



China's low-emission pathways toward climate-neutral livestock production for animal-derived foods

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Animal-derived food production accounts for one-third of global anthropogenic greenhouse gas (GHG) emissions. Diet followed in China is ranked as low-carbon emitting (i.e., 0.21 t CO₂-eq per capita in 2018, ranking at 145th of 168 countries) due to the low average animal-derived food consumption rate, and preferential consumption of animal-derived foods with lower GHG emissions (i.e., pork and eggs versus beef and milk). However, the projected increase in GHG emissions from livestock production poses great challenges for achieving China's "carbon neutrality" pledge. We propose that the livestock sector in China may achieve "climate neutrality" with net-zero warming around 2050 by implementing healthy diet and mitigation strategies to control enteric methane emissions.

Food systems are responsible for a third of global anthropogenic greenhouse gas (GHG) emissions (17.3 GtCO₂-eq yr⁻¹), 57% of which correspond to the production of animal-derived foods (ADFs).¹ Animal-derived foods products, such as meat, milk, eggs, and fish, are rich in protein and contain essential nutrients due to high digestibility for humans, and are especially important for children's health. Animal-derived foods consumption has greatly increased in the past few decades, especially in emerging economies, such as China.² There are increasing concerns about ADF consumption in China which is driven by the rapid increase in income,³ and its potential impacts on China's "carbon neutrality" plan. In addition, pathways toward carbon or climate neutrality for China's ADF consumption and production are also not clear.

To address this knowledge gap, we developed a classification scheme of ADF consumption for 168 countries, primarily based on the per capita consumption of seven types of ADF in 2018 from the FAOSTAT database.² Our results show that countries can be divided into four subgroups based on their distinct ADF consumption rate and structure (Figure 1A). China is grouped with most Asian and African countries characterized by their high proportion of ADF consumption of pork and eggs. Countries in this group are greatly different from countries in Europe and North America, where milk and beef are the main components of ADF. Furthermore, China is ranked in the middle of all countries (82 of 168) in terms of daily ADF consumption per capita (334 g day⁻¹), which is lower than most developed countries, and higher than some African countries.

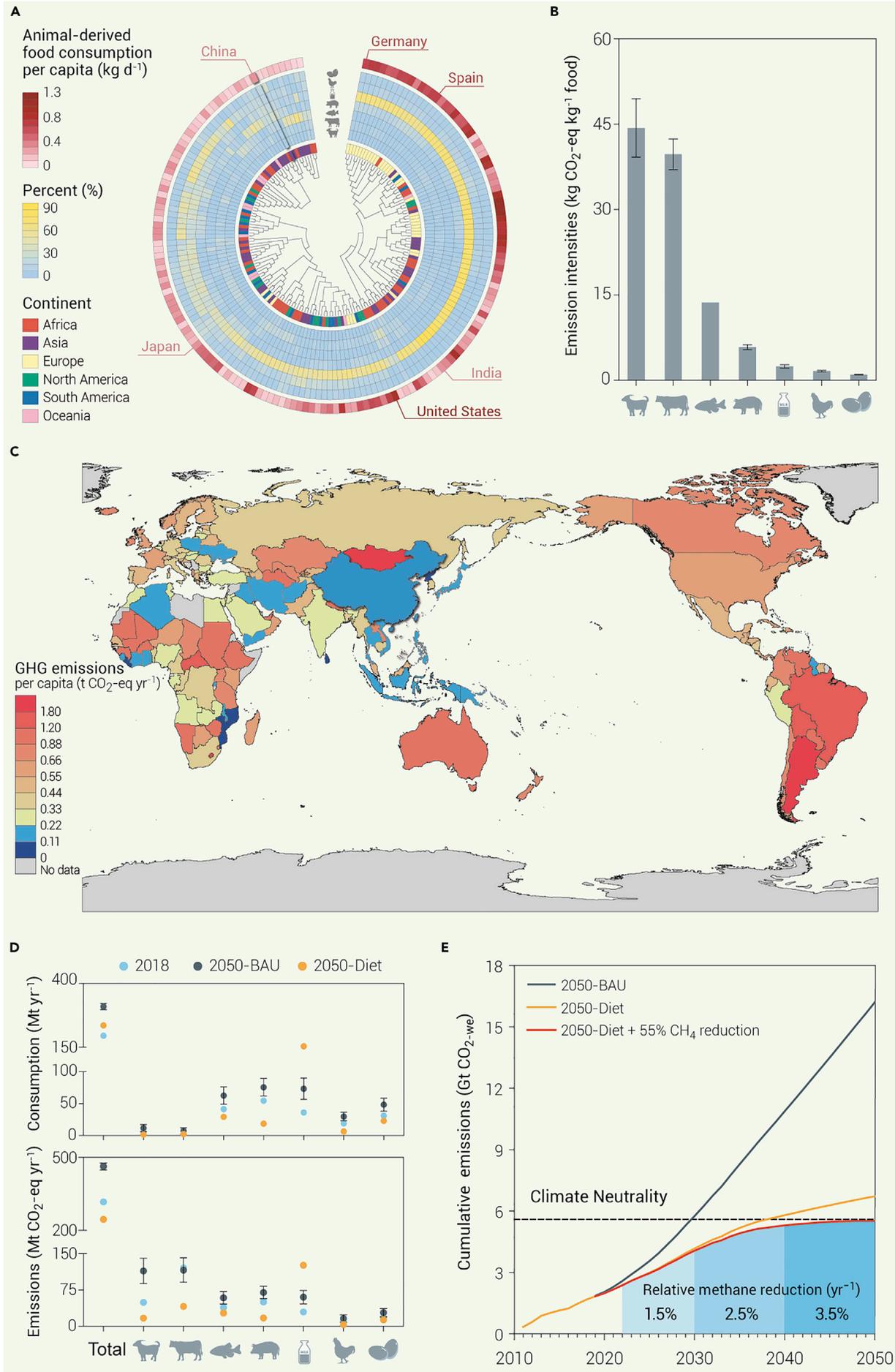
Animal-derived foods is mainly produced by the livestock sector, including ruminant and non-ruminant animals. Ruminants are physiologically distinct from non-ruminant animals since they are foregut fermenters that can convert human-inedible complex carbohydrates to volatile fatty acids and microbial cell protein for the host, accompanied by the generation of physiological by-product methane.⁵ Compared with non-ruminant animals, ruminants have a lower feed conversion efficiency with longer generational and reproductive cycles, and a greater share of energy and feed consumed being used for maintenance rather than weight gain or production. As a result, on-farm GHG emissions per kilogram ADF from ruminant meat (excluding emissions from feed production and post-processing) are 3 to 40 times more than that from non-ruminant animals. For example, the global average on-farm GHG emissions are 39.7 to 44.3 kg CO₂-eq per kg for beef and mutton, while they can be as low as 1.0 to 6.0 kg CO₂-eq per kg for eggs, poultry, meat, and pork (Figure 1B). Hence, consumption of the same amount of ADF but from different sources, can result in very different GHG emissions.

By constructing a detailed food trade matrix, per capita ADF consumption rates, and average GHG emissions of different ADF produced in different countries derived from the FAOSTAT database, we assessed the national ADF-related GHG emissions per capita in 2018 (Figure 1C). China's GHG emissions from ADF consumption were 0.21 t CO₂-eq per capita in 2018, ranking 145th of 168 countries from highest to lowest. That is, the emissions per capita per year of China's ADF consumption are lower than of most countries worldwide. Such low GHG emissions can be attributed to 1) relatively low daily ADF consumption per capita, and 2) the high proportion of ADF with low GHG emission (i.e., pork, poultry and eggs).

However, rising income and urbanization drive a global dietary transition in which traditional diets are replaced by diets high in refined fats, oils, and meats. By 2050, these dietary trends, if not controlled, will be a major contributor to an estimated 80% increase in global agricultural GHG emissions.⁶ We predicted ADF consumption for China in 2050, based on linear or non-linear regression of different types of ADF consumption over the years, urbanization rate, or average gross domestic production value per capita.³ Daily per capita ADF consumption is projected to increase by 58.5% in 2050 under the business as usual (BAU) scenario compared with 2018, driven jointly by a more rapid increase in the consumption of mutton and milk, and an overall increase in the average daily per capita ADF consumption (Figure 1D). This will increase ADF consumption-related GHG emissions up to 463 Mt CO₂-eq yr⁻¹ by 2050 and present a challenge for achieving "carbon neutrality" in China.

We further investigated if such high levels of ADF consumption are necessary for human health. China's current daily per capita consumption of ADF, such as poultry, pork, eggs, and fish, has outstripped the metabolic requirement recommended by the Dietary Guidelines for Chinese Residents (2016). Excessive consumption of red meat increases blood total cholesterol, low-density lipoprotein-cholesterol, and triglycerides while it decreases high-density lipoprotein-cholesterol, resulting in an increased risk of hyperlipidemia, followed by cardiovascular diseases.⁷ Chinese people can become healthier by following the dietary reference intake according to the recommendations of the Chinese Nutrition Society. If the Chinese adopt the recommended dietary guidelines, ADF consumption-related GHG emissions can decrease to 245 Mt CO₂-eq yr⁻¹, which is 47.1% lower than 2050-BAU, similar to the levels in 2018 (Figure 1D). However, milk consumption-related GHG emissions will be tripled by 2050 in the healthy diet scenario, and most of the emissions from milk consumption will be due to CH₄ emissions by ruminants.

Livestock production has not been considered in the ambitious "carbon neutrality" plan yet because of concerns about food security and difficulties in achieving carbon neutrality (net-zero GHG emissions, metric-weighted anthropogenic GHG emissions associated with a subject are balanced by metric-weighted anthropogenic GHG removals) within the sector. However, CH₄ is a short-lived climate pollutant compared with CO₂ and N₂O. At the 26th UN Climate Change Conference of the Parties, China and the United States issued a joint declaration on enhanced climate action, which specifically mentioned stepping up to reduce CH₄ emissions. A reduction of CH₄ emissions may decrease the CH₄ concentration in the atmosphere, and have a cooling effect for offsetting the warming effect of other GHG emissions.⁸ Therefore, livestock production could be climate neutral (net-zero warming, maintaining net emissions at zero CO₂ warming-equivalents).



Global warming potential was then estimated by calculating the total cumulative CO₂-warming equivalent (CO₂-we) of the livestock sector.⁹ If we adopted a healthy diet and decreased enteric CH₄ emissions from ruminants by 55% in the coming decades, livestock production would add no additional warming effects by 2050 (Figure 1E). The plan to mitigate CH₄ emission is proposed in Figure 1E and a 55% reduction in CH₄ emissions from enteric fermentation is technically feasible as follows: 1) via feed management, such as increasing forage digestibility, which could support a 9% to 17% reduction in CH₄ emissions; 2) via diet formulation, such as decreasing dietary forage-to-concentrate ratio and inclusion of oilseeds, as oil and fat could achieve a 9% to 20% reduction in CH₄ emissions; however, altering animal feed formulation may cause GHG emissions to change, which merits further investigation; and 3) via rumen manipulation by CH₄ inhibitors, alternative electron receptors, and dietary inclusion of tanniferous forages, which enable 12% to 35% reduction in CH₄ emissions.¹⁰

Overall, China is ranked at almost the lowest level of ADF consumption-related GHG emissions per capita per year in the world, due to its low average ADF consumption rate, and preferential consumption of low GHG emission-related ADF. However, the projected increase in the consumption of ADF may pose great challenges for achieving the stringent 1.5°C global warming target and China's "carbon neutrality" pledge. Although the livestock sector cannot be carbon neutral, climate-neutral livestock production with net-zero warming may be achieved around 2050, if the Chinese people follow healthy diet recommendations and mitigation strategies for enteric CH₄ emissions at all costs.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

Figure 1. Animal-derived foods (ADF) consumption with GHG emissions and mitigation strategies toward climate-neutral livestock production in China (A) Classification of country-based ADF consumption per capita for 168 countries in 2018. (B) Greenhouse gas (GHG) emission intensities of ADF from mutton, beef, fish, pork, milk, poultry, and eggs; the data for fish are obtained from Poore and Nemecek,⁴ and the rest are from FAOSTAT.² (C) Country-based map of GHG emissions due to ADF per capita in 2018. (D) Animal-derived foods consumption with related GHG emissions in 2018, and under scenarios of 2050 assuming BAU (2050-BAU) or healthy diet (2050-Diet) in China. (E) Cumulative carbon dioxide warming equivalent (CO₂-we) for livestock production under scenarios of 2050-BAU, 2050-Diet, and 2050-Diet with additional 55% of enteric methane reduction (2050-Diet + 55% of methane reduction) from 2011 to 2050 in China. The dotted line indicates the point of climate-neutral livestock production at which annual CO₂-we emissions do not add to further warming. Error bar indicates standard error.