Integrating food loss and waste reduction policies with global dietary shifts: an economic modelling study

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Lancet Planet Health 2025; 9: 101285

Published Online November 3, 2025

https://doi.org/10.1016/j.lanplh.2025.101285

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Summary

Background Food loss and waste undermine the resilience and sustainability of global food systems, jeopardising progress toward the Sustainable Development Goals (SDGs). Adopting healthier and more sustainable diets could help reduce global food loss and waste, but the potential trade-offs on food loss and waste trends and interactions with standalone reduction policies remain largely unexplored. We aimed to investigate the effects of reducing food loss and waste within the context of a global dietary transition by 2050, shedding light on the synergies and trade-offs between two crucial policy areas for the food systems of the future.

Methods In this economic modelling study, we linked the economic and technical modelling of food loss and waste by adding consistent tracing of food loss and waste in physical quantities along global (ie, domestic and international) food supply chains within a global computable general equilibrium (CGE) modelling framework. This framework captures the behavioural responses of economic actors along food and non-food supply chains. We built on the Global Trade Analysis Project (GTAP) Data Base, incorporating data extensions for energy, nutritional accounts, and food loss and waste flows along stages of global supply chains. We first investigated the impact of halving global food loss and waste through technological developments by 2050, in line with the SDG 12.3 target. We then analysed the impact of transitioning to healthier and more sustainable diets by 2050, promoting a global dietary transition through behavioural changes. We explored this dietary transition both with and without the goal of halving global food loss and waste, highlighting how food loss and waste targets interact with dietary changes on a global scale. Our scenarios were chosen to show how the magnitude, composition, location, and reuse potential of food loss and food waste could evolve under different scenarios compared with business-as-usual dietary developments.

Findings Food loss and waste along global supply chains were projected to rise by 52·0% by 2050 under the continuation of historical trends. Diet shifts alone were projected to be insufficient to curb this rise in food loss and waste, with demographic trends and growing incomes driving the total volume of lost and discarded food. Regional spillover effects of healthier diets—whereby low-income countries increase plant-based food production to meet growing demand in high-income countries—exacerbated food loss and waste trends, especially in sub-Saharan Africa and the Middle East and north Africa. In sub-Saharan Africa, rapid population growth and increased per-capita gross domestic product drove food loss and waste when dietary changes were implemented (an increase of 132·2% from 2014 to 2050) and when standalone food loss and waste reduction targets were applied (an increase of 61·8% from 2014 to 2050). Globally, dietary shifts were projected to drive food loss and waste for oilseeds and fish, surpassing baseline levels by 2050. Further spillovers emerged in high-income countries where demand for fresh plant-based foods was shown to drive losses at production stages. Global trade was also found to amplify food loss and waste in exporting regions, as increasing exports of plant-based products from sub-Saharan Africa and Latin America to Europe, the USA, and India increased farm-level food loss and waste. Coupling dietary transitions with targeted food loss and waste reduction policies in line with SDG 12.3 successfully controlled spillover effects on a global scale. A combined strategy could reduce global food loss and waste by 63·2%, eliminating commodity-specific and stage-specific spillovers and enhancing the effectiveness of dietary changes. Potential benefits were particularly notable in sub-Saharan Africa where nutritional availability could increase by an average of 365 calories per capita per day by 2050.

Interpretation Policies promoting healthier diets must consider spillover effects on food loss and waste (eg, a potential rise in loss and waste generation when global consumption shifts towards plant-based products). As shifts in production, consumption, and trade alter the magnitude, location, and composition of food loss and waste, monitoring these changes is crucial to establishing the priority areas for food loss and waste reduction or reuse interventions, especially in low-income regions. Although dietary shifts can improve nutrition, new technologies and market-based approaches to reuse discarded food and food waste—whether linked to domestic consumption or trade—could create economic opportunities and environmental benefits. To maximise these benefits, food loss and waste reduction should be central to discussions on dietary transition policies, as spillover effects risk undermining the positive outcomes of a global dietary shift.

Funding None.

Introduction

Food loss and waste generated along global food supply chains currently undermines the resilience and sustainability of food systems,[1] endangering the environment and threatening our progress towards the Sustainable Development Goals (SDGs).[2] Promoting a global dietary transition towards a healthier and more sustainable diet with complementary reductions in food loss and waste is a

Research in context

Evidence before this study

The relationship between global dietary transitions and food loss and waste has been explored in previous studies. However, these studies often overlook the transition pathways to adopting healthy diets globally, failing to account for feedback mechanisms, such as shifts in food and non-food demand that influence production practices and global trade, and rebound effects, such as price changes due to dietary shifts or food loss and waste policies unintentionally leading to increased consumption of particular products or the redirection of resources to less sustainable uses. For instance, when food loss and waste reduction policies are implemented, food availability increases, food prices decrease, and, as a result, food demand increases (compared with a scenario in which price effects are not considered). Although gross food supply declines in this case, the net effect calculated when taking market mechanisms into account is less substantial than the direct effect estimated without such mechanisms. Furthermore, such effects are heterogeneous across commodities, countries, and supply-chain stages. Most research also does not include a temporal dimension, providing static analyses without insight into future trends or exploring only a partial dietary transition without fully achieving the EAT–*Lancet* dietary recommendations.

Added value of this study

Our analysis advances the understanding of the interaction between dietary transitions and food loss and waste generation by 2050. Our approach combines technical and economic modelling of biomass to endogenously represent market-based policies enhancing dietary shifts. At the core of this approach lies the Global Trade Analysis Project (GTAP) Data Base, a widely used global database, which in combination with previously published extensions, ensures an overall consistency of our data with other databases such as the Food and Agriculture Organization of the UN food balance sheets. From a modelling perspective, a key innovation is the tracing of physical food loss and waste flows across supply chain stages within a global value-based economic framework, relying on an up-to-date food loss and waste database calibrated with country-specific net intakes. Our modelling framework allows for several novelties. We investigate the intersection of dietary transitions and food loss and waste reduction targets, identifying global synergies and spillovers in a dynamic setting in which food production, trade, and consumption react to changing prices over time. This important feature was often overlooked in previous studies, in which static models were adopted. The use of a global general equilibrium model is crucial for understanding interactions between food and non-food sectors, capturing the competition for biomass between these sectors, which influences food production and, consequently, shapes food loss and waste patterns. Through our economy-wide framework, we quantify food loss and waste linked to processed foods and food services, enabling the tracing of food loss and waste both from primary agricultural production to final consumption and across countries, a feature missing in previous investigations, which mainly focused on primary agrifood sectors. Our enhanced food loss and waste tracing framework can investigate the impacts of diets on evolving food loss and waste trends across countries, commodities, and supply chain stages, identifying commodity-specific or stage-specific impacts. By quantifying food loss and waste-related rebound effects—such as increased plant-based food consumption leading to higher food loss and waste levels—our findings can support the design of policies across regions, products, and stages of the food supply chain, addressing cases in which rebounds are stronger in order to enhance the effectiveness of dietary transitions and food loss and waste reductions.

Implications of all the available evidence

Our results indicate that global dietary transitions must address spillover effects leading to rising food loss and waste generation, integrating direct interventions to reduce or reuse lost and discarded foods along global supply chains. In lower-income regions such as sub-Saharan Africa and the Middle East and north Africa, dietary shifts need to be coupled with technological innovations to minimise rising food loss and waste levels, particularly at the production level, to achieve notable benefits for nutritional security. Globally, as spillovers on food loss and waste arise for fish and oil seeds, dietary shifts should be supported by market-based incentives that encourage the reuse of oilcakes and fishmeal as production inputs in the form of feed or fertiliser, maximising the use of discarded products towards more sustainable production systems. Finally, policies in high-income countries should promote the reuse of rising plant-based agricultural losses to prevent environmental spillage and provide a more sustainable input for agrifood production.

central challenge to achieving the SDGs. Although available studies largely focus on synergies between nutritional (SDG 2) and environmental (SDG 13) challenges,[3–5] potential trade-offs with food loss and waste targets (eg, SDG 12.3) are often overlooked, and the interaction between sustainable diets and food loss and waste generation remains largely unexplored.[6]

A healthier and more sustainable plant-based diet[7] requires an increase in the consumption of plant-based foods, which are often linked to the highest levels of food loss and waste.[8] The increased availability of high-quality, plant-based food loss and waste along global food supply chains[9] could promote its reuse in regions where food loss and waste-based inputs can enhance market competitiveness. However, increases in imports of plant-based foods to high-income regions risks greater farm-level losses in exporting middle-income and low-income regions,[10] where reuse of discarded food and food waste is less feasible or competitive. Such spillover effects risk undermining the effectiveness of food loss and waste reduction strategies and reducing the benefits of a more sustainable diet.

Assessing the trade-offs between global dietary changes and food loss and waste reduction requires quantifying lost or discarded food along food supply chains while simultaneously addressing changes in consumer and producer behaviour across the economic system. Although developments in global measurements of food loss and waste[10–13] have helped lessen the challenge of consistent global food loss and waste quantification, missing analysis of trends when production, consumption, and global trade shift due to a higher demand for healthier and more sustainable foods generates several knowledge gaps.

Attempts to quantify food loss and waste within dietary transitions often rely on detailed food loss and waste data but provide poor representation of global food supply chains, focusing on select commodities or countries.[6] Available studies on food loss and waste developments within dietary transitions[14,15] frequently overlook dynamics of the global economic system, failing to account for changes in agents' behaviour (ie, price-related shifts in production and consumption patterns) when dietary shifts occur.[16] Moreover, existing global economic analyses often rely on partial equilibrium models[17] or input–output models,[5,18] which restrict their focus to primary agricultural sectors and ignore changes in the processing and service aspects of food supply chains and interactions with non-food sectors. Finally, although much attention is often given to food loss and waste variations across food commodities and regions, there is little research on how food loss and waste locations shift across different stages of the supply chain when consumption moves towards healthier and more sustainable diets.

Building on these limitations, Gatto and colleagues[9] adopted a global general equilibrium (GE) model to quantify the impact of transitioning towards the EAT–*Lancet* diet[7] on global food loss and waste. This approach provided a multicountry and multisectoral market-based analysis of lost and discarded foods along global food supply chains when diets change. However, the study modelled an initial transition towards a global sustainable diet in which only a third of each dietary target was met, yielding moderate effects compared with a full transition in which the dietary targets would be fully met.

We aimed to consolidate the data and methodological advances of this earlier literature and investigate the impact of a global transition towards a healthier and more sustainable diet on the generation of food loss and waste across global supply chains. We aimed to link the economic and technical modelling of food loss and waste by adding consistent tracing of food loss and waste in physical quantities along global food supply chains within a GE modelling framework, capturing behavioural responses of economic actors along food and non-food supply chains. Our analysis relies on the recent update of the shared socioeconomic pathway (SSP) projections,[19] thus accounting for revised future macroeconomic and demographic trends across countries.

Methods

In this economic modelling study, we first investigated the impact of halving global food loss and waste by 2050, in line with the SDG 12.3 target. We then analysed the impact of transitioning to healthier and more sustainable diets by 2050, adopting the dietary scenario framework defined by the forthcoming EAT–*Lancet* Commission 2.0 report.[20] Specifically, we explored the dietary transition both with and without the goal of halving global food loss and waste, highlighting how food loss and waste targets interact with dietary changes on a global scale.

Socioeconomic, nutritional, and food loss and waste data

The core data input for the development of the modelling framework is a Global Trade Analysis Project (GTAP) Power Data Base.[21,22] GTAP is a global dataset that describes bilateral trade patterns and production, consumption, and intermediate use of commodities and services in countries and regions globally. The tenth release of the GTAP Data Base, used in this study, has multiple reference years (with 2014 being the most recent), covers 141 regions, and disaggregates economies in each region into 76 activities. Agricultural and food activities in the database are represented by 20 sectors, including 12 primary agricultural sectors and eight food-processing sectors.[21] The database reports emissions of CO_2,[23] non-CO_2 greenhouse gases (GHGs),[24] and other air pollutants.[25]

To incorporate nutritional accounts within the developed modelling framework, we relied on the method introduced by Chepeliev.[26] The approach builds on data and nutritive factors from the Food and Agricultural Organization of the UN (FAO) food balance sheets to estimate the nutritional content of primary commodities and derived commodities (which are represented in terms of their primary commodity equivalents in the food balance sheets). Calories, fats, proteins, and carbohydrates were estimated and reported and use categories that accounted for food, feed, seed, losses, and other uses were identified. Food supply was distinguished across GTAP primary commodity sectors, food processing sectors, and service sectors that supply food (eg, restaurants).

See Online for appendix

Food loss and waste were incorporated following the methodology developed by Gatto and Chepeliev,[10] and further refined by calibrating shares of food loss and waste with net food intakes at the country level (appendix p 14). By considering food products in their entirety (ie, both edible and non-edible parts) and excluding non-food biomass flows (ie, feed, seed, and biomass used for industrial purposes) from food loss and waste, this approach overcomes broadly debated methodological inconsistencies of available food loss and waste estimates[8] from FAO,[27] which are subject to a number of data and methodological limitations.[28,29] We defined five stages of food supply chains to quantify food loss and waste: agricultural production; post-harvest handling and storage; manufacturing; distribution and retail; and consumption. At the global level, our data collection covered eight commodity groups, including cereal crops, horticulture, and animal-sourced foods. Incorporation of food loss and waste tracing into the analytical framework allowed us to estimate both food supply and net intakes at the level of final consumers.

Global economic model

To quantify changes in food loss and waste flows along food supply chains when transitioning to healthier and more sustainable diets, we used the global computable GE (CGE) model ENVISAGE[30]—an advanced recursive dynamic variant of the well known GTAP model.[31]

CGE models represent the whole economy as a system of interconnected markets and agents, solving a set of equations that describe supply, demand, and market-clearing conditions. Such models capture price-induced interdependencies across sectors, considering both direct and indirect effects of policy changes. By incorporating endogenous price adjustments, income effects, and substitution between inputs, CGE models allow for the analysis of economy-wide rebound effects (eg, a carbon tax leading to increased consumption in other sectors due to price changes) and spillover effects (eg, agricultural policy changes affecting trade and manufacturing) in response to exogenous shocks, such as dietary transitions or food loss and waste reduction. A key assumption in CGE models is full market clearing whereby all prices adjust to equate supply and demand across all sectors, capturing the macroeconomic feedback mechanisms that influence economic behavior and reflecting neoclassical economic theoretical assumptions such as perfect competition, rational behaviour of agents, profit–utility maximisation, and the equalisation of marginal costs and benefits across sectors.

We ran ENVISAGE tailored to tracing biomass flows, maintaining sectoral details for food and non-food biomass activities to capture their responses to changing biomass flows in detail, and capturing food loss and waste changes when diets shifted. Additional details on the developed modelling framework are provided in the appendix (p 2). For the analysis, a specific sectoral and regional aggregation was developed (appendix p 9). A detailed documentation of the applied modelling framework is available in van der Mensbrugghe.[30]

Healthier and more sustainable diets and food loss and waste reduction scenarios

We used ENVISAGE to investigate how standalone food loss and waste reduction targets, dietary transitions, and a combination of both might change global food loss and waste flows by 2050. Our baseline business-as-usual (BaU) scenario follows macroeconomic and demographic projections from a recent update of the SSP database, relying on the middle-of-the-road SSP2 scenario.[19] We compared our baseline pathway to three scenarios in which food loss and waste generation and dietary shifts were differently targeted. In the BaU_half_FLW scenario, we maintain BaU assumptions, additionally introducing a gradual 50% reduction in food loss and waste achieved by 2050. In the EAT-Lancet scenario, final consumer demand was adjusted to meet the EAT–*Lancet* dietary recommendations in accordance with EAT–*Lancet* targets. The assumptions adopted in this scenario fully reflect those underlying the main dietary scenario in the forthcoming EAT–*Lancet* Commission 2.0 report, allowing for the assessment of dietary trends and changes in food loss and waste within a comprehensive socioeconomic framework. For this assessment, our EAT-Lancet scenario incorporated enhanced agricultural productivity (compared with the BaU case) and mitigation policies consistent with 1·5 °C. In the EAT-Lancet_half_FLW scenario, food loss and waste reduction targets and global dietary shifts based on EAT–*Lancet* targets were simultaneously implemented towards 2050. In each scenario, we assessed how food loss and waste targets and dietary changes redirected food flows, changing food loss and waste magnitude, composition, and location. Further details on scenario definition are available in the appendix (p 18).

Role of the funding source

There was no funding source for this study.

Results

In our BaU scenario, rising food consumption by 2030 was projected to lead to a 13·1% increase in food loss and waste by 2030 (an increase of 306 million tons over the 2014–30 period), further increasing to 52·0% by 2050 (reaching 3·26 billion tons; an increase of 619 million tons over the 2030–50 period) compared with 2014 levels (figure 1). Across high-income and middle-income regions, a projected rise in the consumption of animal-based products resulted in a decrease in food loss and waste per unit of gross food consumption (figure 2A), limiting the total increase in food loss and waste generation. This trend was reverted in sub-Saharan Africa, where higher income and

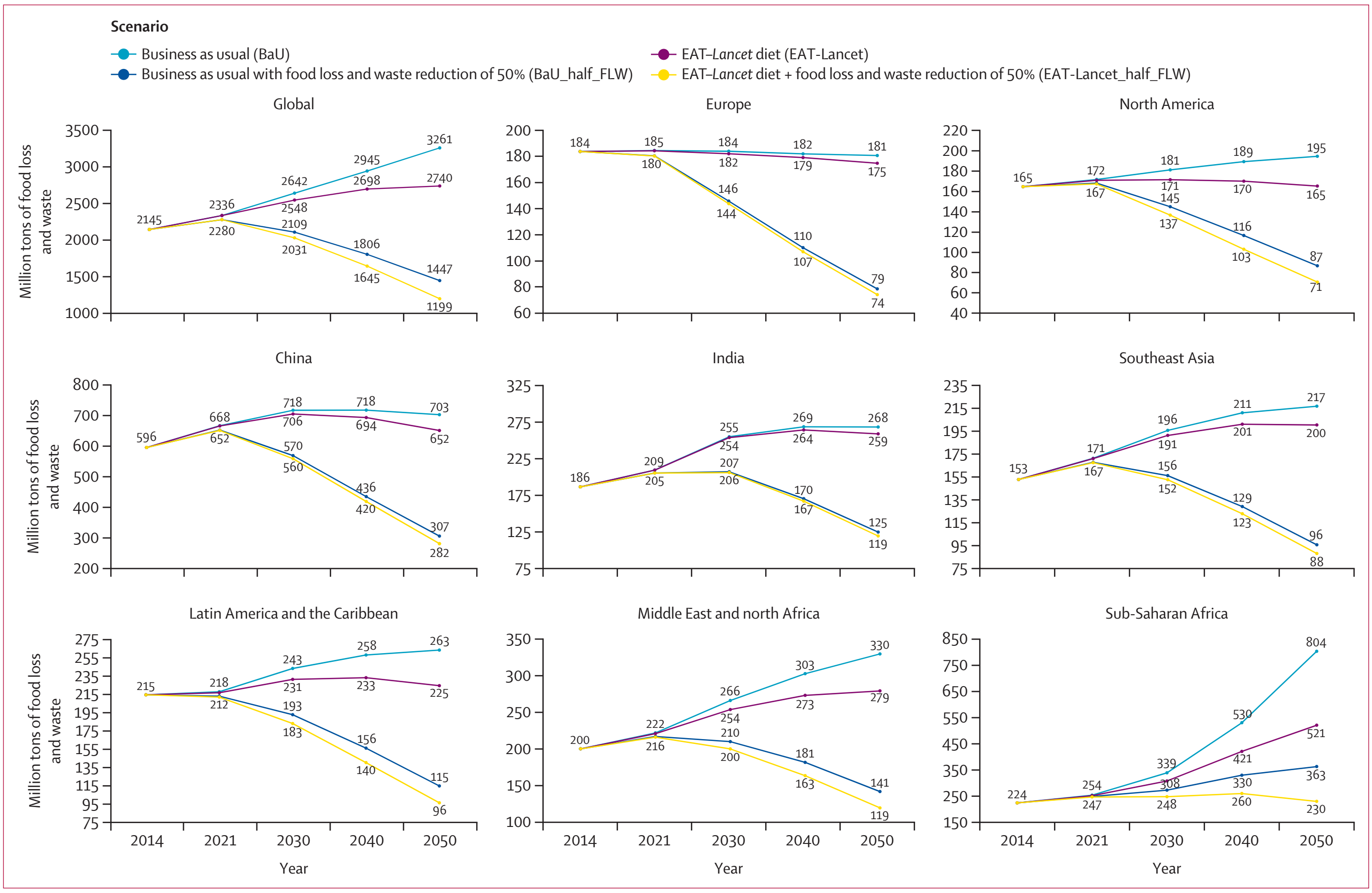


Figure 1: **Trends of food loss and waste (in million tons) by scenario and region, across the investigated years**

Panels illustrate the trajectory of food loss and waste generation (millions of tons) on a global level and in different regions in the investigated policy scenarios and across the analysed timeframe from 2014 to 2050. The scale of the y-axis varies between the illustrated panels to reflect differences in the magnitude of food loss and waste generation. The composition of each macroregion is available in the appendix (p 9).

population growth resulted in increasing food consumption across all commodities (including food loss and waste-intensive, plant-based products), driving both food loss and waste per unit of gross food consumption and total food loss and waste (figure 2A). In low-income regions, but especially in sub-Saharan Africa, food loss and waste was shown to surge by 217% (ie, 547 million tons) by 2050, adding 340 calories per capita per day to lost and wasted food.

Halving global food loss and waste (ie, in the BaU_half_FLW scenario) boosts food availability, lowers prices, and curbs food loss and waste, especially for plant-based foods. By 2050, global food loss and waste was projected to drop by 55·6% (a decrease of 1·81 billion tons compared with the BaU scenario), with the most notable relative reductions occurring in Europe and in the Middle East and north Africa (an average decrease of 55·4%; figure 1). The largest absolute reductions were projected to occur in south Asia, particularly in China, where food loss and waste decreased by 128 million tons (20·2%) in 2030 and 348 million tons (55·3%) in 2050.

In sub-Saharan Africa, rapid population growth and increased per-capita gross domestic product drove food loss even when standalone food loss and waste reduction targets are applied, resulting in an increase of 61·8% from 2014 to 2050 (figure 1).

Implementation of the EAT–*Lancet* dietary targets (ie, the EAT-Lancet scenario) was shown to decrease average food intakes, reducing global food loss and waste by 3·5% (94 million tons) by 2030 and 15·9% (521 million tons) by 2050 (figure 1). Impacts were more pronounced in high-income and upper-middle-income countries, where transitioning to a healthier diet led to a growing demand for plant-based foods associated with a higher intensity of food loss and waste (figure 2C; red); however, this trend was overcompensated by an overall reduction in food demand, as net caloric intakes declined (figure 2C; green). In addition, changing patterns of trade were shown to result in the outsourcing of plant-based food production to low-income regions, such as those in Africa and southeast Asia, where these traded foods were increasingly produced by 2050 (figure 1B; figure 3). Across regions, spillovers arose in sub-Saharan Africa and the Middle East and north Africa, where dietary shifts led to increasing trends of food loss and waste (25·1% by 2050). In the case of sub-Saharan Africa,

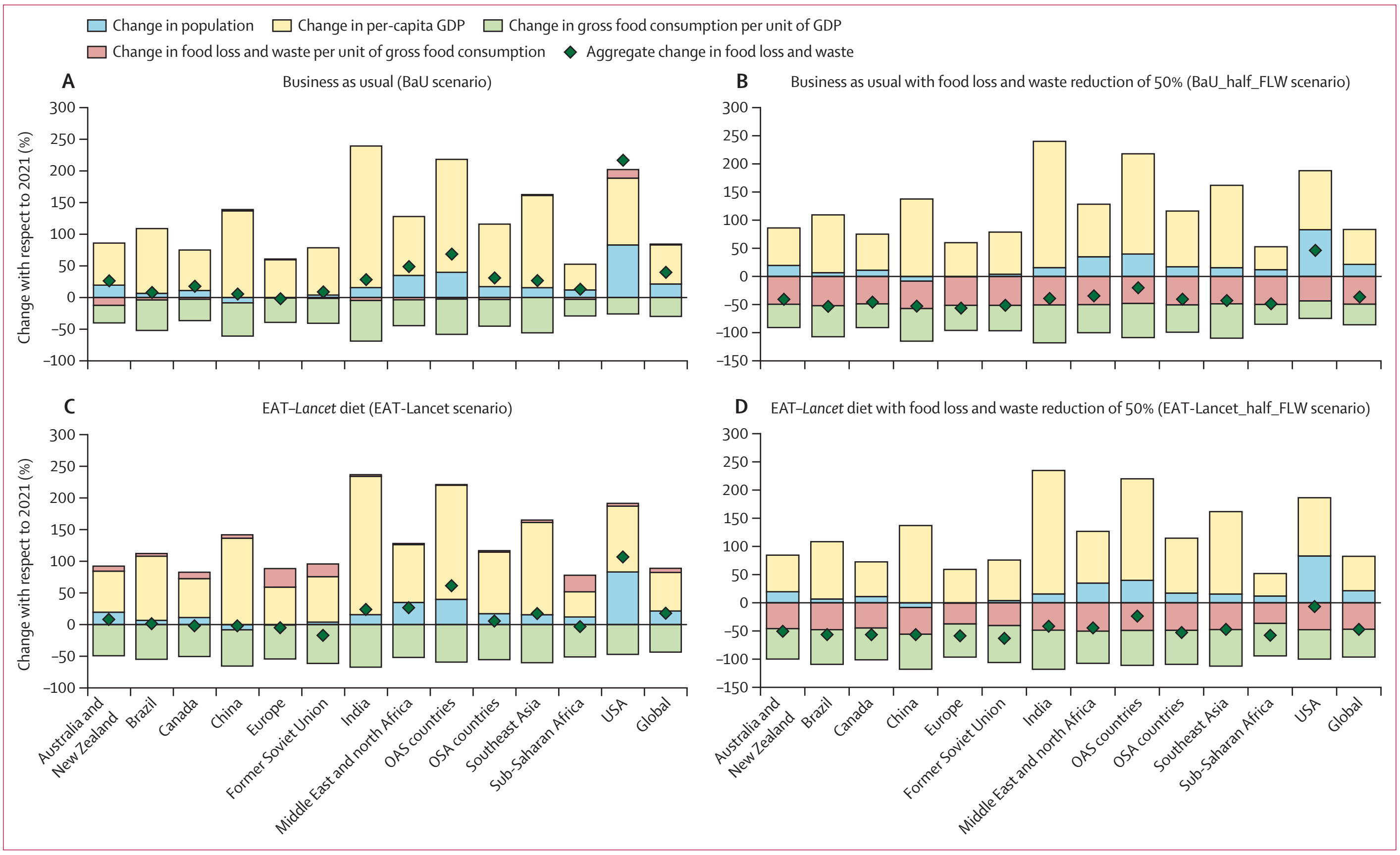


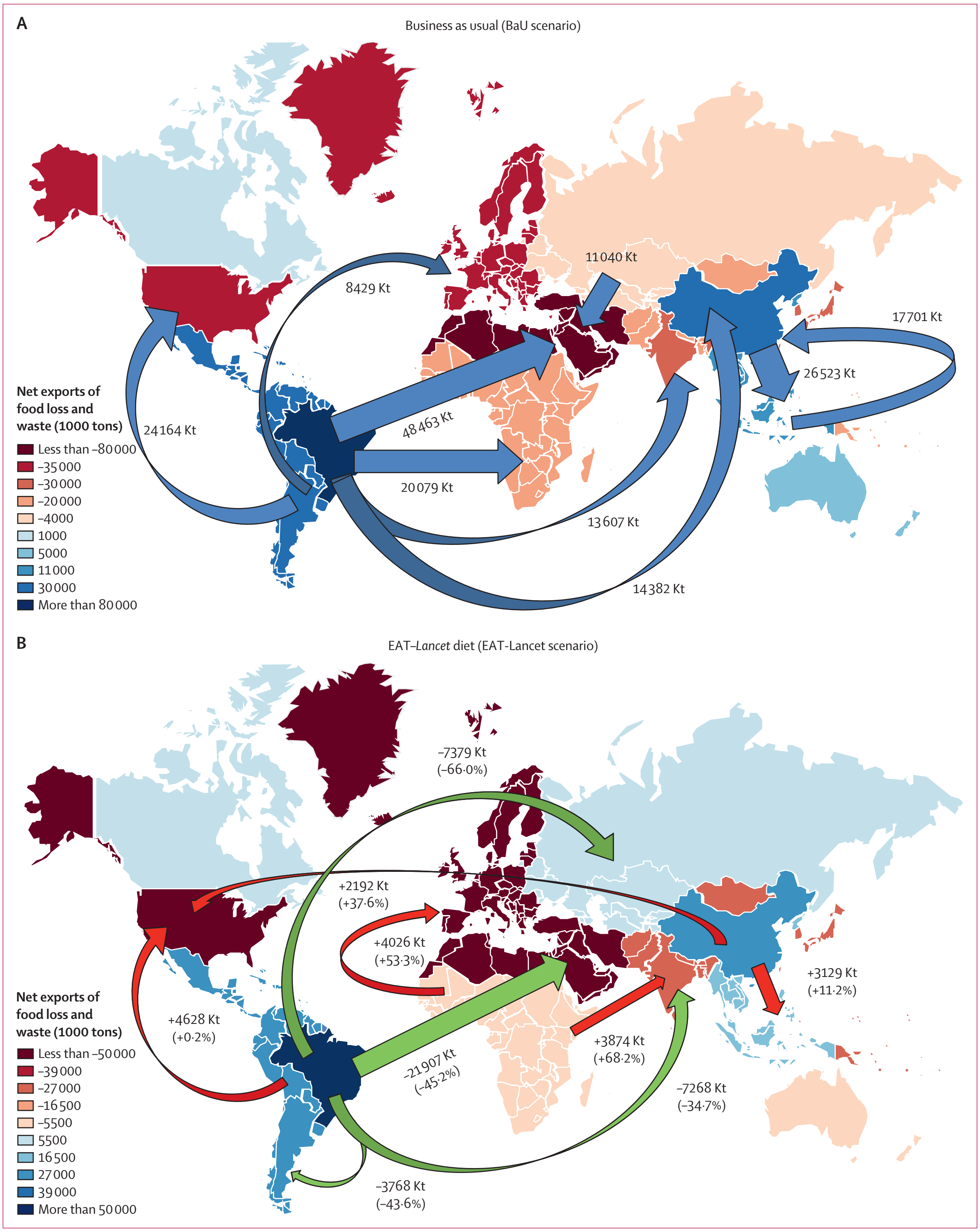
Figure 2: **Kaya identity values for changes in food loss and waste from 2021 to 2050 across the investigated scenarios**

Kaya identity[32] values illustrating percentage changes in food loss and waste from 2021 to 2050 by region and globally across scenarios based on changes in the main drivers of food loss and waste generation. (A) Changes under business-as-usual (ie, in the BaU scenario). (B) Changes in the BaU_half_FLW scenario, in which a food loss and waste reduction target of 50% is implemented. (C) Changes in the EAT-Lancet scenario, in which dietary shifts are implemented but no food loss and waste reduction targets are applied. (D) Changes in the EAT-Lancet_half_FLW scenario, in which dietary targets and food loss and waste reduction targets are simultaneously implemented. The choice of variables in the Kaya identity is based on a direct comparison with the variables often used in the literature to perform Kaya decompositions of changes in energy-related emissions.[33–35] Although changes in population and changes in per-capita GDP were kept the same, variables such as carbon intensity and energy intensity were readapted to our specific study case in the form of food loss and waste intensity (ie, food loss and waste generated per unit of food consumed) and food intensity (ie, changes in gross food consumption per unit of GDP). A similar approach was used in Gatto and Chepeliev.[10] GDP=gross domestic product. OAS=Organisation of American States. OSA=Japan's Official Security Assistance programme.

the rise in plant-based foods exports, coupled with a higher per-capita food consumption linked to dietary shifts, drove a substantial increase in food loss and waste, augmenting by 132·2% or 297 million tons under the EAT-Lancet scenario by 2050.

The EAT-Lancet_half_FLW scenario, combining dietary shifts with food loss and waste reduction goals, was projected to lead to the strongest decrease in global food loss and waste compared with standalone approaches, cutting global food loss and waste by 23·1% (611 million tons compared with the BaU scenario) in 2030 and by 63·2% (2·07 billion tons compared with the BaU scenario) in 2050. Lower food demand and calorie intakes imposed by the diet were projected to decrease global food loss and waste in comparison with the BaU_half_FLW scenario (a decrease of 17·1% or 248 million tons in 2050), in which food intake increased based on BaU food demand trends. Similarly, with respect to the EAT-Lancet scenario, the imposition of food loss and waste reduction targets had the most severe effect, reducing global food loss and waste by 20·3% (or 517 million tons) by 2030 and by 56·2% (or 1·54 billion tons) by 2050 (figure 1). Major absolute reductions were observed in sub-Saharan Africa and China, where, despite the rise in export-embedded food loss and waste linked to the dietary shift (figure 3B), reduction targets resulted in food loss and waste magnitudes that had decreased by 70·1% (574 million tons; sub-Saharan Africa) and 59·8% (421 million tons; China) in 2050. Calorie losses also declined at the global level (an average of 354 calories per capita per day), with peaks observed in sub-Saharan Africa (an average of 365 calories per capita per day) and the Middle East and north Africa (an average of 407 calories per capita per day).

Rising global consumption of processed foods in the BaU scenario, especially in high-income and upper-middle-income regions, was shown to drive higher levels of food loss and waste (figure 4), particularly from fruits, vegetables, and nuts (an increase of 41·4% or 750 million tons), sugar beet or sugarcane (an increase of 29·8% or 163 million tons), and meat (an increase of 32·0% or 78 million tons). In lower-middle-income and low-income regions, food loss and waste mainly consisted of crops (30·1%) and fruits and vegetables (28·5%), although shares of animal-sourced



(Figure 3 continues on next page)

foods grew to 18·2%, as production-level losses from animal products and cereals increased by 41·6% and 23·2%, respectively, reflecting higher demand for animal-sourced foods as incomes rose.

Although introducing food loss and waste reduction targets (ie, in the BaU_half_FLW scenario) led to a roughly equal reduction across commodities (figure 5), in absolute terms, the most notable impact was observed in reducing

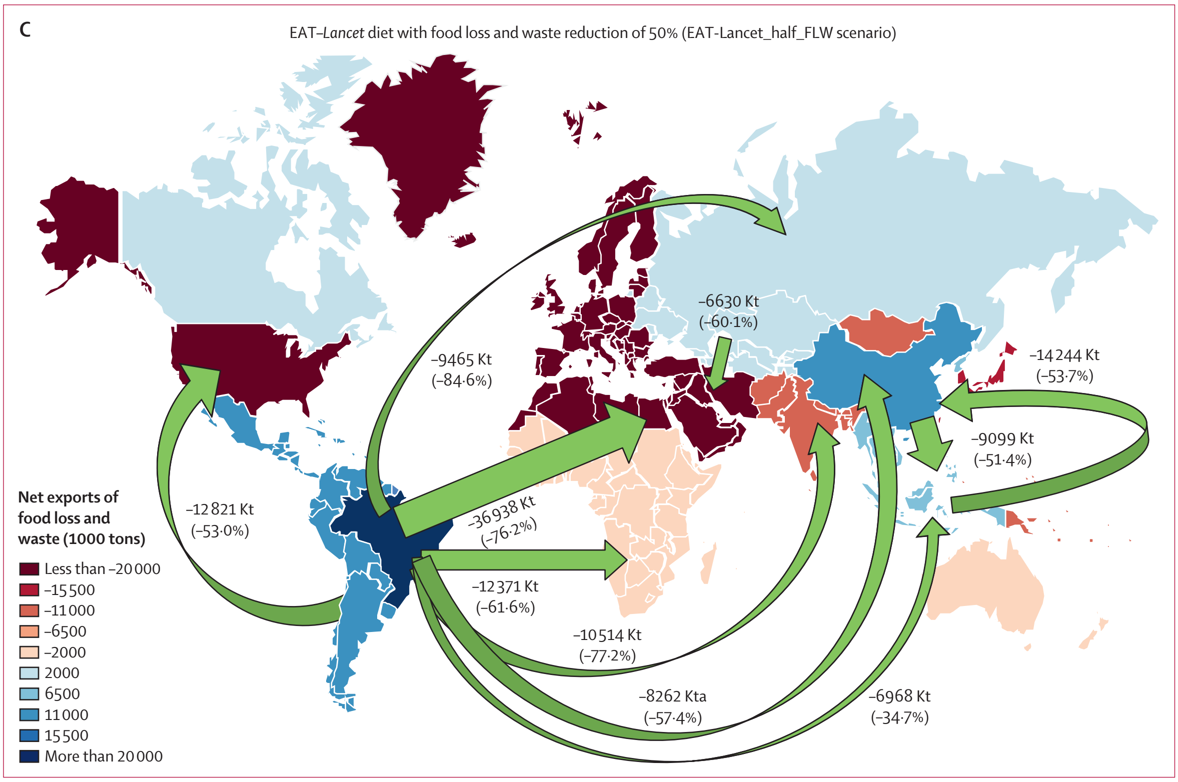


Figure 3: **Net exports of food loss and waste (1000 tons) by macroregion across scenarios in 2050**
Major flows of trade-embedded food loss and waste (1000 tons and percentage change with respect to the business-as-usual scenario [ie, the BaU scenario] in 2050) and food loss and waste-related trade balances (ie, exports of food loss and waste minus imports of food loss and waste) across global regions. The arrows illustrate the direction of the net food loss and waste flows linked to different scenarios in 2050. An arrow from region A to region B indicates that region A is a net exporter of food, and hence of food loss and waste, to country B. For illustrative purposes, the size of the arrows does not necessarily reflect the magnitude of flows. Please note that magnitudes (1000 tons [Kt]) or percentage changes are reported next to each arrow. (A) Quantities of net exports of food loss and waste in the BaU scenario in 2050. The blue colour of the arrows indicates the quantity of food loss and waste flows across different regions. (B) Changes of quantities of net exports of food loss and waste in the EAT-Lancet scenario with respect to the BaU scenario in 2050. (C) Changes of quantities of net exports of food loss and waste in the EAT-Lancet_half_FLW scenario with respect to the BaU scenario in 2050. The different colours of the arrows indicate changes with respect to the flows observed in the baseline BaU scenario in 2050. Red arrows indicate an increase of food loss and waste flows, whereas green arrows indicate a decrease in food loss and waste. Additional figures are available in the appendix (p 18).

food loss and waste from plant-based products, which typically present the highest rates of food loss and waste and account for the largest share of global food loss and waste.[10] Lost and discarded foods from fruits, vegetables, and nuts decreased by 55·9% (or 1022 million tons) in 2050, followed by food loss and waste from cereals and grains, which decreased by 54·2% (or 207 million tons) by 2050 (figure 4). Major reductions in food loss and waste from fruits, vegetables, and nuts were observed in sub-Saharan Africa (a reduction of 342 million tons), China (a reduction of 291 million tons), and MENA (a reduction of 94 million tons), with plant-based calorie losses decreasing by an average of 440 calories per capita per day across these regions. Losses of animal-based products globally decreased by 53·1% (177 million tons) in 2050, primarily in high-income regions, such as north America (a reduction of 36·9% or 32·5 million tons) and Europe (a reduction of 50·0% or 24·6 million tons).

The EAT-Lancet scenario was projected to increase shares of fruit and vegetables and cereals within global food loss and waste, reducing shares of sugarcane and animal-sourced foods while lowering the average loss of calories embedded in global food loss and waste (a reduction of 124 calories per capita per day).

A standalone dietary shift was projected to increase global food loss and waste from fruits, vegetables, and nuts by 2050 compared with previous years (figure 4), leading to a smaller decrease in plant-based food loss and waste than in the BaU_half_FLW scenario in 2050 (average decrease of 37·3% in the EAT-Lancet scenario; figure 5). Additionally, with respect to BaU in 2050, increasing trends of food loss and waste were observed for oilseeds (56·1% increase), other crops (3·4% increase), and fish (9·3% increase), surpassing BaU levels (cumulative increase of 59 million tons or 31·0%) and resulting in the highest food loss and waste generation for these products across all scenarios by 2050 (figures 4, 5). Modest increases in food loss and waste were also observed for fruits, vegetables, and nuts in Europe (21·8% increase or 18·2 million tons) and for wheat, which increased primarily in Europe

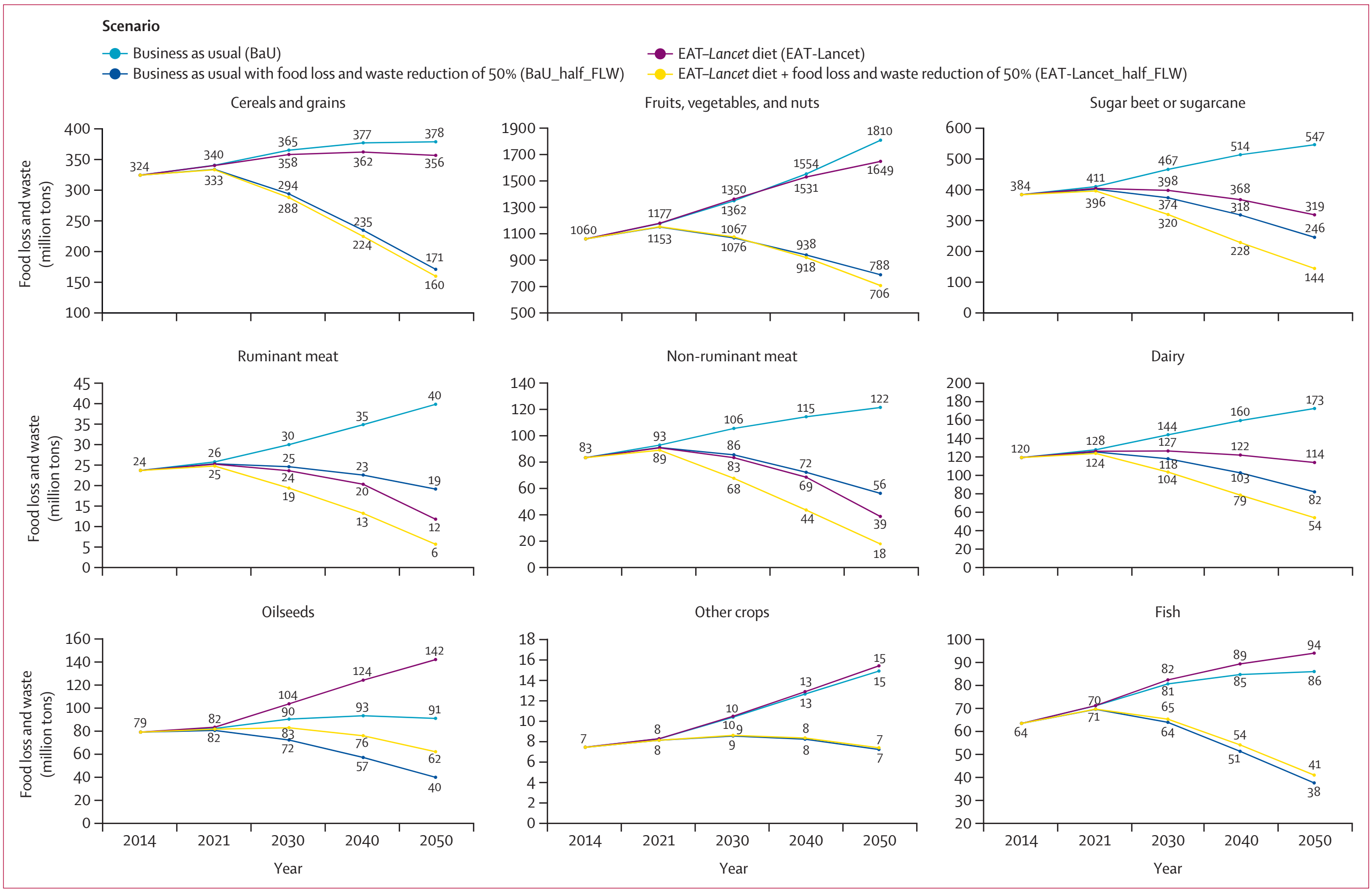


Figure 4: **Trends of food loss and waste (million tons) by scenario and commodity, across the investigated years**
Panels illustrate the trajectory of food loss and waste (millions of tons) globally generated by the production and consumption of different food commodities, in the investigated policy scenarios and across the analysed timeframe from 2014 to 2050. The composition of each commodity macrocategory is available in the appendix (p 9).

and north America by 20·4% (an average 7 million tons). In contrast, dietary targets primarily reduced food loss and waste from meat (a decrease of 69·3% or 112 million tons by 2050), and from sugarcane or sugar beet (a decrease of 41·7% or 228 million tons by 2050), primarily in South America (which showed a decrease of 60·1 million tons) and southeast Asia (including China, which saw a decrease of 45·1 million tons of food loss and waste from non-ruminant meat).

Combining EAT–*Lancet* dietary targets with food loss and waste reduction goals (ie, in the EAT-Lancet_half_FLW scenario) decreased food loss and waste from cereals and grains (by 57·6% or 218 million tons) and fruits, vegetables, and nuts (by 60·9% or 1104 million tons) by 2050, reversing the trend of rising plant-based food loss and waste seen in the EAT-Lancet scenario (figures 4, 5). Animal-based food loss and waste decreased sharply by 89·6% (or 161 million tons), whereas food loss and waste from fish and oilseeds also declined, although less than in the BaU_half_FLW scenario due to increased consumption of these products when diets shift (figure 5).

Evolving trends in food demand and global trade were shown to substantially influence the location of food loss and waste across supply chain stages. By 2050, increasing food demand in the BaU scenario drives farm-level losses at the agricultural production and post-harvest handling and storage stages, particularly from plant-based foods in low-income regions (a 60·2% increase on average), reaching 1·8 billion tons globally (around 56·3% of total food loss and waste). Consumer-level food waste increases by 40·1% globally, reaching 0·7 billion tons, with high-income regions and upper-middle-income regions responsible for nearly 80% of this waste (figure 6). Export-related losses increased in Brazil and South America reaching 415 million tons by 2050, as increasing imports primarily from North America, Europe, and the Middle East and north Africa drove losses for sugar beet or sugarcane and fruits, vegetables, and nuts at the farm-level stages of the supply chain (figure 3A).

Introducing food loss and waste reduction targets (ie, in the BaU_half_waste scenario) primarily decreased losses at the agricultural production and post-harvest stages, with a total decrease of 57·7% (1·06 billion tons) with respect to BaU in 2050 (figure 6). This decrease mainly benefits lower-income regions where the majority of farm-level losses are located. Halving global food loss and waste primarily

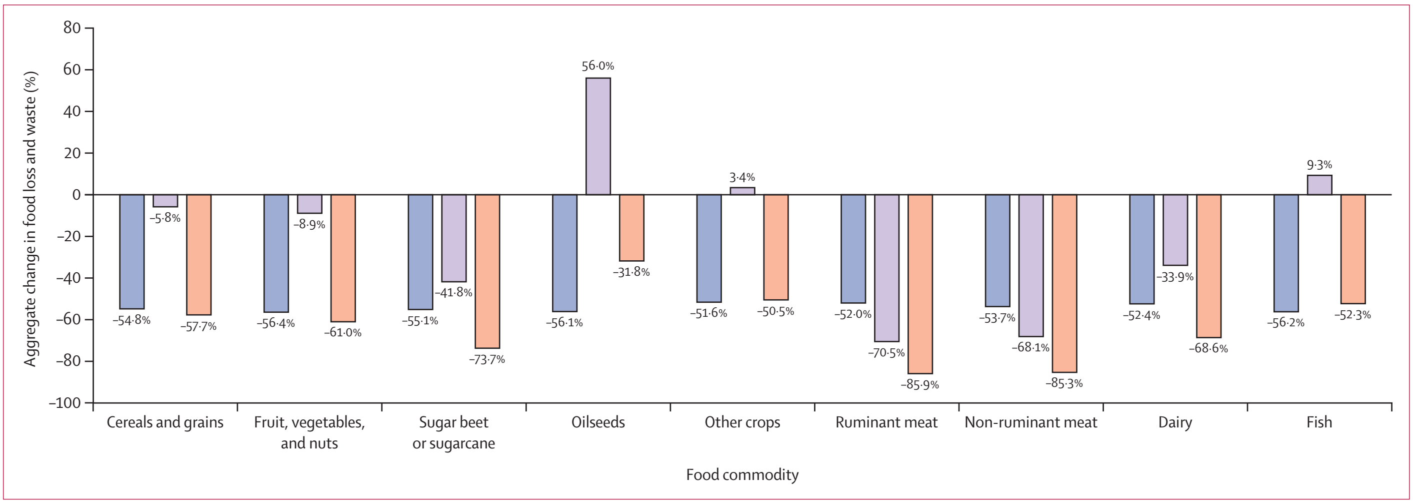


Figure 5: **Change in food loss and waste (%) with respect to business as usual in 2050 across food commodities and scenarios**
Bars in the graph illustrate the aggregate change in food loss and waste generated by the production and consumption of food commodities at a global level across investigated scenarios with respect to the baseline business-as-usual scenario (ie, the BaU scenario) in 2050. Blue bars represent BaU plus 50% reduction in food loss and waste, purple bars represent the EAT-Lancet scenario, and orange bars represent the EAT-Lancet_half_FLW scenario.

reduced trade-related losses in regions exporting large volumes of horticultural commodities such as east Asia and Latin America. Export-related losses in these regions decreased by an average of 55·1%, particularly for fruits, vegetables, and nuts in east Asia (including in China, which saw a decrease of 119·8 million tons) and sugar beet or sugarcane in Latin America (which saw a decrease of 80·1 million tons). Both of these losses were largely driven by import demand from North America, Europe, and the Middle East and north Africa in 2050 (appendix p 21).

In the EAT-Lancet scenario, a dietary shift towards plant-based products relocated food loss and waste from manufacturing to post-harvest handling and storage, as processed food consumption declined and demand for fresh produce increased.

In lower-middle-income and low-income regions, although food losses at the farm-level decreased by 26·5% (or 222 million tons; figure 6), such stages remained a global hotspot for food loss and waste in 2050. Middle-income regions saw a 12·8% reduction (of 58 million tons) in post-harvest handling and storage losses due to lower food production and exports, whereas high-income regions experienced a moderate 2·4% increase in farm-level losses (primarily from fruits, vegetables, and nuts), reducing food waste at the distribution and retail and consumption stages (average decrease of 40·2% or 52 million tons; figure 6).

Lower global intakes of sugars severely reduced exports-embedded losses from sugar beet or sugarcane in Brazil and Latin America by 58·9 million tons, primarily embedded in exports towards the Middle East (20·9 million-ton decrease), former Soviet Union countries (7·1 million-ton decrease), and India (7·6 million-ton decrease; figure 3B). However, higher demand for fruits, vegetables, nuts, and oilseeds increased trade-related losses at the early stages of the food supply chains (51·1 million tons), with stronger effects in sub-Saharan Africa (an increase of 55·0% or 13·7 million tons), China (an increase of 6·5% or 5·1 million tons), and southeast Asia (an increase of 7·3% or 4·5 million tons). In these regions, rising losses were driven by rising imports from India (an increase of 5·3 million tons), Europe (an increase of 4·0 million tons), and the USA (an increase of 1·4 million tons), with US imports also increasing horticultural losses in Latin America (by 9·1 million tons).

Combining food loss and waste reduction targets with the EAT–*Lancet* dietary shift (ie, in the EAT-Lancet_half_FLW scenario) tempered the reallocation of food loss and waste to early supply chain stages, as halving food loss and waste by 2050 offset the relocation effects of food loss and waste driven by the dietary transition. The strongest reductions in food loss and waste were observed for farm-level losses (with a decrease of 65·5% or 1·2 billion tons), particularly in lower-middle-income and low-income regions where losses decreased by 68·8% (569 million tons) compared with the BaU scenario, an additional reduction of 347 million tons (or 57·3%) compared with the standalone EAT-Lancet scenario (figure 6). Reductions in food loss and waste were additionally observed at the distribution and retail and consumption stages, particularly for animal-based food loss and waste (a reduction of 77·9% or 155 million tons).

Reducing food loss and waste within the global dietary transition (ie, in the EAT-Lancet_half_FLW scenario) led to the most substantial reduction in trade-embedded food loss and waste, decreasing by 59·7% (or 306·7 million tons) by 2050 (figure 3C).

The food loss and waste reduction target outweighed the increase in trade-embedded plant-based losses observed under the standalone dietary shift, decreasing the amount of

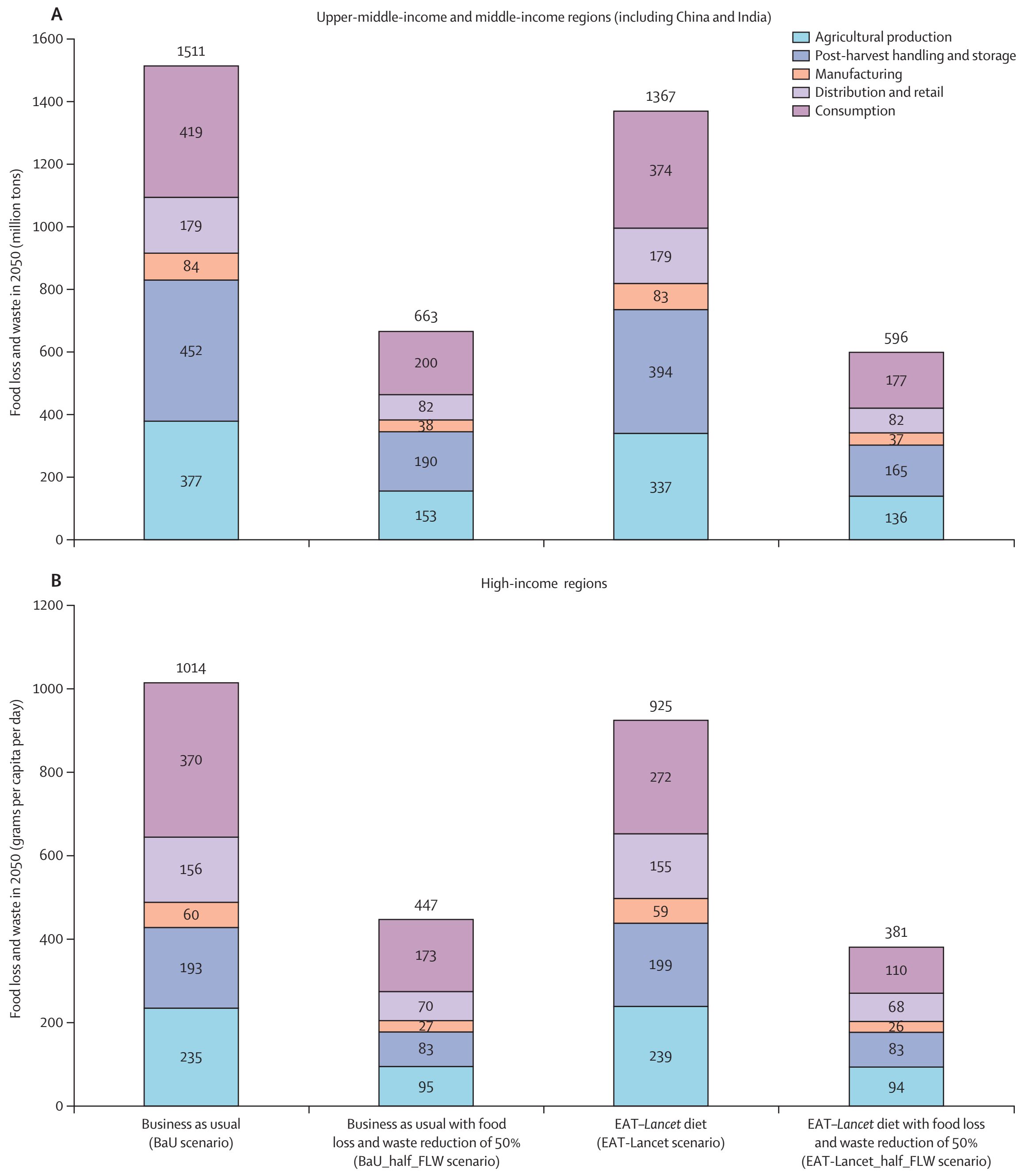


Figure 6: **Food loss and waste volumes across stages of global food supply chains by region and income level across the investigated scenarios in 2050**
(A) Total magnitudes of food loss and waste (million tons) across stages of global supply chains. (B) Magnitudes of food loss and waste generated per capita per day across stages of global supply chains.

trade-embedded losses across all commodities by 2050. Notably, losses from sugar beet or sugarcane exports dropped substantially in Brazil (by 72·1% or 101·1 million tons), driven by lower import-embedded losses in the Middle East and north Africa (which decreased by 36·9 million tons), India (which decreased by 10·1 million tons), and sub-Saharan Africa (which decreased by 11·9 million tons). Export-embedded losses also declined for cereals (a 39·9 million-ton reduction) and oilseeds (a 14·3 million-ton reduction), especially in Europe (which saw a 5·5 million-ton reduction) and former Soviet Union countries (which saw an 8·5 million-ton reduction), due to reduced import-embedded losses from the Middle East and north Africa (a 15·3 million-ton reduction).

Discussion

This study bridges the economic and technical modelling of food loss and waste by adding consistent tracing of food loss and waste in physical quantities along global food supply chains within an economy-wide modelling framework. This is the first study that explores interactions between food loss and waste reduction measures and a global EAT–*Lancet* dietary transition by 2050, relying on the newest set of macroeconomic and demographic projections.[19] Our findings suggest that with the continuation of historical trends, food loss and waste along global supply chains is expected to reach 3·26 billion tons by 2050, a 52·0% increase compared with 2014. Adopting healthier and more sustainable diets could reduce food loss and waste by 15·9% by 2050 compared with a scenario in which food consumption follows historical trends. This benefit adds to the several gains dietary transitions exert on GHG emissions, land use, and water use,[7,36] further reducing the environmental impact of global food systems. However, although plant-based diets are substantially more efficient than animal-based diets in terms of their environmental impact per ton of food produced, they are generally more intensive in terms of food loss and waste (appendix p 20). For this reason, although dietary shifts led to a reduction in the magnitude of food loss and waste, they are not sufficient to reverse the overall projected increase in food loss and waste by 2050 compared with 2014 levels. Across regions, spillovers arise in sub-Saharan Africa and the Middle-East and north Africa, where dietary shifts led to increasing trends of food loss and waste (25·1% by 2050). Particularly in sub-Saharan Africa, the sharp rise in population and per-capita GDP projected by 2050 is expected to increase food loss and waste volumes, even with standalone food loss and waste reduction targets.

Combining dietary shift with food loss and waste reduction targets globally reduces food loss and waste by 63·2%. Bending the curve of food loss and waste generation requires an integrated strategy combining healthy diets with food loss and waste reductions to effectively reduce spillovers at the global level. Spillover effects (ie, higher levels of food loss and waste) are also observed across food commodities. Food loss and waste from oilseeds, other crops, and fish surpass baseline (BaU) levels (by 59 million tons), leading to the highest food loss and waste generation for these products by 2050. As food loss and waste trends for these commodities decline when food loss and waste reduction targets are implemented, coupling dietary shifts with food loss and waste reduction targets could effectively contain commodity-specific spillovers in 2050. Furthermore, spillovers across supply chain stages were found in the increasing amount of food losses generated during agricultural production and post-harvest handling and storage in high-income countries. The shift towards healthier diets drives demand for fresh plant-based foods, which are associated with high levels of food loss and waste, and results in increasing levels of loss at production stages. As such spillover can be tackled when dietary shifts are combined with food loss and waste reduction targets, stage-specific interventions are necessary to increase the effectiveness of dietary transitions in higher-income regions.

Although demographic trends and increasing wealth play a key role in domestic food loss and waste generation (figure 2), we found that additional pressures are generated by changes in global trade. As seen in figure 3, higher exports of plant-based products from sub-Saharan Africa and Latin America towards Europe, the USA, and India increase food loss and waste at the farm level, hampering the reduction pattern induced by the diet change. This finding confirms the trade-related spillovers on food loss and waste locations under a global dietary shift observed by Gatto and colleagues[9], expanding the analysis to 2050. To fully address the spillover effects of food loss and waste caused by the adoption of healthy diets, pairing a global dietary shift with targeted policies to reduce food loss and waste will be essential. Halving food loss and waste yields substantial benefits, especially in low-income regions, where most plant-based food losses occur during production. Our findings show that these spillover effects are eliminated when food loss and waste reduction targets are implemented alongside dietary shifts. The largest reductions in food loss and waste were seen in China and sub-Saharan Africa, with sub-Saharan Africa gaining the most (nutritional availability increased by 365 calories per capita per day), helping to combat malnutrition by 2050.

Contextualising our results within the framework of the SDGs, we find that combining healthier diets with food loss and waste reduction is essential for increasing nutritional availability in low-income regions, supporting progress toward global zero hunger (SDG 2). However, under standalone dietary changes, high-income countries still contribute to substantial food loss and waste in low-income regions (where the potential for food and waste reuse is low) through imports. Because trade-embedded food loss and waste is not captured by SDG 12.3, high-income countries can more easily meet this target, whereas low-income regions will struggle to do so.

Our results highlight several important policy implications. First, we found that under the current set of food-related policies in countries around the world, consumers and producers do not have sufficient incentives to change their behavioural patterns to reduce food loss and waste. Achieving the stated SDG 12.3 target of halving food loss and waste by 2030 (and even beyond this target) would require drastic changes in production practices and consumption choices addressing both supply-side and demand-side drivers of food loss and waste. Bartelings and Philippidis[37] estimated that halving global food loss and waste by 2050 would cost approximately US$350 billion, or 0·2% of global GDP, with higher relative costs in regions such as sub-Saharan Africa, where the cost could reach 1·1% of GDP. Our results suggest that a 50% reduction in food loss and waste implemented via efficiency improvements (ie, the BaU_half_FLW scenario) results in approximately a 0·2% increase in global GDP in

2050. These estimates represent lower-bound economic gains since they do not account for the health or environmental co-benefits of such action. Accounting for the return-on-investment from food loss and waste reduction interventions, Hanson and Mitchell[38] estimated that global benefits could reach $2103 billion (1·2% of GDP), with sub-Saharan Africa alone seeing $512 billion in returns (7·1% of GDP). These figures highlight the strong economic case for investing in food loss and waste reduction, especially in lower-income regions.

Second, transitioning to healthier and more sustainable diets, although a challenging task by itself, is not sufficient to reduce food loss and waste by 2050. In a number of country–commodity cases, a dietary transition could lead to higher food loss and waste volumes as consumers shift towards plant-based foods with higher food loss and waste shares. In this regard, policies promoting healthier diets must consider the potential spillover effects on food loss and waste. Shifts in food production, consumption, and trade alter the magnitude, location, and composition of food loss and waste. Although dietary shifts can improve nutrition, new technologies and market-based approaches to reuse discarded food and waste—whether linked to domestic consumption or trade—can create economic opportunities and environmental benefits. To maximise these benefits, food loss and waste reduction should be central to discussions on dietary transition policies, as spillover effects risk undermining the positive outcomes of a global dietary shift.

Finally, our results highlight heterogeneity in opportunities for reducing and reusing food loss and waste across countries, commodities, and supply stages. Further exploring these differences is crucial to establishing where food loss and waste-related interventions should be prioritised along food supply chains. From a policy perspective, our findings underline the importance of consumption-based food loss and waste accounting, as a complementary approach to widely used, production-based food loss and waste tracing. As with changing diets, food production is being outsourced from high-income to low-income and middle-income economies. In many cases, optimal food loss and waste-focused interventions could be located in countries different from those in which the final product is consumed.

As with any study, our findings have limitations. Due to the absence of macrolevel temporal data, the food loss and waste shares used to estimate food loss and waste flow magnitudes were assumed to remain constant over time, overlooking potential fluctuations in food loss and waste shares, which are nonetheless expected to be minimal on average.[39] Further testing and verifying of the hypothesis of (broadly) constant food loss and waste shares over time would be an important extension of the current analysis. As our definition of food loss and waste aligns with SDG 12.3,[11] we do not account for the impact of dietary shifts on crop losses associated with the production of feed biomass or any other uses outside of the food supply chain (eg, industrial uses). In the scenarios with a 50% reduction in food loss and waste, the projected reduction in food loss and waste assumes technological improvements leading to higher efficiency without accounting for implementation costs. Although this approach risks overlooking price reactions to implementation costs, it is largely driven by the scarcity of data on food loss and waste trends under different technologies and their associated costs. In this respect, we overlook potential stage-specific food loss and waste reduction strategies. For example, promoting reuse at the farm level while tackling reduction at food distribution and consumption stages could have stronger benefits in reducing the size of spillovers. In addition, the high level of sectoral aggregation, driven by food loss and waste data limitations, prevents a precise alignment of the EAT–*Lancet* diet's commodity-specific recommendations with our model. This limitation is particularly evident for horticultural commodities, as we group fruits, vegetables, pulses, nuts, roots, and tubers into a single category simplifying the diet's guidance on individual commodities. By focusing on a single global dietary transition, we do not consider potential variations in dietary shifts at national or subnational levels, nor do we account for different diet types when assessing trade-offs with food loss and waste. Finally, our analysis focused specifically on food loss and waste, overlooking other planetary boundaries and broader food system transformations that could offer a more comprehensive view of the environmental impacts of diets, both with and without food loss and waste reduction targets.

A promising area for future research is exploring food loss and waste reductions through market-based mechanisms, such as taxes on reduction, subsidies on reuse, or technology investments, through which reduction policies incur costs. Although food trade contributes to spillovers, trade-related policies to reduce food loss and waste (eg, tariffs) might be less effective than domestic measures, especially during dietary transitions. International trade is often essential to meet nutritional needs when local production falls short, so food loss and waste reduction efforts must align with the need for open trade supporting healthy diets. Building on our findings, future studies could additionally focus on specific regions, commodities, or stages of the supply chain to establish when it is more effective to prioritise food loss and waste reduction over waste reuse. Additionally, although this research could be updated to rely on the more recent GTAP 11 Data Base,[40] our modelling framework could also be enhanced by incorporating the reuse of discarded food and food waste, by-products, and residues as production inputs. This adaptation would allow for the simulation of policies that support the transition to more circular food systems while simultaneously addressing food loss and waste generation and dietary trends. Despite its limitations, this modelling study provides important insights into the synergies and trade-offs between two crucial policy areas for food systems of the future. We outline that food loss and waste plays a key role in global dietary transitions, and advocate for ad-hoc policy packages that are able to simultaneously maximise the benefits of healthier diets and minimise increases in food loss and waste generation, enhancing the sustainability of global food systems in 2050.

Contributors
Both authors conceived and designed the experiments, performed the experiments, accessed and verified the data, analysed the data, contributed materials and analysis tools, and wrote the manuscript. Both authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests
We declare no competing interests.

Data sharing
The detailed documentation of the Global Trade Analysis Project (GTAP) 10 Data Base is available online. The Data Base is publicly available and can be accessed through the GTAP website.

For the **GTAP 10 Data Base documentation** see https://www.gtap.agecon.purdue.edu/databases/v10/v10_doco.aspx

For the **GTAP 10 Data Base** see https://www.gtap.agecon.purdue.edu/default.asp

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