensity change. It is broadly consistent with the EAT-Lancet reference diet, which allocates a much smaller amount of red meat (14 g/day) than poultry (29 g/day), implying a strong shift away from red meat within animal-source foods (Willett et al., 2019). For Chinese consumers whose animal-source protein is currently dominated by red meat, a 50% substitution represents a substantial but achievable shift in this direction. This choice also reflects evidence that incremental substitutions are more likely to be adopted and sustained than radical dietary changes (Aiking and de Boer, 2020). Finally, it aligns with recent Chinese policy signals that encourage moderating red meat consumption and diversifying animal proteins, with poultry often promoted as a practical alternative (Chinese Society of Nutrition, 2022).

- **Scenario 4 (S4): Partial substitution of animal protein with plant protein.**

Also based on S2, S4 modifies the protein-source composition by replacing 20% of animal-based protein with plant-based protein. Comparing S4 with S2 isolates the potential mitigation benefits of moving from animal- to plant-based protein while keeping the overall diet aligned with the CDG-recommended balanced pattern.

The 20% substitution rate is set as a conservative but meaningful adoption level. First, it is consistent with the Chinese Dietary Guidelines emphasis on plant foods as the foundation of healthy diets and with the National Nutrition Program (2017-2030) “Double Protein” initiative that encourages greater intake of soy and other legumes. Second, it lies within the range of existing dietary practices observed in our sample: individuals in the upper quartile of plant-protein consumption already obtain over half of their protein from plant sources, suggesting that a 20% shift is behaviorally plausible for a broader population. Third, available evidence supports the health and nutritional feasibility of partial substitution: replacing some animal protein with plant protein is associated with lower mortality risk (Song et al., 2016), and well-designed plant-based protein mixes can meet essential amino acid requirements (Mariotti and Gardner, 2019).

Across scenarios, S1 preserves observed protein-source shares, whereas S2 to S4 are anchored to the CDG-balanced pattern with composition adjustments introduced only where specified above (details in the SI). S3 and S4 are designed as illustrative, policy-relevant scenarios rather than optimization outcomes. Alternative replacement intensities would scale impacts accordingly; assessing such sensitivity is a useful direction for future work when more recent micro-level dietary data become available.

3.4 Uncertainty Analysis

We conducted Monte Carlo simulations ($n = 100$ iterations) to quantify uncertainty in the estimated environmental impacts. Food-specific environmental impact coefficients (Land use, GHG emissions, freshwater use, acidification, and eutrophication) were modeled as normally distributed variables. For most food categories, we adopted estimates from Poore and Nemecek (2018), who assumed a normal distribution for environmental impacts and reported the 5th and 95th percentiles. We derived the standard deviation for each food item from these percentiles using the empirical rule for normal distributions. For the few food categories covered in Clark et al. (2019), where only mean values were reported, we imputed standard deviations using the average standard deviation of all food items from Poore and Nemecek (2018). This approach allowed us to propagate uncertainty stemming from variability in life cycle assessment data across food items. The mean and standard deviation of environmental impact coefficients by food category are summarized in Table S7.

4. Results

4.1 A Changing Dietary Pattern of Protein Consumption

Chinese residents' per capita protein consumption levels decreased significantly during the study period. Between 1997 and 2011, the average daily protein intake for adults aged 18-65 declined from 70.2 g to 64.9 g, paralleling a decrease in daily energy intake from 2,104.7 kcal to 1,876.0 kcal (see Figure 1a). Despite this decline, the 2011 average remained 11.3% above the RNI of 58.3 g. Although varied among regions, all four regions' average per capita protein intake exceeded the recommended levels, with East China 14.6% higher, followed by Central China (7.1%), West China (4.9%), and Northeast China (3.9%).

Consistent with prior studies, our findings indicate a dietary shift among Chinese residents toward increased consumption of animal-based proteins (FAO, 2023; Li et al., 2023; National Bureau of Statistics, 2009). While plant-based foods remained the primary source of dietary protein, their share declined from 70.3% in 1997 to 59.0% in 2011. Over the same period, the contribution of animal-based foods rose significantly from 27.1% to 37.1%. In 2011, cereals were the largest source of dietary protein (40.4%), followed by pork (17.6%) and soybeans (10.0%). Eggs, poultry, and fish contributed 5.4%, 4.7%, and 4.6% of average protein consumption, respectively. However, dairy products contributed just 0.9% of total protein in 2011, with per capita daily intake at only 0.6 g—far below the 9.0 g recommended by the CDG.

Protein-source composition differed markedly across regions (Figure 1b). In 2011, East China had the highest per capita daily protein intake (69.4 g) and the most diversified structure, with relatively higher contributions from legumes (11.5%) and aquatic foods (fish and seafood, 6.8%) and a lower reliance on pork (14.3%) than other regions. This pattern is consistent with the “Eastern Healthy Dietary Patterns” described in national dietary guidance (Chinese Society of Nutrition, 2021). By contrast, West China recorded the lowest total protein intake (60.3 g/day) yet the highest dependence on red meat, which accounted for 26.3% of total protein—about twice that in Northeast China (13.6%). Central and Northeast China remained more plant-protein dominant, with plant sources accounting for 65.7% and 65.1% of total protein, respectively, compared with 60.5% in East and 59.1% in West China. These regional disparities likely reflect the combined effects of dietary culture, food availability, and socioeconomic development (Zhang et al., 2023), and they underscore that protein-source choices (e.g. red-meat-heavy patterns) may lead to disproportionately higher environmental pressures even when total protein intake is relatively low.

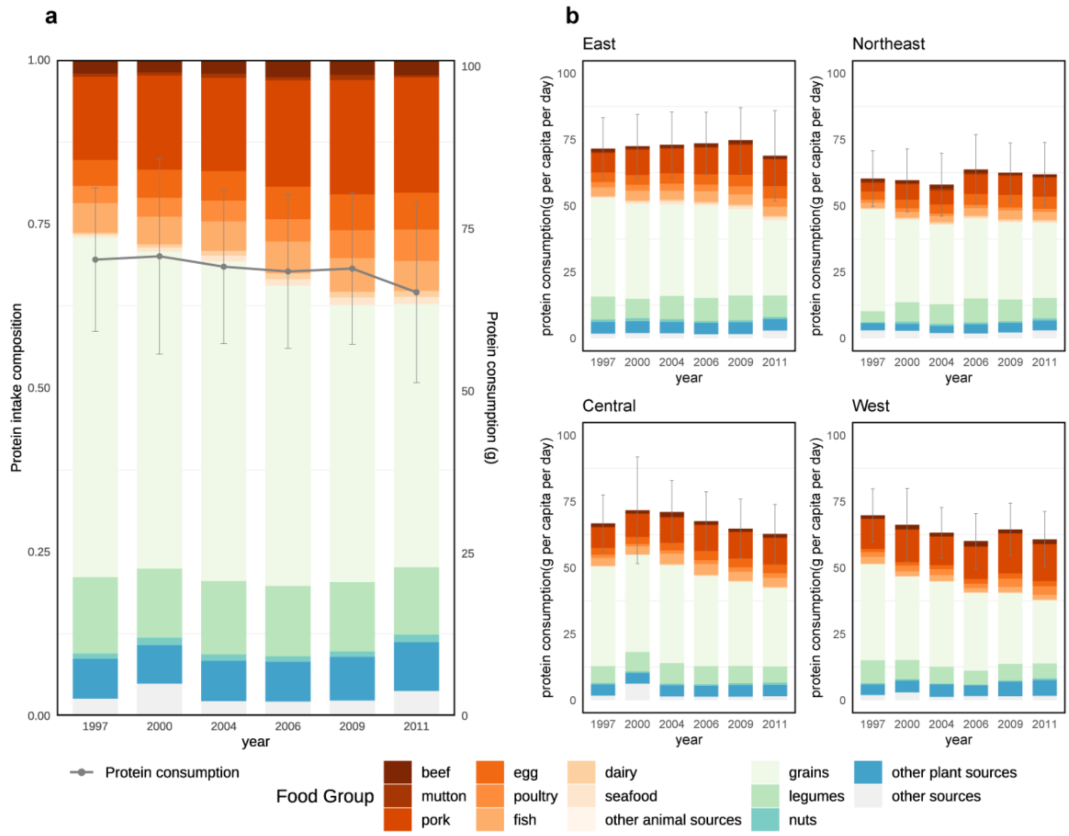

Figure 1. Per capita daily protein intake of adults aged 18-65 from 1997 to 2011. a, National average protein consumption weighted by population; b, Regional protein consumption and source composition. Error bars show one standard deviation from the mean of per capita daily protein intake (16th and 84th percentiles).

4.2 Environmental Impacts of Protein Consumption

Figure 2 illustrates the environmental impacts of Chinese residents' protein consumption from 1997 to 2011. Per capita land use rose from 7.61 m^2/day in 1997 to a peak of 8.39 m^2/day in 2009, before declining to 7.35 m^2/day in 2011. The increased land use footprint from 1997 to 2009 was primarily driven by the rapid rise in beef and pork consumption. Diet-related GHG emissions fluctuated between 4.57 and 4.80 kg CO_2e/day until 2009 and then decreased by 8.5% to 4.39 kg CO_2e in 2011.

Acidification impacts were mainly driven by pork consumption, which accounted for 22.3% to 28.7% of total diet-related acidification across the study period. As pork intake increased, acidification effects peaked at 30.2g SO_2eq/day in 2009, then declined slightly due to reduced cereal consumption. Both eutrophication and freshwater consumption showed a downward trend, largely attributed to the decreased consumption of grains. Eutrophication emissions fell from 27.1 to 24.7 g PO_4^{3-}eq /day, and freshwater use declined from 962.2 to 775.7 L/day.

Changes in both the quantity and composition of protein intake have jointly shaped China's dietary environmental impacts. While the overall decline in protein consumption helped alleviate some environmental pressures, the rising share of animal-based sources—especially red meat—kept overall impacts relatively high. Notably, West China, despite having the lowest protein intake among the four regions, showed the highest diet-related environmental impacts. This was largely driven by higher consumption of beef and pork, as well as a heavier reliance on rice as a staple food, which contributed 47.5% of its plant-based protein intake. Since rice has higher environmental intensity per gram of protein, its prominence in the diet contributed to greater impacts. In Northeast China, higher lamb consumption also led to increased land use impacts. Detailed regional patterns are shown in Figure S1.

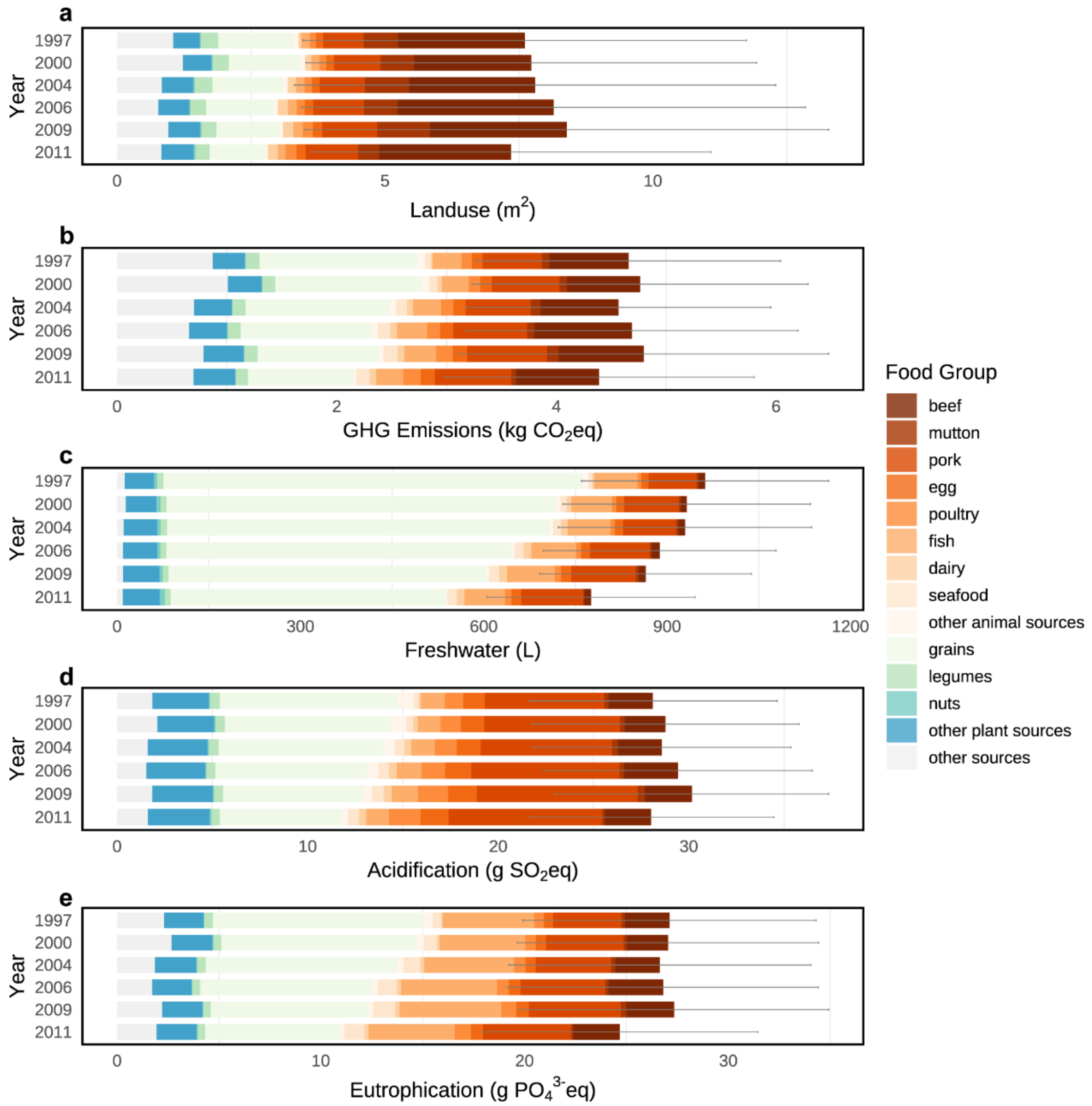

Figure 2. Environmental impacts of per capita daily protein consumption of adults aged 18-65 in China (1997-2011). a, Land Use; b, GHG Emissions; c, Freshwater use; d, Acidification; e, Eutrophication. Error bars show one standard deviation from the mean of total environmental impacts, corresponding to the 16th and 84th percentiles from the 100 Monte Carlo simulation trials.

4.3 Subgroup Variation in Protein Intake and Associated Environmental Impacts

Protein intake levels and related environmental footprints varied considerably across demographic and socio-economic subgroups in each region (see Figure 3). Correlation analyses indicate that gender, age, income, education, urbanization level, and BMI are all significantly associated with both nutritional health and diet-related environmental impacts (see Table S8).

On average, men exhibit higher levels of protein overconsumption and greater environmental footprints than women. Individuals with higher income and education levels also tended to consume more protein, particularly from animal-based sources, resulting in larger environmental impacts. The nutrition-environment relationship between urban and rural residents is more complex. While rural residents consumed 1.2% more protein, they generated lower environmental footprints (except for freshwater use), largely due to urban residents' higher preference for animal-based protein.

While protein overconsumption was common among most Chinese individuals, certain subgroups remain at risk of protein deficiency, especially older adults, low-income groups, and individuals with overweight or obesity. Adults over 65 had an average protein intake 15.6% below the RNI, with a relatively high reliance on plant-based sources (64.4% of total intake). Low-income individuals (lowest 25%) across all regions fell short of the RNI by an average of 2.3%. People with low education levels or excess body weight also showed protein deficits in some regions.

These findings are consistent with earlier studies highlighting protein deficiencies among older adults in China, who face increased nutritional needs due to age-related metabolic and physiological changes and higher health risk of sarcopenia (Liu et al., 2018; Rafii et al., 2015; Xu et al., 2015). Improving the quality and quantity of protein intake for older adults remains critical.

Among individuals under 18, patterns of protein malnutrition differ by region. In East China, children and adolescents generally had protein overconsumption issues, with an average protein intake 27% above the RNI. In contrast, youth in West China faced a protein deficiency issue, with average intake 9% lower than the RNI. These findings are consistent with previous research documenting malnutrition and stunting among children in West China (Wang et al., 2009; Zeng et al., 2003).

Overweight ($24 < \text{BMI} < 28$) and obese ($\text{BMI} > 28$) individuals in Northeast and West China, also exhibited signs of insufficient protein intake. On average, their consumption was 5.0% and 1.7% below the recommended levels respectively in these two regions. This group requires both higher total energy and greater protein intake to meet their nutritional needs. Like older adults, obese individuals relied more heavily on plant-based proteins, which accounted for 62.0% of total protein intake, mainly due to greater consumption of refined grains commonly found in processed and convenience foods.

In general, individuals with protein deficiencies consume more plant-based and fewer high-quality animal proteins than those with adequate protein intake (see Table S9). Addressing these nutritional deficiencies may lead to increased environmental burdens due to the higher impacts associated with animal-based protein sources. Additionally, some subgroups, such as urban residents and highly educated individuals in Northeast China, had average protein intake levels slightly below the RNI but disproportionately high environmental footprints, indicating inefficient dietary structures from a sustainability perspective.

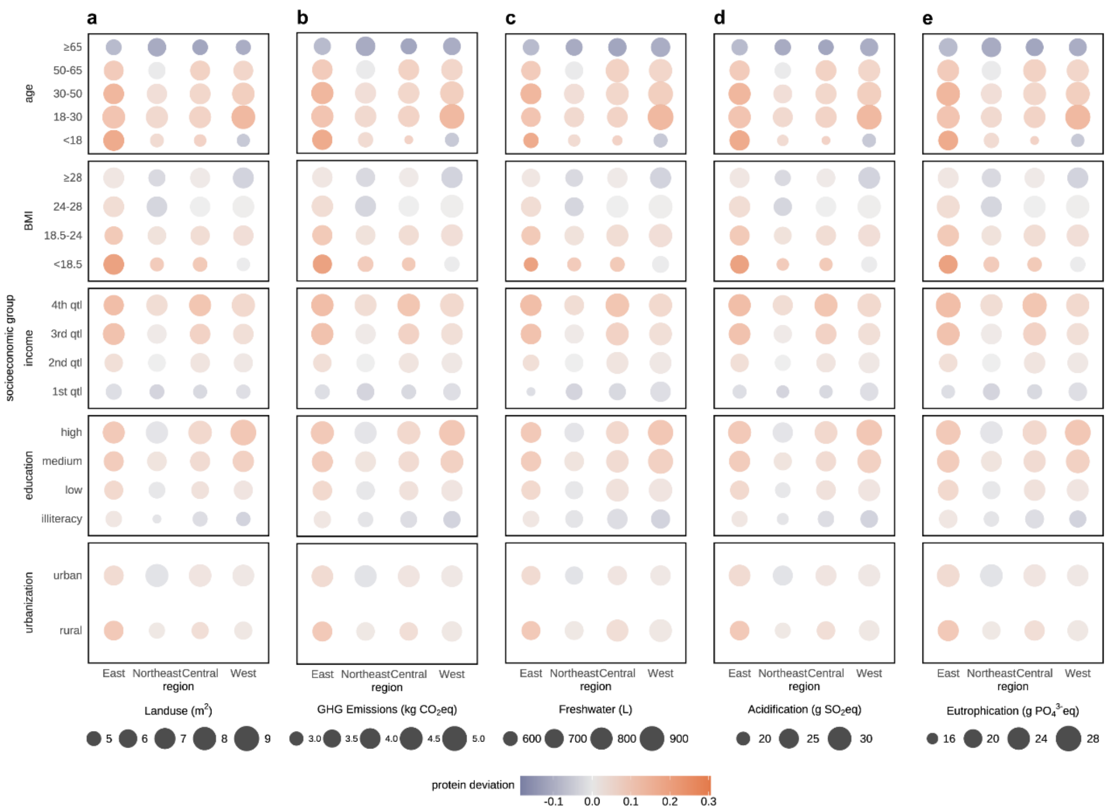

Figure 3. Disparities in Protein Intake and Environmental Impacts in 2011. a, Land Use; b, GHG Emissions; c, Freshwater use; d, Acidification; e, Eutrophication. Circle size indicates the level of environmental impact, and the color represents the deviation of protein intake from the RNI. Red indicates sufficient or excessive intake, while purple indicates insufficient intake.

4.4 Environmental Impact Assessment of Healthy Protein Intake Scenarios

We designed four healthy dietary scenarios to evaluate the environmental impacts of addressing both protein deficiency and overconsumption across different subgroups. Figure 4 shows the changes in total environmental impacts under each scenario relative to the current diet in 2011. Dietary intake structures for each scenario are detailed in Figure S2.

Scenario 1 (S1) assumed that all individuals meet their protein RNI while maintaining their existing dietary structure. Since most Chinese residents consume more protein than required, this adjustment leads to nationwide reductions in all five environmental impact categories. However, in Northeast China and among older adults—groups with prevalent protein deficiency—S1 resulted in 18-22% increase in land use, GHG emissions, freshwater use, acidification, and eutrophication due to increased protein intake.

Scenario 2 (S2) adopts a more balanced diet recommended by the Chinese Dietary Guidelines, with higher intakes of dairy and fish and lower consumption of cereals and red meat (Chinese Society of Nutrition, 2022). Although designed for improved health across age groups, this shift increases environmental impacts by 5.4-26.4% compared to S1, largely due to greater reliance on resource-intensive animal products. However, in West China, S2 leads to reduced environmental burdens, primarily due to a substantial decline in red meat consumption (Figure S3).

Scenario 3 (S3) explores the substitution of 50% of red meat with poultry. This results in modest environmental improvements due to poultry's lower impact per unit of protein. Scenario 4 (S4) replaces 20% of animal-based protein with plant-based alternatives. S4 shows the greatest environmental benefits, reducing land use, GHG emissions, acidification, and eutrophication by 7.0-17.9%. However, S4 is associated with a slight rise in freshwater use.

We further disaggregated the environmental impacts of eliminating protein under-consumption and overconsumption (Figure 5). Under the current dietary structure, meeting the protein requirements of deficit groups would annually increase land use by 0.104 million hectares, GHG emissions by 0.69 million metric tons CO_2eq, freshwater use by 139.5 billion liters, acidification by 4,473.5 metric tons

SO_2eq, and eutrophication by 3,857.0 metric tons PO_4^{3-}eq. In contrast, reducing protein overconsumption yields greater environmental benefits across all impact categories. Nevertheless, achieving adequate and balanced protein intake for deficit populations would still result in higher GHG emissions, freshwater use, and eutrophication than curbing excess consumption.

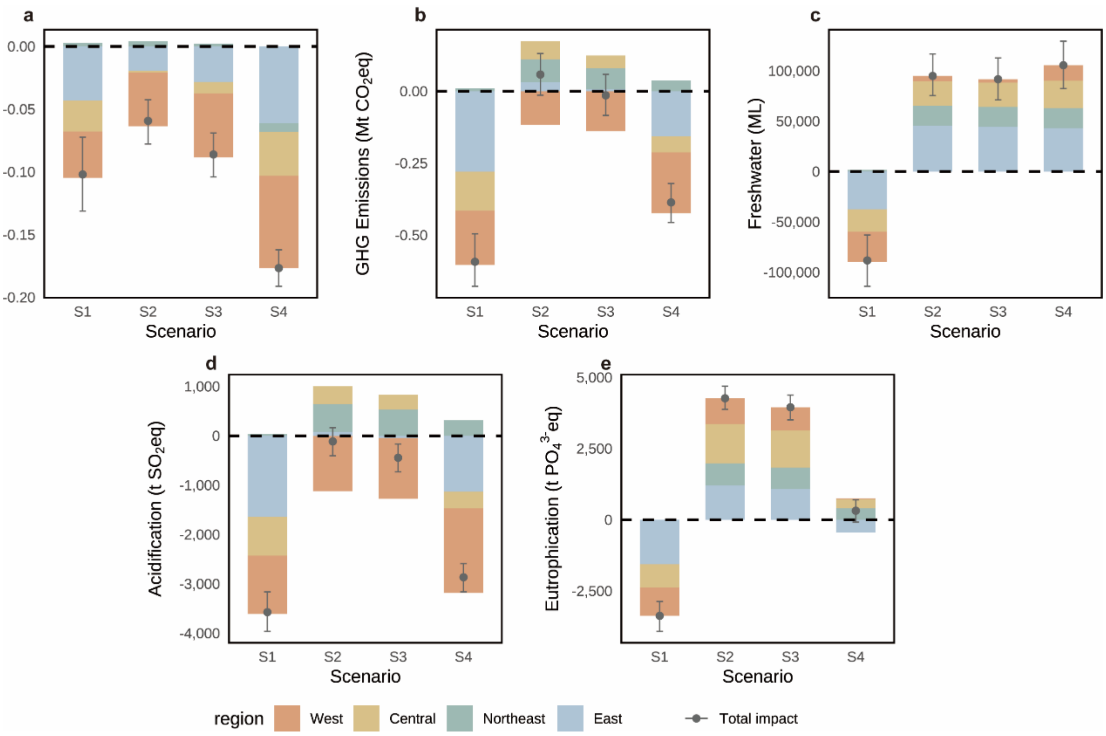

Figure 4. Changes of environmental impacts under four healthy diet scenarios compared to the 2011 baseline at the national level (individuals aged 18-65). a, Land Use; b, GHG Emissions; c, Freshwater use; d, Acidification; e, Eutrophication. Bar colors represent regions; gray dots denote combined changes in environmental impacts. Error bars represent one standard deviation from the mean of total environmental impacts, corresponding to the 16th and 84th percentiles from the 100 Monte Carlo simulation trials.

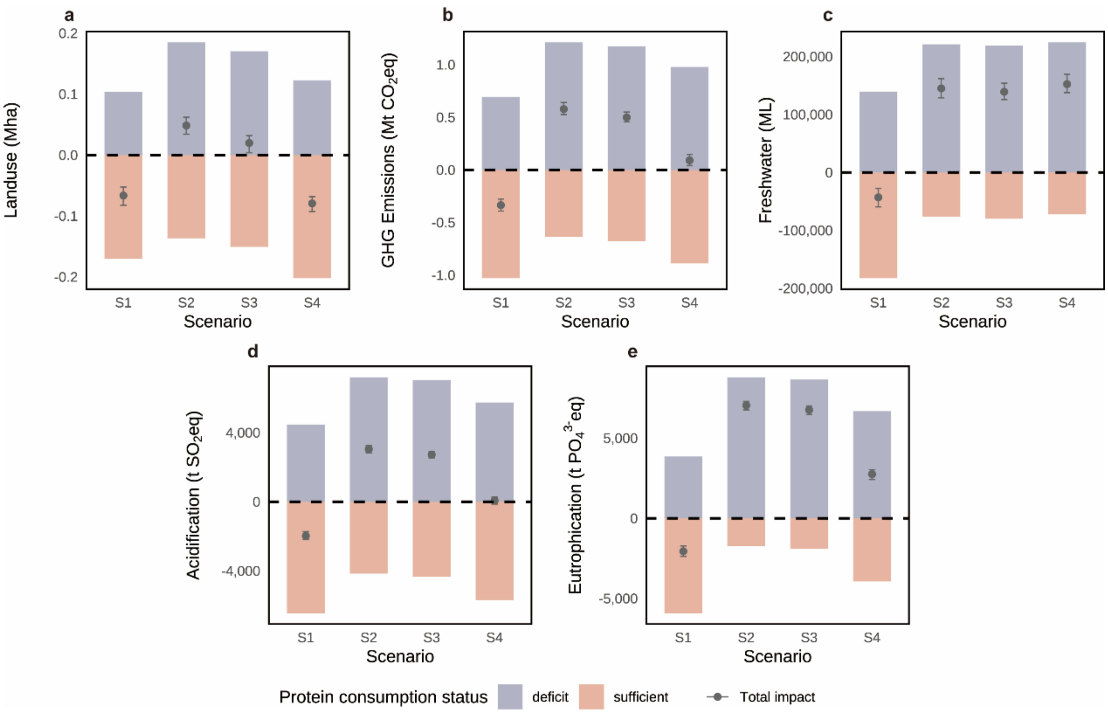

Figure 5. Changes in environmental impacts from eliminating protein overconsumption and deficiency across all ages under four scenarios. a, Land Use; b, GHG Emissions; c, Freshwater use; d, Acidification; e, Eutrophication. Gray dots denote combined changes in environmental impacts. Error bars represent one standard deviation from the mean of total environmental impacts, corresponding to the 16th and 84th percentiles from the 100 Monte Carlo simulation trials.

5. Discussion

5.1 Regional Nutrition-Environment Nexus in China

China's diverse food culture has led to significant regional variation in dietary patterns, which in turn affects both health outcomes and environmental sustainability (Song and Cho, 2017). In East China, abundant access to fish, shrimp and seafoods, coupled with higher urbanization levels, has fostered a more balanced and diversified protein intake (Li et al., 2023; Zhang et al., 2021). This region also exhibits a higher Healthy Eating Index and lower rates of chronic diseases. Reflecting these features, the Chinese Dietary Guidelines have described it as representative of "Eastern Healthy Dietary Patterns" (Cai et al., 2024; Chinese Society of Nutrition, 2021). Consequently, East China faces fewer nutritional or environmental trade-offs when shifting toward recommended healthy diets.

In contrast, West China has the lowest per capita protein intake but the highest share of animal-based proteins, particularly from red meat, which accounted for 26.3% of total protein consumption, a level comparable to Western Europe (FAO, 2023). A transition towards a healthier diet in this region could reduce meat-sourced protein by nearly half, leading to substantial environmental benefits. Compared to other nations at similar development stages, China has a more abundant protein supply, marked by higher intake of vegetables and oil crops but very limited milk consumption (Schmidhuber et al., 2018). These findings highlight the need for region-specific dietary recommendations that balance nutritional goals with environmental sustainability.

5.2 Socioeconomic Disparities in Protein Intake and Environmental Impact

A key contribution of this study is its socioeconomic subgroup analysis of the environmental implications of addressing both protein overconsumption and deficiency. While protein overconsumption is common, certain groups—such as older adults, low-income individuals, and those with overweight or obesity—still face inadequate protein intake. These conditions often overlap. For instance, low-income urban populations in China show higher rates of overweight and obesity, and adults' mean BMI has steadily increased since the 1980s (Wang, L.M. et al., 2021). As China now has the world's largest population of individuals with overweight and obesity individuals (Chen et al., 2023; Wang, Y.F. et al., 2021), it is increasingly important to ensure adequate intake of high-quality protein without increasing health risks related to obesity.

Aging presents another challenge. The share of the population over age 65 increased from 8.9% in 2010 to 13.5% in 2020. Protein deficiency has become a major health concern among older adults. According to the *China Older Adults Nutrition and Health Report*, nearly half of older adults were in poor nutritional status in 2018. Adjusting their diets to meet recommended health standards would require a 21.2% increase in total protein intake, a 26.4% reduction in plant-based proteins, and a 52.0% rise in animal-based protein. While these changes could reduce chronic disease-related economic costs by $84.1 billion, they would also lead to a 41.4-50.9% rise in environmental burdens (Chai et al., 2016).

Our findings highlight the need for policymakers to consider socio-economic diversity when addressing the nutrition-environment nexus. Beyond promoting sustainable diets in developed areas, more targeted guidance is needed for the elderly, people with obesity, and rural low-income populations. Public awareness of healthy and sustainable diets remains limited among these populations, highlighting the need for more effective outreach through local media and other accessible platforms.

5.3 Synergies and Trade-offs between Nutrition and Environment

Previous studies have often concluded that aligning diets with the Chinese Dietary Guidelines (CDG) can reduce environmental burdens, typically based on national-average data or specific substitution assumptions. Our results complement this literature by showing that China's food system remains largely plant-based, yet animal-source foods have continued to expand during the dietary transition. In this context, moving toward a CDG-aligned balanced diet can improve nutritional adequacy but may increase environmental impacts when it entails higher consumption of animal-source foods, particularly for certain regions and subgroups (Deng et al., 2025; He et al., 2018; He et al., 2024; Wu et al., 2022). Importantly, these trade-offs are not inevitable: they can be substantially mitigated by adjusting which protein sources expand, especially by limiting red meat and shifting toward lower-impact alternatives, and by curbing protein overconsumption.

Our scenario results illustrate this source-specific leverage. Relative to S2, S4 delivers larger reductions in environmental impacts, reducing land use by 14.2%, GHG emissions by 17.9%, acidification by 15.3%, and eutrophication by 12.8%. In contrast, S3 yields more modest but still meaningful reductions (-8.7%, -11.2%, -9.4%, and -7.6%, respectively). Freshwater use shows the opposite pattern: S4 slightly increases freshwater use (+3.2%) due to the higher water requirements of certain legume crops, while S3 reduces freshwater use (-2.1%). Overall, these findings align with global evidence that shifting part of protein demand from animal- to plant-based sources generally produces larger environmental gains than within-animal-source substitutions (Poore and Nemecek, 2018; Clark et al., 2019).

Both S3 and S4 maintain adequate total protein intake by design, but they differ in practical nutritional considerations. S3 preserves high biological-value protein through poultry. S4 requires attention to protein quality for some vulnerable groups (e.g., children and older adults), yet a 20% substitution is unlikely to pose protein-quality risks for most adults when implemented through diverse plant sources—particularly soy and legumes—and within an overall balanced diet.

Implementation feasibility also differs. S3 is likely to face lower behavioral resistance because it retains animal-protein-based meal structures and builds on culturally familiar consumption patterns. By contrast, S4 may encounter greater barriers in regions with strong meat-eating traditions and limited access to high-quality plant-protein options. For example, West China combines relatively high red-meat reliance with lower legume intake, suggesting that plant-protein substitution may require complementary measures to improve availability and acceptability.

Taken together, our findings support a staged or blended pathway: promoting feasible within-animal shifts (e.g., replacing red meat with poultry and fish) as a near-term, lower-resistance option, while expanding plant-protein substitution over the longer term through public procurement, nutrition education, and product innovation. Such an approach could help the CDG evolve toward more operational guidance that integrates environmental considerations and differentiates protein sources by their environmental intensity. This pathway aligns with recent China-wide assessments that highlight strong spatial heterogeneity in diet-related footprints and the value of bundling dietary shifts with broader food-system measures (Cai et al., 2025; Wang, X. et al., 2025; Wang, Y. et al., 2025), while underscoring affordability and cultural acceptability as key prerequisites for successful implementation (Zhang et al., 2025).

5.4 Strengths and Limitations

To our knowledge, this study is among the first to examine China's nutrition-environment nexus through the lens of protein transition using micro-level dietary data. Leveraging CHNS, we quantify individual protein intake and associated environmental footprints across four regions and diverse subgroups (gender, age, income, education, urban/rural status, and BMI). This design allows us to identify distributional patterns that are typically obscured in national averages and to estimate the implications of addressing both protein overconsumption and deficiency at the national level. By assessing five environmental impact categories and evaluating scenarios grounded in observed consumption habits, we provide a realistic assessment of potential synergies and trade-offs in shifting toward healthier diets.

Several limitations should be acknowledged. First, the most recent CHNS wave with publicly available individual-level dietary intake data required for our analysis is 2011. Although later CHNS rounds exist, the necessary micro-level dietary modules are not fully accessible for the post-2011 period. Importantly, available evidence suggests that the broad patterns captured here remain relevant. For example, the 2015 China Nutrition and Chronic Diseases Report reports a protein-source composition—46.9% from cereals, 5.9% from legumes, and 35.2% from animal-based foods—that is broadly consistent with our 2011 estimates (Chinese Society of Nutrition, 2021). National statistics also indicate a continued rise in animal-source protein in subsequent years. These comparisons support the interpretation of our results as capturing structural features of China's protein transition, while we also recognize that the absolute levels and some subgroup patterns may have evolved with ongoing urbanization and dietary modernization.

Second, we focus on protein intake and its environmental impacts, without jointly assessing other macronutrients (fats and carbohydrates) or micronutrients (vitamins and minerals). While protein is widely used as a basis for dietary classification, this scope may overlook nutritional trade-offs that emerge when optimizing diets across multiple nutrients. Future research integrating multiple nutrients would help evaluate broader health-environmental interactions.

Third, our LCA coefficients follow a cradle-to-retail boundary and therefore exclude consumer-stage processes such as household cooking, storage, and post-purchase waste. As a result, our estimates should be interpreted as pre-consumer diet-related footprints rather than full cradle-to-plate impacts. This boundary is well suited for comparing relative impacts across protein sources because upstream production dominates most categories; for example, Poore and Nemecek (2018) show that farm-stage processes account for the majority of impacts (approximately 61% of GHG emissions, 79% of acidification, and 95% of eutrophication), whereas packaging, transport, and retail typically contribute only a small share for most products. Extending the framework to incorporate consumer-stage impacts—particularly in

China, where cooking practices and food waste may vary substantially across regions and socioeconomic groups—would further improve the completeness of such assessments.

5.5 Post-2011 Dietary Trends and Contemporary Policy Relevance

While our micro-level analysis is based on CHNS data from 1997 to 2011, subsequent trends indicate that China's protein transition has continued after our study period, reinforcing the contemporary relevance of our conclusions.

National and international statistics confirm the ongoing shift toward animal-based protein in China. According to FAO Food Balance Sheets, China's daily per capita protein supply increased by 15.8 g between 2010 and 2021, reaching 124.6 g—a level that now slightly exceeds that of the United States (124.3 g) and substantially surpasses the global average (FAO, 2023). Although plant sources still account for approximately 60% of total protein supply at the national level, city-level evidence reveals a more pronounced transition: in Beijing, the share of protein from animal-based foods rose from 29.2% in 2010 to 48.0% in 2022, while the contribution from cereals declined from 43.8% to 31.7% over the same period (Chen et al., 2025). Over the same period, meat consumption continued to rise, with poultry consumption increased more rapidly between 2017 and 2021, while pork remained the dominant meat category (USDA ERS, 2023). Recent provincial-scale assessments further document strong spatial heterogeneity in diet-related footprints and identify red-meat reduction as a major mitigation lever in future dietary strategies (Wang, Y. et al., 2025).

These dietary shifts carry significant environmental implications. Recent syntheses estimate that China's food system contributes a substantial emissions burden, with non-CO_2 gases from livestock production playing a major role (Liu et al., 2023). In this context, the key policy-relevant insight from our scenario analyses is not merely whether protein intake increases or decreases, but rather which protein sources change. Our results demonstrate that reducing overconsumption can create environmental "space" to address protein deficits among vulnerable groups, and that adjusting protein composition—by substituting red meat with poultry (S3) or with plant-based protein (S4)—can substantially mitigate environmental pressures. This source-specific logic is increasingly aligned with recent policy signals, including the 2022 Chinese Dietary Guidelines' emphasis on dietary diversity, higher intake of legumes and dairy, and moderation of red and processed meat (Chinese Society of Nutrition, 2022), as well as broader national agendas linking nutrition to green development and climate commitments.

In sum, although our empirical estimates end in 2011, the direction of China's protein transition has continued, implying that the environmental stakes of aligning nutrition goals with protein-source choices are likely even higher today. The mitigation pathways assessed in this study therefore remain directly applicable to contemporary policy design, particularly for tailoring interventions by region and subgroup and for prioritizing feasible shifts away from red-meat-intensive dietary patterns.

6. Conclusion

China's protein consumption has undergone notable changes in both quantity and composition, marked by a clear shift towards animal-based sources. Despite a modest decline in total protein intake, diet-related environmental impacts remain high, driven primarily by increased consumption of animal-based protein.

This study reveals significant disparities across regions and socio-economic subgroups. High-income, male, and more highly educated individuals tend to overconsume protein and generate greater environmental burdens, while older adults, low-income groups, and individuals with obesity often face protein deficiencies. Our scenario analysis demonstrates that reducing protein overconsumption could offset the environmental costs of addressing these deficiencies. Moreover, although adopting the balanced dietary pattern recommended by the Chinese Dietary Guidelines may increase environmental pressures, such trade-offs can be substantially mitigated by adjusting protein sources—specifically, reducing red meat intake and promoting poultry or plant-based alternatives.

These findings underscore the need for integrated dietary policies that simultaneously address health and environmental objectives. Future guidelines should account for regional dietary cultures and the nutritional needs of vulnerable populations, thereby supporting a more balanced, equitable, and environmentally responsible food system. Given the continued post-2011 rise in animal-source protein demand, the environmental stakes of aligning nutrition goals with protein-source choices are likely even higher today, reinforcing the timeliness and relevance of the targeted substitution and overconsumption-reduction strategies proposed in this study.

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