Unequal distribution of GHG emissions from global food consumption

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Chapter 5

Summary and outlook

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This thesis mainly evaluates past and present trends of GHG emissions (including CO_2, CH_4, and N_2O) across global food supply chains, driven by the food consumption of final consumers across regions, countries, and population groups. Additionally, it seeks to investigate the underlying drivers of these emissions and examine mitigation potential through diet shifts, adopting an integrated perspective that considers dietary choices, nutrition, and environmental impacts.

5.1 Summary of chapters

Chapter 2 addresses research question Ⅰ. This chapter: first, develops an accounting framework for consumption-based emissions throughout global food supply chains using a physical trade flow approach; second, evaluates trends in GHG emissions across global food supply chains driven by final consumer demand from 2000 to 2019, with a detailed breakdown by processes and product; third, quantifies emissions embodied in domestic food supply and international trade, including those associated with re-exports; and finally, identifies the driving factors—from production to consumption—contributing to changes in consumption-based emissions through structural decomposition analysis.

i. **How to develop an accounting framework for consumption-based emissions throughout global food supply chains using physical flow data?**

To develop the accounting framework for consumption-based GHG emissions across global food supply chains, the physical trade flow (PTF) approach is applied to trace detailed product flows from production to final consumption across 181 countries or areas. This framework requires four types of data input, including production data, bilateral trade data, conversion factors for processed products, and emission intensity of each supply chain stage. First, the FAOSTAT trade matrix and production data are used to track embodied food consumption and flows. Next, the emission intensity of supply chain stages is calculated by allocating emissions from land use and land use change (LULUC), agricultural production, and beyond-farm activities to food products. Emissions from processed products are linked to primary equivalents using conversion factors. Finally, by combining emission intensity with consumption patterns, we estimate the consumption-based emissions for each food product, accounting for trade and production across different regions, countries, and years. This approach provides a comprehensive assessment of global food-related emissions, tracing them from production to consumption.

ii. **What are the long-term trends in food consumption emissions across countries and products?**

In 2019, global food supply chain emissions totaled approximately 16 Gt CO_2-eq (30±9% of anthropogenic GHG emissions), with China, India, Indonesia, Brazil, and the United States contributing 40%. From 2000 to 2019, food-related emissions increased by 14% (2.0 Gt CO_2-eq), driven primarily by consumption in China (46%), India (24%), and Pakistan (11%).

Animal-based products accounted for 95% of the increase in emissions, with animal-based emissions reaching 7.9 Gt CO_2-eq in 2019. Beef (32%) and dairy (46%) were the key contributors. For plant-based emissions, grains (3.4 Gt) and oil crops (1.9 Gt) dominated, with rice and palm oil being the main sources

Global per capita food-related emissions increased from 1.8 to 2.1 t CO_2-eq between 2000 and 2019, although disparities between countries have narrowed. Developed countries generally emit more animal-based emissions per capita than the global average, with Australia, Brazil and the United States leading due to high red meat consumption. Despite having lower emissions than the global average, China and India saw notable increases in per capita food emissions, rising by 64% and 19%, respectively.

iii. How does international trade influence food consumption emission patterns?

International trade redistributes food-related emissions, with oil crop and beef being two dominant food categories. Indonesia and Brazil are the world's largest exporters of embodied emissions from oil crops, while Australia and Brazil export the largest amounts of beef-related emissions. China became the largest importer of emissions in 2019, largely due to embodied emissions from oil crops and pork. Over 30% of food-related emissions in developed countries are generated overseas, exceeding 60% in low-self-sufficiency countries such as Japan and South Korea. Developing countries, while still generating most emissions domestically, saw this share drop from 91% in 2000 to 85% in 2019, reflecting the growing impacts of trade.

Between 2000 and 2019, the role of developing countries in the international trade of food-related emissions has grown considerably. The share of emissions embodied in international food trade increased from 14% to 19%, with 16% of animal-based and 21% of plant-based food emissions linked to trade in 2019. While imports of embodied emissions by developed countries remained stable at around 1.1 Gt CO_2-eq, their share of global trade dropped from 56% to 39%. By contrast, emissions embodied in food exports to developing countries increased substantially, especially from major food-exporting countries such as Indonesia, Brazil, Australia, Canada, and the United States.

iv. What are the contributions of different driving factors to changes in food consumption emissions across the entire food supply chain?

Structural decomposition analysis (SDA) was used to identify the driving factors behind changes in global and regional food consumption emissions. Between 2000 and 2019, population growth and rising per capita consumption were key drivers of global food emissions, with South Asia, Sub-Saharan Africa, and India seeing the largest increases. Per capita consumption contributed to a 19% rise in emissions, especially in developing countries such as China and India. In contrast, declining demand for animal-based food in developed countries reduced emissions. A decrease in emission intensity, particularly from land use changes, helped offset some of this growth, cutting global emissions by 37%. Changes in the trade structure increased global emissions by 8%, while a decline in food consumption from domestic supply in importing countries reduced emissions by 5%.

Chapter 3 builds on the global consumption-based food emission inventory from Chapter 2 to address research question Ⅱ. This chapter: first, quantitatively evaluates trends in dietary GHG emissions (excluding food loss and waste) during global dietary transitions across age groups from 2000 to 2019; second, explores the co-benefits and trade-offs between changes in dietary emissions and the nutritional quality of dietary patterns across age groups; and finally, examines dietary emission changes attributable to each age group while quantifying the contributions of underlying driving factors through decomposition analysis.

i. **How have dietary emissions changed across age groups and food products over the long-term period?**

Between 2000 and 2019, dietary emissions showed varying trends across different regions and age groups. In high-income countries, emission patterns remained stable, with meat and dairy products contributing the largest share. In contrast, China and India experienced notable increases in emissions, driven by rising meat consumption in China and dairy consumption in India. Regions with high land-use emissions, including Brazil, Indonesia, Oceania, and Sub-Saharan Africa, saw reductions in per capita emissions, despite increased meat and dairy consumption, due to decreased consumption of locally grown plant-based products. Among age groups, adolescents and young adults (ages 11-29) generally had the highest emissions, primarily from meat and dairy, while the 0-10 age group had the lowest emissions. Senior groups (ages 60+) often had higher dairy-related emissions due to nutritional needs. In certain regions, including Sub-Saharan Africa and Oceania, they also had higher meat-related emissions, influenced by cultural beliefs, social status, and improved affordability in retirement.

ii. **What are the co-benefits or trade-offs between changes in emissions and nutritional quality resulting from dietary transitions across age groups?**

Dietary transitions across age groups have led to both co-benefits and trade-offs between emissions and nutritional quality. Dairy, eggs, and seafood were major contributors to emission increases tied to improved nutrition. In high-income countries, reducing added sugars and shifting to unsaturated fats enhanced both nutrition and environmental outcomes. However, excessive meat consumption, especially in upper- and lower-middle-income countries, drove the largest increases in emissions associated with nutritional degradation. In China, over 45% of the emission increase among the 11-40 age group was linked to nutritional degradation, compared to less than 30% in other age groups. In contrast, India's emission increases had minimal negative impacts on nutritional quality across age groups. In Sub-Saharan Africa and South Asia, reduced reliance on starchy staples improved both nutrition and emissions. Notably, populations under 40 in Sub-Saharan Africa achieved emission reductions closely tied to nutritional improvements.

iii. **How do the emission shares from age groups evolve during dietary transitions, and what are the underlying driving forces?**

From 2000 to 2019, the contributions of different age groups to dietary emissions shifted notably. Globally, the 11-20 and 21-30 age groups were the top contributors in 2019, accounting for 21% and 17% of global dietary emissions, respectively. However, older populations experienced the fastest growth, with emissions from the 51-60 and 60+ groups increasing by 72% and 69%. The 60+ group contributed one-quarter of the global emissions increase, with its emission share exceeding 20% in high-income countries such as Japan (29%) and Western Europe (27%). In middle- and lower-income regions, including China, India, and South Asia, emissions from middle-aged and senior groups more than doubled, though their shares remained lower than those of younger groups. Sub-Saharan Africa and South Asia showed minimal changes in emission shares across age groups, with populations under 30 representing the largest percentage of regional increases.

The logarithmic mean divisia index (LMDI) method is applied to decompose the contributions of socio-economic driving forces to changes in dietary GHG emissions across age groups. During the study period, global dietary emissions increased primarily due to population growth (+32%) and higher per capita intake (+24%). Shifts in diet structure contributed to a 10% increase in emissions globally, with notable increases among senior populations in high-income countries and younger populations in the Near East and North Africa, and South Asia. However, declines in nutritional density and emission intensity of nutrients offset these increases, reducing global dietary emissions by 28% and 5%, respectively.

Chapter 4 builds on the global consumption-based food emission inventory from Chapter 2 to address research questions Ⅱ and Ⅲ. This chapter: first, quantifies dietary emissions across different consumer expenditure groups within and across countries using detailed household expenditure data, highlighting disparities in dietary emissions; and second, develops a scenario of shifting from 2019 diets to the planetary health diet to estimate the potential magnitude of emission changes resulting from a global dietary shift.

i. What is the distribution of dietary emissions across different countries?

The total global dietary emissions in 2019 reached 11.4 Gt CO_2-eq, with China (13.5%) and India (8.9%) being the largest contributors. Alongside Indonesia, Brazil, the United States, the Democratic Republic of Congo, Pakistan, Russia, Japan, and Mexico, the top ten contributors represent 57.3% of global dietary emissions but with very unequal per capita emissions within and between countries. Bolivia has the highest per capita footprint (6.1 t CO_2-eq), while countries like Haiti (0.36 t) and Yemen (0.38 t) have the lowest due to limited food affordability.

Animal-based products account for 52% of global dietary emissions while providing only 13% of the calories in global diets. The three major contributors to dietary emissions—red meat (5% of calories), grains (51%), and dairy products (5%)—are responsible for 29%, 21%, and 19% of emissions, respectively.

ii. How are dietary emissions distributed across consumer expenditure groups, and

what is the level of dietary emission inequality within countries?

Affluent countries generally have high-emission diets with lower inequality, while poorer countries tend to have lower-emission diets but greater inequality. As expenditures increase, dietary emissions rise, driven primarily by higher consumption of red meat and dairy products. Richer populations generally exhibit higher emissions from animal-based diets, whereas plant-based dietary emissions show varied patterns. For instance, middle expenditure groups in Sub-Saharan Africa and Southeast Asia exhibit the highest grain-related emissions. Overall, dietary emission inequality declines as a country's GDP per capita grows, with the highest levels of inequality observed in low-income countries, especially in Sub-Saharan Africa.

iii. How would dietary emissions change with the worldwide adoption of the planetary health diet?

In a hypothetical scenario where all countries adopt the planetary health diet, overconsuming groups (56.9% of the global population) could reduce global emissions by 32.4% through dietary shifts, which would more than offset the 15.4% emission increase from under-consuming groups (43.1%) adopting healthier diets. This transition would lead to a net reduction of 2.88 Gt CO_2-eq in dietary emissions across 100 countries, while emissions would increase by 938 Mt CO_2-eq in 39 countries, primarily in low- and lower-middle-income countries in Sub-Saharan Africa and South Asia.

Global emission reductions would be primarily driven by decreases in red meat and grain consumption. Meat, eggs, and fish reductions would account for 2.04 Gt CO_2-eq of emission reduction, with red meat alone contributing 94% of this reduction. China (22%), the United States (15%), and Brazil (14%) would lead to red meat-related emission cuts. Grain reduction would save 914 Mt CO_2-eq, with 56% of this decrease occurring in Asia. Additional reductions of 240 Mt CO_2-eq and 89 Mt CO_2-eq would come from reduced sugar and tuber consumption, respectively. However, increased consumption of proteins (legumes, nuts, and dairy), added fats, and fruits and vegetables would partially offset these reductions by 41%.

5.2 Innovations

The innovations of this thesis can be summarized as follows:

Development of a consumption-based accounting framework for global food supply chain emissions: This thesis develops an innovative accounting framework that tracks GHG emissions across all stages of food supply chains from production to consumption. By allocating production-based emissions to final consumers, the framework enables a detailed, consumption-based assessment of GHG emissions at both process and product levels. It also quantifies emissions embodied in domestic supply and international trade, providing insights into emission outsourcing. This framework lays the groundwork for assessing the unequal distribution of emissions across consumer groups and informs the design of targeted mitigation strategies for changing food choices.

Development of consumption-based food emission inventories by countries and population groups: Building on the accounting framework, this thesis constructs a global consumption-based emission inventory that allocates GHG emissions to final consumers, offering a clearer picture of emissions associated with food consumption. It also introduces a novel methodology for assessing dietary emissions across different consumer groups, focusing on age and expenditure. This approach provides valuable insights for targeting mitigation efforts across the entire supply chain, promoting climate goals, and supporting environmental justice by addressing emission responsibilities from a consumer perspective.

Development of food-related emission reduction potential via dietary shift: This thesis estimates the potential emission reductions from global dietary shifts across population groups and countries. It underscores the importance of tailored dietary shifts targeting specific regions, populations, and products, and advocates for policies that address socio-economic contexts and dietary needs to achieve equitable, sustainable, and effective emission reductions.

5.3 Outlook

Dataset development: This thesis represents a novel attempt at a consumption-based assessment; however, it faces limitations in data availability. First, while the physical trade flow approach enables the quantification of re-exports and is well-suited for relatively simple food supply chains, it may introduce system boundary cut-off errors by overlooking more complex processing and repackaging steps in global supply chains. Additionally, it fails to capture the interconnections with other sectors within the economy, a limitation addressed more effectively by the MRIO-based approach. Second, compared to harmonized and standardized databases, the bilateral trade and emissions data from various sources introduces a large magnitude of unknown uncertainties. Third, some datasets, such as household expenditure data, are outdated and fail to account for price variations across products and consumer groups. Looking forward to seeing recently updated physical MRIO datasets and the development of dynamic trade models that offer promising opportunities to address these challenges. Future research could adopt a more feasible design by integrating such models (e.g., updated MRIO-based frameworks) to better represent the entire supply chain, capturing the heterogeneity of production inputs and the interconnections between food-related and other economic sectors.

Framework refinement: This thesis focuses on upstream emissions along food supply chains before households, excluding those from household consumption, end-of-life processes, and legacy emissions or carbon removals from land, which are difficult to allocate to specific years or products. Future studies could extend these findings by incorporating these additional processes. Additionally, this thesis does not account for sub-national heterogeneity within countries, such as differences in land use, agricultural practices, and related emissions. With improved data availability (e.g., the use of dynamic land-use models), future research could develop a more consistent and comprehensive accounting framework, capturing emissions across detailed products and regions at global, national, and sub-national scales (such as cities).

Scenario setting improvement: In terms of scenario setting, this thesis focuses on the impacts of consumer dietary changes without altering food supply proportions or accounting for income and expenditure shifts, price fluctuations, or spillover effects. Future research could integrate production-side dynamics, supply chain adjustments, and elasticity-based models to provide more realistic scenario simulations, assessing the long-term feasibility and socio-economic consequences of dietary transitions.

Scope extension: This thesis examines the supply chain GHG emission trends driven by current and past food consumption patterns. However, estimating future trends in food consumption, associated emissions, and mitigation potentials at different scales is essential by simulating scenarios that account for the impacts of ongoing population growth, urbanization, and climate change. In addition to focusing on GHG emissions, future research should also consider the broader environmental impacts of food consumption, including the depletion of natural resources (e.g., land, water) and other forms of environmental degradation (e.g., nitrogen pollution, biodiversity loss). Dietary transitions may lead to both synergies and trade-offs across these dimensions, highlighting the need for integrated assessments of the multiple environmental impacts of food consumption to support the sustainability of food systems.