Towards Sustainable Global Food and Biomass Systems: Interactions between Food Loss and Waste reductions, Dietary Shifts, and transitioning to a Circular Bio-based Economy

Alessandro Gatto

Propositions

1. The pricing of animal-sourced food products in high-income countries should embed externalities related to both human health and the environment.
   (this thesis)

2. Sector-specific policies for sustainability should consider potential negative social impacts on food affordability, labor markets and wages.
   (this thesis)

3. Participation costs to international conferences for PhD students should be based on national PhD salaries.

4. Academic job insecurity drives a focus on quantity over quality in scientific publications.

5. International researchers advocating sustainability must “practice what they preach”.

6. Environmental justice will not be achieved if negative impacts on social equity and inclusivity keep being ignored.

7. The Italian brain drain reflects a failure of the ruling class in investing in the potential of the youth.

Propositions belonging to the thesis, entitled

Towards Sustainable Global Food and Biomass Systems: Interactions between Food Loss and Waste reductions, Dietary Shifts, and transitioning to a Circular Biobased Economy

Alessandro Gatto
Wageningen, 12 March 2024

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Alessandro Gatto

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To Edoardo and to all the children in the world.
May tomorrow's world be a better place to play in.

A Edoardo ed a tutti i bambini del mondo.
Possa il mondo di domani essere un luogo migliore in cui giocare.

Acknowledgments

The path to earning a PhD is often likened to a rollercoaster ride, with its rapid changes, highs and lows, and emotional twists and turns. While it certainly felt like an emotional rollercoaster, in hindsight, I would rather remember it as a fairy tale journey. In the classic tradition of fairy tales, there lived a protagonist who, beginning as a humble peasant in a small village, embarked on a series of adventures to reach the castle atop the mountain. It was here that the wizards of knowledge resided, shaping the world of research.

The protagonist, a young and naive Alessandro, embarks on a journey with little knowledge of what lies ahead. Throughout his quest, he will encounter friendly characters who offer wise advice,` helpful tools, and moral support. However, he will face formidable challenges from monstrous and vicious peer reviewers, who place hurdles in his path to success. The journey begins with a mix of emotions—excitement and fear—as the reward is great, but the risk of losing one's mind and body looms ominously.

As our hero ventures forth, the first daunting challenge he encounters is the monstrous and terrifying MAGNET model. Legends and myths about this formidable creature were often recounted by his ancestors, but he never imagined he would one day confront it face to face. Drawing from ancient tales, our character recalls that once the monster is subdued, it can transform into a valuable and loyal ally, greatly easing the journey towards the knowledge castle. This initial challenge could prove fatal, as the character realizes that alone, he stands no chance. Miraculously, two legendary wizards appear before him. "Hans, the Truth-finder" and "Marijke, Mistress of the Codes," two of the most powerful magicians in the universe, arrive to assist. Thousands of models they have tamed and deep knowledge on the required tools to tame the MAGNET legendary creature they provide. With their combined efforts, they equip the character with a unique set of tools essential for success on his journey. These include knowledge, wisdom, strategy, unconditional support, and, above all, love and passion. Things for which our character will never be thankful enough for. Armed with this moral and technical armour, our hero tames the MAGNET creature and together they proceed towards success.

The character embarks on a journey aboard the MAGNET creature, traveling across lands and continents, where they encounter wonderful people who provide our hero with technical and moral tools to face the challenges ahead. In the county of Agricultural Economics and Rural Policy, Grandmaster Justus warmly welcomes our hero, who expresses eternal gratitude to him, as well as to each Grand Duchess: Lisbeth of the Dries, Insa of Thiermann, and Karen of the van der Heides, and each Grand Duke: Koos of the Gardebroeks, Rico of the Ihles, Kutay of the Cingiz, Max of the Kardungsm and Frank, ruler of the Koots. Particularly, our hero expresses love and gratitude to Dusan, Archduke of Schlowakei, whom with the guidance and kindness of an older brother has always advised and led our hero in the right direction. To Esther, Archduchess of Gherkeland, whose friendship, support, and laughs have been determinant in making this journey an easier one to live. And to Jack, Archduke of the Peerlings, whose wise advice and engaging conversations have enriched and grown our hero at three-hundred-sixty degrees around the world of economics. Finally, gratitude is extended to all the little helpers - Frank, Joao, and Stelios, loyal companions of thousand battles, and Ninke, Melody, Mark, Nur, Muyinatu, and Mengshuai. Though they may not yet hold noble titles, their support has been instrumental in aiding our hero on his journey. In particular, special gratitude is extended to the loyal companion, Paoletto the Brave. Fighting side by side with our character each day, Paoletto has provided unwavering support, fostering a friendship that our hero will cherish for many moons to come.

Not far from the county of AEP lies the domain of Wageningen Economic Research, where esteemed expertise is held by ancient families. Our hero expresses eternal gratitude to the MAGNET Team, whose support, welcoming spirit, and boundless energy motivated and inspired our character toward his goal. Deep gratitude is extended to Zuzana, Duchess of Kristkova; Elisa, Duchess of the Bardazzis; Corine, Duchess van de As; David, Duke of the Cuis and the Two Worlds; Jason, Duke of the Levins and ruler of the Koopmans; Saeed, Duke of the Moghayers; Michiel, Duke of the Dijks; Thijs, Ruler of the Langes; Marcos, Colonel of the Dominguez y Viera; and Adam, Duke of the Walkers. Without each of you, the character's journey would not have been the same, and success would not have been assured. Special gratitude is extended to Heleen, Duchess of the Bartelings, whose help and support have always aided our character in his most difficult tasks. Similarly, gratitude is expressed to Duke Willem-Jan, Ruler of Zeist, whose assistance, support, and musical guidance have enriched our character beyond the obscure realm of modeling.

Lastly, in the distant and mythical lands of West Lafayette, concealed within the grand castle of Purdue, another wizard played a pivotal role in ensuring our character's success. Known as "Maksym, Great Runner of Models," he is a combination of outstanding athletic skills and modelling knowledge. His assistance, guidance, friendship, and unwavering support have been indispensable to our character, who expresses boundless gratitude and enduring affection for many centuries to come.

Seated at the research table within the castle, our character, now reflects on how distant he is from his humble beginnings and the person he once was. Nevertheless, deep within his heart, he carries the gratitude for all those who laid the foundations that enabled him to evolve into the person he is today. Deep in his heart resides Lady Sarian, Princess of Madrano, whose unwavering support through every battle and hardship proved instrumental in his ultimate success. Her efforts to maintain her sanity while dealing with the turbo lunacy of our character throughout his journey will be forever immortalized in stories and everyday songs. To her, our character expresses his deepest love – in Madranese, “miao”. Among the creators of our character's core foundations are his brothers from another mother. The ones from the reign of Wageningen, Marco, Luca, Nik, Dimi, Arvi, Ceci, Michele, Edmund, and Mattia, and the ones from the realm of Rome, Ale, Fla’, Maga’, Leo, Fede, Lollo, Matteo, plus Nikky from PG. Each of them represents a share of our character’s person and success, as all of this was only possible thanks to this joint effort. Love and gratitude are extended to his brother Riblo and sister Flori, whose unwavering love and support greatly influenced his attitude and motivation for success. Riblo has always been a source of inspiration to our character, and his advice and encouragements will forever be cherished. Finally, eternal love and gratitude are expressed to Mother and Father Gatto, Paola and Tonino, whose unconditional support, dedication, encouragement, and love shaped our character into the person he is today. To them, he extends his deepest love.

Now seated in the castle atop the mountain, our hero looks back and feels grateful for this remarkable journey. He reflects: "Despite its challenges, knowing its beauty, I would embark on this journey again..."

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Chapter 1

Introduction

1.1 Background

A major societal challenge of the 21st century is how to feed a growing global population in a sustainable and inclusive manner which strengthens resilience to climate change and incorporates concerns for planetary security. This challenge is captured by the global policy commitments of the United Nations Sustainable Development Goals (SDGs) (U.N., 2019) and Paris climate agreement (UNFCCC, 2015). Over the last century humans have been appropriating more biomass than ever before (Haberl et al., 2014; Krausmann et al., 2013). Humans utilise biomass to produce food and feed but also to produce industrial non-food materials (fibre, chemicals) and energy. This production is referred to as the bioeconomy, encompassing the production of renewable biological resources (agriculture, forestry, and fisheries) and their conversion into food, feed, bio-based products (pulp and paper, parts of chemical, biotechnical) and bioenergy (fuels, electricity) (European Commission, 2021a). The bioeconomy contributes to 12% of global gross-domestic-product (GDP) (van Nieuwkoop, 2019) while around 1.23 billion people are employed in the world's agrifood systems (Davis et al, 2023). Current production and consumption trends, however, also exert significant environmental pressures. Biomass production systems occupy 43% of the world's ice- and desert-free land (Poore & Nemecek, 2018) using up to 70% of all freshwater withdrawals (Ringler et al., 2023) while accounting for one-third of global terrestrial acidification (Van Zanten et al., 2019). The global food system alone is responsible for approximately 30% of global greenhouse gas (GHG) emissions (Foley et al., 2011; Poore & Nemecek, 2018), and accounts for 10% to 90% of globally generated air pollutants (Crippa et al., 2022), representing a major environmental mortality risk factor (Lelieveld et al., 2015; GBD, 2019; Murray et al., 2020). In this, around one third of globally produced food could be lost or wasted along global supply chains (FAO, 2019; UNEP, 2021), squandering valuable biomass inputs (i.e. feed, seeding crops, energy crops) as well as limited natural resources. Food loss and waste (FLW) represents a pressing challenge in the design of sustainable food systems as it impacts food security and nutrition, significantly contributing to greenhouse gas (GHG) emissions, air pollution, and degradation of natural ecosystems including biodiversity loss (Kaza at ., 2018; FAO 2019; UNEP, 2021).

Among global biomass systems, the majority of environmental impacts derive from animal-sourced foods (Hilborn et al., 2018; Herrero et al., 2015). While animal-sourced food production systems contribute to 40% of the global value of agricultural output and support the livelihoods and food and nutrition security of almost 1.3 billion people (FAO, 2016), current production and consumption trends place significant pressures on the environment and create health problems (Willett et al., 2019). Global livestock and feed production are responsible for around 17% of global GHG emissions (Herrero et al., 2016), occupying 70% of the global agricultural land (Van Zanten et al., 2018) and utilising 30-40% of human-edible feed crops (Salami et al., 2019). While animal-sourced foods provide nutrients critical for reducing malnutrition in low-income countries, their overconsumption in high-income countries drives a large part of environmental impacts while increasing the burden of non-communicable diseases (GBD, 2019; Willet et al., 2019). High intakes of animal-source foods link with an increasing incidence of chronic non-communicable diseases, especially type II diabetes, coronary heart disease and some cancers (Tilman & Clark, 2014). As historically animal-sourced food consumption increases with rising incomes, the expected global prosperity growth is projected to expand global meat consumption by around 14% by 2030 (OECD/FAO, 2023), exacerbating health and environmental challenges. While a higher availability of nutrients will be beneficiary for tackling the burden of malnutrition, this shift in demand is likely to intensify the environmental pressures of the food system (Springmann et al., 2018) which might soon surpass planetary boundaries. Alongside animal-sourced food demand, growing population and incomes (IMF, 2022) also propel overall food and biomass demand, urging a change in use of biomass to meet global human food and non-food needs while respecting planetary boundaries and reducing negative health impacts.

In the wake of unprecedented global shocks, notably the COVID-19 pandemic, the rise of geopolitical tensions such as the Ukraine crisis, and the increase of climate-related disasters, the vulnerabilities in our current food and biomass systems have been starkly exposed (U.N., 2020; Béné et al., 2021). These crises disrupted supply chains, driven inflation, and exacerbated fossil fuel use and climate change, leading to a surge in food prices while amplifying issues of food affordability and accessibility (FAO et al., 2022; 2023; IMF, 2023a, Van Meijl et al. 2023). The adverse impacts on vulnerable populations have highlighted the urgent need for a rethinking of our food and biomass systems. As we navigate these complex challenges, enhancing the sustainability of these systems emerges as a critical imperative. This transition goes beyond addressing immediate crises as it entails tackling ongoing long-term global uncertainties linked to climate change, limited natural resources, and expanding populations. It necessitates a fundamental reshaping of our approach to biomass production, distribution, and consumption, paving the way for a food system that is not only resilient to crises but is also equitable, environmentally conscious, and capable of meeting the needs of a growing global population.

1.2 Solutions

Achieving the global sustainability goals outlined by the U.N. (2019) requires a comprehensive transformation of our food system and the broader bioeconomy. To address the complex challenges involved, a variety of solutions focusing on the whole supply chain or specifically targeting producers or consumers are proposed. Reducing FLW, promoting renewable energy use, climate change mitigation and adaptation policies (Fekete et al., 2019), nature and biodiversity conservation (Otero et al., 2020), and information and communication technologies (Cardona et al., 2013), are potential options to improve the sustainability of supply chains across countries. On the production side, technological advancements such as innovations for enhancing crop yields and varieties, biotechnologies including GMOs (Bailey-Serres et al., 2019), precision farming techniques (Finger et a., 2019), and employing circular economy principles (Velenturf & Purnell, 2021), can play a crucial role in making our food and biomass systems more efficient and resilient over time. Parallelly, on the consumer side, healthier and more sustainable diets (Willett et a., 2019), taxes and environmentally-driven bans (European Commission, 2021b), eco-incentives (Derchi et al., 2023), and communication and educational campaigns are possible solutions for enhancing the sustainability of food and biomass consumption.

Across the multitude of available solutions, this thesis provides an in-depth exploration of a portion of the potential solutions within the broader context of sustainable food biomass systems. Several studies pointing out that around 30% globally produced food is lost or wasted (FAO 2011; 2019). Adding detail by quantifying FLW along global supply chains would enable the identification of location and composition of FLW, crucial for guiding policies targeting the reduction or reuse of FLW key for food security and resource efficiency. Among possible interventions on the consumer demand side, shifting to more sustainable diets holds great promise in addressing health and environmental concerns (Springmann et al., 2018; Willett et al., 2019). At the same time, moving towards a circular biobased economy, wherein discarded biomass is repurposed as a production input, presents a potential solution to tackle the environmental challenges associated with the growing global biomass production (Herrero et al., 2020; Muscat et al., 2021; Pyka et al., 2022, van Zanten et al., 2023).

Food loss and waste lie at the core of policies for sustainability

Global FLW lies at the core of the transition to a more secure and sustainable food system (U.N., 2019). FLW generated along global food supply chains (FSC) contribute to climate change (Porter et al., 2016) and natural resources depletion (Lipinski et al., 2013), threatening economic stability and endangering our path toward global food security (Foley et al., 2011). Overconsumption in higher income regions coupled with resource-intensive and inefficient production systems in lower income regions are among the main drivers of global FLW (FAO, 2011; 2019; Kaza et al., 2018; Gatto & Chepeliev, 2023). Lost and discarded foods have significant economic, environmental, and social repercussions (FAO, 2019; Gatto & Chepeliev, 2023) including detrimental effects on air quality (IPCC, 2013; Shindell et al., 2020) and an increased risk of premature mortality (Siddiqua et al., 2022). The reduction of lost or discarded food remains therefore a pressing policy priority (U.N, 2019). Moreover, complementary policies facilitating FLW reuse may be beneficial (Gomez San Juan et al., 2019). FLW is a key element for a circular biobased economy as it can be transformed into a valuable input for several production processes along food and biomass supply chains (Vilariño et al., 2017; Principato et al., 2019). Developing effective policies around FLW requires a consistent quantification of lost and discarded foods identifying magnitude, composition, and location along the different stages of global supply chains.

A focus on the supply chain: Food loss and waste reduction to assist dietary transitions and circular biobased solutions

Reducing FLW to enhance global food security and resource efficiency is an ever-urgent policy arena, reflected in the U.N. sustainable development goal 12.3 (U.N, 2019). As one-third of produced food is lost or wasted along global supply chains (FAO, 2011; 2019), decreasing the magnitudes of lost and discarded foods is essential in a world where resource use has increased, and millions of people remain largely affected by chronic malnutrition (FAO et al., 2022). Investments in farming technology and storage facilities can reduce food losses at production stage, especially in food insecure lower income regions (FAO, 2019). Parallelly, waste-based taxations schemes in higher-income regions may induce consumers to waste less foods, lowering high levels of food waste at retail and household level (UNEP, 2021). In this, FLW reductions may have synergistic effects with other food system challenges. On the demand-side, reducing high levels of household waste in high-income countries could assist increasing the availability of nutrient-rich foods in lower income regions, assisting poorer households in achieving adequate diets and nutritional intakes (FAO, 2019; Willett et al., 2019). Simultaneously, reducing FLW is part of a strategy for a circular biobased economy (Vilariño et al., 2017) as it promotes resource efficiency while decreasing the amounts of discarded biomass to be recycled, increasing the feasibility of circular production systems.

A focus on the demand-side: shift towards a healthier and more sustainable diet

Today, unhealthy and unsustainable food consumption represents a global risk for health and environment, with over 820 million people experiencing food insufficiency while many overconsuming unhealthy foods linked to premature death and illness (Clark et al., 2018; Springmann et al., 2018; Willett et al., 2019). As current dietary trends persist and the world population approaches 10 billion by 2050 (U.N., 2022), there is a growing recognition of the imperative to shift consumption patterns towards a healthier and more sustainable diet from both a public health and environmental perspective (FAO & WHO, 2019). This transition entails reducing the consumption of resource-intensive and environmentally detrimental foods, such as animal products high in saturated fats and GHG emissions, while promoting the consumption of plant-based alternatives, whole grains, fruits, and vegetables. A dietary shift can yield substantial benefits, including improved cardiovascular health, reduced risk of chronic diseases, and a lower ecological footprint (Tilman & Clark, 2014; Clark et al., 2019). For this, aligning dietary choices with sustainability principles, may allow to mitigate the negative environmental impacts associated with food production, including deforestation, water pollution, and biodiversity loss (Willet et al., 2019).

A focus on the supply-side: transition production towards a circular biobased economy

A circular economy is characterised by circular flows of materials, where losses from one process become inputs for another. Circularity is reducing, reusing, recycling, and cascading raw materials and energy, on the producer and on the consumer side (Ellen MacArthur Foundation, 2013). Within a circular biobased economy, a circular food system entails an economic and biophysical sensible use of all biomass, transforming bio-based losses into inputs to create value for society (Stegmann et al., 2020). Based on biophysical principles, plant biomass is the core of circular food systems (Muscat et al., 2021). Biobased residues and by-products should be used to produce human food, as well as sustainable feed, fibre, and energy, obtaining valuable bio-derivatives and ecosystem services (Hetemaki et al., 2017; Pyka et al., 2022). To decrease the impacts of ASF production, animals should be fed inedible residual biomass streams (by-products, agricultural residues, and FLW, decoupling production from land and natural resource overuse (De Boer & van Ittersum, 2018; Van Zanten et al., 2018; 2019). Following these biophysical principles requires system changes (including valuation of side products) affecting both production and consumption to minimise biomass competition.

These solutions each hold promise for enhancing the resilience and sustainability of future food and biomass systems but may affect each other, either strengthening or weakening the shift to a more sustainable future.

1.3 Obstacles

Several obstacles stand in the way of the potential solutions for achieving global sustainability goals in food systems and the broader bioeconomy. An uneven distribution of resources, financial constraints, and poor infrastructure, limit access and use of technological innovations, hindering more sustainable practices while widening the gap between higher-income and lower-income regions (Venables et al., 2016; Thacker et al., 2019). Restricted access to credit, income insecurity, and cost concerns prevent investments in sustainable production technologies (de Jesus & Mendonca, 2018; Neri et al., 2019; Gupta et al., 2020) and limit consumers from adopting healthier and more sustainable diets (Hirvonen et al., 2020; Gatto et al., 2023). Political barriers add complexity, requiring delicate navigation of international cooperation amid geopolitical tensions and diverse national priorities. Alongside these broader societal challenges, advancing research in this field encounters additional obstacles related to data and research methods. Critical data gaps exist in understanding global supply chains, ecosystem services valuation, FLW, and the circular economy, hindering our ability to make informed decisions for sustainable transitions (IMF, 2023b). Simultaneously, many models used to simulate or forecast sustainability policies often lack a comprehensive, multidisciplinary perspective, additionally omitting innovative production systems (e.g. circular production principles, precision agriculture, vertical farming, etc.). They tend to focus on specific approaches or disciplines, providing partial solutions while neglecting the complex and interconnected aspects of a global food and biomass system transformation.

This thesis focuses on two specific research challenges that, if addressed, would simultaneously help overcome research related obstacles: (i) filling data gaps related to FLW along global supply chains, and (ii) enhancing the multidisciplinary modelling of global biomass systems. The choice of this focus lies in the potential multidisciplinary synergies achievable by addressing these obstacles. From a data perspective, enhancing FLW data could allow expanding research across economic and technical fields, simultaneously broadening environmental and nutritional inquiries. The frequent absence of FLW quantification stems from lack of harmonised estimates from available global databases. This poses a substantial challenge in pinpointing areas of inefficiency within global food systems. Overcoming this obstacle requires merging and consolidating existing databases into a unified global database, specifically designed to overcome the coverage limitations inherent in individual databases. This is in turn crucial for consistently incorporating FLW into applied global models used for policy design and analyses aimed at reducing or reusing FLW. From a modelling perspective, while global economy-wide models such as multiregional input-output (MRIO) or general equilibrium (GE) models are often the preferred tool for analyses of global policy issues, their lack of a proficient representation of biomass systems and biophysical constraints represents a significant hurdle in the investigation of a global transition towards more sustainable food and biomass systems. Moreover, as such models are built on data reflecting current linear economy principles ("take-make-waste" - Ellen MacArthur Foundation, 2013), to consistently address circular bioeconomy challenges they need to capture a change in production systems to account for possible future circularity principles. Bringing technical and economic approaches closer to better represent current and future global biomass systems would allow devising more consistent policy measures that jointly address biophysical and socioeconomic challenges, key for guiding sustainable consumption and production patterns (U.N., 2019).

Quantifying food loss and waste is crucial for reduction policies, dietary shifts, and the transition to a circular biobased economy

Tackling global FLW in line with United Nations' Sustainable Development Goal (UN-SDG) 12.3 requires quantifying the magnitude, composition, and geographical location of lost and discarded foods, outlining where policy interventions may provide the highest socioeconomic and environmental benefits. However, a consistent quantification of lost and discarded food biomass across global FSC remains a major challenge. Available global FLW estimations are rather outdated (Sheahan & Barrett, 2017; Xue et al., 2017) or provide a limited spatial coverage, hindering the integrated assessments of policies concerning FLW reduction or reuse (UNEP, 2021). In the absence of a common FLW definition data vary in the inclusion/exclusion of inedible food parts in FLW flows (Delgado et al., 2021), and in the (non-)consideration of food flows diverted to other uses (e.g. animal feed) as FLW (Corrado et al., 2019). Different specifications of supply chain stages and different scales of analysis (Delgado et al., 2021) result in further inconsistent estimates and databases (Xue et al., 2017), rendering contents of studies difficult to compare (Corrado et al., 2019). These limitations hinder the development of consistent FLW reduction policies, as the lack of an harmonized global database that consistently merges data on FLW quantity, quality, and location limits the development of consistent policy interventions. Furthermore, existing data limitations impede integral assessments of related food systems policies, as interactions with other interventions cannot be fully assessed. From a consumer perspective, while healthier and more sustainable diet has potential positive effects on reducing FLW (Springmann et al., 2018; Gatto et al., 2023), the lack quantification of FLW along global FSC limits the understanding of how changes in FLW may enhance or thwart net food intakes across countries. Similarly, lacking data on location and quality of FLW makes it challenging to assess options to repurpose, recover, and utilize FLW as valuable production input in a more circular biobased economy.

Food loss and waste reductions, dietary shifts, and circular biobased economic policies require enhancing biophysical details into economywide frameworks

In addition to the existing data limitations, research on food system transformations has predominantly focused on technical and nutritional aspects, leaving the associated economic impacts largely unexplored. FLW quantifications rely on detailed physical mass flows to derive volumes (Kummu et al., 2012; Liu et al., 2013; Caldeira et al., 2019), but often ignore socioeconomic drivers of FLW (Chaboud & Daviron, 2017). Despite rapid globalisation of the food system FLW quantifications lack a consistent representation of international trade crucial to analyse food flows from farm to fork along global FSC (Gatto & Chepeliev, 2023). As global food trade shapes food availability and accessibility worldwide, understanding global food production, distribution, and consumption allows quantifying FLW embedded in food imports and exports, identifying major drivers and contributors to FLW generation. With regard to dietary shifts, while direct health and environmental benefits are increasingly recognized following the publication of the EAT–Lancet diet (Willet et al., 2019), the broader economic and social effects linked to such a transition remain widely unassessed. Similarly, the biophysical benefits of a circular biobased economy have been broadly investigated (De Boer & van Ittersum, 2018; van Hal et al., 2019; van Zanten et al., 2018; 2019; 2023) but limited knowledge is available on the broader social and economic implications within interconnected food and non-food systems (Ominski et al., 2021).

From a methodological perspective, biophysical models (see for example Springmann et al., 2021; Sandrstom et al., 2022; van Zanten et al., 2019; 2023) provide detailed knowledge on physical material flows, dietary intakes/requirements, and biomass reuse potential, developing solutions based on optimized biomass production, use, or intake. While these models present valuable insights for nutritional and biophysical inquiries, they overlook consumer and producer behaviour, ignoring potential market and economy-wide dynamics, trade-offs, and rebound effects linked to changing agent behaviour in response to policies and changing prices. In parallel, global economic models (see for example van der Mensbrugghe, 2010; Woltjer et al., 2014; Corong et al., 2017) are highly suited to investigate economy-wide changes in agent behaviour, markets, prices, and international trade when policies targeting global food and biomass systems are applied. However, global economy-wide models such as MRIO or GE models, often operate on monetary value terms, misrepresenting biophysical balances of material flows key for quantifying FLW flows, dietary shifts, and circular solutions. Moreover, as such modelling frameworks often only capture current linear economy principles, they tend to exclude options for upcycling of FLW and other discarded materials as production input, key for a circular biobased economy. Provided solutions are then partial as they do not fully grasp technicalities and opportunities linked to changing biophysical flows of primary and discarded biomass.

1.4 Objective and research questions

This thesis integrates biophysical details linked with FLW and agri-food production in a global economy-wide MRIO and GE model to allow analyses of interactions between economic policies and biomass use and flows within a global market economy. It investigates the shift towards more sustainable global food and biomass systems. By adopting various supply-chain focuses and methods (Figure 1.1) it provides an overview of synergies and trade-offs between FLW reductions, dietary shifts, and the transition towards a circular biobased economy.

This thesis begins with a pure data approach (Chapter 2), building an up-to-date database merging existing estimates available from literature. Employing a multidisciplinary approach it quantifies the generation of FLW throughout global food supply chains. Through applying a environmentally-extended MRIO framework this first data-focused step of this thesis aims to create a new global FLW database, serving as a fundamental resource for analysing food and biomass system interventions aimed at sustainability.

Building on the foundation provided by this new database this thesis delves into three core transformations of global food and biomass systems, focused at different stages of the supply chain. First, this thesis expands and places the database of Chapter 2 in a societal context, investigating a potential FLW reduction using a MRIO model (Chapter 3). Here, a supply-chain perspective is taken, analysing synergy effects and trade-offs of a global FLW reduction along all stages of the supply chain, and specifically addressing impacts on pollution and related health risks. The MRIO framework allows use of full country and sector detail provided by the database developed in Chapter 2. Moreover, a MRIO is closer to a technical perspective with a detailed and disaggregated framework and fixed. It may thus provide a better illustration of the use of the newly constructed multidimensional databases for technical focused studies of a global FLW reduction.

From this, this thesis expands the level of complexity, investigating producer- and consumer-side interventions with the use of a GE model where prices and behaviour are endogenized, but analyses are more aggregated in terms of sector and country detail. On the consumer side, this thesis explores the economic, social, and environmental consequences of transitioning towards a healthy and environmentally sustainable diet (Chapter 4). On the producer side, it examines the economic, social, and environmental effects of policies aimed at fostering a circular food system, with a particular emphasis on the role of livestock (Chapter 5). The use of a GE allows depicting both the direct and indirect effects of policies, with the latter being crucial in this thesis as indirect effects are key elements influencing the socioeconomic acceptance of sustainability transitions.

The core research question of this thesis can be summarized as:

"What are the synergy effects and trade-offs between global food loss and waste reductions, dietary transitions, and a livestock-focused circular food system in terms of economic, social and environmental consequences?"

From this, four distinct research questions emerge, each designed to explore a specific approach to achieving more sustainable global food and biomass systems by 2030:

From a data perspective:

1. What is the magnitude, composition, location, and environmental footprint of food loss and waste generated along global supply chains? (Chapter 2)

From a supply-chain perspective:

2. What are the potential benefits of a global food loss and waste reduction on air pollution and pollution-related mortality risks? (Chapter 3)

From a consumer perspective:

3. What are the economic, social, and environmental impacts of a global transition towards a healthier and more sustainable diet? (Chapter 4)

From a producer perspective:

4. What are the economic and environmental impacts of policies promoting the upcycling of food loss and waste and other secondary biomass as animal feed? (Chapter 5)

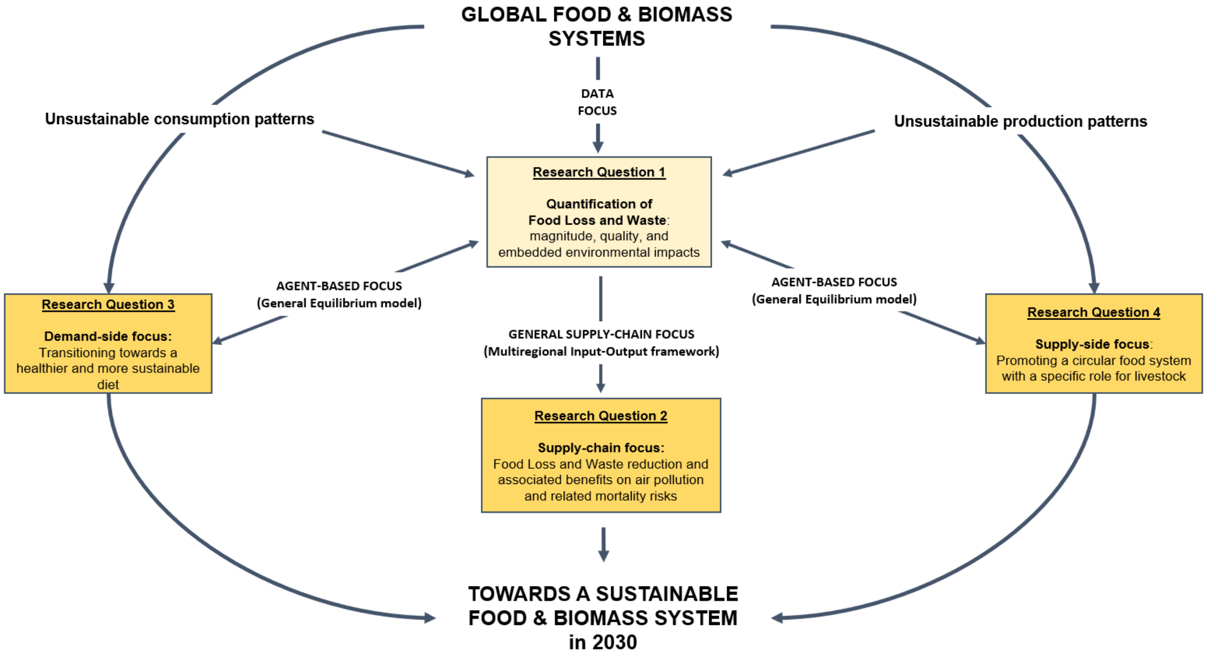

Figure 1.1. Overview of the research design used in this thesis.

1.5 Methodology

1.5.1 Theoretical Framework & Methods

To address the first and second research question, this thesis utilises a MRIO model (Lenzen et al., 2012; Merciai & Schmidt, 2018; Bruckner et al., 2019). A MRIO framework allows to analyze the economic relationships between different regions or countries, extending traditional Input-Output (IO) models to account for trade and economic interactions across multiple regions. MRIO models provide an understanding of how economic activities in one region affect other regions, making them valuable for studying global trade, environmental impacts, and supply chains. Their high level of disaggregation permits economy-wide analyses on specific products, sectors, or countries. However, MRIO models have several limitations. First, MRIO models assume linear relationships between industries, depicting a snapshot of the economy at a specific point in time, and assuming that production coefficients (inputs required for each unit of output) remain constant (Leontief, 1955). MRIO models thus only depict partial effects of policy interventions, as price feedbacks and behavioural changes are ignored, overlooking potential income changes, substitution and rebound effects. The use of a MRIO framework for the first and second research question is linked to the need of a high disaggregation level to conduct country-specific analyses and develop new databases specific to each country. Moreover, as a MRIO framework shares characteristics, such as fixed production technologies and no price adjustment processes, akin to the input-optimization models frequently employed in biophysical analyses, the use of such framework may be more understandable from a different disciplinary perspective, enhancing the possibilities for using such data in non-economic models. As MRIO models omit price-induced behavioral changes of producers and consumers they can only capture short-run impacts, providing a first order approximation of the impacts of a change in the economic system.

A more complete analysis of pathways towards a more sustainable food and biomass system requires an ex-ante system approach encompassing primary food, food processing, services, and non-food sectors while capturing global changes in behavior of different agents (producers, consumers, government) in a market economy. As price-related feedback effects and income changes are key to address research question 3 and 4 here a GE model is used. A global GE model allows policy experiments simultaneously involving multiple agents, countries, and systems of sectors connected through a market environment. A global GE framework can capture complex circular biomass flows and changing interactions between different agents, analyzing endogenous price responses (including substitution and rebound effects) and socioeconomic and environmental impacts of policy instruments at different stages of global supply chains (Hertel, 1997). It provides impacts on economic variables key to the societal acceptance of shifts (like income and employment), obtaining relevant economic-wide feedback and flow-through effects. This neoclassical consistent framework provides a closed system covering circular flows of money between income and expenditures (Mas-Colell et al., 1995; Dixon et al., 2002). Agents (firms, government, and households) are assumed to behave perfectly rational (utility-maximisation behaviour), with only prices (and quantities) identified as explicit drivers moderated through elasticities capturing a wide but implicit array of preferences and restrictions (Burfisher et al., 2011; Dixon et al., 2012).

A GE framework is often preferred to a MRIO due to the possibility of devising the link between income creation and spending, determined by endogenous market prices which do not play a determinant role in IO frameworks (Dixon et a., 2012). Nonetheless, existing GE models have limitations key to the investigated research questions. First, technologies derived from input-output data often reflect current (linear) technologies. Due to the use of nested constant-elasticity-of-supply (CES) production functions GE models cannot capture new circular systems where sectors use inputs not already used in the database on which the model is calibrated (Kuiper & van Tongeren, 2006).New circular flows in production systems by explicit changes to the model. Second, GE models often misrepresent physical flows of materials through economies. Biophysical balances matching economic input-output data are scarce, while balances are violated by monetary value-based input substitutions using CES production functions, typical of GE models. The lack of biophysical grounding represents a crucial obstacle for modelling targeted dietary intakes, FLW reductions, and a circular bioeconomy. Through a multidisciplinary approach this thesis aims to represent biophysical limitations and global biomass flows critical more accurately for analysing the transition towards a more sustainable food and biomass system. These improvements allow more precisely study of economic effects, enabling us to develop comprehensive economy-wide analyses that consider both technical and biophysical limitations.

To ensure data consistency and have a uniform starting point throughout all chapters, the MRIO framework and GE model utilized in this thesis are extensions of the standard Global Trade Analysis Policy (GTAP) database version 10 (Aguiar et al., 2019). The MRIO framework is derived from Aguiar et al., (2019) and provides country-specific economy-wide input-output tables constituting the foundation for our analytical approach. The GE model is the global macroeconomic model MAGNET (Modular Applied GeNeral Equilibrium Tool). It is an advanced recursive dynamic variant of the well-known Global Trade Analysis Project (GTAP) model (Corong et al., 2017). MAGNET has been widely used for simulating global policies on agriculture, trade, and the bioeconomy (Van Meijl et al., 2018), assessing impacts on a wide range of indicators including agricultural markets, food security and nutrition (van Meijl, et al., 2020a; van Meijl, et al., 2020b; Gatto et al., 2023), and sustainability (Leclère et al., 2020; Pérez-Domínguez et al., 2021). In the model, food/non-food and production-factor (various types of labour, capital, land) demand is endogenously determined by income changes, relative prices, preference shifts and dynamic income elasticities. As factor markets are segmented between agricultural and non-agriculture markets for two types of labour (skilled and unskilled), wage developments differ between the types and sectorial use of labour. Additionally, a detailed representation of endogenous land markets (van Meijl et al., 2006) and the bioeconomy, with innovative biobased materials including by-products and residues from agriculture and forestry, enables modelling food system transformations and circular economy processes in which resource-intensive inputs are replaced by sustainable alternatives. This pre-existing bioeconomy detail (Pyka et al., 2022) renders MAGNET preferred over other GE models.

More specifically, each research question is answered in a dedicated chapter, building upon the preceding one while growing in complexity in terms of capturing economic feedback mechanism (Figure 1.2).

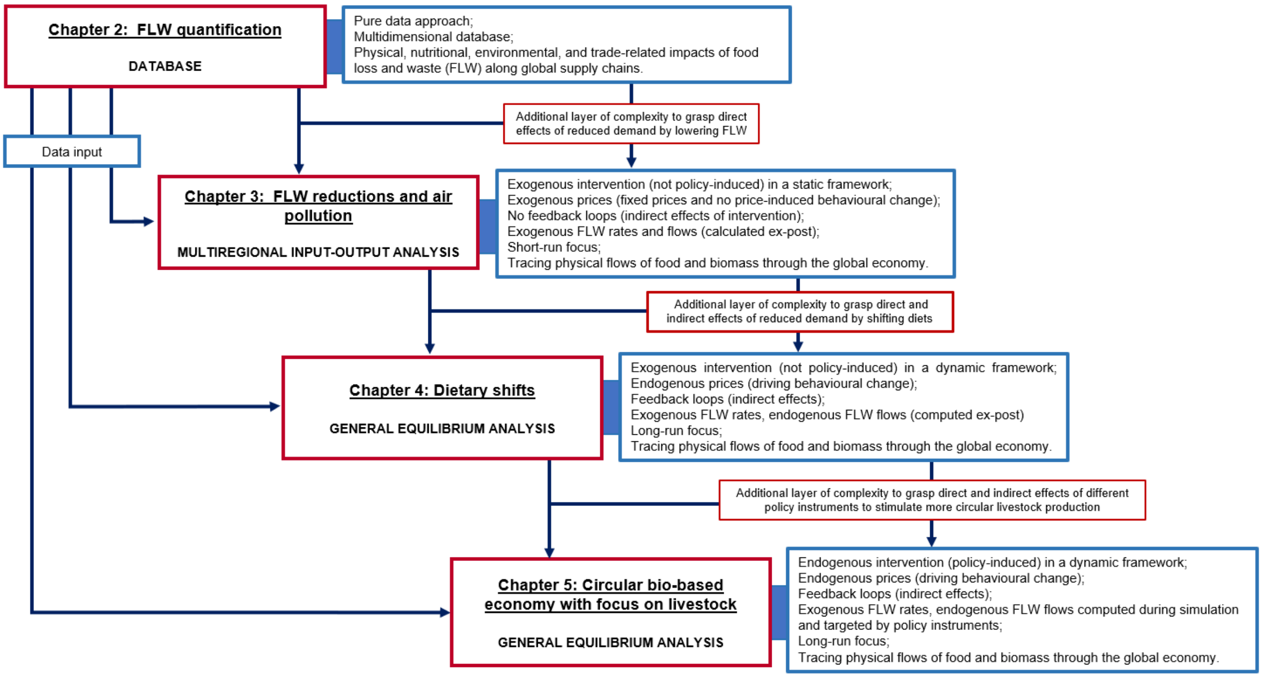

Figure 1.2. Overview of the methodological approach adopted in each chapter of this thesis.

Research question 1: what is the magnitude, composition, location, and environmental footprint of food loss and waste generated along global supply chains?

To answer the first research question, technical and economic analyses of FLW are merged to capture physical flows of lost or discarded food biomass along each stage of global supply chains. Building on a recent approach to incorporate physical and nutritional flows in a global economic framework (Chepeliev, 2022), this chapter focuses on tracing food and nutritional supply across stages of global FSC within a global multi-region input-output (MRIO) framework. A global economy-wide approach for quantifying FLW along global value chains is implemented, addressing a key barrier of existing FLW quantifications, which often rely on mass flow analyses and omit supply chain dynamics and international trade. The chapter analyses magnitude, nutritional content, and environmental footprint of FLW by supply chains stage and food commodity, developing a global database for 121 countries and 20 composite regions. Additionally, by merging the constructed FLW estimates with gross food and nutrient supply provided in the FAO Food-Balance-Sheets (FBS) it provides new estimates of net food and nutritional intakes at the country level, further expanding the possibility of investigating future policies on food security and FLW.

Research question 2: what are potential co-benefits of a global food loss and waste reduction on air pollution and pollution-related mortality risks?

To address the second research question, this chapter assesses the impact of FLW reduction on non-GHG air pollutants embedded along global FSC. First, an overview of evolving trends of air pollutants embodied in FLW across a 10-year timeframe (2004-2014) is provided, outlining drivers and hotspots across countries and stages of the FSC. Then the FLW-extended MRIO developed in the previous chapter is extended with air pollution data. Using this extended MRIO framework this chapter then investigates changes in air pollutants embedded in the final consumption of food products linked to FLW reduction and demand changes. FLW are reduced by halve following the UN-SDG12.3 target (U.N., 2019) under three alternative scenarios of changing final demand patterns. Linking the resulting changes in air pollution to a global atmospheric source-receptor model (Van Dingenen et al., 2018) allows exploration of the impact of FLW reductions and demand changes on the premature mortality risks and assess health-related co-benefits across global regions.

Research question 3: what are the economic, social, and environmental impacts of a global transition towards a healthier and more sustainable diet?

To assess the research question 3, this chapter simulates the transition towards the EAT-Lancet diet (Willet et al., 2019). Imposing a taste shifter to final consumers in the MAGNET model, this chapter investigates how a transition towards a healthier and more sustainable diet affects global biomass production, economy, and FLW generation, posing particular attention to social impacts often lacking in current dietary transition analyses. In this, existing value-based tracing in GTAP-based GE models (Rutten et al., 2013; Britz, 2020; Chepeliev, 2022) are improved by enhancing the standard GTAP 10 database (Aguiar et al., 2019) with regionalized material balances to get closer to physical (Tons) material flows. Furthermore, primary food biomass flows are integrated into MAGNET's results using weight-based FLW estimates to compute the biomass amounts contained in final demand, respecting material balances in both monetary and physical units. This chapter uses a food affordability indicator relating price developments of a specific food consumption basket (Willet et al., 2019) to income developments of a particular income group (Gatto et al., 2023). Further, changes in the wages of unskilled workers are used as a proxy for the income component of poor people working in different sectors of the economy. With regards to environmental impacts, effects on greenhouse gas (GHG) emissions and land use changes are investigated. Finally, deriving the Leontief Inverse (Leontief, 1970) from the regionalized material balances, this chapter traces all direct and indirect material flows throughout the entire global economic system, addressing global competition for endowments (e.g. land, labour) and biomass. This tracing is key for processed and imported goods where biomass from various locations can be combined through multiple processing and trading steps before finally being consumed.

Research question 4: what are the economic, social, and environmental impacts of policies promoting a circular food system with a specific role for livestock in which food loss and waste and other secondary biomass are upcycled as animal feed?

Finally, to address the fourth research question this chapter investigates the impact of policies towards more circular livestock systems in the European Union, adjusting the modelling of livestock production in the MAGNET model with technical details from livestock sciences. The provided analysis compares the impact of subsidies stimulating the use of low-cost-opportunity feed (LCF) such as agricultural residues, by-products, and FLW, and feed import tariffs promoting a more domestic sourcing of feed crucial for circularity. As modelling circularity in livestock production requires an explicit representation of physical biomass flows to account for the nutritional constraints of upcycling LCF as livestock feed, physical quantities are introduced into the MAGNET model, enlarging its framework to consider four different feed sectors supplying animal-specific feed based on the suitability of each feed type per livestock category. In this, physical balances across model simulations are preserved to consistently calculate feed conversion ratios key for devising livestock-specific energy balances (gross energy and crude protein) before and after circular economy policies are introduced.

1.5.2 Data

The MRIO framework and the GE model employed for this research rely on the Global Trade Analysis Project (GTAP) database version 10 (Aguiar et al., 2019). Research questions 1 and 2 additionally rely on data from the GTAP-FBS database (Chepeliev, 2022) and from the GTAP-air pollution database (Chepeliev, 2021). Moreover, the used MRIO framework is extended with biophysical data from FAOSTAT and EARTHSTAT on macronutrients and land use. Further, additional data concerning water-use is derived from Haqiqi et al. (2016) and AQUASTAT , while greenhouse-gas (GHG) emissions data is obtained from Aguiar et al., (2019) and Chepeliev (2021). For addressing research questions 3 and 4, the database of MAGNET is enhanced including new FLW flows and input-output links between sectors, key for circularity. The baseline used by MAGNET as a reference to judge changes in the economy is defined within the “business-as-usual” shared-socioeconomic-pathway number two (SSP2 - O’Neill et al., 2017) and the IMF socio-economic pathways (IMF, 2022). The time horizon of model simulations focuses on 2030, the target year of the Sustainable-Development-Goals (U.N., 2019).

1.6 Overview

The reminder of this thesis is organised as follows. Chapter 2 answers the first research question by investigating magnitude, composition, and location of FLW along current global supply chains, simultaneously quantifying embedded nutritional and environmental impacts. Chapter 3 explores the impact of FLW reductions, specifically analysing benefits for air pollution and related premature mortality risks. Chapters 4 and 5 focus on agent-specific interventions along global supply chains. Chapter 4 zooms in on the consumer-side, analysing the economic, social, and environmental consequences of a global transition towards a healthier and more sustainable diet in 2030. Chapter 5 concentrates on producer-side interventions, exploring the economic and environmental impacts of different policies to promote animal feed for a circular food system in the European Union in 2030. Finally, Chapter 6 answers the overall research question investigated in this thesis, providing an overview of synergies and trade-offs between the possible food and biomass systems interventions explored in this thesis. It also discusses key research findings, limitations, and policy implications.

Chapter 2

New Estimates of Food Losses and Waste Along Global Supply Chains Show Increasing Nutritional and Environmental Pressures

Abstract

This study addresses the challenge of quantifying global food losses and waste (FLW). We compile a comprehensive country-level database that assesses FLW across global value chains and quantifies the nutritional and environmental impact of lost and discarded food for 121 countries and 20 composite regions. Between 2004 and 2014, FLW increased significantly (+24.0%), especially in sub-Saharan Africa (+43.1%) and southeast Asia (+37.1%), where growing nutritional losses (average 550 calories/capita/day) impact food security. Growing food imports by high-income countries and fast-growing economies worsened FLW and related environmental footprints in exporting low-income regions. For this, reducing overconsumption and FLW in high-income countries may have positive effects in mid- and low-income countries, where food exports largely drive farm-level losses. Here, policies should focus on promoting the profitable reuse of unavoidable FLW parallelly enhancing agricultural production efficiency to improve water-use and nutritional security.

This chapter is based on:

Gatto, A., Chepeliev, M. (2024). Global food loss and waste estimates show increasing nutritional and environmental pressures. Nature Food. https://doi-org.ezproxy.library.wur.nl/10.1038/s43016-023-00915-6

2.1 Main

Reducing global food losses and waste (FLW) lies at the core of the transition to a more secure and sustainable food system (U.N., 2019). FLW generated along global food supply chains (FSC) contribute to climate change (Porter et al., 2016) and natural resources depletion (Lipinski et al., 2013), threatening economic stability (Parry et al., 2015) and endangering humanity's path toward global food security (Foley et al., 2011). Tackling global FLW in line with United Nations' Sustainable Development Goal (UN-SDG) 12.3 requires quantifying the magnitude, composition, and geographical location of lost and discarded foods, outlining where policy interventions may provide the highest socioeconomic and environmental benefits. Today, three major barriers hinder the development of consistent policies for tackling FLW.

The first barrier is represented by the lack of harmonized global FLW estimates (UNEP, 2021). The Food and Agriculture Organization FLW database (FAO, 2011) produced over a decade ago, despite being widely criticized as internally inconsistent (Sheahan & Barrett, 2017; Xue et al., 2017), continues to be used as one of the key data sources for the FLW quantification (Springmann et al., 2018; Willett et al., 2019). Several more recent studies attempted to improve the quantification of the global FLW, however with limited success (Kuiper & Cui, 2020). While the global databases from FAO (2019) or OECD (2021) provide a rather limited regional or commodity coverage, other global databases (FAO, 2011; Kaza et al., 2018; Kummu et al., 2012; Parfitt et al., 2010; Xue et al., 2017) use different FLW definitions and supply chain coverage approaches, making estimates largely incomparable (Delgado et al., 2021).

A second barrier is associated with the lack of comprehensive approaches to quantifying FLW. Technical studies (Caldeira et al., 2019; FAO, 2011; Kummu et al., 2012; Liu et al., 2013) rely on detailed physical mass flows to derive FLW volumes, but often ignore socioeconomic drivers of FLW (Chaboud & Daviron, 2017). Simultaneously, economic studies on FLW (Britz et al., 2019; de Gorter et al., 2020) consistently address agents' behaviour along FSC but often circumscribe to monetary analyses, lacking information on physical flows key for quantifying FLW. As the globalisation of the food system has been rapidly growing (Godfray et al., 2010), FLW quantifications additionally lack a consistent representation of international trade crucial to devise food flows from farm to fork along global FSC. As global food trade may shape food availability and accessibility worldwide, understanding global food production, distribution, and consumption allows quantifying FLW embedded in food imports and exports, devising major drivers and contributors to FLW generation. In this, trade analyses may help identifying the geographical location of lost or wasted foods, determining how food consumption in one region can generate food losses and related challenges in a trading foreign region. This may additionally provide information on the potential for matching the surplus of food in one region with the deficits in another, reducing FLW while addressing food security challenges.

Finally, a third barrier lies in the absence of a multidisciplinary framework able to address wide-ranging challenges around FLW. Several studies link FLW estimates with nutritional losses (Alexander et al., 2017; Chen et al., 2020; Wesana et al., 2019) but report no information on how food and nutritional intakes are affected by FLW along the FSC. Additionally, single-country assessments on the environmental footprint embedded in FLW is currently missing but remains an ever-urgent policy arena for contextualizing FLW in the multidisciplinary framework of the Sustainable-Development-Goals.

In this paper, we compile a global FLW database to address the main inquiries regarding the magnitude, composition, location, and environmental footprint of global FLW and its development across recent years. First, we collect the best available estimates on shares of lost and discarded foods across commodity groups, food supply stages and geographical regions, aligning with the FLW definition provided by the U.N. (2019)[1]. Second, building on a recent development that incorporates physical and nutritional flows in a global economic framework (Chepeliev, 2022), we trace food and nutritional supply across stages of global FSC within a global multi-region input-output (MRIO) framework[2]. Finally, relying on the constructed database we explore country-level FLW developments across a ten-year time frame (2004-2014), quantifying the magnitude, composition, geographical location, and nutritional contents of FLW, consistently accounting for the role of international trade in the global food system. In addition, we integrate data on land use, water use, and greenhouse gas (GHG) emissions, quantifying the environmental footprint embedded in FLW generation along the global FSC.

Our analysis aims to bridge knowledge gaps on global FLW developments, providing an innovative link to nutritional security and environmental impacts. We aim to further embed FLW in the multidisciplinary framework of the Sustainable Development Goals, assisting potential future policies on FLW reduction and circularity.

2.2 Results

Magnitude, composition, and location of food loss and waste along global food supply chains

Global FLW generated across the FSC amounts to 1.92 billion Tonnes in 2014 (a +24.0% or 372 million Tonnes from 2004). Between 2004 and 2014, the largest relative increase in FLW has been observed at the Manufacturing stage (+26.8%) (Panels A and B - Figure 2.1) due to the rising consumption of processed foods. Despite this, the major global hotspots of FLW in 2014 remained Agricultural Production and Post-harvest Handling & Storage which cumulatively generated 956 million Tonnes of FLW or around 49.6% of the global share. Compared to 2004, the largest increase in FLW concerns plant-based FLW, in particular, horticulture (i.e. fruit, vegetables, pulses, and nuts) and sugar beet/cane. In the former case, the FLW has grown by 25.5% (or 185 million Tonnes), primarily in the Manufacturing and Distribution & Retail stages, while sugar beet/cane FLW increased by 27.4% (or 70.6 million Tonnes), mostly at the farm-level stages. A relatively lower increase is observed in losses and waste from cereals (26.3% or 66.0 million Tonnes) and oilseeds (8.9% or 6.2 million Tonnes), reporting peaks at Post-Harvest Handling & Storage and at the Consumption stage. FLW of ruminant and nonruminant meat has grown by 20.7% (or 17.5 million Tonnes), increasing primarily at the Agricultural Production and Post-Harvest Handling & Storage stages, while Dairy FLW (+13.2% or 14.8 million Tonnes) has mainly concentrated at Consumption stage. The largest relative increase is observed for fish FLW (+27.1% or 12 million Tonnes) which particularly grew at the Manufacturing and Consumption stages.

In 2014, the largest absolute amounts of FLW are generated in North America (mainly the United States), China, and India (Panels A and C - Figure 2.2), constituting around 42.6% of global FLW. However, exploring the per-capita estimates (Panel C - Figure 2.2) it is noticeable that while in the case of North America, the large absolute amounts of FLW are associated with high per-capita losses (United States, 1549 grams/capita/day and Canada, 1442 grams/capita/day), this is not the case for China and India. Despite the fact that both China's and India's population is almost four times larger than the United States and Canada combined (World Bank, 2023), a lower per-capita gross domestic product (GDP) (income) and gross per-capita food supply in these two middle-income countries, result in a substantially lower FLW generation per person (Panels A and B – Figure 2.3).

[1] We define FLW as "*food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses, and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products*".
[2] Here we use the Global Trade Analysis Project (GTAP) version 10 Data Base (Aguiar et al., 2019). This is the most up-to-date publicly available version of the GTAP Data Base at the time of the paper's writing.

Highest per-capita FLW estimates are observed primarily in high-income countries, such as Australia (1316 grams/capita/day), New Zealand (1456 grams/capita/day), Singapore (1380 grams/capita/day) and Hong Kong (1322 grams/capita/day) where per-capita GDP and gross food supply are on average substantially above global averages (Panels A and B – Figure 2.3). Specularly, the lowest amounts of FLW generation (both per capita and total) are observed in low-income countries in sub-Saharan Africa and Southeast Asia where a lower food purchasing power results in an average of 200 grams of FLW generated per capita/day – six to seven times lower than in many high-income countries. With higher income and increasing food consumption, the consumer's marginal benefit of food declines (Chavas, 2017), thus households at the top of the income spectrum have substantially less economic incentives to minimize their FLW footprints compared to the consumers at the bottom of the global income distribution.

In the case of low-income countries, the majority of losses occur in the early stages of the supply chain, whereas higher-income economies tend to generate larger amounts of FLW in the final stages. Such distribution of the FLW across supply stages is driven both by the differences in the marginal benefit of food across the income spectrum, as well as the limited availability of the technological and infrastructural solutions for reducing losses during the farm-level stages in developing countries, as compared to the high-income economies (Ali et al., 2021; Joardder and Masud, 2019). At the farm level, FLW is concentrated in Latin America & Caribbean, Southeast Asia, and Sub-Saharan Africa. Differently, at the consumption stage, food waste mainly occurs in North America & Oceania, Europe, and high-income Asia. On the per-capita basis, agricultural production losses are most significant in the Middle-East and North Africa, particularly in Turkey, Armenia, Tunisia, Libya, and Algeria. On the other hand, post-harvest losses are more prominent in Latin America, specifically in Brazil, Costa Rica, and Colombia. Per-capita manufacturing losses are highest in higher-income countries such as South Korea, Norway, Hong Kong, and Singapore. Similarly, the highest levels of per-capita food waste can be observed in North America (Canada and the United States), Australia, and New Zealand.

Across the analysed timeframe FLW has substantially increased in Southeast Asia (+37.2%) and Sub-Saharan Africa (+43.2%) particularly during the 2007-2011 period (an average global increase of +10.4% - Panel C of Figure 2.1). The largest relative increases in FLW occurred in South-central Africa (Malawi, 105.2%; Angola, 104.5% and Congo DRC, 104.5%), Central Asia (former Soviet Union block – an average of 86.5%), and Southeast Asia (mainly Lao PDR, 90.5%) (Panel B of Figure 2.2 and Panel C of Figure 2.3). In these countries, the sharp increase in per-capita GDP (and incomes) represents a key driver of FLW generation. In addition, a growth in population by at least 10% in such regions as Sub-Saharan Africa, Middle East and North Africa, India, Southeast Asia, and North America further contributes to increasing food demand and rising FLW during the analysed period. On the other hand, the sharp decrease in "food intensity" - measured by changes in gross food consumption per unit of GDP - in Southeast Asia, China, and India plays a key role in limiting the increase in FLW across years. A lower "*food intensity*" has led to a decrease in FLW in Europe (an average of -1.5%) and in high-income Asian countries such as Japan and South Korea (an average of -7.3%).

To better understand the drivers behind changing FLW over time, we have further incorporated the logarithmic mean Divisia index (LMDI) I additive decomposition method (Ang, 2015), which allows us to disentangle FLW trends across activity, structure and intensity effects (see Supplementary Information for additional details and country-level results). Consistent with the KAYA decomposition results (Panel C of Figure 2.3), we find that the activity level (increasing food demand) is the key driver of rising FLW, explaining 96% of the overall increase over the analysed time period at the global level (Supplementary Information, Table S16). Selected countries that managed to achieve major reductions in FLW, including Japan, Italy and Greece, also see the most substantial declines coming from the activity channel. On the other hand, in Mexico and Germany, a substantial portion of declining FLW is associated with changing composition of food consumption (structure channel), while in Spain and the United Kingdom (UK), a reduction in FLW food intensity is the major contributing factor driving down the FLW volumes (Supplementary Information, Table S16).

Around 15.7% of global FLW in 2014 are associated with traded food, with the remaining amount being generated by non-traded foods, hence both produced and consumed domestically. From the exports side, flows of exports-embedded FLW in 2014 (Panel E – Figure 2.2) are largest in Brazil (54.8 million Tonnes, 53.0% of total FLW), United States (20.9 million Tonnes, 11.1% of total FLW), and Mexico (12.1 million Tonnes, 31.5% of total FLW). In these countries, large exports of horticulture and cereals particularly towards the Middle East, North America, and East Asia represent a main driver of food loss generation at Agricultural Production and Post-Harvest Handling & Storage.

Import-embedded FLW are largest in China (35.2 million Tonnes, 6.6% of total FLW), Japan (12.1 million Tonnes, 49.2% of total FLW), North Africa (Libya, Algeria, Morocco, and West Sahara, 10.0 million Tonnes, 46.6% of total FLW), and United States (29.8 million Tonnes, 16.1% of total FLW). Major flows of imported FLW in China derive from Thailand (12.6 million Tonnes) and Brazil (6.5 million Tonnes), while high-income Asian countries such as Japan and South Korea largely import FLW from Australia (total 3.9 million Tonnes). Food imports by Canada and the United States directly drive FLW generation in Argentina and particularly in Brazil, where export-embedded FLW towards North America increased by an average of 38.7% (or 1.8 million Tonnes) since 2004. Additional details regarding magnitudes of trade-embedded FLW flows by country are reported in the Supplementary Information (Table S17).

Changing patterns of bilateral trade over the analysed period, have been driving changes in trade-related FLW across countries. In China, a sharp increase in food imports since 2004 (154.1%) has contributed to export-embedded FLW in Thailand (+167.4% or 7.9 million Tonnes) and Brazil (+545.9% or 5.5 million Tonnes). Growth in the Brazilian export-embedded FLW was further driven by expanding food demand in the Middle East, particularly by food imports from Saudi Arabia (+117.9% or 1.8 million Tonnes). Similarly, an expansion in the food trade between the United States and Mexico has resulted in higher amounts of export-embedded FLW in Mexico (+310.2% or 7.4 million Tonnes), as well as in the United States (+18.9% or 0.6 million Tonnes). Finally, while food imports by Japan and South Korea have contributed to significant export-embedded FLW in Australia, such amounts have been decreasing (an average of 18.1% reduction in the aggregate export-embedded FLW in Australia).

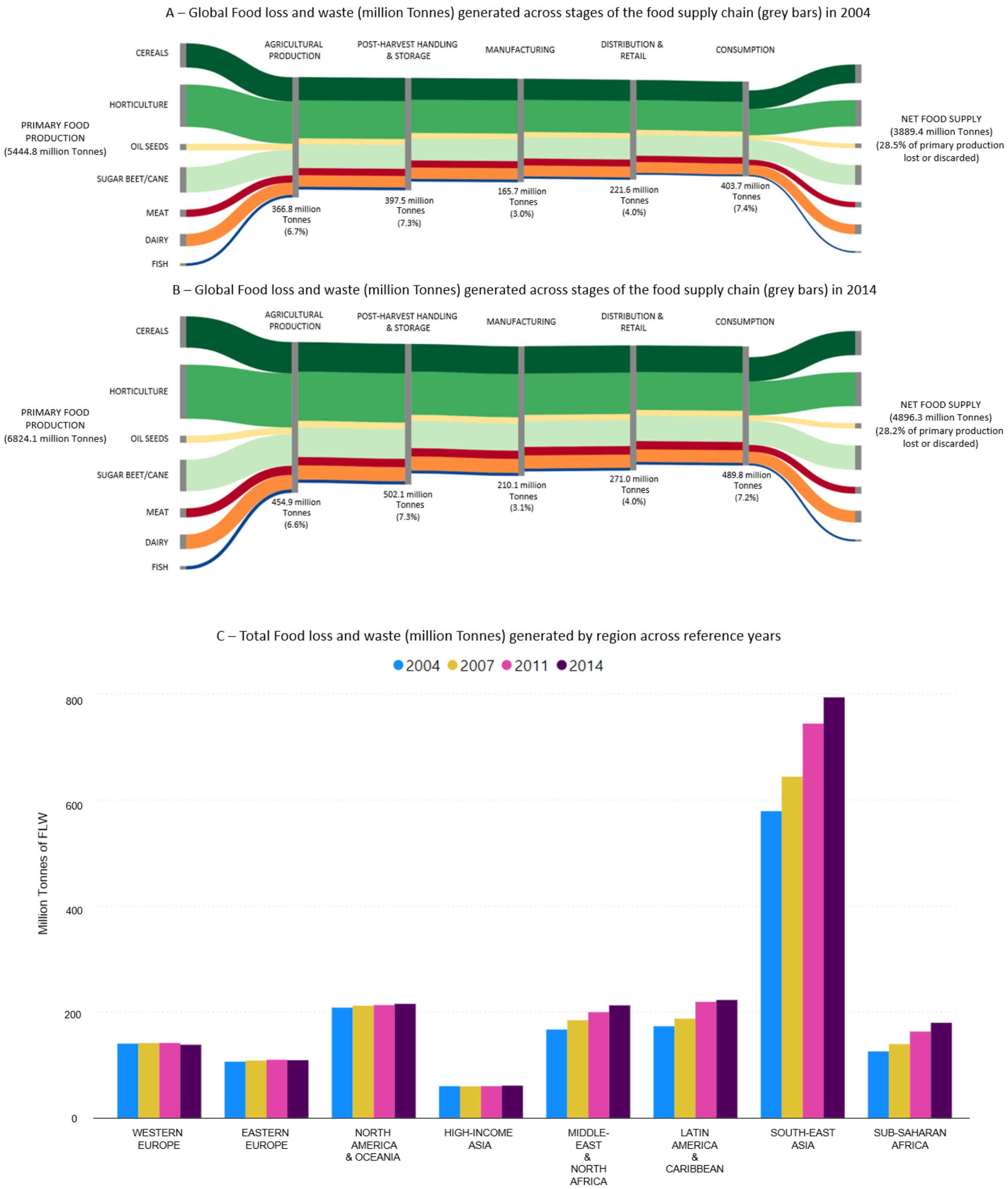

Figure 2.1. Flows of FLW (Million Tonnes) by primary food product generated along different stages of global food supply chains (by reference year). Estimates report million Tonnes of generated FLW from primary production to final consumption. Panel A reports global FLW generation by FSC stage (illustrated by long grey bars) in 2004. Panel B reports global FLW generation by FSC stage in 2014. Finally, Panel C illustrates total food loss and waste generated by region and globally across analysed reference years 2004, 2007, 2011 and 2014. Additional figures on FLW trends are reported in the Supplementary Information (see figures S2-S4, Supplementary Information).

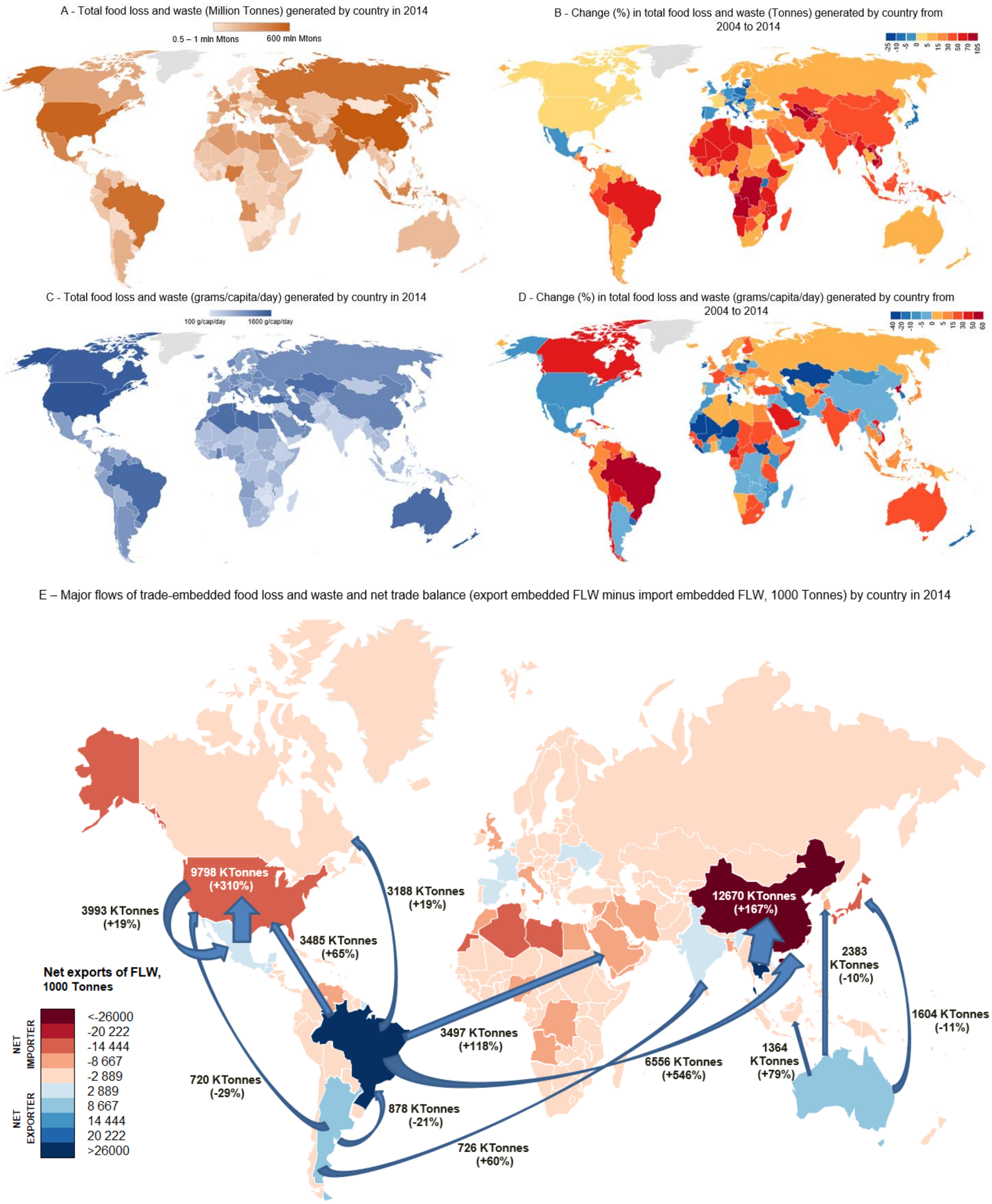

Figure 2.2. Total food loss and waste generation (Million Tonnes), per-capita food loss, and waste generation (grams/capita/day) and trade-embedded food loss and waste by country. Estimates reported in the figure refer to FLW generation and are specified in different metrics according to the panel. Panel A illustrates the total FLW generation (Million Tonnes) by country in 2014. Panel B illustrates changes (%) in total FLW generation by country in the time period between 2004 and 2014. Panel C reports FLW generation (grams/capita/day) by country in 2014. Panel D illustrates changes (%) in grams/capita/day FLW generation between 2004 and 2014 by country. Finally, Panel E illustrates major global flows of trade-embedded FLW across global regions (1000 Tonnes and change (%) with respect to 2004), additionally indicating FLW-related trade balances (exports of FLW minus imports of FLW) across regions. The arrows reported in the figure illustrate the direction of the net FLW flows linked to the food trade in 2014. An arrow from country A to country B indicates that country A is a net exporter of food, hence FLW, to country B. For illustrative purposes, the size of the arrows does not necessarily reflect the magnitude of FLW flows. For this, please note that magnitudes (1000 Tonnes) and percent changes (between 2004 and 2014) are reported next to each arrow.

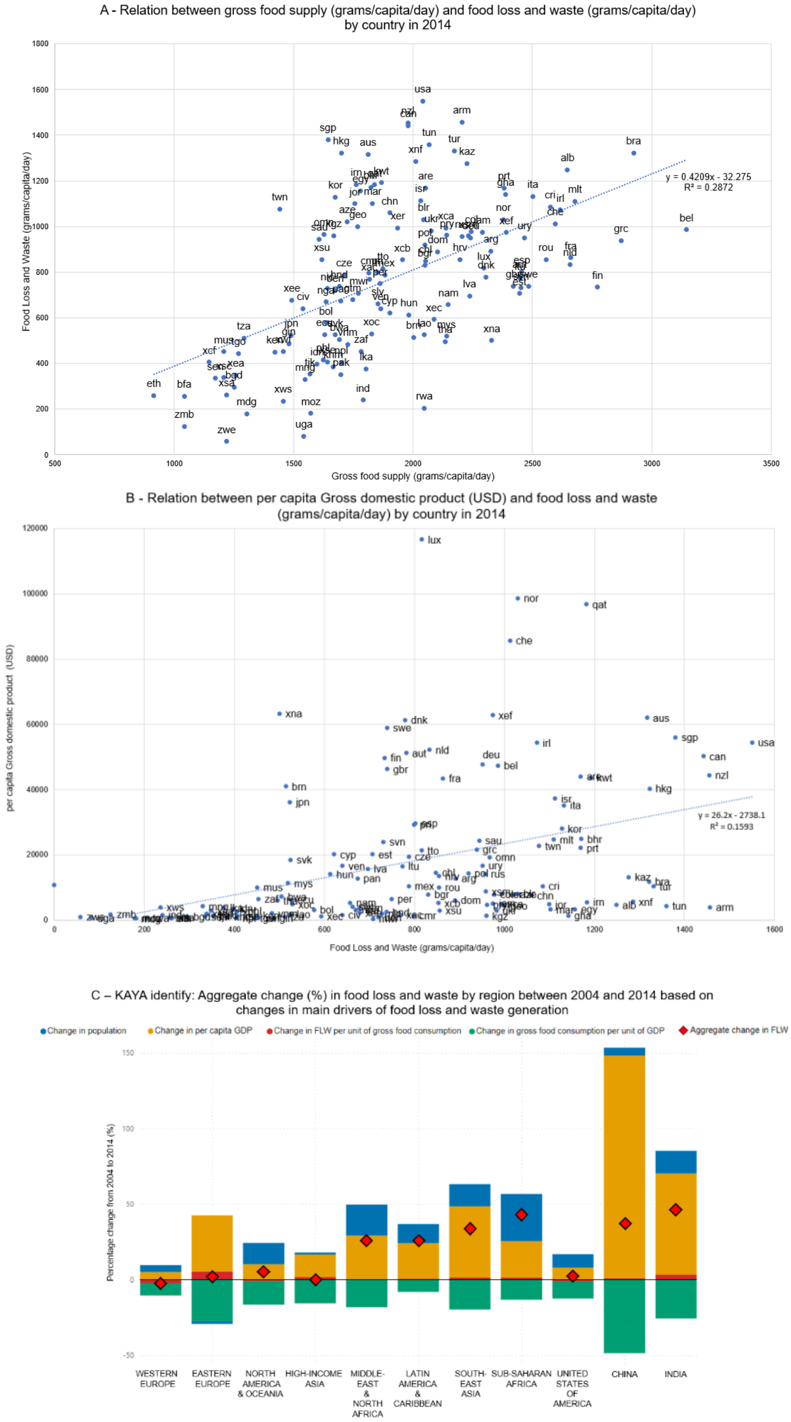

Figure 2.3. Relation between food loss and waste, gross food supply and gross domestic product by country in 2014 and changes in food loss and waste based on KAYA identity from 2004 to 2014. Panel A illustrates the relation between food loss and waste generation (grams/capita/day) and gross food supply (grams/capita/day) by country in 2014. Panel B reports the relation between food loss and waste generation (grams/capita/day) and per-capita gross domestic product (GDP) by country in 2014. In Panel A, estimates of gross food supply match the estimates reported in the FAO Food Balance Sheets. In Panel B, per-capita GDP estimates are derived from (Aguiar et al., 2019). From Panel A and Panel B is possible to observe that higher availability of food (gross food supply) and an averagely higher income per capita (GDP-per capita) are direct drivers of FLW generation in 2014. In Panel B, the relatively lower R^2 value is influenced by small high-income countries (Luxembourg, Switzerland, Qatar, Norway) in which FLW generation appears to be lower due to differences in the composition of food consumption and varying FLW shares across commodities. Finally, Panel C reports a KAYA identity illustrating percent changes in food loss and waste from 2004 to 2014 by region based on changes in the main drivers of food loss and waste generation. 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 (see for example IPCC, 2007; Yang et al., 2020; Peters et al., 2017). While "changes in population" and changes in per-capita GDP" are kept the same, variables such as "carbon intensity" and "energy intensity" have been readapted to our specific study case in the form of "FLW intensity" i.e. FLW generated per unit of food consumed, and "food intensity" i.e. changes in gross food consumption per unit of GDP.

Nutritional and environmental losses embedded in food loss and waste along global food supply chains

The increasing magnitude of global FLW results in growing amounts of nutritional losses along global supply chains. On average, 775 calories/capita/day are lost or wasted along FSC at the global level (Table 1). The highest loss of calories are observed in high-income regions, in particular, in North America (an average of 1960 calories/capita/day), Australia (1316 calories/capita/day), and New Zealand (1454 calories/capita/day) where high intakes of animal-sourced foods (ASF), processed foods, and sugars, enlarge the calorie content of FLW (Panel A - Figure 2.4). Large amounts of calorie losses also occur in Latin America (mainly Brazil – an average of 1500 calories/capita/day) and North Africa (an average of 1600 calories/capita/day), where production of calorie-rich foods such as oils, oilseeds, and sugar beet/cane exacerbates the loss of calories along the FSC. Inadequate calorie intakes in food insecure regions coupled with relatively high consumption of calorie-poor foods result in lower nutritional losses in Sub-Saharan Africa (an average of 527 calories/capita/day) and Southeast Asia (an average of 571 calories/capita/day). Calculations of net calorie intakes by country and the distribution of lost calories across stages of the FSC are available in the Supplementary Information (Table S17). Between 2004 and 2014, calorie losses have increased primarily in North Africa (an average of 14.6%) and South-central Africa (an average of 16.7%). These have been driven by increasing food consumption and/or rising volumes of food exports (Panel B - Figure 2.4). Similarly, calorie losses have also increased in Brazil (an average of 23.2%) and Southeast Asia (including China and India) (an average of 30.1%), while declining in North America (an average of 2.4%) and Europe (an average of 1.8%). The latter has been largely associated with a reduction in the contribution by calorie-rich oilseeds within total FLW.

On average higher consumption of protein-rich ASF in high-income countries results in a higher concentration of protein losses along FSC (Panel C - Figure 2.4). The largest amounts of proteins embedded in FLW are observed in North America (an average of 57.6 grams of proteins/capita/day), high-income Oceania (an average of 57.9 grams of proteins/capita/day), and Europe (including Russia) (an average of 56.1 grams of proteins/capita/day). Differently, high shares of cereals and plant-based products in the diets of households in low-income countries result in lower losses of proteins. In particular, in Sub-Saharan Africa, the average loss of proteins is 6.0 grams of proteins/capita/day – almost ten times lower than in many high-income economies. Across the analysed time frame protein losses have primarily increased in East and Southeast Asia (an average of 16.4%) while showing a moderate decline in North America (an average of -3.2%) and Europe (an average of -2.1%) (Panel D - Figure 2.4) due to an increase in shares of protein-poor plant-based FLW within total FLW.

Losses of fats (Panel E – Figure 2.4) follow the average trend observed for calorie losses and are largely concentrated in high-income regions such as North America (an average of 72.3 grams of fats/capita/day), high-income Oceania (an average of 61.0 grams of fats/capita/day), Europe (an average of 39.4 grams of fats/capita/day), and Middle-East (an average of 33.1 grams of fats/capita/day). Contrarily, lower amounts of fats embedded in FLW are observed in regions where average food intakes are lower, particularly in Sub-Saharan Africa (an average of 3.4 grams of fats/capita/day). A severe increase in per-capita fats losses is observed in Brazil (104.2%) and South-central Africa (an average of 70.6%) due to the increasing production of oilseeds and a relatively high intake of sugars.

While losses of carbohydrates have similar geographical distribution compared to other macronutrients (Panel G - Figure 2.4), their volumes have been decreasing over time in most regions (Panel H – Figure 2.3). A change in average global diets away from cereals and starchy vegetables (often rich in carbohydrates and abundant in lower-income regions' diets) and towards ASF (with lower carbohydrate content) has reduced the total amounts of carbohydrates embedded in FLW. This is particularly noticeable in Sub-Saharan Africa where losses of carbohydrates decreased by an average of 22.2% since 2004. Upward trends of carbohydrates embedded in FLW are instead observed in Eastern Europe and Western Asia (an average of +4.2%) where large volumes of exports of carbohydrates-rich foods (i.e. cereals) impact the loss of nutrients along FSC. In 2014, losses of carbohydrates were primarily concentrated in North Africa (an average of 310.4 grams of carbohydrates/capita/day), North America (an average of 261.5 grams of carbohydrates/capita/day), and the Middle East (an average of 274.3 grams of carbohydrates/capita/day). Low-income regions such as Sub-Saharan Africa (an average of 80.5 grams of carbohydrates/capita/day) and Southeast Asia (an average of 105.6 grams of carbohydrates/capita/day) are associated with the lowest amounts of carbohydrates losses, which is primarily driven by the low levels of per capita food consumption.

In what follows, we briefly summarize the environmental footprints embedded in global FLW. Additional country-specific information, figures, and data are available in the Supplementary Information. In 2014, around 19.7% of global agricultural land was used to produce food that was lost or wasted along the FSC (Table 1). Areas of the land use embedded in FLW are large in major agrifood-producing regions such as Latin America & Caribbean and Southeast Asia. In the case of Sub-Saharan Africa the level of land use embedded in FLW is relatively high due to the relatively low efficiency of agricultural production. Between 2004 and 2014, global land use embedded in FLW increased by 4.4% (see Panel B - Figure S2 in the Supplementary Information) with the largest increases observed in Latin America & Caribbean (an average of 25.2%), Central Asia (an average of 12.5%), and Southeast Asia (an average of 14.4%).

Around 19.8% of the global water used for food crops is embedded in lost or discarded food along the supply chains (Table 1). Similarly to land-use, the largest amounts of water use embedded in FLW are observed in large agricultural-producing regions such as Southeast Asia and North America & Oceania. In Europe, a relatively high agricultural production efficiency, as well as different crop mix and geographical conditions, result in low levels of water use per ton of food produced. Low amounts of FLW and limited water availability in Sub-Saharan Africa, act as key drivers for reducing water footprints of the FLW in this region. Despite the relatively low water intensity of the FLW in selected countries and regions, between 2004 and 2014 global FLW-embedded water use increased substantially – by 33.6% (see Panel D - Figure S2 in the Supplementary Information). In relative terms, major growth in this environmental indicator has been observed in Central and Southern African countries (an average of 77.5%) and in Central-East Asia (an average of 57.5%) further exacerbating the burden of water scarcity in these developing economies.

Finally, global greenhouse gas (GHG) emissions generated in the production of food that is lost or discarded along the FSC in 2014 amount to 1.8 billion Tonnes of CO2 equivalent accounting for around 4.4% of global GHG emissions (Table 2.1). The largest amounts of FLW-embedded GHG emissions were generated in Southeast Asia, North America & Oceania, and Sub-Saharan Africa. Compared to 2004, GHG emissions embedded in FLW increased by an average of 8.5%. In relative terms, the growth took place primarily in low-income regions such as Sub-Saharan Africa, Southeast Asia, and Latin America & Caribbean (see Panel F - Figure S2 in the Supplementary Information). On the other hand, decreasing trends were observed in Europe (average -29.1%), North America & Oceania (-7.9%), and East Asia (excluding China) (average -25.3%). These patterns are associated with changing composition of FLW, wherein the share of plant-based foods has increased as compared to (the more GHG-intensive) animal-based products, leading to a reduction in emissions embedded within discarded or lost food.

Table 2.1. Nutritional and environmental pressures of global food loss and waste by region in 2014.

	Gross energy supply* (kcal/cap/day)	Loss of calories embedded in FLW (kcal/cap/day)	Total Land use (1000 ha)	Land use embedded in FLW (1000 ha)	Total Water-use (billion m^3)	Water use embedded in FLW (billion m^3)	Total GHG-emissions (Million Tonnes of CO_2 equiv.)	GHG emissions embedded in FLW (Million Tonnes of CO_2 equiv.)
European Union – 27	3,652	1,018 (27.9%)	208,219	38,170 (18.3%)	139.9	27.1 (19.4%)	4,392	189.3 (4.3%)
North America & Oceania	3,815	1,457 (38.2%)	581,889	158,352 (27.2%)	263.1	66.7 (25.4%)	7,451	290.8 (3.9%)
Hi-Income Asia	3,029	985 (32.5%)	112,856	18,554 (16.4%)	134.0	38.8 (29.0%)	2,585	76.9 (3.0%)
Rest of Europe & Central Asia	3,387	1,025 (30.3%)	504,407	99,582 (19.7%)	192.6	37.7 (19.6%)	3,624	168.8 (4.7%)
Middle East & North Africa	3,475	1,035 (29.8%)	564,967	108,630 (19.2%)	427.3	116.9 (27.4%)	3,478	151.3 (4.4%)
Latin America & Caribbean	3,418	954 (27.9%)	604,908	100,665 (16.6%)	208.6	47.4 (22.8%)	3,283	205.1 (6.2%)
Southeast Asia**	2,953	621 (21.0%)	1,159,065	179,150 (15.5%)	1,866.7	308.1 (16.5%)	15,681	595.8 (3.8%)
Sub-Saharan Africa	2,749	591 (21.5%)	905,088	212,557 (23.5%)	126.0	19.8 (15.8%)	1,941	208.3 (10.7%)
Global	**3,116**	**775 (24.9%)**	**4,641,401**	**915,662 (19.7%)**	**3,358.3**	**662.9 (19.8%)**	**42,438**	**1,886.7 (4.4%)**

***** Regional average weighted on country population and matching FAO-Food-Balance-Sheets gross energy supply estimates.
** Including China and India.

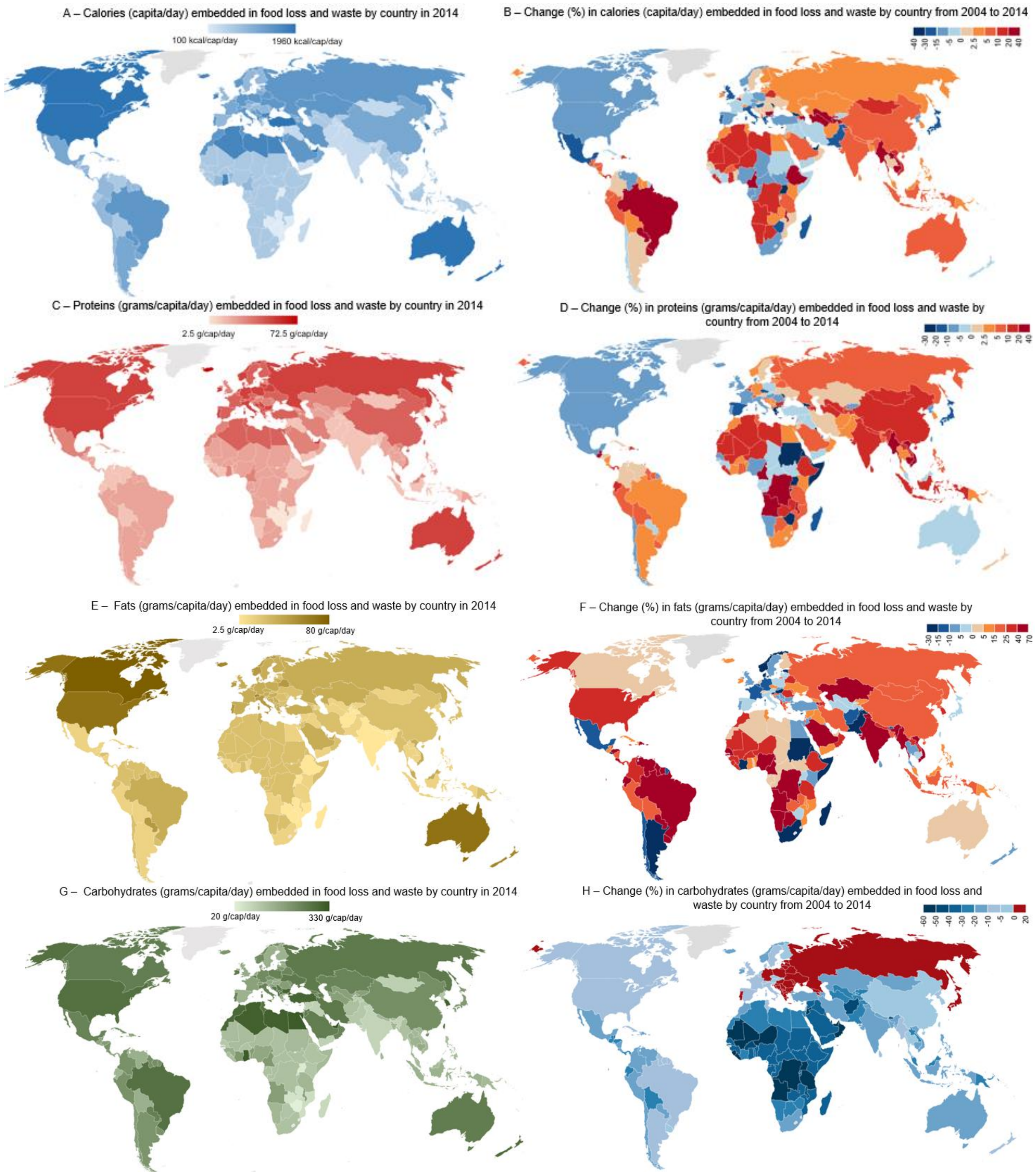

Figure 2.4. Nutritional composition of FLW (grams/capita/day) generated along global FSC.
Estimates reported in the figure refer to the amount of macronutrients (capita/day - calories and grams of macronutrients) embedded in lost or discarded food (grams/capita/day). Panel A illustrates the total amount of calories (capita/day) embedded in FLW generated by countries in 2014. Panel B illustrates the change in the total amount of calories (capita/day) embedded in FLW generated by the country from 2004 to 2014. Panels C, E, and G report respectively the total amount of proteins (grams/capita/day), fats (grams/capita/day), and carbohydrates (grams/capita/day) embedded in FLW generated by the country in 2014. Finally, Panels D, F, and H illustrate the change in the total amount of macronutrients (respectively proteins, fats, and carbohydrates - grams/capita/day) embedded in the FLW generated by the country from 2004 to 2014. The magnitude and composition of lost and discarded food are two key drivers of nutritional losses along global FSC. On average, as higher income regions have relatively higher food consumption rates, with large shares of animal-sourced foods and sugars, losses of nutrients result more severe. However, changing dietary composition and higher food intakes across our analysed time frame result in increasing nutrient losses for lower-income regions, especially in calories, proteins, and fats in sub-Saharan Africa.

2.3 Discussion

Our study shows that from 2004 to 2014, a larger and richer population intensified the nutritional and environmental pressures caused by FLW. We estimate that between one-third and one-fourth (1.92 billion Tonnes) of food produced for human consumption was lost or wasted in 2014. This estimate is higher than the 1.3 billion Tonnes estimated by Gustavsson et al. (FAO, 2011), as we consider the entirety of food commodities, not just the edible shares of food products. We find key hotspots of FLW generation in Agricultural Production and Post-Harvest Handling & Storage in low- and middle-income countries and at the Consumption stage in high-income regions. These findings align with previous studies (Parfitt et al., 2021; UNEP, 2021; Verma et al., 2020; WRI, 2019) and support the need for policy interventions at the farm level in low- and middle-income countries and at the consumer level in high-income countries (FAO, 2011, 2019; Kaza et al., 2018).

While the diverging computational methodologies in the FAO-FLW database hinder a direct comparison with our estimates, cross-check analyses can be performed with selected country/region-level studies. For the case of EU27, Caldeira et al. (2019) report approximately 130 million Tonnes of FLW along the FSC, which is consistent with our estimate of 140 million Tonnes. According to the same study, primary production losses amount to 32.2 million Tonnes, which is close to our estimate of 33.0 million Tonnes. In Latin America & Caribbean, FAO (2022) reports around 220 million Tonnes of FLW, matching our estimate of 222 million Tonnes. For Sub-Saharan Africa, Lipinski et al. (2013) report an average of 545 calories/capita/day lost or discarded along the FSC. This is in alignment with our estimate of 591 calories/capita/day, with our number being slightly higher due to the inclusion of inedible food parts in the FLW calculation, while Lipinski et al. (2013) only consider the edible food parts.

To facilitate the comparisons with the OECD Food waste database (OECD, 2021), given the limited geographical coverage of this data source, we are focusing on selected representative countries for each continent. In Mexico, the OECD reports around 8 million Tonnes of food waste, closely matching our estimate of 7.6 million Tonnes. Similarly, for Turkey, the volumes are 11 million Tonnes (OECD-reported) and 10.8 million Tonnes (estimated here), while for Japan these are 2.9 (OECD) and 3.1 (this study) million Tonnes. Further comparisons were done with respect to the single countries with high-confidence data reported by the UNEP (2021). In China, 160 million Tonnes of food waste are reported well-aligning with our estimate of 166 million Tonnes. Our estimate of total FLW in China (527 million Tonnes) is significantly higher than that of Xue et al. (2021), who report 349 million Tonnes but use a different FLW definition, considering only edible food parts. For the United Kingdom and Australia, UNEP (2021) reports 6.3 million Tonnes and 3.5 million Tonnes of food waste, respectively, in line with our estimates of 7 million Tonnes and 4.3 million Tonnes. Similarly, for Saudi Arabia, our estimate of 0.7 million Tonnes of food waste closely aligns with the 0.67 million Tonnes reported by UNEP (2021). Lastly, for the United States, we estimate approximately 67 million Tonnes of food waste, consistent with the EPA (2023) study, which reports 62-66 million Tonnes of food waste.

With respect to global-average nutritional losses, we estimate a loss of 277 calories/capita/day embedded in food waste (excluding food losses), closely aligning with the 273 calories/capita/day reported by Chen et al. (2020). Food waste-related protein losses amount to an average of 9.8 grams/capita/day, consistently lying within the range of 2.6-32.8 grams/capita/day provided by Brennan & Browne (2021). Similarly, we find losses of carbohydrates embedded in food waste to be an average of 39.2 grams/capita/day, falling within the range of 10.5-146.4 grams/capita/day reported in Brennan & Browne (2021), Khalid et al. (2019), and Spiker et al. (2017). Finally, losses of fats are estimated to reach 8.5 grams/capita/day in 2014 aligning with the 2.1-57.2 grams/capita/day range provided in Brennan & Browne (2021), Khalid et al. (2019), and Spiker et al. (2017).

Our study reveals that across years the FLW has been increasing particularly rapidly for horticulture, cereals, and sugar beet/cane at the early stages of the FSC, resulting in a growing share of non-processed plant-based biomass within total FLW. While presenting a concerning trend, this also highlights a major opportunity for implementing circularity practices within the food system. Compared to the animal-based sources, plant-based FLW offers a broader range of reuse possibilities (Parfitt et al., 2010), creating opportunities to use the lost and discarded food as feed for livestock (van Hal et al., 2019) or as a fertilizer for crop production (de Boer & van Ittersum, 2018).

An expansion of domestic and international markets has increased the share of food losses associated with traded food (leakage effect). While farm-level losses are mainly located in low- and middle-income countries, substantial portion of these losses are linked to food consumption in high-income regions. This further increases social and environmental pressures in low- and middle-income countries, where the lack of proper infrastructure and technologies hampers the opportunities for the FLW reuse (Kaza et al., 2018). At the same time, high-income regions that have better FLW reuse infrastructure, now have less opportunities to benefit from this as they increase reliance on food imports from developing countries, thus 'outsourcing' the FLW abroad. And while FLW reuse still represents a valid option for high-income economies it should be noted that substantial amounts of food waste available for reuse may remain largely unemployable due to the current food-safety laws (Toma et al., 2020).

Our results suggest that global losses of macronutrients have increased over time. The only exception includes carbohydrates, which losses have decreased due to a shift in global dietary patterns away from cereals and starchy vegetables (rich in carbohydrates) and toward ASF. Calorie and protein losses have increased primarily in low-income regions such as Southeast Asia, North Africa, and Sub-Saharan Africa, posing a major challenge to food security. In absolute terms, nutritional losses are concentrated in high-income regions where overconsumption of ASF results in large amounts of protein losses, particularly at the final stages of the FSC. We also find that the Agricultural Production is found to be the single largest hotspot for losses of calories across regions (318 calories/capita/day), thus implying that interventions to improve agricultural production efficiency, especially in low-income countries, can significantly aid food security.

The need for interventions in agricultural production to decrease food losses is additionally supported by the fact that almost 20% of the global agricultural land and water used for growing crops is dedicated to producing food that is ultimately lost or discarded. Our results suggest that the land used for agricultural production and embedded in FLW has been increasing particularly substantial in low-income regions, such as sub-Saharan Africa. While food exports can be a major source of income in many developing countries, such trends have the potential to exacerbate the burden of land used to produce food that is ultimately wasted. To address this issue, technological improvements to assist agricultural production efficiency and conservation procedures at the post-harvest handling & storage stage may increase land productivity and improve ratios of land use per ton of production. This, in turn, could potentially free up additional land for increasing domestic food supply and ultimately contribute to improved food security and economic prosperity in these regions.

Similarly, the concerning trend of increasing water use embedded in FLW, particularly in Central and Southern African countries and Central Asia, advocates for policy interventions aimed at reducing the water footprint of FLW. In this regard, measures to improve water use efficiency in agriculture, reduce food waste at the producer level, and incentivize the recovery and reuse of food waste as animal feed or for energy sources are among most promising options. Additionally, the support of sustainable agricultural practices (and water management), such as agroforestry and conservation agriculture, may serve as efficient adaptation strategies, reducing water demand while promoting resilience to climate change.

Considering future population trends (U.N., 2022), our analysis indicates that FLW generation may have a greater impact on food security, particularly in lower-income regions such as Sub-Saharan Africa and Southeast Asia, where population and per-capita GDP are expected to increase significantly. Policies and strategies aimed at reducing FLW need to consider the complex interplay between food production, trade, consumption patterns, and their social and environmental impacts. Given the significant role of final food demand in driving FLW, policies must encourage sustainable consumption patterns. Our findings show that processed foods, especially from animal sources, are the main contributors to nutritional losses and represent a substantial share of the environmental footprint of FLW. Therefore, policies should prioritize targeting the production and consumption of these products. To reduce overconsumption in high-income regions and achieve SDG12.3 targets, policies such as price mechanisms (taxation) should be considered, which could reduce health and environmental burdens (Springmann et al., 2018; Willet et al., 2019) while simultaneously lowering farm-level losses in exporting low- and middle-income regions. While accepting a certain level of FLW is inevitable for global food security, policy interventions should promote the reuse of FLW as animal feed, supporting ASF production in low-income regions, which is crucial for fighting malnutrition. Additionally, plant-based FLW should be promoted as a production input across food and non-food sectors, supporting more sustainable economic growth. Lastly, policies should continue to focus on improving agricultural production efficiency in low- and middle-income countries, while also supporting the profitable reuse of unavoidable FLW as a production input.

As usual, these findings are subject to limitations and potential extensions. The main methodological limitation lies in the application of fixed food loss and waste shares across reference years. Despite shares of FLW are relatively stable across years (Fabi & English, 2018), we do not investigate how FLW rates may respond to changes in economic structure or income within the considered time frame. Additionally, as we derive FLW shares from current literature, the lack of representative high-quality FLW data (Delgado et al., 2021) is particularly apparent for low- and middle-income regions, especially at the final stages of the FSC. For this, the application of a consistent gap-filling procedure based on FLW shares in comparable regions urges a careful utilization and interpretation of our database as data assumptions and aggregations may impact the magnitude of estimates. As we aggregate data through physical mass, our methodology does not allow a direct assessment of SDG12.3, for which an indicator based on economic weights (Fabi & English, 2018) is adopted as a quantification approach. Data limitations become evident when the best available FLW estimates across different supply and use stages are combined with gross per-capita food intakes at the country level. In particular, we find that in several low- and middle-income countries, the resulting net intakes are unrealistically low and thus the FLW shares had to be adjusted downward. While the corresponding issue has been identified only in a small subset of countries, future research should focus on conducting detailed and comprehensive surveys at the country level aiming at improving the consistent quantification of the FLW at different stages of the supply chain. In this, further research could expand the nutritional analysis of FLW, integrating a consistent estimation of lost micronutrients embedded in FLW, which is crucial for devising policies towards food security. Finally, future research should focus on understanding the variation in food quality across countries and uses. Currently, the lack of global-level data on food quality presents a major challenge in assessing the differences in products meant for exports and those for domestic consumption, hindering a more detailed analysis of the FLW composition and its reuse opportunities.

Despite the identified limitations, we believe that the assessment presented here addresses an important knowledge gap by providing a comprehensive analysis of FLW generation along the global FSC, improving on the methodological consistency of the earlier studies. A detailed database with FLW quantification across 141 countries and regions developed in this study can serve as a starting point for future multidisciplinary investigations into FLW, particularly with regard to supporting policies for a more sustainable food system. One promising avenue for future research would be to build upon our database and model the dynamic effects of FLW reduction and reuse policies on both nutritional security and environmental sustainability. Such an approach would further aid policymakers in designing effective and holistic strategies to address the issue of FLW toward a more sustainable global food system.

2.4 Methods

An economic framework for tracing biomass flows along global supply chains

With post-farmgate food value chains representing over 80% of food-related expenditures in many country cases (Yi et al., 2021), it is important to trace food flows beyond the farm gate in order to properly capture the environmental, social, and economic dimensions of the related FLW flows. To achieve this, we rely on the approach developed by Chepeliev (2022). The method traces quantities of food, calories, fats, proteins, and carbohydrates along the value chains of the global multi-region input-output Global Trade Analysis Project (GTAP) Data Base (Aguiar et al., 2019). We rely on the latest publicly available version 10 of the GTAP Data Base with the 2014 reference year, which has 141 regions and 65 sectors (Aguiar et al., 2019). To provide a more consistent representation of the output of agricultural sectors we apply a special procedure of the FAO-based agricultural production targeting following Chepeliev (2020). This approach allows to better target the values of agricultural output across GTAP sectors providing better harmonization between GTAP and FAO agricultural accounting (see Supplementary Information for additional details on the procedure). We further rely on the FAO food balance sheets (FBS) data and nutritive factors to estimate the nutritional content of primary commodities and derived commodities represented in primary commodity equivalents within FBS. Calories, fats, proteins, and carbohydrates are estimated and reported. We identify use categories that account for food, feed, seed, losses, and other uses. In terms of the food supply, we identify GTAP primary commodity sectors, food processing sectors, and service sectors that supply food. To trace nutritional data by GTAP sectors, we construct Leontief inverses, operating only over those sectors (and uses) that supply food. Such inverses are constructed separately for the tracing of domestic, exported, and imported commodities. Constructed nutritional database (GTAP-FBS) provides food and biomass flows that are fully consistent with FAO's FBS accounting framework.

Tracing food loss and waste along global food supply chains

To quantify FLW along global supply chains, we compile a new global FLW database. By considering entire food commodities (i.e. edible and non-edible parts) and excluding non-food biomass flows (i.e. feed, seed, and biomass used for industrial purposes) from FLW, we overcome broadly debated methodological inconsistencies of available FLW estimates (Delgado et al., 2021), providing a consistent alternative to the heavily criticized (Sheahan & Barrett, 2017; Xue et al., 2017) estimates from Gustavsson et al. (FAO, 2011). We define five stages of the FSC to quantify FLW at each stage of the global FSC. We collect data for eight commodity groups covering cereal crops, horticulture, and animal-sourced foods. The core of our database is the FAO–FLW database (FAO, 2019). From the FAO-FLW database, we select estimates on physical percentage shares of lost and discarded food along different stages of global FSC. As physical (Tonnes) FLW estimates often do not account for potential variations in food production related to evolving economic and environmental factors, we build our FLW database focusing on percentages of lost and discarded food, as such estimates are more consistent across years (Fabi & English, 2018). We perform a literature review on the coverage limitations of the FAO-FLW database, principally building on previous reviews (Porter et al., 2016; OECD, 2021; Xue et al., 2017). First, we collect sources reporting, among other typologies of FLW data (i.e. physical FLW, monetary FLW, etc.), estimates on percentages of loss/waste within total food quantity. Following, we further filter gathered sources by methodology, maintaining only data computed consistently with our FLW definition. Finally, we select sources providing estimates specifically missing in the FLW-FAO database. Here, we distinguish between macro and micro approaches, giving priority to estimates reported for macro commodity groups (e.g. fruit & vegetables) or geographical regions (e.g. Europe). An overview of the outcome of our literature review on shares of FLW, and the enhanced data coverage with respect to the FAO-FLW database is provided in Figure 2.5 below. Further details and the adopted shares of lost and discarded foods along global supply chains and are provided in the Supplementary Information.

Figure 2.5. Overview of the global data coverage (shares (%) of FLW) of the constructed database by commodity, region, and supply chain stage, and data coverage comparison with the FAO-FLW database (2019). The figure illustrates the outcomes of our literature review on estimates reporting shares (%) of FLW along food supply chains, comparing the availability of estimates with respect to the FAO-FLW database. EU = Europe; NAMO = North America & Oceania; HI-ASIA = High-income Asia; LAC = Latin America & Caribbean; MENA = Middle East & North Africa; SEA = Southeast Asia; SSA = Sub-Saharan Africa.

From the GTAP-FBS database, we derive gross food biomass supply in physical quantities (Tonnes) along global supply chains. We trace food biomass from production to final consumption, quantifying physical flows of commodities through different food sectors before reaching final consumers. In the GTAP-FBS database, we distinguish three main stages of the food supply chain i.e. primary production, intermediate production, and final consumption. Primary production consists of agricultural production of primary food commodities i.e. food produced at the farm level. Differently, intermediate production represents non-primary food production, i.e. food produced by processing sectors that receive primary agri-food products and process them into final products. Finally, the final consumption consists of household food consumption of both primary and processed food commodities. In the GTAP-FBS framework, primary production coincides with the outputs of primary agricultural sectors while intermediate production and final consumption are respectively quantified by intermediated food demand from food sectors and final food demand from households. To trace FLW along global food supply chains we link our FLW database to food supply derived from the GTAP-FBS database. To do so, we combine the three stages of the GTAP-FBS database with the five supply chain stages available in our newly compiled global FLW database, identifying FLW amounts at each stage of global FSC. Agricultural Production and Post-Harvest Handling & Storage stages are associated with primary production in the GTAP-FBS database, while Manufacturing and Consumption stages are linked respectively to intermediate food production and final consumption. From the GTAP-FBS database, it is not possible to explicitly quantify physical flows related to food distribution and retailing. For this, we assign our Distribution & Retail stage in the FLW database to food flows flowing from intermediate production to final consumption i.e. from Manufacturing to Consumption.

In merging FLW shares we assume that physical amounts of food flows decrease after each supply chain stage. This entails that shares of food products are lost or discarded at different stages and food flows enter the next stage net of losses that occurred in previous stages. As final consumers demand primary and processed food, we distinguish between food flows entering the manufacturing stage (i.e. consumed as processed) and foods not entering the manufacturing stage (i.e. consumed as fresh). Moreover, as in the GTAP-FBS framework households consume food via food services – out-of-home food consumption (e.g. restaurants, hotels, etc.), we further trace food consumed via food services as fresh (not entering manufacturing) or processed (entering manufacturing) properly quantifying losses at manufacturing stages based on the consumption of final products. Finally, we attribute trade (transportation) losses to importing regions, assuming food spoiled or damaged during transportation will be physically available and possibly treated within the importing region. Figure 2.6 below illustrates the methodological framework used to merge our FLW database into the GTAP-FBS database. Additional information on merging FLW estimates into the GTAP framework is available in the Supplementary Information. With this approach, we trace and quantify FLW in physical units (Tonnes), consistently accounting for global food and non-food trade, and the economic behaviour of agents along global supply chains. These results are particularly determinant for defining the geographical location of generated FLW as food consumption in one region can result in the generation of food losses in other regions. Moreover, we define processed foods and food services in primary equivalents, accounting for the region-specific heterogeneous composition of non-primary foods. Finally, as in the GTAP-FBS database nutritional data is obtained from the FAO-FBS, we account for the differences in nutritional contents of primary and processed foods across global regions, consistently quantifying the heterogenous nutritional composition of FLW.

To quantify the environmental footprint embedded in FLW flows we use land use data from (Baldos, 2017) which incorporates estimates from FAOSTAT and EARTHSTAT. Water use data is derived from (Haqiqi et al., 2016) and AQUASTAT while GHG emissions data are obtained from (Aguiar et al., 2019; Chepeliev, 2020). In our approach, we assume that water, land, and GHG emissions have been used/generated for the production of food products that will be successively lost or discarded. First, we quantify the amount of GHG emissions, land use, and water use embedded in the primary production of food products. Following, we compute the amount of lost and discarded foods associated with food consumption and proportionally compute the amount of environmental footprint embedded in FLW flows. To trace amounts of environmental impacts associated with FLW we adopt a full multi-region input-output (MRIO) based accounting, identifying resource use and GHG emissions along global supply chains according to the geographical location of different production/consumption stages. As we account for different food production intensities in the countries around the world, FLW-embedded emissions reflect the type of food production system adopted within a specific country. The full database containing the magnitude, composition, and location of global FLW, as well as nutritional and environmental losses embedded in FLW by country/region is available in the Supplementary Information.

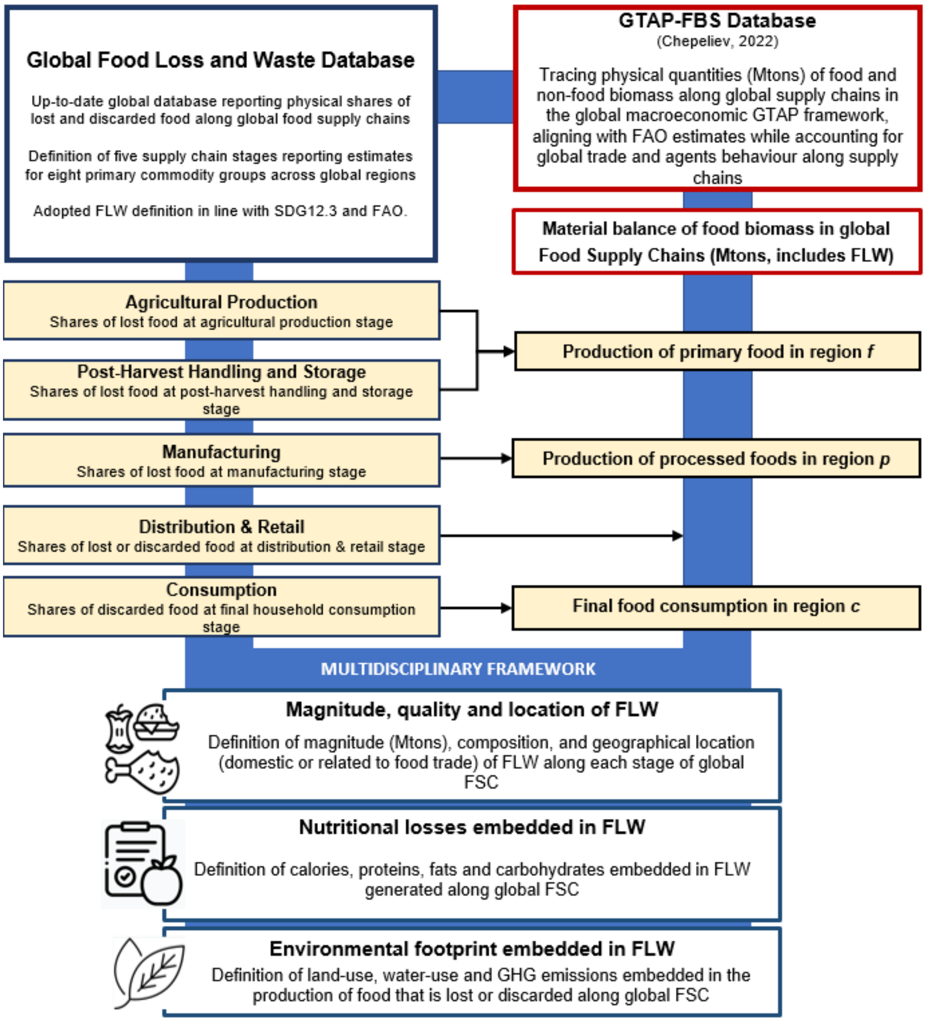

Figure 2.6. Methodological framework adopted to trace food loss and waste along global food supply chains.

Supplementary Information for

New Estimates of Food Losses and Waste Along Global Supply Chains Show Increasing Nutritional and Environmental Pressures

Contents

Global Trade Analysis Project Data Base with extended agricultural production targeting

One of the key features of the Global Trade Analysis Project (GTAP) Data Base (Hertel, 1997) is the detailed representation of the agricultural sector. Since GTAP version 5, there are 12 agricultural and 8 food processing sectors included in the GTAP sector classification (Aguiar et al., 2019). Naturally, not all contributed input-output (IO) tables, which are used to develop the GTAP Data Base, have this level of agricultural and food sector representation. Under the current setup of the GTAP Data Base construction process, this issue is addressed in two ways.

First, a special agricultural and food IO table is developed (Peterson, 2016). It is based on the set of IO tables from representative countries as well as Food and Agricultural Organization (FAO) data and is used to split up the agricultural sector and related activities in the countries, which require disaggregation. Second, an agricultural production targeting (APT) procedure is applied to selected countries (Chepeliev & Corong, 2019). The purpose of this procedure is to adjust the IO tables to match the agricultural production targets mainly in the Organisation for Economic Co-operation and Development (OECD) countries and some large agricultural producers (53 countries in total). Key data are sourced from the OECD producer and consumer support estimates (PCSE) database (OECD, 2020) and provided by the Joint Research Center (JRC) for the EU countries in line with the OECD database estimates (Boulanger et al., 2019).

While providing a valuable contribution to the GTAP Data Base development framework, such approach to the APT has some limitations and potential for further improvements:

- First, following the OECD agricultural commodity classification, input data includes a high share of unclassified/undistributed[3] commodities (in some cases this category represents over 40%, like for China in 2011 or Chile in 2014), which should later be distributed among agricultural sectors, based on additional assumptions (OECD, 2020).
- Second, while covering 53 regions, production values represent around 84% of global agricultural output in 2014 but still miss most of the developing countries.
- Finally, currently used OECD data do not cover some agricultural commodities and as a result, processed food commodities' output is used to complement the dataset in those cases. For instance, sugar output is used to derive targets for sugar cane.

In an attempt to overcome these limitations, for the case of the 2014 reference year, we have implemented a revised approach to APT values estimation based on the FAO data and some additional data sources. Apart from addressing the aforementioned limitations in the production targeting, this approach provides a better opportunity for developing GTAP-consistent nutritional accounts, utilizing the available FAO data.

The implemented approach includes an estimation of the value of agricultural output for 133 countries and regions represented in the GTAP 10A Data Base. The data collection relies primarily on the FAOSTAT values of agricultural output at the commodity level, complemented by a combination of the FAO's quantity and price data, EUROSTAT, US Census of Agriculture and Crops outlook, United States Department of Agriculture, and selected other data sources. A detailed overview of the corresponding data sources is available in Chepeliev (2020).

With estimated values of agricultural output for 12 primary agricultural sectors covering 133 GTAP countries and regions, we re-target the value of agricultural output using the standard GTAP Data Base build procedures as discussed in Aguiar et al. (2019). Based on the comparison with national statistics of selected countries and estimates from reports by international organizations, such a procedure results in a more consistent representation

[3] Non-market price support (non-MPS) commodities under the OECD notation (OECD, 2009).

of the agricultural production patterns in countries around the world compared to the standard GTAP Data Base. For further details on the corresponding procedure an interested reader is referred to Chepeliev (2020). It should also be noted that starting from release 11 of the GTAP Data Base, this extended APT approach would be incorporated into the standard GTAP Data Base.

Tracing Food Loss & Waste along global food supply chains

To trace flows of food loss and waste (FLW) along global food supply chains (FSC) we adopt a full supply-chain approach, linking FLW estimates to the supply chain stages of countries where food is produced, processed and/or finally consumed (Figure S1).

From the constructed FLW database (see Data section, Tables A-H) we derive commodity- and country-specific shares of lost and discarded food along the FSC and define the following coefficient

$$FLW\_SHR_{c,d}^{r,g} \tag{1}$$

where *r* represents the country where losses or waste are generated, *g* represents a stage of the food supply chain at which the losses/waste are occurring,[4] *c* represents a primary food commodity being lost or wasted and *d* represents a dummy variable that has a value of “1” when a commodity enters the manufacturing stage (i.e. is finally consumed as a processed food product) and a value of “0” when it does not (i.e. is finally consumed as a fresh food product).

To quantify physical (Tonnes) food supply we retrieve information from the Global Trade Analysis Project Food Balance Sheets (GTAP-FBS) database (Chepeliev, 2022) defining a food supply coefficient as following

$$FOOD_{r,s,t}^{c,f,k} \tag{2}$$

where *c* represents a primary food commodity flowing into primary food, processed food or food services which provides information on the primary composition of non-primary foods, f represents the final food product (primary, processed or from food services) consumed by households, *k* represents a metric category on which the food supply is specified i.e. metric tons, calories, proteins, fats, or carbohydrates, *r* and *s* represent regional source (*r*) and destination (*s*) of the food supply (if *r* = *s,* food is produced and consumed domestically within a country), and *t* represents a reference year of food supply i.e. 2004, 2007, 2011 or 2014. The computation of equation (2) is available in (Chepeliev, 2022) and is briefly illustrated in the left side of Figure S1 below. The information provided in coefficient (2) is developed to match the physical and nutritional food supply estimates from the FAO Food Balance Sheets.

To quantify physical flows of FLW, we multiply the FLW coefficient (1) by the physical food flows represented by a coefficient (2), tracing FLW along global food supply chains as following

$$FLW\_FSC_{a,f,t}^{r,s,d} = FLW\_SHR_{c,d}^{r,g} * FOOD_{r,s,t}^{c,f,k} \tag{3}$$

where *r* represents the region where primary commodity *a* is produced (source region), hence where losses from Agricultural Production up to Distribution & Retail stages occur, *s* represents the region where final consumption occurs (destination region) hence where Consumption waste is generated, *f* represents the food commodity or food service consumed by final consumers in region *s* and to which primary food flows *a* are flowing to, t represents the stage of the supply chain at which losses are occurring and *k* represents a metric category i.e. metric tons, calories, proteins, fats, or carbohydrates.

[4] As discussed below, we consider the following FLW stages: (1) Agricultural production; (2) Post-harvest handling and storage; (3) Manufacturing; (4) Distribution and retail and (5) Consumption.

The five stages of the food supply chain defined from the developed FLW database in coefficient (1) are combined with the information obtained from coefficient (2). Agricultural Production and Post-Harvest Handling & Storage stages are associated with primary production, while Manufacturing and Consumption stages are linked to the intermediate/final food production and final demand, respectively. As a Distribution & Retail stage is not explicitly available from the material flows of equation (2) we allocate Distribution & Retail losses to food flowing from the Manufacturing to Consumption stage.

Since FLW data is mainly available in primary equivalents, we define the food supply within coefficient (2) in primary equivalents, applying (1) to primary food commodities as they flow to the point of final consumption (primary food, processed food or food service sectors). This allows us to avoid the double counting of losses/waste when a processed commodity is employed in the production of another processed commodity or food service along the supply chain. FLW data are from the perspective that the physical supply of a food commodity decreases after each supply chain stage, entering the next stage net of losses that occurred in previous stages. The definition of a dummy variable in (1) allows to divide between products consumed as processed and fresh, applying manufacturing losses only to the processed foods.

In cases where $r = d$ (the food commodity is produced and consumed in the same country/region), FLW is entirely generated domestically within a country. Differently, when $r \neq d$ food is produced in country *r* and consumed in country *s* hence FLW are attributed differently. If food is imported by *s* as fresh, farm-level losses i.e. Agricultural Production and Post-Harvest Handling & Storage losses are attributed to exporting country *r* (and not to the importing country *s*). If food is imported by *s* as processed, Manufacturing losses are also attributed to exporting country *r* (and not to the importing country *s*). Differently, if a product is imported by *s* as fresh and successively domestically processed, Manufacturing losses are attributed to the importing country *s.* As Distribution & Retail and Consumption stages are by definition linked to the point of consumption, waste generated at these stages is always attributed to the country where food is finally consumed. An attribution discussed above is used to link the country/region-specific FLW shares across stages (as estimated within the coefficient (1)) with the food flows along the global FSC. From the FLW tracing point of view, either consumption (attribution to the point of final consumption) or production (attribution to the point of production) approaches can be implemented for quantifying the related flows (of FLW and/or environmental impacts).

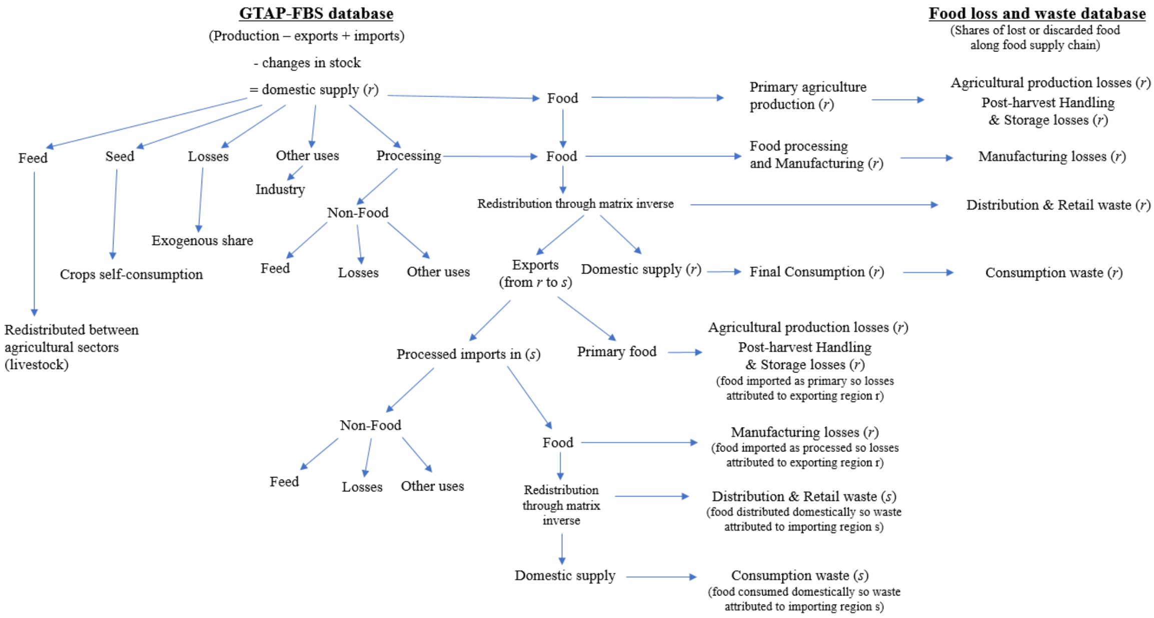

Figure S1. Methodological framework for tracing food loss and waste along global food supply chains.

Tracing emissions in the multi-region input-output (MRIO) framework

The relationship between the demand and supply sides in the global MRIO framework can be represented by the following equation:

$X = AX + (Y\mathbf{1})$,

where X is the vector of the output of commodity i in region s (with elements $x_{s,i}$); A is the matrix of technological coefficients with elements $a_{si,rj}$, which represent the cost share of commodity i supplied by region s used in the production process of commodity j produced in region r; Y is the matrix of final demand with elements $y_{s,i,r}$ corresponding to the direct final consumption of commodity i produced in region s and consumed in region r; **1** is the vector of "1" with a dimension r.

Solving for X we obtain the following:

$X = (I-A)^{-1}(Y\mathbf{1})$,

Where I is the identity matrix and $(I-A)^{-1}$ is the Leontief inverse, which represents the aggregate amount of direct and indirect inputs that are required to satisfy the one unit of final demand.

Assuming that the emission intensity of the output of commodity i in region s is given by $e_{s,i}$ and E is the vector of the corresponding emission intensities with the dimension of s x i, one can estimate the complete emission coefficient or the emission intensity of final consumption as follows:

$E_P = E(I-A)^{-1}$,

The (indirect) emission footprint of the final consumption (C) can then be estimated as follows:

$C_I = E_P Y$,

To calculate the total emissions embodied in final consumption one also needs to take into account direct emissions produced by final users, such as emissions from burning natural gas during the cooking process. Adding direct (C_D) and indirect (C_I) consumption emissions completes the consumption-based tracing of all emissions. With such an approach the consumption-based emission total ($C_D + C_I$) exactly matches the production-based (or territorial) emissions at the global level.

Food Loss and Waste Data

Food Loss and Waste Data

Definitions

We define FLW as "*food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses, and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products*". With this classification, we align with SDG12.3 considering only food produced for human consumption, including all food types, disposal routes and stages of the FSC. We consider the entirety of food products, including inedible foods parts. Including this (unavoidable) type of FLW we overcome a broadly debated (Delgado et al., 2021) on the methodological limitations of the FLW estimates in Gustavsson et al. (FAO, 2011). Moreover, we exclude from FLW food produced for other purposes than human consumption, to avoid counting biomass for biofuels or biobased industrial products as FLW. Finally, we report data as percentage losses of total food weight since the percentage estimates are more stable and representative across years (Fabi & English, 2018).

Database

Our literature review starts from the FAO-FLW database[5] (FAO, 2019). The FAO-FLW database predominantly covers low-income regions, with sub-Saharan Africa and South-East Asia having the most available data. Conversely, high-income regions such as Europe and North America & Oceania, and mid-income regions such as Latin America & Caribbean and North Africa & Middle East, present limited observations. This geographic focus results in a limited data availability for certain commodities and supply chain stages. Notably, losses are primarily reported at early stages of the supply chain, specifically Agriculture Production and Post-Harvest Handling & Storage, and mostly involve horticultural commodities and cereals, which are typically prevalent in low-income regions' diets. Furthermore, data is scarce for animal-sourced products, particularly in the final stages of the supply chain, such as Distribution & Retail and Consumption. Despite the extensive temporal coverage of the database (1945-2021), observations are concentrated between 2000 and 2017, with notable peaks between 2009 and 2011. Within the FAO–FLW database we use the standard data computation method building on edible and inedible shares of commodities, excluding other non-food biomass flows (i.e. feed, seed, etc.) from FLW[6]. To assure consistent FLW estimates we restrict additional data merged with the FAO-FLW data to sources using this method. We group FAO-FLW data in eight global regions, complemented with 3 single countries (China, India, and United States) defining eleven commodity groups produced along five macro-stages of the FSC. While this aggregation procedure influences detail in the final estimates it is necessary due to unavailability of data at single country/commodity level.

To address the coverage limitations of the FAO-FLW database we perform a literature review, building on previous reviews (Affognon et al., 2015; Porter et al., 2016; OECD, 2021; Xue et al., 2017) and gathering additional published and unpublished (grey) literature from 1960 to date. We perform a first literature screening based on the typology of data presented, selecting only sources reporting, among other typologies of data (e.g. physical quantities, monetary losses, environmental losses, quality losses, etc.), values indicating the percentage of the total weight of a food commodity lost or discarded along the supply chain.

Following, we apply a second screening based on the underling methodology used to compute FLW. First, we select only studies defining FLW consistently with our reference FLW definition. Second, we distinguish methodologies by the scale of approach. We intently discard studies conducted on a scale lower than the national, as studies on conducted on a regional or municipal level are often not comparable and their representativeness is highly sensitive to sampling choices (Delgado et al., 2021). Finally, we further differentiate between the types of percentage losses reported in the collected studies. Here, we intentionally exclude studies that do not provide clear information on the metric specification of reported shares, such as whether they pertain to the share of food supply or the share of purchased food in physical or monetary units. Our focus is solely on the physical shares of FLW along the food supply chain, and therefore, we only consider studies that provide this specific metric. At this stage, we apply a third screening selecting studies that specifically provide data missing from (FAO, 2019). In the case of the availability of data at single country level, estimates are matched directly to a specific country.

From our literature review, Europe emerges as the only macro region reporting multiple estimates for a given region-commodity-supply chain stage combination. To cope with multiple sources, we elaborate a selection process based on a hierarchy of four weighting criteria. The first criteria is based on the geographical coverage of a source. As the unavaility of data at county level forces us to generalise data at a macro-regional level, observations directly referring to a macro region (i.e. Europe) are preferred. Subsequently, we gradually lower our preferences to sources

[5] https://www.fao.org/platform-food-loss-waste/flw-data/en/

[6] DG12.3 - Food Loss Index (FLI) and Food Waste Index (FWI) – see Fabi & English, 2018. For an integral explanation see FAO, 2019, p. 32-34.

that report data on a national level. Among different countries, we prioritize those that are more extensive and present a larger population. For instance, when generalizing data for Europe, we would give preference to Germany over Switzerland as Germany would provide a more representative data sample. The second criteria is based on the proximity of observations to our reference year. Since the GTAP 11 Data Base has adopted 2017 as reference year, we prioritize sources that report data estimated in 2017. If such data is unavailable, we gradually reduce our preference to sources that are closer to 2017, beginning with a one-year difference (such as 2016 or 2018) and gradually expanding the time gap. Among sources that report data for years equidistant from 2017, we prioritize more recent estimates. The third selection criteria is determined by the representativeness of a particular supply chain stage. We prioritize sources that report data for a defined stage (i.e. manufacturing, consumption), rather than for a subgroup of a stage (i.e. pacakging, household consumption, food services), as it may not be inconsistent to generalize estimates for the entire supply chain stage if observations refer only to a specific sub-stage. Lastly, the fourth criteria is determined by the representativeness of a commodity group. We prioritize sources that report data for macro-commodity groups (i.e. fruits, dairy) over sources that report data for individual commodities (i.e. apples, milk). In the case multiple sources are identified as equally valid, we create confidence intervals representing lowest and highest estimates from selected sources. The data selection based on these criteria concerns only data for specific stages and commodities in Europe and accounts for less than 5% of the data provided in our final database. Nontherless, as data gaps remain evident especially for the final stages of the food supply chain in low-income regions, we finalise our database replacing non-available data with a consistent gap-filling methodology based on FLW in comparable regions, commodities, and stages of the FSC. Such gap-filling procedure urges for a careful utilization and interpretation of final estimates as data assumptions and aggregations may impact the magnitude of estimates. Moreover, as we aggregate data through physical mass, our methodology does not allow a direct assessment of SDG12.3, for which an indicator based on economic weights (Fabi & English, 2018) is adopted as a quantification approach. To integrate FLW data into the global multi-region input-output GTAP framework we map commodity groups to the sectors available in GTAP. Tables S1-S11 report estimates of percentage losses and waste of total food weight, illustrating respective data sources. In case of estimates reporting intervals, the mean between the lower and upper bound of the interval has been adopted as reference value. To link our regional estimates to single countries in GTAP we map regional FLW shares to single countries available in GTAP. Table S12 reports the mapping between countries available in GTAP and macro-regions defined to gather FLW data. Finally, Table S13 provides the mapping between FBS commodities, FLW commodity group, and GTAP sectors.

Table S1 – Western Europe

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	13.7[2]
Wheat (wht)	9.4[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	13.7[2]
Paddy rice (pdr)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	28.0[1]
Fruits & Vegetables (v_f)	12.8[1]	9.0[1]	8.5[1]	6.2[1]	15.4[1]
Other crops (ocr)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	13.7[2]
Oil seeds (osd)	2.5[2]	2.5[2,3]	6.0[2]	0.3[2]	4.8[2]
Sugar cane/beet (c_b)	2.6[2]	3.0[3]	3.2[2]	0.3[2]	1.3[2]
Cattle meat (ctl)	0.8[2,3]	0.1[4,5]	7.8[1]	2.7 – 3.8[2,9]	8.0 – 50.3[2,7,10,11]
Dairy (rmk)	0.3[2,3]	0.1 – 0.3[2,4,5]	3.0[1]	0.2 – 0.8[2,7,8]	3.2 – 12.1[2,7,10,11]
Other animal prod. (oap)	3.6 – 4.8[2,3,4]	1.0[4,5]	1.6[2]	1.4 – 1.6[2,7]	22.6 – 36.0[2,7,10]
Fish (fsh)	0.0 – 0.7[2,3]	0.1[4,5]	37.8[2]	2.4 – 3.6[2,7]	9.7 – 22.3[2,7,10]

[1] FAO – Food Loss and Waste Database 2019 http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
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Table S2 – Eastern Europe

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	13.7[2]
Wheat (wht)	11.4[1]	18.0[1]	11.5[1]	12.3[1]	13.7[2]
Paddy rice (pdr)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	28.0[1]
Fruits & Vegetables (v_f)	13.3[1]	18.3[1]	10.7[1]	7.3[1]	15.4[1]
Other crops (ocr)	4.2[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	13.7[2]
Oil seeds (osd)	2.5[2]	2.5[2,3]	6.0[1]	0.3[2]	4.8[2]
Sugar cane/beet (c_b)	2.6[2]	3.0[3]	3.2[2]	0.3[2]	1.3[2]
Cattle meat (ctl)	0.8[2,3]	0.1[4,5]	7.8[1]	2.7 – 3.8[2,9]	8.0 – 50.3[2,7,10,11]
Dairy (rmk)	0.3[2,3]	0.1 – 0.3[2,4,5]	9.0[1]	9.5[1]	3.2 – 12.1[2,7,10,11]
Other animal prod. (oap)	3.6 – 4.8[2,3,4]	1.0[4,5]	1.6[2]	1.4 – 1.6[2,7]	22.6 – 36.0[2,7,10]
Fish (fsh)	0.0 – 0.7[2,3]	0.1[4,5]	37.8[2]	2.4 – 3.6[2,7]	9.7 – 22.3[2,7,10]

[1] FAO – Food Loss and Waste Database 2019 http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Calculated from Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011
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Table S3 – North America & Oceania

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	7.2[2]	4.0[4]	3.2[13]	15.0[7]	18.5[6]
Wheat (wht)	7.2[2]	4.0[4]	3.2[13]	15.0[7]	18.5[6]
Paddy rice (pdr)	7.2[2]	4.0[4]	3.2[13]	15.0[7]	18.5[6]
Fruits & Vegetables (v_f)	13.2[1]	19.8[4]	17.5[1]	9.3[1]	17.0[7]
Other crops (ocr)	7.2[2]	4.0[4]	3.2[13]	15.0[7]	18.5[6]
Oil seeds (osd)	12.0[10]	2.5[12]	6.0[13]	15.0[7]	18.5[6]
Sugar cane/beet (c_b)	10.0[2]	4.0[4]	3.2[13]	11.0[1]	18.0[7]
Cattle meat (ctl)	3.5[11]	1.0[11]	7.8[13]	3.5[1]	34.0[7]
Dairy (rmk)	3.5[11]	0.4[4]	3.0[13]	12.0[1]	18.0[1]
Other animal prod. (oap)	4.0[3]	1.0[13]	1.6[13]	9.0[6]	20.9[9]
Fish (fsh)	12.0[11]	0.5[11]	37.8[13]	2.7[5] – 8.0[6]	31.6[6]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Clarke, J.M. 1989. Drying rate and harvest losses of windrowed versus direct combined barley. Canadian Journal of Plant Science 1989; 69(3):713-20.
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[4] USDA ERS – food availability (per capita) data system; Available from: http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx. Accessed 1 Sept 2015. (calculated on whole commodity, including inedible food parts).
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[11] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[12] Assumption made by taking the higher boundry of the interval reported for West Europe.
[13] Assumption based on values for West Europe.
[14] Assumption based on values for United States of America.

Table S4 – High-income Asia

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	12.6[1]	13.5[1]	13.0[1]	15.0[1]	11.1[1]
Wheat (wht)	10.5[1]	12.5[1]	15.0[1]	15.0[1]	11.1[1]
Paddy rice (pdr)	11.8[1]	15.0[1]	16.0[1]	10.0[1]	16.6[1]
Fruits & Vegetables (v_f)	10.3[1]	20.5[1]	15.9[1]	35.0[1]	17.2[2]
Other crops (ocr)	12.6[1]	13.5[1]	13.0[1]	15.0[1]	11.1[1]
Oil seeds (osd)	6.0[5]	2.5[5]	6.0[7]	0.3[7]	4.8[7]
Sugar cane/beet (c_b)	12.6[1]	13.5[1]	13.0[1]	15.0[1]	11.1[1]
Cattle meat (ctl)	8.7[2]	2.0 – 3.6[2]	1.3[2]	3.5[2]	16.3[2]
Dairy (rmk)	3.5[5]	1.0[5]	3.0[7]	0.2[6]	2.6[4]
Other animal prod. (oap)	6.0[3]	1.0[7]	1.6[7]	1.4[6]	13.5[2]
Fish (fsh)	3.6[2]	7.3[2]	37.8[7]	5.8[2]	26.1[2]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Liu, G., 2014. Food Losses and Food Waste in China: A First Estimate. https://doi.org/10.1787/5jz5sq5173lq-en (calculated on whole commodity, including inedible food parts).
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[4] Song, G., Li, M., Semakula, H.M., Zhang, S. 2015. Food consumption and waste and the embedded carbon, water and ecological footprints of households in China. Sci Total Environ 2015, Oct 1; 529:191-7. http://dx.doi.org/10.1016/j.scitotenv.2015.05.068
[5] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[6] Assumption made by taking the lower boundry of the interval reported for West Europe.
[7] Assumption based on values for West Europe.
[8] Assumption based on values for North America.

Table S5 – Middle East & North Africa

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	15.0[1]	15.0[1]	2.0[2]	1.0[2]	5.0[2]
Wheat (wht)	14.6[1]	7.1[1]	2.0[2]	0.3[1]	5.0[2]
Paddy rice (pdr)	15.0[1]	15.0[1]	2.0[2]	1.0[2]	5.0[2]
Fruits & Vegetables (v_f)	19.6[1]	10.0[1]	7.0[1]	11.2[1]	10.0[1] – 35.4[3]
Other crops (ocr)	15.0[1]	15.0[1]	2.0[2]	1.0[2]	5.0[2]
Oil seeds (osd)	15.0[2,3]	5.0[2]	7.0[2]	1.0[2]	4.0[2]
Sugar cane/beet (c_b)	15.0[1]	29.3[1]	2.0[2]	1.0[2]	5.0[2]
Cattle meat (ctl)	10.0[2]	0.2[2]	5.0[2]	0.5[2]	7.4[3]
Dairy (rmk)	10.0[2]	1.0[2]	1.5[2]	6.0[2]	5.5[3]
Other animal prod. (oap)	5.0[1]	1.0[2]	2.0[2]	3.1[1]	2.0[3]
Fish (fsh)	10.0[2]	0.02[2]	0.05[2]	0.01[2]	4.8[3]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Koester, U., Empen, J., Holm, T. 2013. Food Losses and Waste in Europe and Central Asia. Draft synthesis report. FAO – Regional Office for Europe and Central Asia. http://www.fao.org/3/a-au843e.pdf
[3] OCED Food Waste Database. https://www.oecd-ilibrary.org/agriculture-and-food/data/waste/food-waste_ba9da2b7-en (Accessed 03 2023).

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Table S6 – Latin America & Caribbean

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	10.7[1]	22.5[1]	3.4[1]	0.5[1]	5.0[3]
Wheat (wht)	3.0[1]	9.9[1]	3.0[1]	0.5[1]	5.0[3]
Paddy rice (pdr)	4.0[1]	11.3[1]	3.4[1]	0.5[1]	5.0[3]
Fruits & Vegetables (v_f)	13.1[1]	6.4[1]	5.6[1]	10.1[1]	3.4[1]
Other crops (ocr)	10.7[1]	22.5[1]	3.4[1]	0.5[1]	5.0[3]
Oil seeds (osd)	6.0[2]	15.0[1]	7.0[3]	1.0[3]	4.0[3]
Sugar cane/beet (c_b)	10.7[1]	22.5[1]	3.4[1]	1.2[1]	5.0[3]
Cattle meat (ctl)	5.6[2]	1.1[2]	5.0[3]	0.5[3]	7.4[3]
Dairy (rmk)	3.5[2]	1.0[3]	1.5[3]	6.0[3]	5.5[3]
Other animal prod. (oap)	6.0[2,3]	1.0[3]	2.0[3]	1.0[3]	2.0[3]
Fish (fsh)	5.7[2]	5.0[2]	0.05[3]	0.1[3]	4.8[3]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[3] Assumption based on values for North Africa & Central-West Asia.

Table S7 – Southeast Asia

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	2.6[1]	8.7[1]	3.0[1]	0.6[1]	4.0[3]
Wheat (wht)	8.7[1]	3.4[1]	3.0[1]	2.9[1]	4.0[3]
Paddy rice (pdr)	6.5[1]	5.8[1]	2.1[1]	2.0[1]	4.0[3]
Fruits & Vegetables (v_f)	6.3[1]	8.5[1]	2.4[1]	7.1[1]	4.0[1]
Other crops (ocr)	0.6[1]	1.2[1]	3.0[1]	5.4[1]	4.0[3]
Oil seeds (osd)	0.9[1]	1.3[1]	13.0[1]	1.0[6]	4.0[6]
Sugar cane/beet (c_b)	1.2[1]	0.4[1]	3.0[1]	5.4[1]	4.0[3]
Cattle meat (ctl)	5.6[4]	0.3[4]	5.0[6]	0.5[6]	7.4[6]
Dairy (rmk)	3.5[4]	3.4[5]	1.5[6]	6.0[6]	5.5[6]
Other animal prod. (oap)	34.7[1]	1.0[6]	2.0[6]	7.5[1]	2.0[6]
Fish (fsh)	8.2[4]	6.0[4]	0.05[6]	12.3[2]	4.8[6]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Hossain, M.M., Rahman, M., Hassan, M.N., Nowsad, A.A. 2013. Post-harvest loss of farm raised Indian and Chinese major carps in the distribution channel from Mymensingh to Rangpur of Bangladesh. Pak J Biol Sci 2013, Jun 15; 16(12):564-9.
[3] Hossain, A., Miah, M. 2009. Post-harvest losses and technical efficiency of potato storage systems in Bangladesh. *Final Report CF # 2/08* Bangladesh Agricultural Research Institute.
[4] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[5] Assumption based on FAOSTAT, 2020 and on values for North Africa & Central-West Asia.
[6] Assumption based on values for North Africa & Central-West Asia

Table S8 – Sub-Saharan Africa

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	3.1[1]	2.6[1]	3.1[1]	1.2[1]	4.0[7]
Wheat (wht)	3.5[1]	2.5[1]	3.1[1]	1.7[1]	4.0[7]
Paddy rice (pdr)	2.5[1]	2.6[1]	4.5[1]	1.8[1]	4.0[7]
Fruits & Vegetables (v_f)	13.2[1]	10.7[1]	7.4[1]	14.9[1]	4.0[7]
Other crops (ocr)	11.1[1]	2.6[1]	3.1[1]	10.8[1]	4.0[7]
Oil seeds (osd)	4.6[1]	16.8[1]	9.5[1]	16.6[1]	4.0[7]
Sugar cane/beet (c_b)	3.1[1]	2.6[1]	3.1[1]	1.2[1]	4.0[7]
Cattle meat (ctl)	19.0[4]	3.0[2]	5.0[7]	0.5[7]	7.4[7]
Dairy (rmk)	6.0[4]	8.2[2]	1.5[7]	13.8[3]	5.5[7]
Other animal prod. (oap)	1.8[1]	1.0[5]	2.0[7]	7.5[7]	2.0[7]
Fish (fsh)	5.7[4]	14.3 – 27.3[2]	9.0[6]	12.3[7]	4.8[7]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Affognon, H., Mutungi, C., Sanginga, P., Borgemeister, C. 2015. Unpacking postharvest losses in sub-Saharan Africa: A meta-analysis. World Development 2015, Feb; 66:49-68. http://dx.doi.org/10.1016/j.worlddev.2014.08.002
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[4] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[5] Assumption based on values for North Africa & Central-West Asia.
[6] Davies, R. M., Davies, O.A. 2009. "Traditional and Improved Fish Processing Technologies in Bayelsa State, Nigeria." European Journal of Scientific Research 26: 539-548.
[7] Assumption based on values for South & South-East Asia.

Table S9 – China

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	5.0[1]	9.4[1]	2.7[1]	1.2[1]	11.1[6]
Wheat (wht)	5.0[1]	5.9[1]	2.7[1]	1.2[1]	11.1[6]
Paddy rice (pdr)	5.0[1]	7.1[1]	2.7[1]	0.5[1]	16.6[6]
Fruits & Vegetables (v_f)	5.5[1]	17.7[1]	14.6[1]	7.0[1]	17.2[2]
Other crops (ocr)	5.0[1]	9.4[1]	2.7[1]	1.2[1]	11.1[6]
Oil seeds (osd)	5.0[1]	9.4[1]	2.7[1]	1.2[1]	4.8[5]
Sugar cane/beet (c_b)	5.0[1]	9.4[1]	2.7[1]	1.2[1]	11.1[6]
Cattle meat (ctl)	1.7[1]	3.1[1]	1.3[1]	3.5[2]	16.3[2]
Dairy (rmk)	3.5[4]	0.1[5]	3.0[5]	0.2[7]	2.6[3]
Other animal prod. (oap)	8.9[1]	1.0[7]	1.6[5]	1.4[7]	13.5[2]
Fish (fsh)	3.6[2]	7.3[2]	37.8[5]	5.8[2]	26.1[2]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Calculated from Liu, G., 2014. Food Losses and Food Waste in China: A First Estimate. https://doi.org/10.1787/5jz5sq5173lq-en (calculated on whole commodity, including inedible food parts).
[3] Calculated from Song, G., Li, M., Semakula, H.M., Zhang, S. 2015. Food consumption and waste and the embedded carbon, water and ecological footprints of households in China. Sci Total Environ 2015, Oct 1; 529:191-7.
[4] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.

Table S10 – United States of America

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	1.6[1]	4.0[5]	3.2[10]	12.0[1]	15.0[1]
Wheat (wht)	1.6[1]	4.0[5]	3.2[10]	12.0[1]	15.0[1]
Paddy rice (pdr)	1.6[1]	4.0[5]	3.2[10]	12.0[1]	15.0[1]
Fruits & Vegetables (v_f)	13.2[2]	19.8[5]	5.5[1]	15.3[1]	23.6[1]
Other crops (ocr)	1.6[1]	4.0[5]	3.2[10]	12.0[1]	15.0[1]
Oil seeds (osd)	12.0[3]	2.5[1]	6.0[10]	12.0[1]	15.0[1]
Sugar cane/beet (c_b)	10.0[2]	4.0[5]	3.2[10]	12.0[1]	18.0[6]
Cattle meat (ctl)	3.5[7]	1.0[7]	13.3[1]	3.5[9]	34.0[6]
Dairy (rmk)	3.5[7]	0.4[5]	3.0[10]	12.0[1]	14.0[6]
Other animal prod. (oap)	4.0[4]	1.0[10]	1.6[10]	9.0[1]	20.9[8]
Fish (fsh)	12.0[7]	0.5[7]	37.8[10]	2.7 – 8.0[9]	31.6[9]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Clarke, J.M. 1989. Drying rate and harvest losses of windrowed versus direct combined barley. Canadian Journal of Plant Science 1989; 69(3):713-20.
[3] Kulkarni, S. (Undated). Importance of minimizing field losses during soybean harvest, Division of agriculture, University of Arkansas.
[4] Clarke, J.M. 1989. Drying rate and harvest losses of windrowed versus direct combined barley. Canadian Journal of Plant Science 1989; 69(3):713-20.
[5] USDA ERS – food availability (per capita) data system; Available from: http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx. Accessed 1 Sept 2015. (calculated on whole commodity, including inedible food parts).
[6] Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States. SSRN Electron. J. https://doi.org/10.2139/ssrn.2501659 (calculated on whole commodity, including inedible food parts).
[7] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[8] OCED Food Waste Database. https://www.oecd-ilibrary.org/agriculture-and-food/data/waste/food-waste_ba9da2b7-en (Accessed 03 2023).
[9] Assumption based on values for North America & Oceania.
[10] Assumption based on values for West Europe.

Table S11 – India

Commodity (GTAP)	Agricultural production	Post-harvest handling & storage	Manufacturing	Distribution & Retail	Consumption
Grains (gro)	2.0[1]	1.2[1]	5.3[1]	2.6[1]	4.0[2]
Wheat (wht)	0.9[1]	1.0[1]	5.3[1]	3.3[1]	4.0[2]
Paddy rice (pdr)	0.9[1]	1.5[1]	5.3[1]	0.2[1]	4.0[2]
Fruits & Vegetables (v_f)	3.3[1]	1.3[1]	14.6[4]	3.5[1]	4.0[2]
Other crops (ocr)	1.4[1]	1.6[1]	5.3[1]	0.2[1]	4.0[2]
Oil seeds (osd)	1.2[1]	0.5[1]	5.3[1]	3.5[1]	4.0[2]
Sugar cane/beet (c_b)	1.7[1]	0.4[1]	5.3[1]	0.2[1]	4.0[2]
Cattle meat (ctl)	1.4[1]	0.5[1]	1.3[4]	2.7[1]	7.4[2]
Dairy (rmk)	0.3[1]	0.2[1]	1.5[5]	0.04[1]	5.5[2]
Other animal prod. (oap)	1.5[1]	1.3[1]	2.0[5]	1.1[1]	2.0[2]
Fish (fsh)	8.2[3]	6.0[3]	0.05[5]	5.8[4]	4.8[2]

[1] FAO – Food Loss and Waste Database 2019. http://www.fao.org/platform-food-loss-waste/flw-data/en/ (Accessed 03 2023).
[2] Assumption based on values for South East Asia.
[3] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[4] Assumption based on values for China.
[5] Assumption based on values for North Africa & Middle East.

Table S12. Mapping between GTAP countries and FLW data regions.

GTAP Country	Description	Mapping to FLW data regions
aus	Australia	North America & Oceania
nzl	New Zealand	North America & Oceania
xoc	Rest of Oceania	North America & Oceania
chn	China	China
hkg	Hong Kong	High-income Asia
jpn	Japan	High-income Asia
kor	Korea	High-income Asia
mng	Mongolia	Southeast Asia
twn	Taiwan	High-income Asia
xea	Rest of East Asia	Southeast Asia
brn	Brunei Darussalam	Southeast Asia
khm	Cambodia	Southeast Asia
idn	Indonesia	Southeast Asia
lao	Lao People’s Democratic Republic	Southeast Asia
mys	Malaysia	Southeast Asia
phl	Philippines	Southeast Asia
sgp	Singapore	Southeast Asia
tha	Thailand	Southeast Asia
vnm	Viet Nam	Southeast Asia
xse	Rest of Southeast Asia	Southeast Asia
bgd	Bangladesh	Southeast Asia
ind	India	India
npl	Nepal	Southeast Asia
pak	Pakistan	Southeast Asia
lka	Sri Lanka	Southeast Asia
xsa	Rest of South Asia	Southeast Asia
can	Canada	North America & Oceania
usa	United States of America	United States of America
mex	Mexico	Latin America & Caribbean
xna	Rest of North America	North America & Oceania
arg	Argentina	Latin America & Caribbean
bol	Bolivia	Latin America & Caribbean
bra	Brazil	Latin America & Caribbean
chl	Chile	Latin America & Caribbean
col	Colombia	Latin America & Caribbean
ecu	Ecuador	Latin America & Caribbean
pry	Paraguay	Latin America & Caribbean
per	Peru	Latin America & Caribbean
ury	Uruguay	Latin America & Caribbean
ven	Venezuela	Latin America & Caribbean
xsm	Rest of South America	Latin America & Caribbean
cri	Costa Rica	Latin America & Caribbean
gtm	Guatemala	Latin America & Caribbean
hnd	Honduras	Latin America & Caribbean
nic	Nicaragua	Latin America & Caribbean
pan	Panama	Latin America & Caribbean
slv	El Salvador	Latin America & Caribbean
xca	Rest of Central America	Latin America & Caribbean
dom	Dominican Republic	Latin America & Caribbean
jam	Jamaica	Latin America & Caribbean
pri	Puerto Rico	Latin America & Caribbean
tto	Trinidad and Tobago	Latin America & Caribbean
xcb	Caribbean	Latin America & Caribbean
aut	Austria	Western Europe
bel	Belgium	Western Europe
bgr	Bulgaria	Eastern Europe
hrv	Croatia	Eastern Europe
cyp	Cyprus	Eastern Europe
cze	Czech Republic	Eastern Europe
dnk	Denmark	Western Europe
est	Estonia	Eastern Europe
fin	Finland	Western Europe
fra	France	Western Europe
deu	Germany	Western Europe
grc	Greece	Western Europe
hun	Hungary	Eastern Europe
irl	Ireland	Western Europe
ita	Italy	Western Europe
lva	Latvia	Eastern Europe
ltu	Lithuania	Eastern Europe
lux	Luxembourg	Western Europe
mlt	Malta	Western Europe
nld	Netherlands	Western Europe
pol	Poland	Eastern Europe
prt	Portugal	Western Europe
rou	Romania	Eastern Europe

GTAP Country	Description	Mapping to FLW data regions
svk	Slovakia	Eastern Europe
svn	Slovenia	Eastern Europe
esp	Spain	Western Europe
swe	Sweden	Western Europe
gbr	United Kingdom	Western Europe
che	Switzerland	Western Europe
nor	Norway	Western Europe
xef	Rest of EFTA	Western Europe
alb	Albania	Eastern Europe
blr	Belarus	Eastern Europe
rus	Russian Federation	Eastern Europe
ukr	Ukraine	Eastern Europe
xee	Rest of Eastern Europe	Eastern Europe
xer	Rest of Europe	Eastern Europe
kaz	Kazakhstan	Middle-East & North Africa
kgz	Kyrgyzstan	Middle-East & North Africa
tjk	Tajikistan	Middle-East & North Africa
xsu	Rest of Former Soviet Union	Middle-East & North Africa
arm	Armenia	Middle-East & North Africa
aze	Azerbaijan	Middle-East & North Africa
geo	Georgia	Middle-East & North Africa
bhr	Bahrain	Middle-East & North Africa
irn	Iran Islamic Republic of	Middle-East & North Africa
isr	Israel	Middle-East & North Africa
jor	Jordan	Middle-East & North Africa
kwt	Kuwait	Middle-East & North Africa
omn	Oman	Middle-East & North Africa
qat	Qatar	Middle-East & North Africa
sau	Saudi Arabia	Middle-East & North Africa
tur	Turkey	Middle-East & North Africa
are	United Arab Emirates	Middle-East & North Africa
xws	Rest of Western Asia	Middle-East & North Africa
egy	Egypt	Middle-East & North Africa
mar	Morocco	Middle-East & North Africa
tun	Tunisia	Middle-East & North Africa
xnf	Rest of North Africa	Middle-East & North Africa
ben	Benin	Sub-Saharan Africa
bfa	Burkina Faso	Sub-Saharan Africa
cmr	Cameroon	Sub-Saharan Africa
civ	Cote d'Ivoire	Sub-Saharan Africa
gha	Ghana	Sub-Saharan Africa
gin	Guinea	Sub-Saharan Africa
nga	Nigeria	Sub-Saharan Africa
Sen	Senegal	Sub-Saharan Africa
tgo	Togo	Sub-Saharan Africa
xwf	Rest of Western Africa	Sub-Saharan Africa
xcf	Central Africa	Sub-Saharan Africa
xac	South Central Africa	Sub-Saharan Africa
eth	Ethiopia	Sub-Saharan Africa
ken	Kenya	Sub-Saharan Africa
mdg	Madagascar	Sub-Saharan Africa
mwi	Malawi	Sub-Saharan Africa
mus	Mauritius	Sub-Saharan Africa
moz	Mozambique	Sub-Saharan Africa
rwa	Rwanda	Sub-Saharan Africa
tza	Tanzania	Sub-Saharan Africa
uga	Uganda	Sub-Saharan Africa
zmb	Zambia	Sub-Saharan Africa
zwe	Zimbabwe	Sub-Saharan Africa
xec	Rest of Eastern Africa	Sub-Saharan Africa
bwa	Botswana	Sub-Saharan Africa
nam	Namibia	Sub-Saharan Africa
zaf	South Africa	Sub-Saharan Africa
xsc	Rest of South African Customs	Sub-Saharan Africa
xtw	Rest of the World	Sub-Saharan Africa

Table S13. Mapping between FBS commodities, FLW commodity groups, and GTAP sectors.

FBS commodity	FLW commodity group	GTAP sector
Wheat and products	Wheat	wht
Rice and products	Paddy Rice	pdr
Barley and products	Grains	gro
Maize and products	Grains	gro
Rye and products	Grains	gro

Oats	Grains	gro
Millet and products	Grains	gro
Sorghum and products	Grains	gro
Cereals, Other	Grains	gro
Cassava and products	Fruit & Vegetables	v_f
Potatoes and products	Fruit & Vegetables	v_f
Sweet potatoes	Fruit & Vegetables	v_f
Yams	Fruit & Vegetables	v_f
Roots, Other	Fruit & Vegetables	v_f
Sugar cane	Sugar cane/beet	c_b
Sugar beet	Sugar cane/beet	c_b
Sugar non-centrifugal	Sugar cane/beet	c_b
Sugar (Raw Equivalent)	Sugar cane/beet	c_b
Sweeteners, Other	Sugar cane/beet	c_b
Honey	Other animal products	oap
Beans	Fruit & Vegetables	v_f
Peas	Fruit & Vegetables	v_f
Pulses, Other and products	Fruit & Vegetables	v_f
Nuts and products	Fruit & Vegetables	v_f
Soyabeans	Fruit & Vegetables	v_f
Groundnuts (Shelled Eq)	Fruit & Vegetables	v_f
Sunflower seed	Oil seeds	osd
Rape and Mustardseed	Oil seeds	osd
Coconuts - Incl Copra	Fruit & Vegetables	v_f
Sesame seed	Oil seeds	osd
Olives (including preserved)	Oil seeds	osd
Oilcrops, Other	Oil seeds	osd
Soyabean Oil	N/A*	N/A*
Groundnut Oil	N/A*	N/A*
Sunflowerseed Oil	N/A*	N/A*
Rape and Mustard Oil	N/A*	N/A*
Cottonseed Oil	N/A*	N/A*
Palmkernel Oil	N/A*	N/A*
Palm Oil	N/A*	N/A*
Coconut Oil	N/A*	N/A*
Sesameseed Oil	N/A*	N/A*
Olive Oil	N/A*	N/A*
Ricebran Oil	N/A*	N/A*
Maize Germ Oil	N/A*	N/A*
Oilcrops Oil, Other	N/A*	N/A*
Tomatoes and products	Fruit & Vegetables	v_f
Onions	Fruit & Vegetables	v_f
Vegetables, Other	Fruit & Vegetables	v_f
Oranges, Mandarines	Fruit & Vegetables	v_f
Lemons, Limes and products	Fruit & Vegetables	v_f
Grapefruit and products	Fruit & Vegetables	v_f
Citrus, Other	Fruit & Vegetables	v_f
Bananas	Fruit & Vegetables	v_f
Plantains	Fruit & Vegetables	v_f
Apples and products	Fruit & Vegetables	v_f
Pineapples and products	Fruit & Vegetables	v_f
Dates	Fruit & Vegetables	v_f
Grapes and products (excl wine)	Fruit & Vegetables	v_f
Fruits, Other	Fruit & Vegetables	v_f
Coffee and products	Other crops	ocr
Cocoa Beans and products	Other crops	ocr
Tea (including mate)	Other crops	ocr
Pepper	Other crops	ocr
Pimento	Other crops	ocr
Cloves	Other crops	ocr
Spices, Other	Other crops	ocr
Wine	N/A*	N/A*
Beer	N/A*	N/A*
Beverages, Fermented	N/A*	N/A*
Beverages, Alcoholic	N/A*	N/A*
Alcohol, Non-Food	N/A*	N/A*
Bovine Meat	Cattle meat	ctl
Mutton & Goat Meat	Cattle meat	ctl
Pigmeat	Other animal products	oap
Poultry Meat	Other animal products	oap
Meat, Other	Cattle meat	ctl
Offals, Edible	Other animal products	oap
Butter, Ghee	N/A*	N/A*
Cream	N/A*	N/A*

FBS commodity	FLW commodity group	GTAP sector
Fats, Animals, Raw	Other animal products	oap
Eggs	Other animal products	oap
Milk - Excluding Butter	Dairy	rmk
Freshwater Fish	Fish	fsh
Infant food	N/A*	N/A*
Miscellaneous	N/A*	N/A*
Fish, Body Oil	N/A*	N/A*
Fish, Liver Oil	N/A*	N/A*
Demersal Fish	Fish	fsh
Pelagic Fish	Fish	fsh
Marine Fish, Other	Fish	fsh
Crustaceans	Fish	fsh
Cephalopods	Fish	fsh
Molluscs, Other	Fish	fsh
Aquatic Animals, Others	Fish	fsh
Aquatic Plants	Fish	fsh
Palm kernels	Oil seeds	osd
Cottonseed	Oil seeds	osd
Meat, Aquatic Mammals	Fish	fsh

*As FLW shares refer to primary commodities only, we did not apply such shares to processed foods directly but only to the primary commodities composing the processed food products.

Data adjustments

Merging gross food supply data from FAO-FBS with available FLW estimates provides information on net food intakes by country. In certain cases, net food intakes estimated using this procedure might be too low and inconsistent with the plausible (expected) net energy intakes in specific countries. To compare net food intakes obtained in this study with estimates available from the literature we define a range of plausible estimates of net food intakes (calories/capita/day) for each macro-region reported in tables S1-S8, retrieving data from currently available sources. For cases in which the net food intake estimates are below the lower bound of the target range we adjust FLW shares based on similar regions to remain within the estimated range of values (reaching the lower bound). This procedure shows the current mismatch between available nutritional data and FLW data and advocates for further (country-specific) research in the field of FLW and nutrition to enhance the link between two key aspects of the global food system. Table S14 illustrates the minimum plausible target net-intake ranges and associated sources used as benchmark for the macro-regions associated with FLW shares (Tables S1-S8). Additionally, Table S15 reports the changes applied to county-specific FLW shares for obtaining net-intake estimates in line with the benchmarks reported in Table S14.

Table S14. Minimum plausible net intake (kcal/cap/day) ranges by region

Region	Range of plausible net intake (kcal/capita/day)	Source
European Union – 27	2200-2500	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Willett et al., 2019 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
North America & Oceania	2200-2500	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Willett, et al., 2019 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
High-income Asia	2100-2400	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
Rest of Europe & Central Asia	2100-2300	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
Middle East & North Africa	2100-2300	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
Latin America & Caribbean	2100-2300	Lazarte, 2014 Lopez Barrera & Hertel, 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
Southeast Asia	2000-2200	Verma et al., 2020 Lopez Barrera & Hertel, 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018
Sub-Saharan Africa	1850-2100	Verma et al., 2020 Mekonnen et al., 2020 Schmidhuber et al., 2018 Smith et al., 2016 Global Nutrient Database, 2018

Table S15. Adjustments of FLW shares (%) by country, supply chain stage and commodity based on acceptable ranges of net food intakes

Macro-region	Country	Supply chain stage	Commodity	Original value (%)	Adjusted value (%)	Ratio of adjustment
European Union – 27	Croatia	Agricultural Production	wht	11.4	9.4	based on Western Europe values
			v_f	13.3	12.8	
			oap	8.4	4.2	
North America & Oceania	Australia New Zealand Canada Rest of Oceania	Agricultural Production	pdr	7.2	4.2	based on Western Europe values
			wht	7.2	4.2	
			gro	7.2	4.2	
			v_f	13.2	12.8	
			osd	12.0	2.5	
			ocr	7.2	4.2	
High-income Asia	Japan South Korea Taiwan Hong-Kong	Agricultural Production	pdr	11.8	4.2	based on Western Europe values
			wht	10.5	4.2	
			gro	12.6	4.2	
			osd	6.0	2.5	
			ocr	12.6	4.2	
			ctl	8.7	0.8	
			oap	6.0	3.6	
Rest of Europe & Central Asia	Tajikistan Rest of Soviet Union	Agricultural Production	pdr	15.0	4.2	based on Eastern Europe values
			wht	14.6	11.0	
			gro	15.0	4.2	
			v_f	19.6	13.0	
			osd	15.0	2.5	
			c_b	15.0	2.6	
			ocr	15.0	4.2	
			ctl	10.0	0.8	
			oap	5.0	3.6	
			rmk	10.0	0.03	
			fsh	10.0	0.03	
Latina America & Caribbean	Honduras	Agricultural production	gro	10.7	4.2	based on Eastern Europe values
			osd	15.0	2.5	
	Bolivia Guatemala Ecuador Venezuela El Salvador	Agricultural production	gro	10.7	4.2	based on Eastern Europe values
			osd	15.0	2.5	
			c_b	10.7	2.6	
			ocr	10.7	4.2	
			ctl	5.6	0.8	
			oap	6.0	3.6	
			rmk	3.5	0.03	
			fsh	5.7	0.03	
South-East Asia	Rest of southeast Asia	Agricultural production	oap	34.7	6.0	based on High-income Asia values
		Post-Harvest Handling & Storage	rmk	3.4	0.01	
		Manufacturing	oap	2.0	1.6	
		Distribution & Retail	fsh	12.3	5.8	

Additional Results

Decomposition analysis of food loss and waste trends across years (2004-2014) by countries and regions

In addition to the application of the KAYA identity to the decomposition of historical drivers of changing FLW, we rely on the logarithmic mean Divisia index (LMDI) I additive decomposition method (Ang, 2015). By integrating an additional decomposition method (LMDI) to complement the KAYA analysis we aim to further clarify what are the main drivers of FLW across countries and regions. While the KAYA method adopts a multiplicative (in percent changes) decomposition procedure, the LMDI method is based on the additive (in levels) decomposition approach. In the case of KAYA decomposition, changes in population, per capita GDP and food consumption per unit of GDP correspond to the activity effect in the LMDI decomposition (representing a change in food demand). In this regard, the KAYA approach provides a more granular representation of the demand/activity channel, when compared to the LMDI method. On the other hand, an LMDI approach, by distinguishing the structure and intensity effects provides a more detailed representation of the FLW intensity of the food consumption channel of the KAYA decomposition (Change in FLW per unit of gross food consumption). Thus, the two methods complement each other not only in terms of additive and multiplicative representation of results but also by detailing different aspects of drivers behind changes in FLW.

Using the LMDI approach, we decompose changes in FLW between 2004 and 2014 years into activity, structure and intensity effects. Such decomposition is implemented for all 141 countries and regions in the GTAP 10A Data Base (Table S16). The implementation begins from the following identity (for each considered country/region):

$$FLW = \sum_i FLW_i = \sum_i C\ \frac{C_i}{C}\frac{FLW_i}{C_i} = \sum_i C\ S_i\ I_i,$$

where *FLW* is the total amount of food loss and waste embodied into final consumption in the country/region; FLW_i is the volume of FLW embodied into final consumption in sector *i* (set *i* covers all sectors that supply food to final consumers, including primary agriculture, processed food sectors and service activities); $C = \sum_i C_i$ is the volume of total gross (FLW-inclusive) food consumption in the country; $S_i = \frac{C_i}{C}$ represents the share of specific food-supplying sector (*i*) in the aggregate food consumption in the country; $I_i = \frac{FLW_i}{C_i}$ corresponds to the share of FLW in total food consumption of sector *i*.

For the additive decomposition analysis, we can further represent a change in FLW between 2004 and 2014 years in the following way:

$$\Delta FLW_{tot} = FLW^{2014} - FLW^{2004} = \Delta FLW_{act} + \Delta FLW_{str} + \Delta FLW_{int},$$

where subscripts *act*, *str*, and *int* denote the effects associated with overall activity level, activity structure, and sectoral FLW intensity, respectively.

The following formulas are further used to calculate the effects in the LDMI-I additive model:

$$Activity: \quad \Delta FLW_{act} = \sum_i L(FLW_i^{2014}, FLW_i^{2004}) \ln\left(\frac{C^{2014}}{C^{2004}}\right),$$

$$Structure: \quad \Delta FLW_{str} = \sum_i L(FLW_i^{2014}, FLW_i^{2004}) \ln\left(\frac{S_i^{2014}}{S_i^{2004}}\right),$$

$$Intensity: \quad \Delta FLW_{int} = \sum_i L(FLW_i^{2014}, FLW_i^{2004}) \ln\left(\frac{I_i^{2014}}{I_i^{2004}}\right),$$

where

$$L(FLW_i^{2014}, FLW_i^{2004}) = \frac{FLW_i^{2014} - FLW_i^{2004}}{\ln(FLW_i^{2014}) - \ln(FLW_i^{2004})}.$$

Table S16. Decomposition of FLW trends across years (2004-2014) based on the LMDI-I additive method, 1000 tonnes.

Country/region code	Activity	Structure	Intensity	Aggregate change, 1000 Tonnes
aus	751.5	-103.4	201.6	849.8
nzl	141.6	-20.7	23.0	144.0
xoc	501.2	-14.7	-5.9	480.6
chn	130810.9	-129.1	6163.3	136845.1
hkg	307.8	72.8	-65.6	315.1
jpn	-2223.2	431.0	-118.3	-1910.5
kor	1858.4	-157.8	-65.8	1634.8
mng	94.0	8.0	-0.2	101.8
twn	124.0	78.3	-148.1	54.1
xea	145.7	23.5	-13.8	155.5
brn	8.7	0.1	0.2	9.0
khm	956.6	-10.1	-17.5	929.1
idn	10320.7	569.6	157.6	11047.8
lao	616.3	1.5	-8.7	609.1
mys	1567.1	-171.1	104.5	1500.5
phl	2841.2	462.2	-62.9	3240.5
sgp	793.3	57.6	-12.8	838.1
tha	1593.4	52.4	-345.2	1300.6
vnm	4448.3	962.3	159.1	5569.7
xse	3028.8	-15.7	56.1	3069.2
bgd	6329.3	109.5	11.9	6450.6
ind	33248.5	2439.7	953.2	36641.4
npl	1334.4	80.1	3.2	1417.8
pak	3536.5	519.8	67.9	4124.2
lka	523.0	-214.7	192.4	500.8
xsa	1226.7	-14.7	-6.2	1205.8
can	263.6	-154.3	160.3	269.7
usa	7405.9	-702.2	-1375.7	5328.0
mex	425.1	-926.7	-182.9	-684.5
xna	3.2	-0.8	-0.2	2.3
arg	2035.9	-196.5	-145.4	1694.0
bol	490.3	-32.2	-13.2	444.9
bra	33987.4	2766.1	271.9	37025.5
chl	869.3	37.2	85.3	991.7
col	2611.6	375.7	-568.1	2419.2
ecu	579.2	54.7	32.2	666.1
pry	397.1	30.4	26.7	454.2
per	2104.0	-40.8	-38.9	2024.3
ury	182.5	0.0	11.9	194.3
ven	1124.6	-131.3	-131.4	861.9
xsm	84.3	4.3	-3.3	85.3
cri	320.2	-17.6	-9.4	293.1
gtm	934.6	-18.3	6.6	923.0
hnd	473.5	31.4	21.0	525.9
nic	445.5	-0.7	2.4	447.2
pan	255.2	15.0	-23.1	247.2
slv	110.1	-10.1	-5.9	94.1
xca	31.4	5.1	3.1	39.6
dom	976.2	-59.3	-29.9	887.0
jam	77.2	13.3	5.8	96.3
pri	-297.3	-17.9	-20.1	-335.3
tto	-31.6	-8.9	-0.4	-40.9
xcb	412.5	-1.7	-173.3	237.4
aut	-68.4	21.3	7.9	-39.3
bel	847.5	-83.4	-80.3	683.8
bgr	-112.8	-52.3	115.5	-49.7

Country/region code	Activity	Structure	Intensity	Aggregate change, 1000 Tonnes
hrv	-72.8	-51.4	40.3	-83.8
cyp	-63.6	2.2	16.2	-45.2
cze	-338.9	98.8	70.3	-169.9
dnk	-143.6	-7.1	-27.1	-177.8
est	-50.2	21.0	8.0	-21.2
fin	198.6	9.0	-57.9	149.7
fra	1530.1	-770.5	-362.3	397.3
deu	-73.2	-192.6	73.5	-192.3
grc	-842.0	-60.5	-128.6	-1031.1
hun	-398.7	34.0	-34.0	-398.6
irl	182.1	182.0	-214.2	149.9
ita	-1451.7	-210.4	-211.9	-1874.0
lva	-47.3	27.2	-7.5	-27.6
ltu	-129.3	-22.7	-21.5	-173.5
lux	17.9	0.6	-5.4	13.2
mlt	-5.9	-2.3	3.4	-4.8
nld	-514.2	104.7	227.7	-181.8
pol	-677.0	-231.6	19.0	-889.6
prt	-289.9	47.6	-74.5	-316.8
rou	-553.1	32.5	248.0	-272.6
svk	-206.1	57.5	21.4	-127.1
svn	33.8	-9.9	-22.6	1.3
esp	498.5	-47.7	-855.4	-404.6
swe	80.4	45.9	13.9	140.1
gbr	352.5	-44.8	-494.9	-187.2
che	189.8	119.1	199.8	508.8
nor	62.9	49.5	42.1	154.6
xef	14.6	-7.6	2.6	9.5
alb	179.9	25.7	2.9	208.5
blr	-176.1	329.4	59.1	212.4
rus	2208.6	1492.4	377.4	4078.4
ukr	-1290.3	1308.9	862.4	880.9
xee	-231.7	67.4	4.8	-159.5
xer	-252.9	50.0	180.9	-22.0
kaz	1806.1	313.8	-56.9	2062.9
kgz	270.4	12.0	-12.7	269.9
tjk	389.9	3.4	5.7	399.2
xsu	3350.2	1647.1	212.2	5209.4
arm	321.8	17.7	7.0	346.4
aze	862.4	-46.6	12.6	828.4
geo	-393.0	-26.2	29.3	-389.8
bhr	205.1	19.7	17.3	241.3
irn	4448.2	-415.6	529.0	4561.6
isr	201.8	-35.6	-71.2	95.0
jor	892.0	-43.4	69.2	917.9
kwt	616.4	69.4	29.0	714.4
omn	605.5	-30.0	-12.6	563.0
qat	583.9	24.4	25.9	633.7
sau	3196.6	103.7	-149.7	3150.6
tur	5742.9	-537.1	-177.6	5028.2
are	1154.4	-87.1	-88.1	979.0
xws	1566.9	99.3	-96.7	1569.4
egy	8196.0	-346.4	52.6	7902.3
mar	2271.8	-95.0	-104.4	2072.3
tun	947.9	7.4	75.7	1031.0
xnf	6808.8	224.5	450.4	7483.7
ben	1093.5	0.4	-22.6	1071.2

Country/region code	Activity	Structure	Intensity	Aggregate change, 1000 Tonnes
bfa	547.2	-24.1	15.3	538.4
cmr	2662.2	135.3	50.9	2848.3
civ	1197.2	-162.2	-13.0	1021.9
gha	3748.1	-18.7	33.5	3762.9
gin	632.1	-106.1	-29.2	496.7
nga	9163.5	-307.6	-106.2	8749.7
sen	526.2	-77.6	-37.4	411.1
tgo	383.2	-100.8	14.4	297.2
xwf	3586.4	21.9	146.6	3754.8
xcf	974.2	-121.5	-10.4	842.3
xac	13154.7	439.2	602.3	14196.2
eth	3450.9	11.4	-16.8	3445.4
ken	2119.6	-127.9	86.5	2078.3
mdg	444.7	-35.7	-15.7	393.3
mwi	1936.3	282.8	-7.9	2211.2
mus	-91.1	4.6	23.3	-63.2
moz	608.2	49.6	-2.1	655.7
rwa	198.9	29.3	0.3	228.5
tza	3407.9	18.7	1.0	3427.6
uga	-71.7	-0.1	4.2	-67.5
zmb	204.4	10.7	-4.4	210.7
zwe	26.4	3.9	0.0	30.3
xec	2902.4	-331.2	-780.8	1790.4
bwa	146.4	-2.0	-17.6	126.8
nam	243.1	-33.1	20.5	230.5
zaf	1357.1	-36.7	-154.3	1166.1
xsc	3.1	9.7	20.4	33.1
xtw	0.0	0.0	0.0	0.0
World	**358165.2**	**8773.3**	**5674.8**	**372612.2**

Notes: Country/region code descriptions are available at:
https://www.gtap.agecon.purdue.edu/databases/regions.aspx?Version=10.211

Additional Tables and Figures

Table S17. Sourcing of FLW flows (Million Tons) by country in 2014.

GTAP Region	Country description	Total FLW generated from domestic consumption (of domestically produced and imported food)	Import-embedded FLW	Export-embedded FLW	Total Trade-embedded FLW (imports + exports)
aus	Australia	11.28	1.50	10.76	12.26
nzl	New Zealand	2.39	1.06	3.06	4.12
xoc	Rest of Oceania	2.05	0.65	0.53	1.17
chn	China	527.43	35.22	8.41	43.62
hkg	Hong Kong	3.49	3.42	0.17	3.58
jpn	Japan	24.28	12.05	0.10	12.15
kor	Korea	20.75	8.86	0.29	9.14
mng	Mongolia	0.35	0.10	0.00	0.11
twn	Taiwan	9.18	4.64	0.11	4.75
xea	Rest of East Asia	3.26	0.46	0.03	0.49
brn	Brunei Darussalam	0.08	0.06	0.00	0.06
khm	Cambodia	2.16	0.38	0.31	0.69
idn	Indonesia	36.94	4.96	4.70	9.66
lao	Lao People's Democratic Republic	1.28	0.07	0.08	0.15
mys	Malaysia	5.67	3.00	2.69	5.69
phl	Philippines	15.07	1.43	2.27	3.70
sgp	Singapore	2.76	2.70	0.09	2.79
tha	Thailand	12.25	0.68	28.04	28.72
vnm	Viet Nam	16.02	1.81	7.77	9.59
xse	Rest of Southeast Asia	8.11	0.38	0.57	0.94
bgd	Bangladesh	17.16	3.50	0.10	3.60
ind	India	113.42	2.95	8.86	11.82
npl	Nepal	4.16	0.48	0.03	0.51
pak	Pakistan	23.76	0.68	2.87	3.54
lka	Sri Lanka	2.86	1.24	0.17	1.41
xsa	Rest of South Asia	3.13	1.21	0.15	1.36
can	Canada	18.71	7.61	10.01	17.62
usa	United States of America	180.40	29.79	20.95	50.75
mex	Mexico	36.03	5.51	12.18	17.69
xna	Rest of North America	0.02	0.02	0.01	0.03
arg	Argentina	13.98	0.22	9.20	9.42
bol	Bolivia	2.22	0.14	0.46	0.59
bra	Brazil	99.36	2.21	54.86	57.07
chl	Chile	5.50	2.53	2.98	5.50
col	Colombia	17.04	1.48	2.37	3.85
ecu	Ecuador	3.05	0.32	2.90	3.22
pry	Paraguay	2.30	0.06	1.68	1.74
per	Peru	8.47	1.25	3.01	4.26
ury	Uruguay	1.19	0.47	0.88	1.34
ven	Venezuela	7.17	2.93	0.01	2.95
xsm	Rest of South America	0.54	0.13	0.30	0.43
cri	Costa Rica	1.88	0.25	2.61	2.86
gtm	Guatemala	3.97	0.43	5.83	6.26
hnd	Honduras	2.14	0.30	1.05	1.36
nic	Nicaragua	1.60	0.20	1.12	1.32
pan	Panama	0.95	0.26	0.27	0.52
slv	El Salvador	1.48	0.42	1.32	1.74
xca	Rest of Central America	0.13	0.02	0.32	0.33
dom	Dominican Republic	3.38	0.47	0.40	0.86
jam	Jamaica	0.97	0.20	0.02	0.22
pri	Puerto Rico	1.03	0.92	0.02	0.94
tto	Trinidad and Tobago	0.40	0.36	0.02	0.38
xcb	Caribbean	7.35	1.77	1.09	2.86
aut	Austria	2.44	0.82	0.68	1.50
bel	Belgium	4.04	2.74	2.77	5.51
bgr	Bulgaria	2.19	0.61	0.96	1.57
hrv	Croatia	1.32	0.38	0.15	0.52
cyp	Cyprus	0.26	0.14	0.06	0.19
cze	Czech Republic	3.02	1.02	1.44	2.46
dnk	Denmark	1.60	0.41	1.57	1.99
est	Estonia	0.34	0.14	0.16	0.30
fin	Finland	1.47	0.56	0.15	0.71
fra	France	20.65	4.81	9.14	13.95
deu	Germany	28.11	7.67	5.35	13.02
grc	Greece	3.73	0.98	0.93	1.91
hun	Hungary	2.21	0.34	1.54	1.88
irl	Ireland	1.81	0.91	0.72	1.63

ita	Italy	25.13	8.91	5.29	14.19
lva	Latvia	0.51	0.16	0.36	0.52
ltu	Lithuania	0.83	0.29	1.00	1.29
lux	Luxembourg	0.17	0.14	0.04	0.18
mlt	Malta	0.17	0.11	0.00	0.11
nld	Netherlands	5.13	2.26	5.17	7.42
pol	Poland	12.77	1.19	3.82	5.01
prt	Portugal	4.44	1.87	0.48	2.36
rou	Romania	6.21	1.06	1.17	2.23
svk	Slovakia	1.04	0.42	0.45	0.87
svn	Slovenia	0.55	0.26	0.07	0.33
esp	Spain	13.60	3.57	8.17	11.74
swe	Sweden	2.62	1.18	0.34	1.51
gbr	United Kingdom	17.44	8.33	0.49	8.83
che	Switzerland	3.02	1.28	0.10	1.38
nor	Norway	1.93	0.97	0.81	1.78
xef	Rest of EFTA	0.13	0.08	0.66	0.74
alb	Albania	1.32	0.27	0.03	0.29
blr	Belarus	3.56	0.34	1.37	1.72
rus	Russian Federation	50.21	6.85	5.57	12.42
ukr	Ukraine	16.26	0.60	5.35	5.95
xee	Rest of Eastern Europe	0.88	0.11	0.50	0.61
xer	Rest of Europe	5.12	0.71	0.90	1.61
kaz	Kazakhstan	8.06	2.71	1.28	3.99
kgz	Kyrgyztan	2.04	0.51	0.08	0.59
tjk	Tajikistan	1.07	0.39	0.08	0.47
xsu	Rest of Former Soviet Union	11.27	2.11	0.35	2.45
arm	Armenia	1.60	0.45	0.02	0.47
aze	Azerbaijan	3.55	1.11	0.09	1.20
geo	Georgia	1.36	0.81	0.06	0.87
bhr	Bahrain	0.58	0.50	0.01	0.51
irn	Iran Islamic Republic of	33.76	5.93	0.98	6.91
isr	Israel	3.34	1.62	0.38	2.01
jor	Jordan	2.98	2.12	0.30	2.43
kwt	Kuwait	1.63	1.43	0.04	1.48
omn	Oman	1.49	1.10	0.08	1.19
qat	Qatar	0.94	0.82	0.02	0.85
sau	Saudi Arabia	10.64	8.71	0.52	9.23
tur	Turkey	37.67	2.09	3.27	5.36
are	United Arab Emirates	3.88	3.74	0.23	3.97
xws	Rest of Western Asia	7.76	5.10	0.42	5.52
egy	Egypt	37.82	6.52	1.27	7.78
mar	Morocco	13.64	4.55	0.79	5.33
tun	Tunisia	5.46	2.28	0.42	2.70
xnf	Rest of North Africa	21.46	10.02	0.01	10.03
ben	Benin	2.79	0.36	0.04	0.39
bfa	Burkina Faso	1.64	0.35	0.07	0.42
cmr	Cameroon	6.63	0.44	0.14	0.57
civ	Cote d'Ivoire	5.17	0.51	0.62	1.13
gha	Ghana	11.16	1.03	0.22	1.25
gin	Guinea	2.18	0.35	0.01	0.36
nga	Nigeria	43.35	4.11	0.08	4.19
sen	Senegal	1.79	0.63	0.10	0.74
tgo	Togo	1.15	0.21	0.02	0.23
xwf	Rest of Western Africa	9.13	1.63	0.21	1.84
xcf	Central Africa	3.78	0.45	0.00	0.45
xac	South Central Africa	27.80	4.76	0.00	4.76
eth	Ethiopia	9.20	0.70	0.28	0.98
ken	Kenya	7.37	0.84	0.18	1.03
mdg	Madagascar	1.54	0.15	0.05	0.20
mwi	Malawi	4.31	0.06	0.16	0.22
mus	Mauritius	0.21	0.15	0.44	0.59
moz	Mozambique	1.80	0.21	0.16	0.36
rwa	Rwanda	0.85	0.14	0.02	0.17
tza	Tanzania	9.67	0.40	0.23	0.64
uga	Uganda	1.13	0.07	0.16	0.24
zmb	Zambia	0.72	0.04	0.25	0.30
zwe	Zimbabwe	0.32	0.07	0.13	0.20
xec	Rest of Eastern Africa	14.93	2.93	0.10	3.03
bwa	Botswana	0.41	0.26	0.01	0.27
nam	Namibia	0.58	0.35	0.23	0.58
zaf	South Africa	8.96	1.16	2.38	3.54
xsc	Rest of South African Customs	0.42	0.16	0.52	0.69

Table S18. Gross food supply (calories/capita/day), Net food supply (calories/capita/day) and nutritional losses (calories/capita/day) by region at each stage of the FSC in 2014.

GTAP Region	Gross food supply*	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retail	Consumption	Net food supply
aus	3628.8	191.7	149.6	152.9	363.0	567.7	2203.8
nzl	3619.7	204.1	167.2	160.7	352.6	567.1	2168.1
xoc	2709.0	170.7	31.9	34.5	53.4	306.4	2112.2
chn	3460.6	194.4	260.2	84.3	58.6	383.3	2479.7
hkg	3359.7	158.5	283.9	238.7	252.7	297.6	2128.3
jpn	2785.8	120.9	193.3	238.0	170.9	98.2	1964.4
kor	3540.7	160.9	370.0	320.5	97.1	325.1	2266.9
mng	2635.2	168.9	73.7	47.9	43.8	113.2	2187.7
twn	3066.9	137.3	270.8	221.9	227.2	244.3	1965.4
xea	2266.8	149.6	129.5	45.2	58.0	74.2	1810.3
brn	3119.0	254.2	104.8	81.7	102.3	102.6	2473.3
khm	3254.9	207.8	163.0	56.6	84.4	110.0	2633.1
idn	3041.0	180.6	146.1	87.8	80.4	102.1	2444.1
lao	2877.3	202.4	151.0	32.3	81.7	96.5	2313.4
mys	3435.6	241.8	109.2	148.6	101.4	112.1	2722.4
phl	2650.2	232.6	118.5	55.7	79.9	84.3	2079.3
sgp	3393.7	295.5	272.9	215.0	246.7	290.8	2072.9
tha	3080.9	221.3	128.9	80.2	92.5	100.6	2457.4
vnm	3202.0	319.0	141.7	65.8	92.2	99.9	2483.4
xse	2838.9	222.2	123.8	51.3	88.6	93.6	2259.4
bgd	2665.4	161.5	129.3	60.8	66.8	91.0	2155.9
ind	2524.6	36.5	26.6	92.1	44.7	95.2	2229.4
npl	2971.7	159.2	152.8	41.7	77.9	104.5	2435.6
pak	2471.7	146.0	84.1	45.7	80.3	91.9	2023.8
lka	2831.2	153.6	117.4	57.8	82.4	97.9	2322.1
xsa	2444.3	173.0	78.1	32.8	70.6	87.6	2002.1
can	3687.6	196.3	176.5	145.4	382.6	558.5	2228.2
usa	3883.4	242.7	162.1	154.0	364.4	565.5	2394.7
mex	3313.7	315.2	442.4	63.7	50.7	109.6	2332.0
xna	2227.0	22.3	20.9	20.8	50.0	295.3	1817.8
arg	3606.8	278.1	338.3	96.8	58.9	136.3	2698.4
bol	2470.9	121.8	265.9	48.7	53.2	89.9	1891.5
bra	4042.5	366.5	469.3	107.0	74.8	138.2	2886.7
chl	3096.9	238.3	310.6	75.5	56.5	108.7	2307.3
col	3025.3	282.0	334.6	69.6	73.3	101.8	2164.0
ecu	2660.8	105.0	295.5	69.3	46.7	98.8	2045.4
pry	3806.8	404.8	468.2	92.8	77.8	121.3	2642.0
per	3017.2	270.1	297.7	53.4	92.5	99.6	2203.9
ury	3714.3	287.9	369.2	99.3	66.7	138.8	2752.4
ven	2650.8	110.9	330.8	70.2	47.4	95.2	1996.3
xsm	3370.1	254.4	367.5	88.6	52.1	119.2	2488.4
cri	3321.4	289.7	352.6	79.8	80.9	114.6	2403.8
gtm	2651.1	130.5	388.9	44.3	53.6	92.2	1941.7
hnd	2908.4	174.2	421.7	54.9	46.8	102.2	2108.6
nic	2924.9	265.0	388.1	55.7	48.6	100.9	2066.7
pan	2821.6	218.0	296.1	62.6	48.5	102.9	2093.6
slv	2774.9	126.7	388.0	44.5	57.5	100.0	2058.1
xca	2938.3	253.5	349.5	70.6	52.8	99.4	2112.6
dom	2886.8	272.9	294.1	67.9	73.8	94.9	2083.2
jam	3228.0	287.6	349.3	62.1	62.0	109.6	2357.4
pri	3077.4	243.4	325.8	82.0	53.2	106.2	2266.7
tto	3076.8	244.9	325.2	82.9	53.6	106.4	2263.7
xcb	2970.8	260.5	321.9	65.1	73.2	99.6	2150.6
aut	3807.1	200.3	86.5	116.8	63.2	430.7	2909.6
bel	4900.3	301.1	104.2	166.9	83.9	534.6	3709.6
bgr	3807.3	284.2	320.8	110.3	193.5	370.2	2528.3
hrv	3163.2	176.5	224.5	123.7	140.6	321.6	2176.1
cyp	2965.8	170.1	64.5	97.4	49.4	335.4	2249.0
cze	3371.0	211.3	213.9	130.5	142.9	337.3	2335.1
dnk	3666.2	199.8	79.2	146.1	66.5	444.7	2729.9
est	3224.2	179.7	72.2	76.5	59.5	369.9	2466.4
fin	3436.6	171.3	62.5	101.0	59.5	431.2	2611.1
fra	4003.1	225.2	85.8	129.7	67.2	457.2	3038.1
deu	3643.2	228.6	229.3	149.8	149.5	355.9	2530.1
grc	3723.5	215.4	94.3	118.5	65.6	387.9	2841.8
hun	3272.7	195.7	69.1	78.3	54.3	391.5	2483.8
irl	3919.0	248.8	266.6	198.3	170.7	392.3	2642.4
ita	3577.9	249.5	281.6	157.6	163.6	341.9	2383.6
lva	3327.7	180.9	74.3	87.6	58.1	377.4	2549.5
ltu	4002.0	238.5	83.3	109.5	70.0	468.3	3032.3
lux	3567.3	191.8	73.3	136.2	62.7	443.9	2659.4
mlt	3646.4	265.7	293.4	161.6	172.2	362.8	2390.7
nld	3460.3	184.1	85.7	134.6	59.6	384.4	2611.9

GTAP Region	Gross food supply*	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retail	Consumption	Net food supply
pol	3576.3	251.1	253.2	108.1	158.1	371.0	2434.8
prt	3524.4	238.6	237.9	165.7	141.9	399.5	2340.8
rou	3662.1	219.6	84.3	87.7	67.3	423.2	2779.9
svk	3176.8	192.5	63.2	74.2	53.2	365.6	2428.1
svn	3605.7	213.3	75.7	87.2	67.8	425.5	2736.3
esp	3379.6	185.8	83.1	115.7	57.2	381.0	2556.7
swe	3411.9	182.7	70.2	107.5	56.2	384.4	2610.8
gbr	3409.0	192.4	78.2	92.8	59.9	403.8	2582.0
che	3533.3	216.3	219.2	181.0	144.2	346.6	2426.1
nor	3312.1	221.6	233.6	200.6	154.0	348.6	2153.5
xef	3617.5	209.3	227.6	236.1	183.5	375.1	2385.8
alb	3663.3	268.3	313.5	110.5	209.6	370.6	2390.7
blr	3645.3	249.2	250.8	141.1	141.8	383.1	2479.5
rus	3515.5	247.2	277.9	144.2	164.8	339.3	2342.1
ukr	3536.1	254.6	277.3	75.1	159.6	344.5	2424.9
xee	3092.8	191.7	178.5	65.0	128.2	331.3	2198.0
xer	3531.6	249.5	258.2	157.1	154.6	369.5	2342.6
kaz	3614.8	507.0	251.8	46.8	84.5	192.9	2531.9
kgz	2880.1	412.2	208.0	31.6	63.9	158.4	2005.9
tjk	2196.4	108.5	136.0	24.7	18.4	89.8	1819.0
xsu	2775.4	240.8	201.9	27.8	53.6	169.2	2082.2
arm	3186.8	448.4	229.3	44.6	76.4	175.6	2212.4
aze	3438.1	496.3	251.8	36.1	56.3	173.2	2424.3
geo	3223.9	454.0	271.2	32.8	53.7	147.5	2264.7
bhr	3705.0	530.0	333.5	53.7	77.5	191.2	2519.1
irn	3305.3	497.5	267.0	46.2	75.8	193.5	2225.4
isr	3575.4	500.5	252.2	62.4	74.5	179.6	2506.1
jor	3580.8	520.2	313.3	55.9	54.7	166.0	2470.8
kwt	3588.0	513.2	322.3	50.4	75.0	185.4	2441.7
omn	3003.1	437.4	256.0	45.1	73.7	170.5	2020.5
qat	3698.8	529.0	331.9	57.9	77.3	190.7	2512.1
sau	3537.5	507.0	313.9	56.5	60.6	164.3	2435.2
tur	4118.2	606.7	313.4	63.9	90.0	222.6	2821.6
are	4313.7	627.2	368.2	63.2	93.6	232.2	2929.4
xws	2375.7	91.4	75.9	66.0	18.4	100.2	2023.8
egy	3768.7	562.7	352.4	53.7	60.5	188.2	2551.3
mar	3706.3	547.1	325.0	37.7	57.2	182.1	2557.3
tun	3736.8	552.5	283.4	83.9	66.4	190.9	2559.6
xnf	3809.3	570.6	291.3	82.9	81.3	210.3	2572.9
ben	3097.8	222.0	201.3	61.3	202.7	96.3	2314.2
bfa	2929.9	144.8	158.4	50.3	128.0	99.3	2349.1
cmr	3252.9	247.6	234.3	42.3	235.1	100.2	2393.4
civ	2940.4	225.9	207.3	38.2	214.0	90.3	2164.7
gha	3983.1	374.2	325.4	50.7	349.7	115.6	2767.5
gin	2991.7	173.8	188.4	29.8	174.3	98.5	2326.8
nga	2909.3	208.9	197.6	18.4	195.6	91.9	2196.8
sen	2550.3	114.4	148.4	64.0	116.2	85.8	2021.5
tgo	2721.7	176.8	169.8	56.4	157.6	86.4	2074.7
xwf	3012.8	160.7	170.0	36.9	149.4	102.5	2393.5
xcf	2371.1	152.8	156.2	35.8	142.6	76.9	1806.8
xac	2737.4	218.1	187.6	47.3	198.6	82.3	2003.5
eth	2387.0	140.4	111.9	12.3	103.7	82.4	1936.2
ken	2354.8	145.5	123.2	19.1	118.8	81.9	1866.4
mdg	2169.1	54.1	40.2	38.7	35.4	81.3	1919.5
mwi	3180.9	210.5	173.3	33.1	169.8	103.3	2490.9
mus	3113.9	146.1	182.1	86.1	161.0	101.9	2436.7
moz	2262.3	55.8	34.7	12.7	35.6	84.4	2039.1
rwa	2376.5	32.6	30.9	21.5	34.2	91.2	2166.3
tza	2480.4	168.2	165.2	30.3	158.1	80.0	1878.6
uga	2192.7	27.5	29.2	8.8	30.0	21.0	2076.3
zmb	2038.9	28.9	33.4	27.1	28.5	77.6	1843.4
zwe	1832.0	18.3	18.1	8.4	17.9	17.7	1751.6
xec	3179.9	184.0	169.8	50.6	154.5	112.5	2508.5
bwa	2885.1	141.7	143.5	70.8	129.8	99.6	2299.7
nam	2735.0	165.3	151.3	69.8	143.6	89.2	2115.9
zaf	3120.3	148.4	138.2	75.2	117.3	106.6	2534.5
xsc	2383.6	116.3	98.2	48.6	81.2	83.0	1956.5

*Gross food supply matches estimates reported by the FAO – Food Balance Sheets

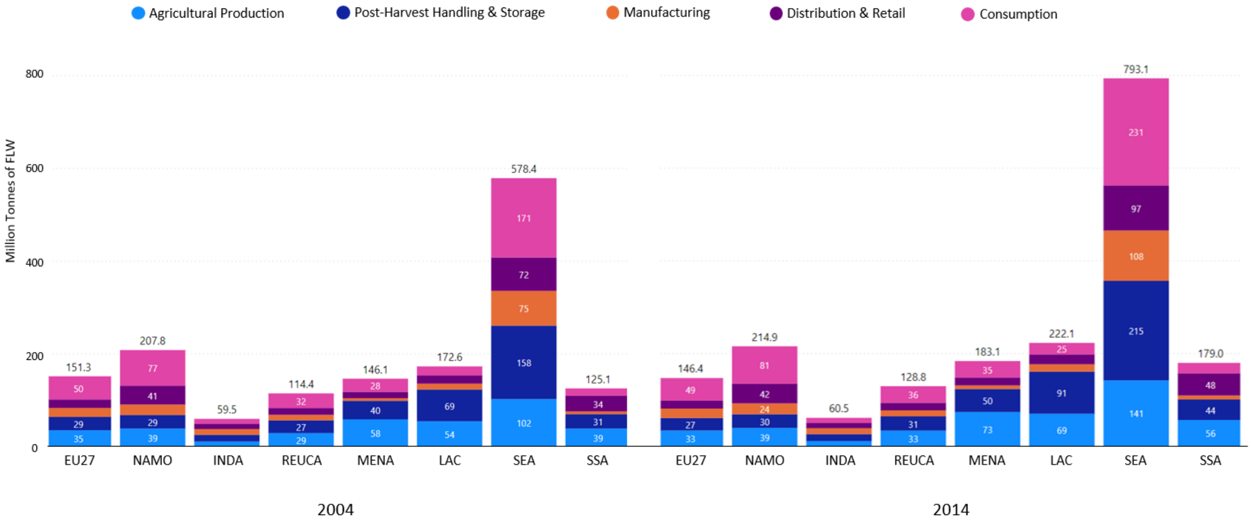

Figure S2. Food Loss and Waste (million Tonnes) generated along stages of the food supply chain, by region and reference year.

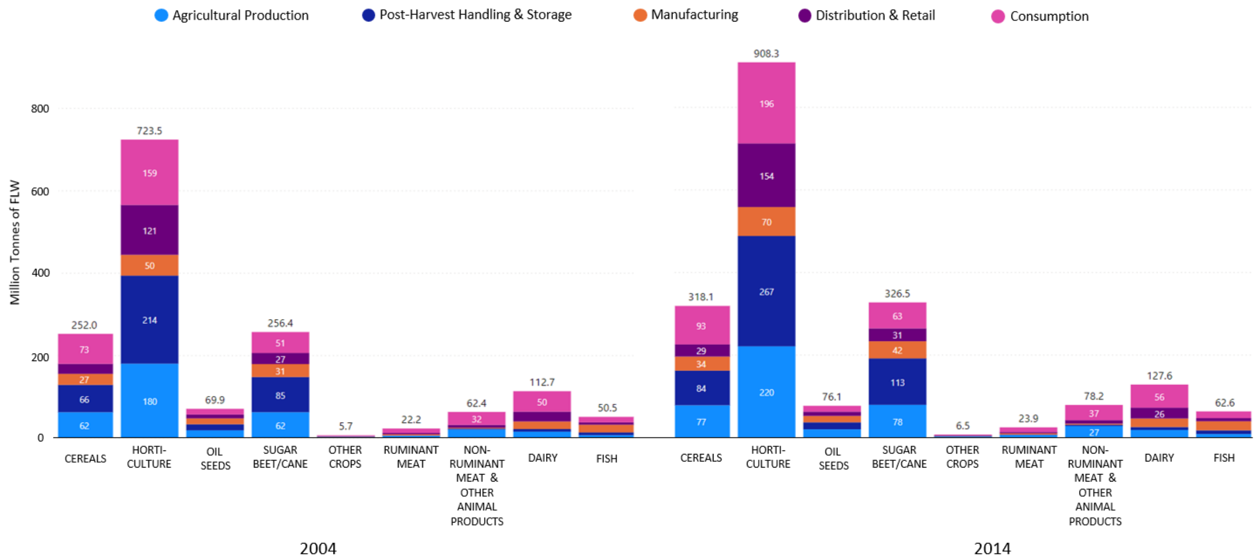

Figure S3. Food Loss and Waste (million Tonnes) generated along stages of the food supply chain, by commodity and reference year.

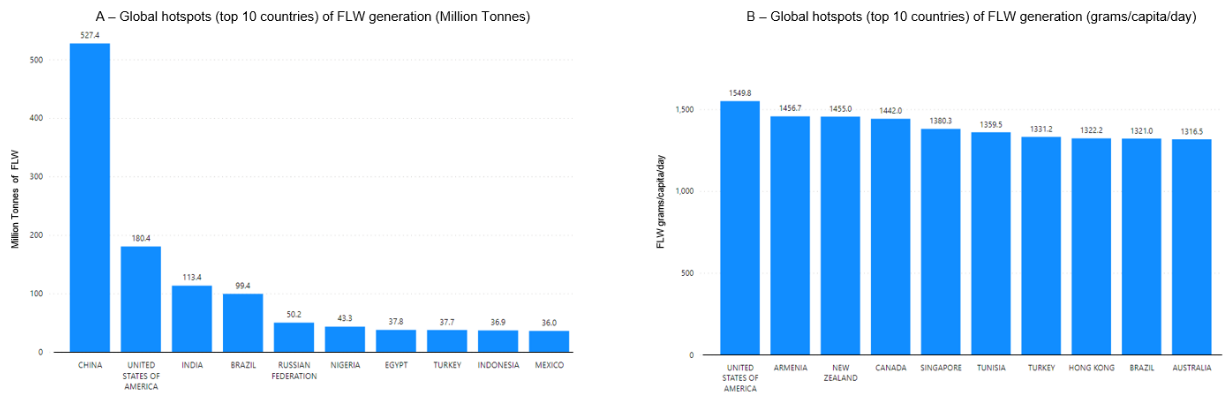

Figure S4. Global hotspots (top 10 countries) of FLW generation (million Tonnes and grams/capita/day) along global supply chains in 2014.

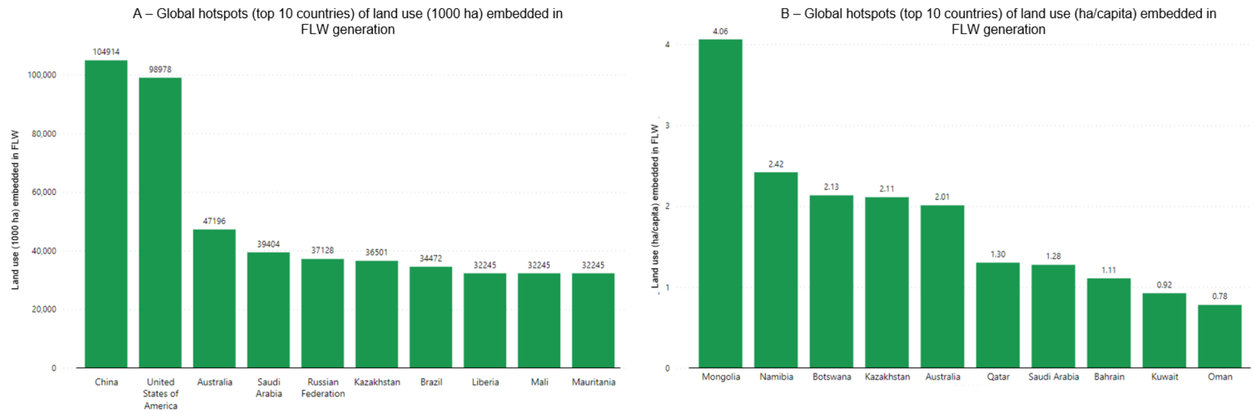

Figure S5. Global hotspots (top 10 countries) of land use (1000 hectares and hectares per capita/year) embedded in FLW generation along global supply chains in 2014.

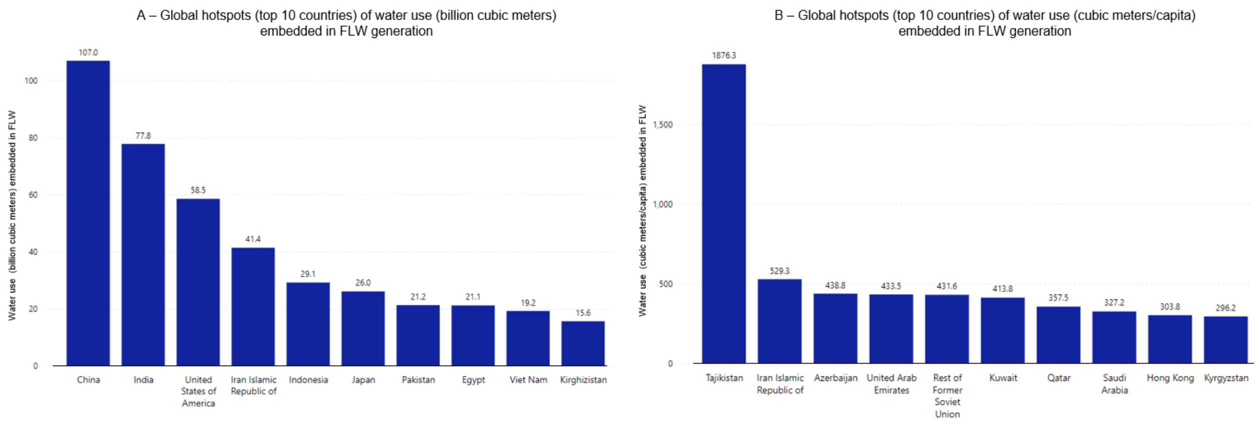

Figure S6. Global hotspots (top 10 countries) of water use (billion cubic meters and cubic meters per capita/year) embedded in FLW generation along global supply chains in 2014.

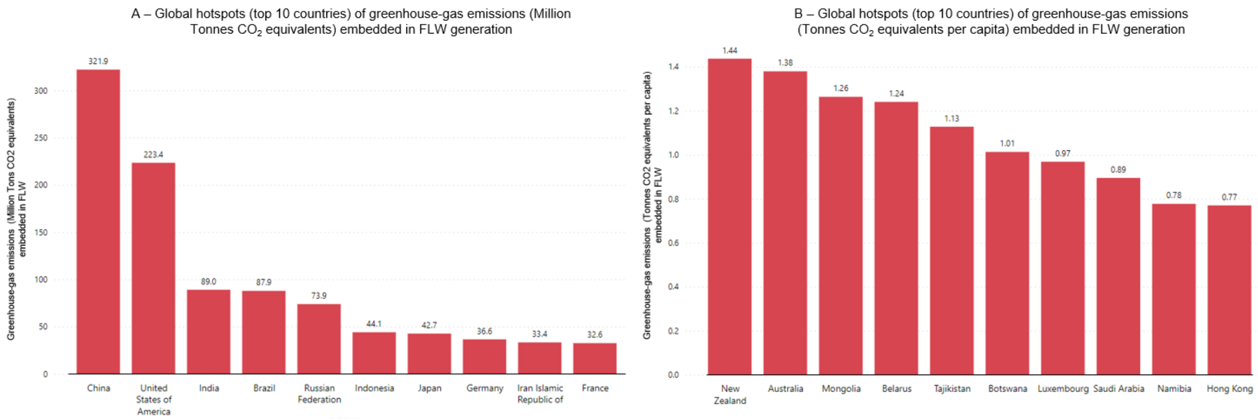

Figure S7. Global hotspots (top 10 countries) of greenhouse-gas emissions (Million Tonnes CO_2 equivalents and Tonnes CO_2 equivalents per capita/year) embedded in FLW generation along global supply chains in 2014.

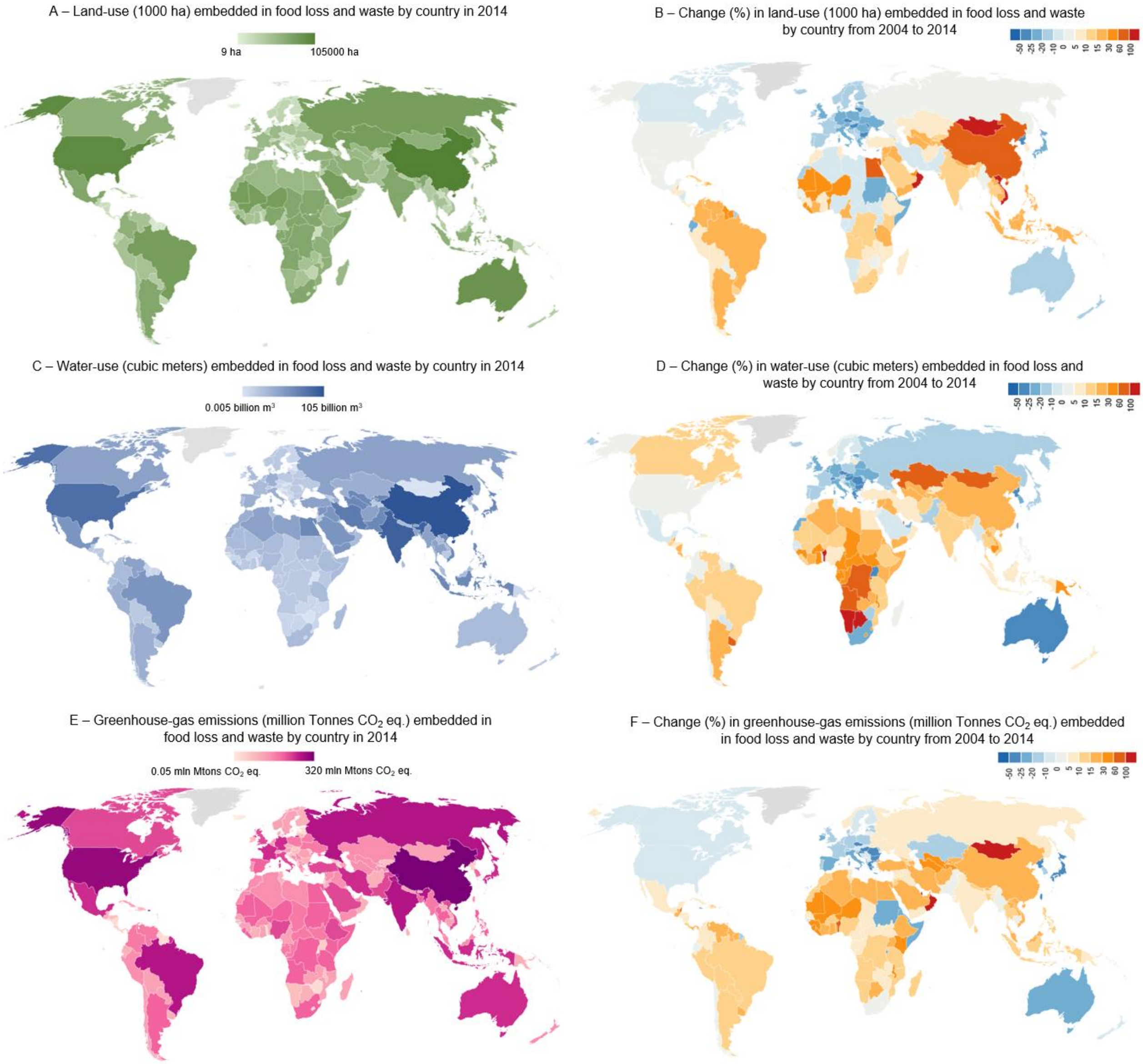

Figure S8. Land use, Water use, and greenhouse-gas emissions embedded in food loss and waste generated along global food supply chains. Estimates reported in the figure refer to the amount of land use, water use, and greenhouse-gas emissions embedded in tons of lost or discarded food along all the stages of global food supply chains. Panel A illustrates the amount of land use (1000 hectares (ha)) embedded in Tonnes of FLW generated by country in 2014. Panel B illustrates the change in total land use (1000 hectares (ha)) embedded in FLW generated by country from 2004 to 2014. Panel C reports the amount of water-use (cubic meters) embedded in Tonnes of FLW generated by country in 2014. Panel D illustrates the change in total water-use (cubic meters) embedded in FLW generated by country from 2004 to 2014. Panel E reports total greenhouse-gas emissions (million Tonnes of CO2 equivalent) embedded in Tonnes of FLW generated by country in 2014. Finally, Panel F illustrates the percentage change in total greenhouse-gas emissions (million Tonnes of CO2 equivalents) embedded in FLW generated by country from 2004 to 2014.

Chapter 3

Reducing global food loss and waste could improve air quality and lower the risk of premature mortality

Abstract

While the global food system substantially contributes to environmental degradation and climate change, significant amounts of lost or wasted foods along the food supply chain actively contribute to global air pollution and related health risks. In this study, we use an environmentally-extended input-output model to quantify air pollution embedded in global food loss and waste (FLW) and investigate how FLW reduction policies can mitigate air pollution linked to food consumption, decreasing associated premature mortality risks across global regions. While estimating a positive impact of FLW reduction policies on decreasing air pollution levels (from -1.5% of SO_2 emissions to -10.2% of NH_3 emissions) and mortality reductions (over 67,000 lives worldwide) our findings highlight that rebound effects, wherein a reallocation of consumption from food to non-food commodities, decrease health and environmental benefits by over three quarters (compared to the case with no rebound). Such rebound effects can be substantially mitigated when final consumption shifts towards less pollution-intensive products, such as service activities, rather than conforming to the current composition of non-food consumption. Our results suggest that FLW-related policies would benefit from complementary measures that incentivise sustainable non-food consumption to effectively foster the transition towards a healthier and more sustainable planet.

This chapter is based on:

Gatto, A., Chepeliev, M. (2024). Reducing global food loss and waste could improve air quality and lower the risk of premature mortality. Environmental Research Letters 19 014080. DOI 10.1088/1748-9326/ad19ee

3.1 Introduction

The global food system significantly contributes to environmental degradation and climate change (IPCC, 2019; FAO et al., 2021), accounting for about 30% of global greenhouse gas (GHG) emissions (Poore & Nemecek, 2018), as well as a substantial share of air pollution - between 10% for the case of sulphur dioxide (SO_2) and up to 90% of ammonia (NH_3) emissions (Crippa et al., 2022). While food is essential for a steadily growing world population, air pollution is responsible for 4.2 million premature deaths per year worldwide (WHO, 2022) and increasing air pollution embedded in food consumption represents a major environmental mortality risk factor (Murray et al., 2020; GBD, 2019).

Approximately one-third of food is lost or wasted along the food supply chain (FSC) (FAO, 2019), accounting for 6-10% of global GHG emissions (Poore & Nemecek, 2018; UNEP, 2021). While indirect emissions result from the production, processing, and transportation of food that is ultimately lost or discarded, direct emissions are driven by the disposal of FLW. Landfilled food waste is a major contributor to global warming (IPCC, 2013), accounting for 16% of global methane emissions (Shindell et al., 2020). Air pollution has a direct impact on the productivity of agricultural systems with the potential to reduce crop yields and impair the nutritional quality of food (Domingo et al., 2021; Lelieveld et al., 2015), inducing farmers to discard produce (Giannadaki et al., 2018; Lipinski et al., 2013) or sell their crops at lower prices. Additionally, it can impact the storage and transportation of food, as contaminated air can infiltrate storage facilities, transportation vehicles, and packaging materials. At the consumer level, air pollutants affect the shelf life of food, accelerating spoilage and intensifying waste generation (UNEP, 2021). Adverse implications of rising air pollution on ecosystems and biodiversity have also been widely recognized in the literature (Paoletti et al., 2010; Lovett et al., 2009). Short- and long-term exposures to landfilled FLW pollution have also been linked with premature mortality and reduced life expectancy (Kampa & Castanas, 2008; Siddiqua et al., 2022).

The contribution of FLW to global GHG emissions has been assessed in earlier studies (Katajajuuri et al., 2014; Poore & Nemecek, 2018; Porter et al., 2016; Xue et al., 2017) but limited information is available on air pollutants embedded in FLW along global FSC and their impact on premature mortality Agricultural production and post-harvest handling & storage represent a global hotspot of food loss generation especially in low-income regions (Kaza et al., 2018; FAO, 2019; UNEP, 2021). As crop and livestock production globally contribute around 75% of the nitrous oxide (N_2O) (Tubiello et al., 2021; FAO, 2020b), and substantial volumes of particulate matter (PM) (Madden et al., 2008), decreasing farm-level losses could reduce the anthropogenic emissions from agriculture easing the burden of pollution-induced diseases (Murray et al., 2020; GBD, 2019). It could further reduce critical levels of ammonia (NH_3) emissions (Lassaletta et al., 2016; Giannadaki et al., 2018) often linked to chronic respiratory illnesses and premature mortality (Wyer et al., 2022). Tackling FLW during transportation, processing, and retailing, could reduce carbon monoxide (CO) emissions linked to these stages of the FSC (Tubiello et al., 2021). A reduction in food waste, particularly in high-income regions, could decrease emissions of ammonia, sulphides, and carbon monoxide (Kaza et al., 2018; UNEP, 2021) alleviating impacts on climate change and health-related issues (Shindell et al., 2020).

Implementing FLW reduction policies may simultaneously have a positive impact on food availability (UNEP, 2021), decreasing average food demand and lowering average food prices (Rutten, 2013). While this is crucial for a global food security, it has the potential to decrease consumer expenditures on food simultaneously boosting the consumption of various non-food items (Read et al., 2020; Salemdeeb et al., 2017) with higher pollution intensity. The existence of such rebound effects in the context of FLW reduction policies has been discussed in the earlier literature (Martinez-Sanchez et al., 2016; Reynolds et al., 2019; Salemdeeb et al., 2017) and must be considered when policies are devised.

While widely used global FLW databases (FAO, 2011; Xue et al., 2017; Kaza et al., 2018; FAO, 2019; UNEP, 2021) omit a comprehensive representation of global food trade and FLW embedded in non-primary foods (Gatto & Chepeliev, 2023), a multi-regional input-output (MRIO) framework inclusive of FLW allows to trace lost and discarded foods and embodied air pollutants along FSC. MRIO models are economic and environmental frameworks apt to quantify the interdependencies between different sectors of the global economy, allowing the examination of cross-border relationships and global supply chains. FLW-extended MRIO include the flow of lost and discarded foods across different countries, providing ad-hoc assessments of the environmental and economic impacts of FLW and related activities. The majority of FLW-extended MRIOs (Read et al., 2020; Reutter et al., 2017; Usubiaga et al., 2018) rely on data from Gustavsson et al. (FAO, 2011), offering a potentially outdated (Sheahan & Barrett, 2017; Xue et al., 2017) representation of flows of lost and discarded foods. Gatto and Chepeliev (2023) develop a consistent FLW-extended MRIO coupled with a global nutritional database (Chepeliev, 2022), relying on up-to-date estimates computed consistently with the methodology and definitions adopted by UN-SDG12.3 (United Nations, 2019).

We build on this FLW-extended MRIO to quantify air pollutants embedded in FLW along global FSC, successively testing how potential FLW reduction policies may mitigate air pollution and related health risks. First, we provide an overview of evolving trends of air pollutants embodied in FLW across a 2004-2014 timeframe outlining drivers and hotspots across countries and stages of the FSC. Following, we explore the impact of the UN-SDG12.3 target of 50% cut in FLW , investigating the variation of air pollutants embedded in the final consumption of food under three alternative final demand patterns. The resulting changes in air pollution across scenarios are further linked to the global atmospheric source-receptor model allowing to assess health-related co-benefits across global regions.

We find FLW reduction policies decrease air pollution, but the overall magnitude of the achieved health and environmental benefits substantially varies across assumed changes in consumption patterns. As rebounds are lower when consumption shifts towards less pollution-intensive products, our findings highlight the benefits of FLW-related policies for fostering a healthier and more sustainable global food system but stress on the need of complementary measures to direct consumer choices towards more sustainable non-food products.

3.2 Methods

Estimates of FLW across global supply chains are obtained from Gatto & Chepeliev (2023) and are defined as

$$FLW\_SHR_{c,d}^{r,g} \quad (1)$$

where *r* represents the country where losses or waste are generated, *g* represents a stage of the FSC at which the losses/waste are occurring, *c* represents a primary food commodity being lost or wasted and *d* represents a dummy variable that has a value of "1" when a commodity enters the manufacturing stage (i.e. is finally consumed as a processed food product) and a value of "0" when it does not (i.e. is finally consumed as a fresh food product).

To quantify physical (Tonnes) food supply we retrieve information from the GTAP-FBS database (Chepeliev, 2022)[7] defining a food supply as

$$FOOD_{r,s}^{c,f} \quad (2)$$

[7] The GTAP-FBS Data Base incorporates nutritional accounts from the FAO Food Balance Sheets into the Global Trade Analysis Project Data Base, tracing quantities of food, calories, fats, proteins, and carbohydrates along global value chains.

where *c* represents a primary food commodity flowing into primary food, processed food or food services which provides information on the primary composition of non-primary foods, *f* represents the final food product (primary, processed or from food services) consumed by households, *r* and *s* represent regional source (*r*) and destination (*s*) of the food supply (if *r* = *s,* food is produced and consumed domestically within a country). The computation of coefficient (2) is available in (Chepeliev, 2022) and is briefly illustrated in Supplementary Information. Coefficient (2) represents the food matrix derived from our MRIO framework to which FLW shares are applied.
We multiply the FLW coefficient (1) by the physical food flows represented by coefficient (2), tracing FLW along global food supply chains as following

$$FLW\_FSC_{a,f,t}^{r,s,d} = FLW\_SHR_{c,d}^{r,g} * FOOD_{r,s,t}^{c,f} \quad (3)$$

where *r* represents the region where primary commodity *a* is produced (source region), hence where losses from Agricultural Production up to Distribution & Retail stages occur, *s* represents the region where final consumption occurs (destination region) hence where Consumption waste is generated, *f* represents the food commodity or food service consumed by final consumers in region *s* and to which primary food flows *a* are flowing to and *t* represents the stage of the supply chain at which losses are occurring. A more in-depth description of the methodological process to merge FLW estimates into our MRIO framework is provided in the Supplementary information.
We link FLW estimates to air pollutants derived from the EDGAR Version 5.0 database (Crippa et al., 2020) following Chepeliev (2021). First, we map this data to food flows from farm to fork devising air pollutants embedded in food and non-food production and consumption across global supply chains. From this, we quantify air pollution embedded into FLW along five stages of the FSC (namely Agricultural Production, Post-Harvest Handling & Storage, Manufacturing, Distribution & Retail, and Consumption) for nine air pollutants (Chepeliev, 2021). The full database providing country- and commodity-specific air pollutants embedded in FLW along the FSC is available in the Supplementary Information.
We use the FLW-pollution-extended MRIO, to assess the impact of a 50% reduction in global FLW based on the SDG12.3 target (U.N., 2019). We decrease the FLW shares by 50% to simulate a FLW-reduction policy, quantifying the associated decrease in food supply assuming a decrease in FLW shares entails a more efficient food production, supply, storage, and consumption. As net food consumption does not change, we assume total gross food demand proportionally decreases, reducing food-related expenditures. We find that 50% reduction in FLW decreases average global food demand by 13.0%. We implement uniform FLW reduction policies across scenarios, assuming expenditures on food decrease by the same amount in each scenario. However, different trends of demand reallocation toward non-food items are assumed across scenarios (Table 3.1). In the "No Rebound Effect" (NO_REBOUND) scenario, the decrease in food expenditures is assumed to generate no increase in expenditures on non-food products, assuming non-food demand remains constant, hence no rebound is generated. This scenario corresponds to the potential FLW reduction policy implementation in the partial equilibrium-type models, where interactions and expenditures outside the agri-food sectors are not explicitly represented. In contrast, in the "Status Quo" (STATUS_QUO) scenario the reduction in food expenditures leads to an increase in the demand for non-food products following the current patterns of consumption outside the food sector. Finally, in the "Environmental Awareness" (ENV_AWARE) scenario the decrease in food expenditures is reallocated toward demand for products that have the lowest pollution intensity, assuming that consumers decide to shift their preferences towards "pollution-friendly" goods and services. In addition to lower emission intensity, increasing expenditures on such service activities, including education, can benefit human capital development and benefit economic growth in the long-run (Gyimah-Brempong et al., 2006; Haldar & Mallik, 2010).

We rely on the TM5-FASST model (Van Dingenen et al., 2018) to address the impact of evolving air pollutants on human health and premature mortality risks under the FLW reduction policies. We estimate pollutant-related premature mortality rates across global regions, investigating PM2.5-related diseases and respiratory O_3 exposure mortality. Based on the TM5-FASST methodology (see Van Dingenen et al., 2018; Sampedro et al., 2022; Belis et al., 2022), health-relevant exposure metrics considered in the present study are population weighted annual mean PM2.5 at 35% relative humidity and seasonal daily maximum 8h average O_3 concentration metric (SDMA8h). The mortality associated with the exposure metrics used to compute health impacts in line with epidemiological studies (Jerrett et al., 2009; Krewski et al., 2009; Pope III et al., 2002). Mortality associated with PM2.5 is calculated, using the integrated exposure-response model (IER) adopted in the Global Burden of Disease (GBD, 2017) assessment (Stanaway et al., 2018), as the number of annual premature mortalities from six causes of death: chronic obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory airway infections (LRI), type 2 diabetes mellitus (DM), ischemic heart disease (IHD), and stroke. To monetize the health co-benefits of improved air quality we rely on the value of social life (VSL) approach outlined in Markandya et al. (2018). A more detailed description of our methodology and estimates of total air pollutants generated across scenarios are available in the Supplementary Information.

Table 3.1. Definition of investigated scenarios and quantification of changes in final demand.

Scenario	Description	Global-average percentage change in food expenditures due to 50% reduction in FLW	Global-average increase in non-food demand linked to a reallocation of decreased food expenditures	
No Rebound effect (NO_REBOUND)	A 50% reduction in global FLW is imposed. The decrease in consumer expenditures for food is assumed to not increase demand for any other food or non-food product.	-13.0%	No increase in non-food demand is assumed	
Status quo (STATUS_QUO)	A 50% reduction in global FLW is imposed. The decrease in consumer expenditures for food is assumed to parallelly increase demand for non-food products, assuming the share of non-food products in overall non-food consumption remains constant.	-13.0%	agricultural non-food	3.8%
			fossil fuels	2.0%
			manufacturing	31.4%
			services	1.0%
Environmental Awareness (ENV_AWARE)	A 50% reduction in global FLW is imposed. The decrease in consumer expenditures for food is assumed to parallelly increase demand for low pollution-intensive products*, assuming consumers are aware of air pollution embedded in their consumption choices and decide to shift preferences towards more sustainable products.	-13.0%	Low pollution-intensive products*	15.0%

* The definition of "low pollution-intensive products" is based on the volume of air pollutants embedded in $1 of final consumption for each country and sector represented in the GTAP database (Chepeliev, 2021; Aguiar et al., 2019). We then rank all non-food sectors represented in the GTAP Data Base and determine four sectors with the lowest global average emission intensity of final consumption. Corresponding sectors include the following activities: information & communication (cmn), other financial intermediation (ofi), insurance (ins), and education (edu).

3.3 Results

Global hotspots and trends of air pollutants embedded in food loss and waste

Air pollutants embedded in the global FLW range from 2.2% for the case of SO_2 emissions to 18.9% of NH_3 pollution worldwide. The largest volumes of the FLW-embedded pollutants across global supply chains correspond to carbon monoxide (CO – 19,802 Gigagrams (Gg) or 5.0% of total emissions – panel A of Figure 3.1), and ammonia (NH_3 - 8,708 Gg or 18.9% of total emissions – panel B of Figure 3.1), followed by organic carbon (OC – 9.3%), particulate matter (PM10 – 5.4% and PM2.5 – 5.2% - panel C of Figure 3.1), nitrogen oxides (NO_X – 4.2% - panel D of Figure 3.1), and sulfur dioxide (SO_2 – 2.2%). Agricultural Production and Consumption represent global hotspots of air pollutants, accounting for 53.8% (16,970.4 Gigagrams (Gg)) of air pollutants associated with discarded or wasted food, and for 1.1% (SO_2) to 11.2% (NH_3) of the total global pollutants emitted. Key pollutants at these stages are CO and NH_3, originating from farm operations, organic matter decomposition, and landfill activities.

Largest amounts of FLW-embedded CO are found in southeast Asia (2433 Gg), China (2426 Gg) and Brazil (2286 Gg), while largest hotspots of FLW-embedded NH_3, are found in China (1611 Gg), European Union (EU27 – 1133 Gg) and the United States (USA – 958 Gg). Similarly, largest levels of PM2.5 are found in China (244 Gg) and southeast Asia (231 Gg) while NO_X related pollutants are primarily concentrated in China (556 Gg) and USA (435 Gg) (Figure 3.1).

Across lower income regions such as Southeast Asia (SEA) and Sub-Saharan Africa (SSA), the majority of air pollutants embedded in FLW is generated at the farm-level stages of the supply chain, accounting for an average of 4.3% to 8.9% of total air polluting emissions. Differently, in high income countries largest FLW-embedded pollution levels are found at consumer stage and represent an average 2.5% to 5.2% of total air pollution generated in these regions.

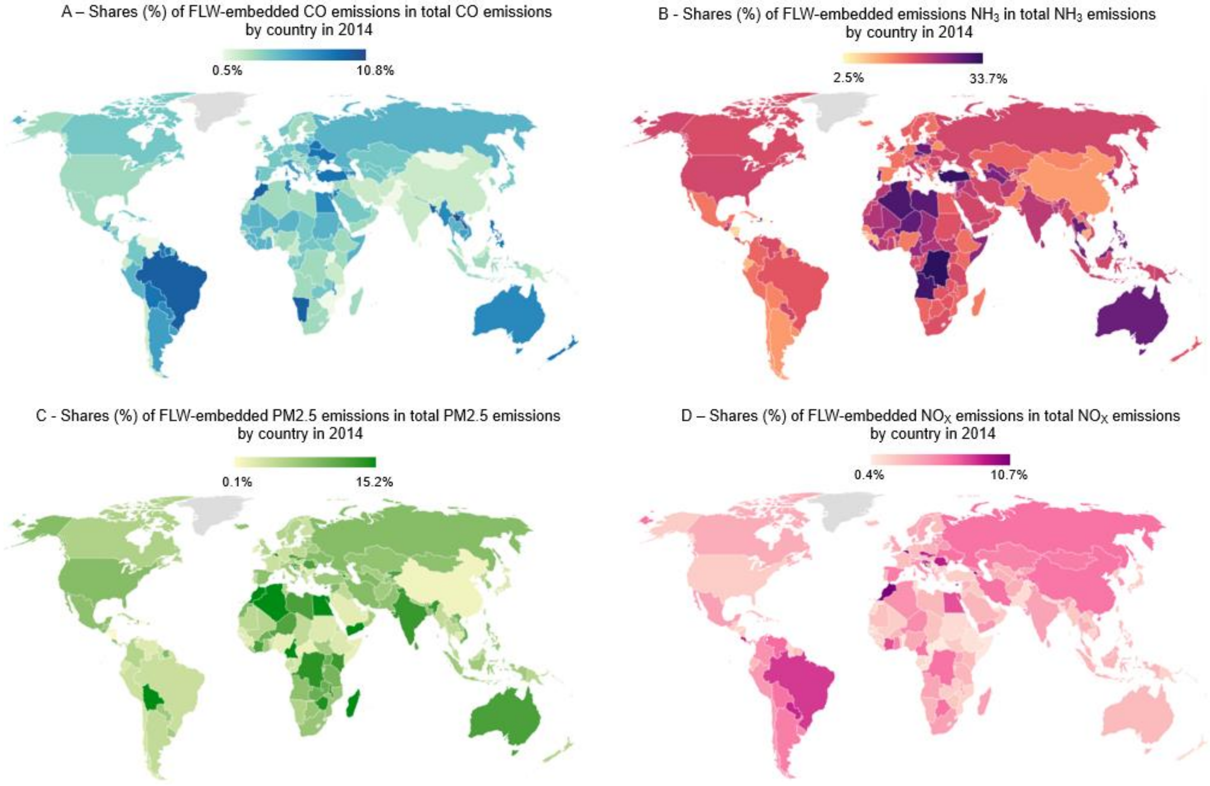

Figure 3.1. Shares (%) of FLW-embedded air pollutants in total air pollution for four pollutants generated across global countries in 2014. Panel A illustrates shares of FLW-embedded Carbon Oxide (CO) in total CO emissions by country in 2014. Panel B illustrates shares of FLW-embedded Nitrogen Oxides (NO_X) emissions in total NO_X emissions by country in 2014. Panel C illustrates shares of FLW-embedded Ammonia (NH_3) emissions in total NH_3 emissions by country in 2014. Finally, Panel D illustrates shares of FLW-embedded particulate matter 2.5 (PM2.5) emissions in total PM2.5 emissions by country in 2014. Additional data and figures on other air pollutants embedded in FLW are available in the Supplementary Information.

Between 2004 and 2014, air pollutants embedded in FLW increased primarily in mid- and low-income regions while in general decreased in high-income countries (Figure 3.2). In SSA, main drivers are found in increasing per-capita gross domestic product (GDP) and population. While these factors have similar effects in southeast Asia, an exception is represented by China and high-income Asian countries (HI-ASIA) where a stronger decrease in generated air pollutants per unit of FLW (in light blue in Figure 3.2) and in food consumption per unit of GDP (in grey in Figure 3.2), resulted in a contained increase or in decreasing amounts of FLW-embedded pollutants. Across global regions, air pollution from services decreased (-2.7%) while increasing from manufacturing (3.6%). As GDP growth was primarily driven by the expansion in service sectors with relatively lower pollution intensity, this structural shift channel had an important contribution to the reduction in pollution-intensity of the final consumption. Parallelly, the changing composition of consumed foods across high-income regions, such as Europe, USA and North America and Oceania (NAMO), has additionally resulted in lower air pollutants embedded in FLW.

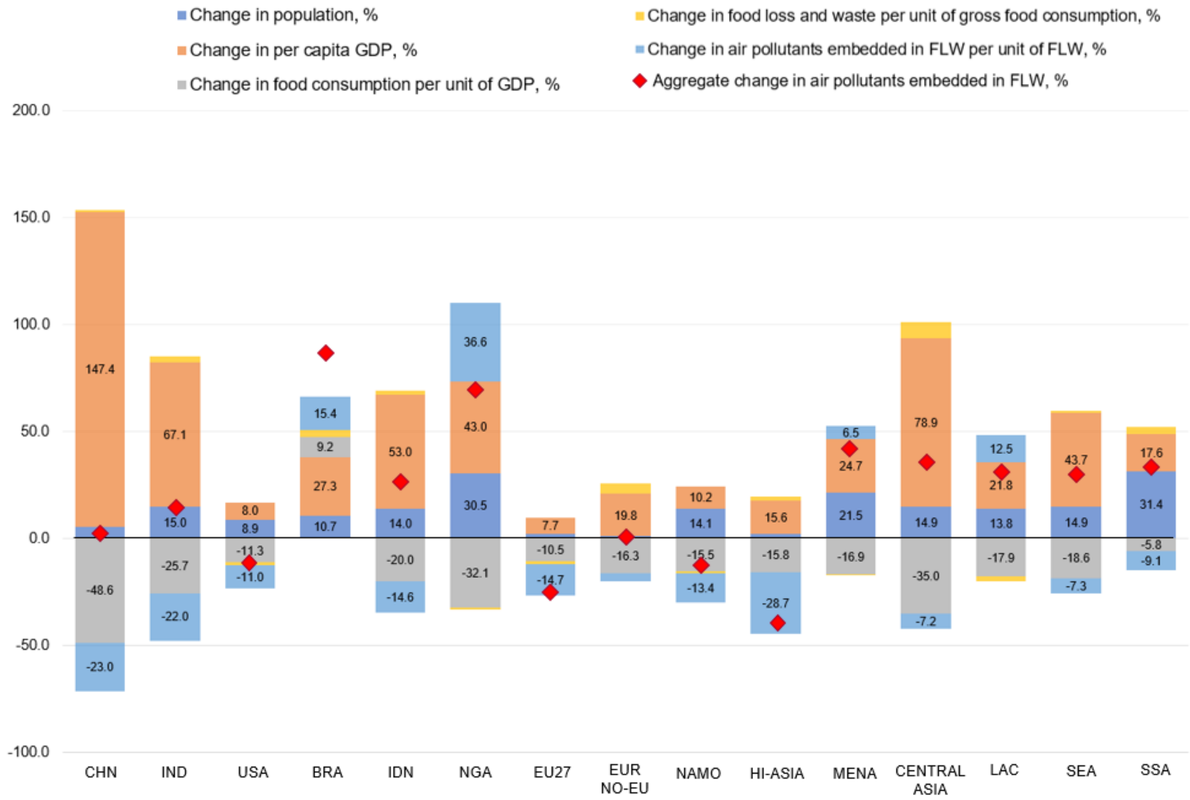

Figure 3.2. Aggregate change in air pollutants embedded in food loss and waste from 2004 to 2014 based on KAYA identity. Estimates refer to percentage changes in the period between 2004 and 2014. The illustrated estimates are based on changes in the main drivers of air pollutants embedded in food loss and waste and are computed following the approach of Kaya & Yokoburi (1997). A list of countries composing each macro-region reported in the figure is available in the Supplementary Information.

The impact of FLW reduction policies on air pollution

Reducing FLW by 50% can exert significant benefits on global air pollution but such benefits substantially depend on the changing consumer demand.[8] In our "No Rebound Effect" (NO_REBOUND) scenario, the observed decrease in air pollution is highest compared to other scenarios in which non-food demand is assumed to increase. In NO_REBOUND, a 50% reduction in global FLW decreases CO (2.8% or 11,216.5 Gigagrams (Gg)), NO_x (1.7% or 1985.7 Gg) and PM2.5 (3.1% or 870.9 Gg) pollution, globally. When FLW reduction policies are applied worldwide, the most substantial reductions in pollutants are observed in China, Brazil, or Southeast Asia (SEA) (Panel A – Figure 3.3). Production-related pollution decreases mainly in large net food exporting regions such as Brazil, Latin America & Caribbean (LAC), North America & Oceania (NAMO) and Indonesia. In these regions, the largest reduction in pollution is achieved when FLW is reduced globally (average -4.4% or 656.6 Gg in CO emissions; average -4.8% or 46.1 Gg in PM2.5 emissions) but also when policies are applied only domestically (Panel A – Figure 3.3).

In our "Status Quo" (STATUS_QUO) scenario, the FLW reduction policy proportionally increases demand for non-food products, maintaining current shares of non-food products in total non-food consumption across regions. As

[8] A supplementary spreadsheet "Changes in demand patterns across scenarios.xlsx" reports country- and commodity-specific changes in demand patterns across investigated scenarios.

non-food products may have higher pollution intensities compared to food products, a global FLW reduction decreases CO (0.3% or 1256 Gg) and PM2.5 (1.4% or 403.3 Gg) pollution but increases NO_X (0.2% or 262.9 Gg) pollution, generating heterogenous effects across regions. A global 50% reduction in FLW increases CO and NO_X pollution in China (an average of 0.4%), Nigeria (average 9.3%), high-income Asia (HI-ASIA) (average 0.8%), and Sub-Saharan Africa (SSA) (average 1.0%), as shifting consumer demand specifically towards transportation and construction sectors increases production, hence pollution, in these regions.

Similar effects are observed when policies are applied to a single country/region (Panel B - Figure 3.3). Region-specific policies primarily increase NO_X pollution, impacting large pollution-intensive non-food producers such as China or Nigeria. An exception is represented by Brazil and Indonesia, where the reduction in pollution associated with a lower food demand dominates the increase in non-food pollution notwithstanding whether policies are applied only domestically or worldwide. In relative terms, decreasing FLW in low-income regions such as Nigeria and SSA, exerts a strong increase in domestic (average 7.2% or 1274.7 Gg of CO; average 5.5% or 27.7 Gg of NO_x) and global pollution (average 6.8% or 1262.1 Gg of CO; average 4.4% or 30.8 Gg of NO_x). A Similar pattern is also observed when the FLW reduction policy is applied only in China (0.3% or 280.9 Gg of CO; 0.4% or 103.6 Gg of NO_x; 0.1% or 9.7 Gg of PM2.5) as non-food emission (principally from manufacturing and construction sectors) overrun the decrease in pollution from the food system. All three regions (Nigeria, SSA and China) have relatively high emission-intensity of energy supply as the power generation mix is dominated by fossil fuels (EIA, 2023).

The "Environmental Awareness" (ENV_AWARE) scenario presents the lowest pollution rates. Here, the decrease in air pollution (-0.7% or 29997.5 Gg of CO; -2.6% or 724.3 Gg of PM2.5; NO_X -1.1% or 1183.1 Gg of NO_X) is almost twice the size of the decrease under STATUS_QUO scenario (Panels B and C of Figure 3.3) showing the benefit of controlling for rebound effect when devising FLW reduction policies. Major reductions in pollution are observed for large food exporting regions such as Brazil, Indonesia, and LAC (average -2.8% or 656.1 Gg of CO; average -1.2% or 59.3 Gg of NO_X; average -3.4% or 48.8 Gg of PM2.5 principally linked to rice and horticulture production) while CO and NO_X pollution grow in Nigeria (17.5% or 3275 Gg of CO; 8.3% or 41.4 Gg of NO_X principally linked to transportation and construction sectors and other services). In relation to the STATUS_QUO scenario, region-specific FLW reduction policies generate reverse effects on global air pollution. In China a FLW reduction of 50% in the ENV_AWARE scenario decreases global CO pollution by 1000.7 Gg compared to STATUS_QUO scenario. Differently, CO pollution is higher under the ENV_AWARE scenario for Nigeria and SSA, as CO emission intensity of service sectors, which experience increasing consumption, is relatively high.

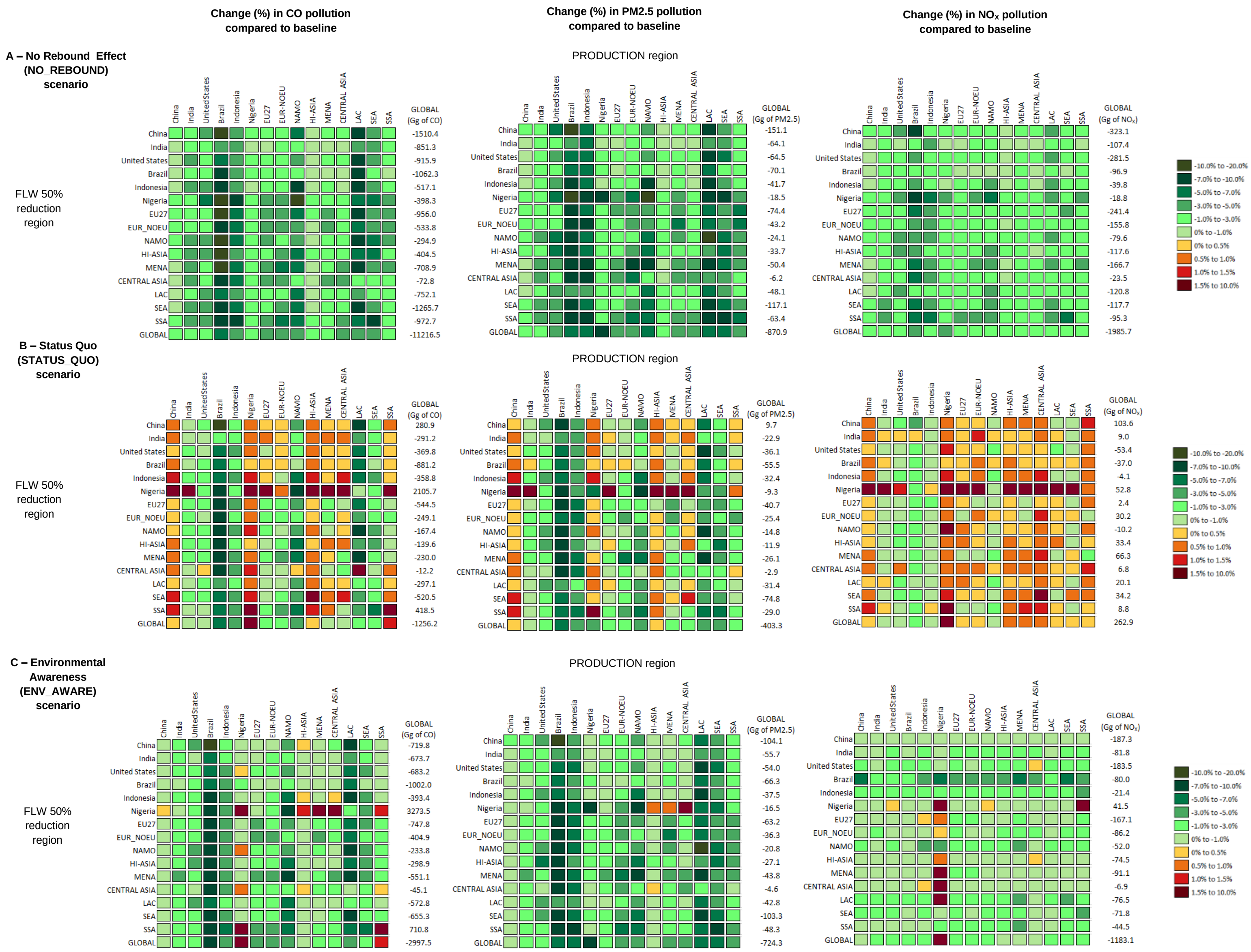

Figure 3.3. Change (%) in CO, PM2.5, and NO_X pollution in production and consumption regions generated by a 50% reduction in FLW by country and globally in 2014, by scenario. Estimates refer to change (%) in total polluting emissions (from food and non-food products) compared to our baseline where no FLW reduction policy is applied. Regions displayed on the vertical side of each square indicate where final consumption occurs and where the FLW reduction policy is applied, while regions displayed on the horizontal side of each square indicate where changes in emission linked to the production of food and non-food products occur. In the displayed squares, each row indicates that the FLW policy is uniquely applied in the corresponding region. The "GLOBAL" region (row) represents the case in which the FLW reduction policy is uniformly applied to all global countries. The "GLOBAL" production region (column) represents the impact of a FLW reduction policy (by country or global) on global food and non-food production. Panel A illustrates changes in CO, PM2.5, and NO_X pollution in production and consumption regions in the "No Rebound Effect" (NO_REBOUND) scenario. Panel B illustrates changes in CO, PM2.5, and NO_X pollution in production and consumption regions in the "Status Quo" (STATUS_QUO) scenario. Finally, Panel C illustrates changes in CO, PM2.5, and NO_X pollution in production and consumption regions in the "Environmental Awareness" (ENV_AWARE) scenario. As changes with respect to our baseline are reported in percentage (%), absolute variations (gigagrams) for the illustrated pollutants as well as for other pollutants across the investigated scenarios are reported in the Supplementary Information.

Air pollution-related health and mortality impacts from FLW reductions

Evolving trends of air pollution exert a direct impact on pollution-related diseases influencing premature mortality risks. In the NO_REBOUND scenario, the decrease in air pollution reduces premature mortality risks across countries, saving a total of 67,325 lives (Panel A – Figure 3.4). Mortality risks mainly decrease from lower respiratory infections (9,625 saved lives), primarily in low-income regions, and from chronic obstructive pulmonary disease (11,324 saved lives), primarily in high-income regions. Major benefits in terms of saved lives are observed in China (14,510 saved lives) and India (12,225 saved lives). Relatively high benefits are additionally observed in the European Union (EU27) and SEA where reductions in air pollution save a total of 9,035 and 6,973 lives, respectively. The number of lives saved in the NO_REBOUND scenario has direct global economic benefit ranging from 55.3 to 138.3 billion USD (0.07-0.17% of global GDP), with highest benefits in terms of savings observed in China (from 7.1 to 17.7 billion USD per year equivalent to 0.06-0.17% of GDP), EU27 (from 15.0 to 37.5 billion USD or 0.09-0.24% of GDP), and the United States (USA) (from 12.4 to 31.0 billion USD or 0.07-0.17% of GDP) (Panel A – Figure 3.5).

In the STATUS_QUO scenario the decrease in premature mortality risks is around 55.3% lower than in the NO_REBOUND scenario, with a total of 30,032 lives saved (Panel B – Figure 3.4). While major benefits remain observed in China (5,505 saved lives) and EU27 (6,521 saved lives), changing consumption trends in low-income regions such as Nigeria and SSA result in an increase in pollution-related mortality risk with additional 1,455 and 1,438 lives being exposed to premature mortality, respectively. In these regions growing pollution linked to non-food consumption primarily increases the risk of lower respiratory infection diseases, exposing a total of 1,903 people to premature mortality risk per year. This directly translates to higher health-related costs (Panel B – Figure 3.5) which compared to NO REBOUND, increase from 20 to 50 billion USD per year (0.02-0.06% of GDP). Globally, while across diseases mortality risks decline, an exception is represented by respiratory O_3 exposure mortality risk which increases principally in mid-low-income regions, exposing an additional 496 people to premature mortality per year.

Finally, changing consumer choices towards less polluting products in the ENV_AWARE scenario results in an increase of 62.9% of saved lives compared to the STATUS_QUO scenario, with a total of 48,931 lives saved globally (Panel C – Figure 3.4). In absolute terms, exposure to premature mortality from chronic obstructive pulmonary diseases and lung cancer decreases mainly in China (4,322 saved lives) and EU27 (2,582 saved lives), while the risk of lower respiratory infection diseases decreases primarily in India (1,797 saved lives) and SEA (1,502 saved lives). However, mortality risks increase in Nigeria and SSA by a 42.2% compared to STATUS_QUO, exposing an additional 4,116 lives. In comparison to the STATUS_QUO scenario, health-related costs linked to the rise in premature mortality risk in these regions increase by a 42.2-45.0%, and amount to an additional cost of 11.3 to 28.2 billion USD per year (average 0.01-0.07% of GDP) (Panel C – Figure 3.5). On the other hand, the high absolute reduction in pollution results in an increase in health-related co-benefits in China (from 5.4 to 13.6 billion USD or 0.05-0.13% of GDP), in EU27 (from 13.4 to 33.6 billion USD or 0.08-0.21% of GDP) and the USA (from 11.1 to 27.8 billion USD or 0.06-0.16% of GDP).

Figure 3.4. Decreased mortality risk by disease (saved lives (thousand people) in 2014 and per million of population) by a 50% reduction in global FLW, by scenario. Estimates refer to thousand people saved by the reduction in mortality risk linked to air pollution-induced diseases. Positive numbers illustrate a decrease in mortality risks while negative numbers illustrate an increase in mortality risks. Estimates have been calculated based on regional population in 2014 derived from the GTAP 10 Data Base (Aguiar et al., 2019). Panel A illustrates changes in premature mortality risk (1000 saved lives and lives save per million of population) linked to air pollution-induced diseases when a 50% reduction in global FLW is applied in the "No Rebound Effect" (NO_REBOUND) scenario in 2014. Panel B illustrates changes in premature mortality risk (1000 saved lives and lives save per million of population) linked to air pollution-induced diseases when a 50% reduction in global FLW is applied in the "Status Quo" (STATUS_QUO) scenario in 2014. Finally, Panel C illustrates changes in premature mortality risk (1000 saved lives and lives save per million of population) linked to air pollution-induced diseases when a 50% reduction in global FLW is applied in the "Environmental Awareness" (ENV_AWARE) scenario in 2014. Stroke and IHD-related mortalities are not reported as the variations in pollutants across scenarios are found not to affect mortality rates linked to such diseases.

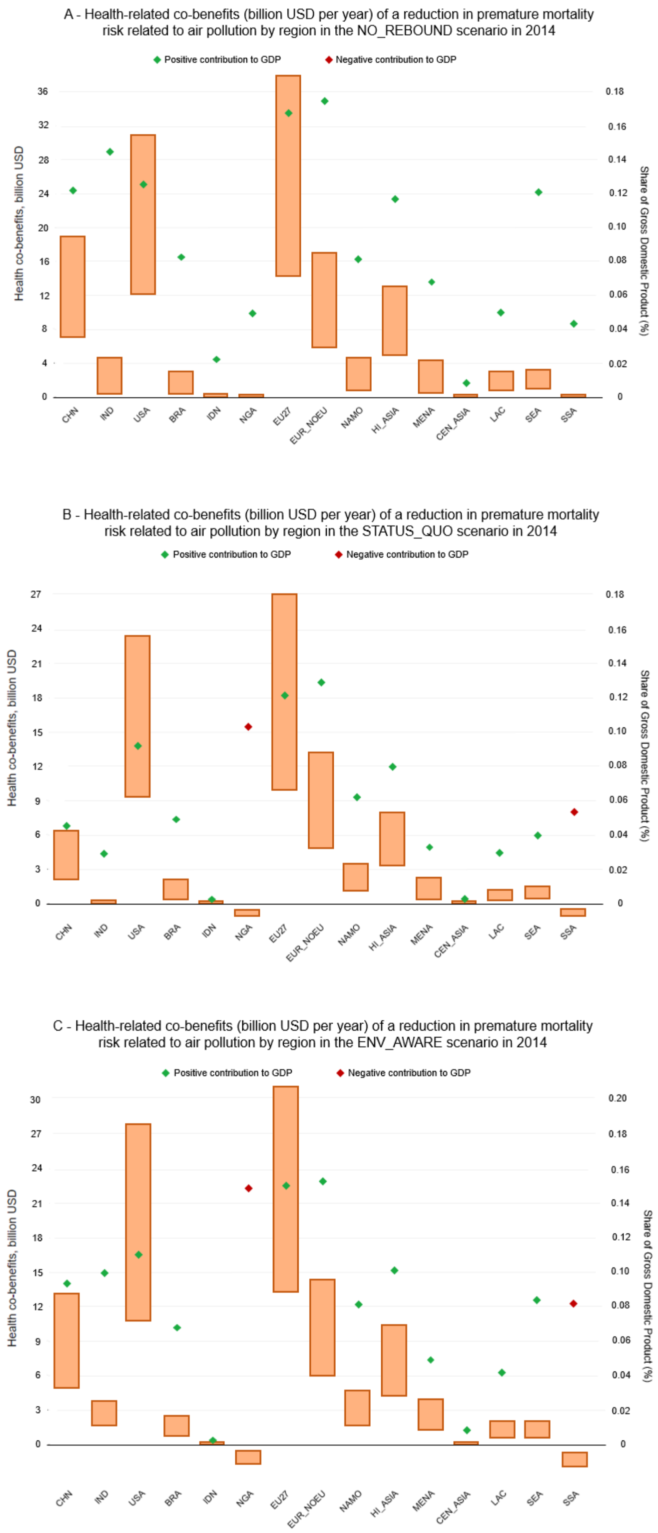

Figure 3.5. Health-related co-benefits (billion USD per year) of a reduction in premature mortality risk related to air pollution across global regions in 2014, by scenario. Estimates refer the amount of saved billion USD dollars from the decrease in mortality risks associated to lower polluting emission generated by FLW reduction policies across our scenarios. Negative estimates refer to an increase in health-related expenses due to rising mortality risks linked to increasing air pollution trends. Illustrated estimates have been calculated on regional GDP in 2014 derived from the GTAP 10 Data Base (Aguiar et al., 2019) and assuming a Value of Statistical Life of 1.8 mn USD for the lower bound and of 4.5 mn USD for the upper bound. Panel A illustrates health-related co-benefits (billion USD per year) of a reduction in premature mortality risk related to air pollution across global regions in 2014, in the "NO Rebound Effect" (NO_REBOUND) scenario. Panel B health-related co-benefits (billion USD per year) of a reduction in premature mortality risk related to air pollution across global regions in 2014, in the "Status Quo" (STATU_QUO) scenario. Finally, Panel C illustrates health-related co-benefits (billion USD per year) of a reduction in premature mortality risk related to air pollution across global regions in 2014, in the "Environmental Awareness" (ENV_AWARE) scenario.

3.4 Discussion

In this study, we explore the relationship between FLW and air pollution, providing a quantification of pollutants embedded in FLW and assessing the potential impact of FLW reduction policies on air quality and associated premature mortality risks. We enhance a FLW-extended MRIO framework by estimating air pollutants embedded in FLW, identifying global hotspots, trends, and driving factors across countries and stages of the global FSC. Using this framework we analyze three scenarios with different final demand patterns.

While available waste-extended input-output models (Kagawa et al., 2004; Lenzen & Reynolds, 2014; Read et al., 2020; Towa et al., 2020) primarily concentrate on waste treatment strategies, our study expands current input-output analyses, offering a comprehensive assessment of the impact of FLW changes on air pollution. As studies on FLW-related emissions limit their scope to greenhouse gases (GHG) (Porter et al., 2016; Poore & Nemecek, 2018), we provide an innovative quantification of air pollutants embedded in FLW to assist future policy designs. Global FLW-embedded air pollutants account for around 5.2% of total air pollutants. In the absence of prior studies specifically addressing the quantification of air pollutants associated with global FLW, we compare food system emissions from the literature with our food-related emissions. In our study air pollution from the food system represents 22.5% of total pollution, in line with the 10-35% range provided by previous studies (Crippa et al., 2021, 2022; IPCC, 2019; Rosenzweig et al., 2021; Tubiello et al., 2021). For each pollutant, we meet the shares of food-related emissions in total emissions reported in the literature (Balasubramanian et al., 2021; Chepeliev, 2021; Crippa et al., 2022). In particular, we find that PM2.5 accounts for a 25.2% (20-35%)[9] of total emissions, NH_3 for a 76.6% (72-87%), SO_2 for a 10.4% (9-12%), NO_X for a 12.8% (13-20%), NMVOC for a 19.0% (16-19%), and BC for a 22.5% (20-28%).

Global hotspots of FLW-embedded air pollutants are found in Agricultural Production and Consumption stage. Largest levels of FLW-embedded air pollution are found East Asia, notably in China, India, and Indonesia. However, as shares of FLW-embedded pollutants in total pollution are relatively low in these regions due to a higher reliance on pollution-intensive energy supply options, FLW reduction policies may provide lower benefits. Differently, in regions like Brazil, Lao, Vietnam, and Bangladesh, shares of FLW-embedded air pollution in total pollution are relatively high, and FLW policies may provide higher benefits on reducing overall pollution levels.

FLW reductions can decrease air pollution but changes in consumer demand play a key role. In the absence of a rebound effect (NO_REBOUND scenario), a 50% decrease in FLW reduces global air pollution by a 3% (25,050 Gg). This is still far from air pollution targets (WHO, 2021; EC/EEA, 2020) but illustrates the interlinked benefit of decreasing FLW on air quality. Moreover, positive effects are found on premature mortality risks which decrease (67,325 lives saved globally), especially in China and India where pollution-related mortality rates are highest (WHO, 2021). However, the presence of potential rebound effects associated with FLW policies has been widely discussed in the earlier literature (Druckman et al., 2011; Martinez-Sanchez et al., 2016; Read et al., 2020; Salemdeeb et al., 2017; Reynolds et al., 2019) and changes in demand must be considered once policies targeting FLW are introduced.

We find rebound effects decrease health and environmental benefits linked to FLW reduction policies. Regions such as China, Nigeria, high-income Asia (HI-ASIA), and Sub-Saharan Africa (SSA) experience increased pollution

[9] Estimates reported in parenthesis represent variation across the shares of food-related emissions in total emissions provided in Balasubramanian et al., (2021); Chepeliev, (2021); Crippa et al., (2022).

levels due to the shift in consumer demand towards non-food products (STATUS_QUO scenario) such as transportation, construction, and manufacturing, which have higher pollution rates compared to food products. This leads to an increase in pollution-related mortality risk and health-related costs, primarily elevating the risk of lower respiratory infection diseases. Differently, in Indonesia or Brazil, a decrease in food demand and production results in a lower level of total pollution as primary food production sectors represent the main drivers of air pollution. Shifting consumption towards "cleaner" sectors (ENV_AWARE scenario) decreases pollution compared to the STATUS_QUO scenario. Major reductions are observed in large food exporting regions such as Brazil, Indonesia, and Latin America and the Caribbean (LAC). However, Nigeria and SSA exhibit higher levels of CO pollution due to the relatively higher emission intensity associated with the domestic production of services, which are considered less polluting at a global scale.

The findings of our study have important social implications. In low-income regions, where FLW reduction is necessary to increase food security, policies may lead to increased pollution-related mortality risks, showing the need for parallel interventions to direct consumer choices or reduce production-side emissions. This is additionally highlighted by the increase in health-related costs associated with the rise in premature mortality risk and underscores the importance of considering the economic feedbacks of FLW policies on final consumers. The provided estimation of the economic benefits linked to decreased pollution-related mortality risks can contribute to the reduction in FLW policy costs, a channel often overlooked in earlier studies but fundamental to incentivise regional interventions. As economic benefits are evaluated on an annual basis and are enduring, it is essential to acknowledge that investments in FLW reduction policies can yield returns not only during the policy implementation period but also in the long-run. Nonetheless, it is crucial to parallelly promote sustainable production and consumption practices, encourage the use of clean technologies, and invest in pollution control measures in regions where the shift towards non-food products contributes to increased pollution.

It is essential to acknowledge the broader context of causal impact pathways that are not fully accounted for in our analysis. While we highlight the positive spillover effects of decreasing FLW on reducing air pollution levels and premature mortality risks, it is important to recognize that other pathways may play a more significant role in shaping health outcomes. Dietary changes, technological advancements, and broader environmental policies can influence health and mortality risks through different and more direct channels (Willet et al., 2019). Reductions in FLW could have more direct impacts on health through an increased food availability (HLPE, 2014; Kuiper & Cui, 2020) or improved nutritional quality (Kummu et al., 2012; Buzby et al., 2014; Delgato et al., 2021). Additionally, several health-related co-benefits could emerge through decreased environmental footprints (Shafiee-Jood & Cai, 2016; Lopez-Barrera & Hertel, 2020; Wang et al., 2021) beyond impacts on air pollution, as reduced FLW may parallelly decrease GHG emissions (Zhu et al., 2023), water and land use (Kummu et al., 2012; Read et al., 2020), as well as improve biodiversity (Read et al., 2022). Here, further research that explores the relative importance of these dynamics and their interconnectedness, may provide a more comprehensive understanding of the diverse set of factors influencing health and mortality risks, as well as broader environmental dimensions. While our study contributes valuable insights into the FLW-air pollution-health nexus, it is only a part of a larger puzzle that warrants further exploration and investigation.

As always, our study is subject to limitations. The use of an input-output framework does not allow to fully grasp the impact of policies on the income side of final consumers, omitting changing preferences linked to income shifts. As impacts on wages could affect purchasing power of consumers across regions, demand trends could differ across sectors, influencing total pollution levels. Additionally, as our analysis revolves around 2014, further research could expand our analysis with the use of a dynamic computable general equilibrium or integrated assessment models which allow to investigate impacts of FLW reduction policies on incomes while casting future trends of air pollution. With regards to the applied uniform 50% FLW reduction across all supply chain stages, it is crucial to acknowledge the inherent limitations of such an approach. While the uniform reduction serves as a simplifying assumption for the purpose of our analysis, we recognize that the real-world FLW reduction strategies would likely involve targeted interventions at specific stages of the supply chain. In high-income countries, most FLW occurs at household and retail levels, and interventions should primarily focus on reduction across these stages. Similarly, in low-income countries the majority of FLW occurs at the farm-level and FLW policies should primarily target production stages, as further decreasing household food waste in food insecure regions may not be realistic and/or economically feasible. Nonetheless, in the context of this study, the supply chain location in which the FLW reduction occurs is not a major determining factor for grasping the synergies between FLW policies and air pollution impacts. For this, our decision to adopt a uniform reduction in FLW across stages is motivated by the need for an illustrative reduction scenario to assess the overall impact on air pollution. However, we caution that this approach may not fully capture the nuanced and context-dependent nature of FLW reduction strategies. Future research would benefit from an assessment of a more refined, stage-specific interventions providing a more realistic representation of how FLW reduction policies might unfold across countries and food commodities.

Within the interplay between FLW reduction policies, air pollution, and associated mortality risks, it is imperative to highlight the limitations of the behavioural assumptions underpinning our scenario analysis. The assumption that efforts to reduce food waste have no consequential impact on food demand simplifies our assessment relative to the complexity of real-world behavioural responses. Oversimplification of the demand response to FLW policies could lead to results that may diverge from real-world impacts. As we focus only on secondary rebound effects (i.e. increase in consumption of other products nonrelated with the products directly affected by a policy) we do not investigate the impact of higher food availability and thus lower food prices on food demand. This relates to the negative income elasticity of demand for food observed across global regions (Cirera & Masset, 2010; Clements & Si, 2018), which reduces the possibilities of the existence of a direct primary rebound effect. At the same time, we also do not assume any explicit costs associated with an implementation of the FLW reduction measures, which could further increase food prices and act as a channel that reduces food demand (compared to the case of cost-free FLW policies implementation). These aspects underscore the need for additional research to refine the representation of the connection between FLW policies and shifts in food demand, ensuring a more accurate reflection of the dynamics at play. Nonetheless, it is important to acknowledge that this study's scope is confined to exploring rebound effects primarily within the non-food sector. Future research could expand this scope by considering the potential existence of direct rebound effects within the food sector. By employing a dynamic modelling framework, it could be possible to showcase how Engel's law might simultaneously influence pollution levels and health outcomes across both food and non-food sectors, providing a more comprehensive understanding of the interconnected dynamics and outcomes in relation to rebound effects.

Finally, in the case of Nigeria and SSA, the higher levels of CO emission intensities outside the food sector are associated with the use of biomass and other fuels in residential and other sectors.[10] In the air pollution data sourced from Crippa et al. (2020), corresponding emission flows are not explicitly distributed across activities and the process for such distribution implemented in the current study follows Chepeliev (2021). In this regard, a more refined identification of the air pollution flows across specific activities might provide additional valuable insights into the implications of the FLW reduction policies on changing emissions throughout the GVC.

[10] These sectors correspond to the IPCC 2006 classification code 1A4: "Fuel combustion activities: other sectors".

In conclusion, our study emphasizes the complex relationship between FLW reduction policies, air pollution and related mortality risks. We provide an innovative quantification of air pollutants embedded in the global FLW, expanding the multidisciplinary relevance of FLW-related polices. We illustrate that decreasing FLW can generate positive spillover effects on reducing air pollution levels, but complementary policies are required to incentivise sustainable non-food consumption, improving air quality while decreasing associated mortality risks. Policymakers need to account for region-specific factors, consumer behaviour, and the potential social implications, to effectively reduce FLW creating a healthier and more sustainable planet.

Supplementary Information for

Reducing global food loss and waste could improve air quality and lower the risk of premature mortality

Contents

Regional Aggregation

Table S1. Regional aggregation

GTAP Country	Description	Regional Aggregation	Description
aus	Australia	NAMO	North America & Oceania
nzl	New Zealand	NAMO	North America & Oceania
xoc	Rest of Oceania	NAMO	North America & Oceania
chn	China	CHN	China
hkg	Hong Kong	INDA	High-income Asia
jpn	Japan	INDA	High-income Asia
kor	Korea	INDA	High-income Asia
mng	Mongolia	SEA	Southeast Asia
twn	Taiwan	INDA	High-income Asia
xea	Rest of East Asia	SEA	Southeast Asia
brn	Brunei Darussalam	SEA	Southeast Asia
khm	Cambodia	SEA	Southeast Asia
idn	Indonesia	IDN	Indonesia
lao	Lao People's Democratic Republic	SEA	Southeast Asia
mys	Malaysia	SEA	Southeast Asia
phl	Philippines	SEA	Southeast Asia
sgp	Singapore	INDA	High-income Asia
tha	Thailand	SEA	Southeast Asia
vnm	Viet Nam	SEA	Southeast Asia
xse	Rest of Southeast Asia	SEA	Southeast Asia
bgd	Bangladesh	SEA	Southeast Asia
ind	India	IND	India
npl	Nepal	SEA	Southeast Asia
pak	Pakistan	SEA	Southeast Asia
lka	Sri Lanka	SEA	Southeast Asia
xsa	Rest of South Asia	SEA	Southeast Asia
can	Canada	NAMO	North America & Oceania
usa	United States of America	USA	United States of America
mex	Mexico	LAC	Latin America & Caribbean
xna	Rest of North America	NAMO	North America & Oceania
arg	Argentina	LAC	Latin America & Caribbean
bol	Bolivia	LAC	Latin America & Caribbean
bra	Brazil	bra	Brazil
chl	Chile	LAC	Latin America & Caribbean
col	Colombia	LAC	Latin America & Caribbean
ecu	Ecuador	LAC	Latin America & Caribbean
pry	Paraguay	LAC	Latin America & Caribbean
per	Peru	LAC	Latin America & Caribbean
ury	Uruguay	LAC	Latin America & Caribbean
ven	Venezuela	LAC	Latin America & Caribbean
xsm	Rest of South America	LAC	Latin America & Caribbean
cri	Costa Rica	LAC	Latin America & Caribbean
gtm	Guatemala	LAC	Latin America & Caribbean
hnd	Honduras	LAC	Latin America & Caribbean
nic	Nicaragua	LAC	Latin America & Caribbean
pan	Panama	LAC	Latin America & Caribbean
slv	El Salvador	LAC	Latin America & Caribbean
xca	Rest of Central America	LAC	Latin America & Caribbean
dom	Dominican Republic	LAC	Latin America & Caribbean
jam	Jamaica	LAC	Latin America & Caribbean
pri	Puerto Rico	LAC	Latin America & Caribbean
tto	Trinidad and Tobago	LAC	Latin America & Caribbean
xcb	Caribbean	LAC	Latin America & Caribbean
aut	Austria	EU27	Europe (EU27)
bel	Belgium	EU27	Europe (EU27)
bgr	Bulgaria	EU27	Europe (EU27)
hrv	Croatia	EU27	Europe (EU27)
cyp	Cyprus	EU27	Europe (EU27)
cze	Czech Republic	EU27	Europe (EU27)
dnk	Denmark	EU27	Europe (EU27)
est	Estonia	EU27	Europe (EU27)
fin	Finland	EU27	Europe (EU27)
fra	France	EU27	Europe (EU27)
deu	Germany	EU27	Europe (EU27)
grc	Greece	EU27	Europe (EU27)
hun	Hungary	EU27	Europe (EU27)
irl	Ireland	EU27	Europe (EU27)
ita	Italy	EU27	Europe (EU27)

GTAP Country	Description	Regional Aggregation	Description
lva	Latvia	EU27	Europe (EU27)
ltu	Lithuania	EU27	Europe (EU27)
lux	Luxembourg	EU27	Europe (EU27)
mlt	Malta	EU27	Europe (EU27)
nld	Netherlands	EU27	Europe (EU27)
pol	Poland	EU27	Europe (EU27)
prt	Portugal	EU27	Europe (EU27)
rou	Romania	EU27	Europe (EU27)
svk	Slovakia	EU27	Europe (EU27)
svn	Slovenia	EU27	Europe (EU27)
esp	Spain	EU27	Europe (EU27)
swe	Sweden	EU27	Europe (EU27)
gbr	United Kingdom	EUR NO-EU	Europe (non-EU)
che	Switzerland	EUR NO-EU	Europe (non-EU)
nor	Norway	EUR NO-EU	Europe (non-EU)
xef	Rest of EFTA	EUR NO-EU	Europe (non-EU)
alb	Albania	EUR NO-EU	Europe (non-EU)
blr	Belarus	EUR NO-EU	Europe (non-EU)
rus	Russian Federation	EUR NO-EU	Europe (non-EU)
ukr	Ukraine	EUR NO-EU	Europe (non-EU)
xee	Rest of Eastern Europe	EUR NO-EU	Europe (non-EU)
xer	Rest of Europe	EUR NO-EU	Europe (non-EU)
kaz	Kazakhstan	CENTRAL ASIA	Central Asia
kgz	Kyrgyzstan	CENTRAL ASIA	Central Asia
tjk	Tajikistan	CENTRAL ASIA	Central Asia
xsu	Rest of Former Soviet Union	CENTRAL ASIA	Central Asia
arm	Armenia	CENTRAL ASIA	Central Asia
aze	Azerbaijan	CENTRAL ASIA	Central Asia
geo	Georgia	CENTRAL ASIA	Central Asia
bhr	Bahrain	MENA	North Africa & Middle East
irn	Iran Islamic Republic of	MENA	North Africa & Middle East
isr	Israel	MENA	North Africa & Middle East
jor	Jordan	MENA	North Africa & Middle East
kwt	Kuwait	MENA	North Africa & Middle East
omn	Oman	MENA	North Africa & Middle East
qat	Qatar	MENA	North Africa & Middle East
sau	Saudi Arabia	MENA	North Africa & Middle East
tur	Turkey	MENA	North Africa & Middle East
are	United Arab Emirates	MENA	North Africa & Middle East
xws	Rest of Western Asia	MENA	North Africa & Middle East
egy	Egypt	MENA	North Africa & Middle East
mar	Morocco	MENA	North Africa & Middle East
tun	Tunisia	MENA	North Africa & Middle East
xnf	Rest of North Africa	MENA	North Africa & Middle East
ben	Benin	SSA	Sub-Saharan Africa
bfa	Burkina Faso	SSA	Sub-Saharan Africa
cmr	Cameroon	SSA	Sub-Saharan Africa
civ	Cote d'Ivoire	SSA	Sub-Saharan Africa
gha	Ghana	SSA	Sub-Saharan Africa
gin	Guinea	SSA	Sub-Saharan Africa
nga	Nigeria	NGA	Nigeria
sen	Senegal	SSA	Sub-Saharan Africa
tgo	Togo	SSA	Sub-Saharan Africa
xwf	Rest of Western Africa	SSA	Sub-Saharan Africa
xcf	Central Africa	SSA	Sub-Saharan Africa
xac	South Central Africa	SSA	Sub-Saharan Africa
eth	Ethiopia	SSA	Sub-Saharan Africa
ken	Kenya	SSA	Sub-Saharan Africa
mdg	Madagascar	SSA	Sub-Saharan Africa
mwi	Malawi	SSA	Sub-Saharan Africa
mus	Mauritius	SSA	Sub-Saharan Africa
moz	Mozambique	SSA	Sub-Saharan Africa
rwa	Rwanda	SSA	Sub-Saharan Africa
tza	Tanzania	SSA	Sub-Saharan Africa
uga	Uganda	SSA	Sub-Saharan Africa
zmb	Zambia	SSA	Sub-Saharan Africa
zwe	Zimbabwe	SSA	Sub-Saharan Africa
xec	Rest of Eastern Africa	SSA	Sub-Saharan Africa
bwa	Botswana	SSA	Sub-Saharan Africa
nam	Namibia	SSA	Sub-Saharan Africa
zaf	South Africa	SSA	Sub-Saharan Africa
xsc	Rest of South African Customs	SSA	Sub-Saharan Africa
xtw	Rest of the World	NAMO	North America & Oceania

Source: developed by authors based on Aguiar et al. (2019).

Food Loss and Waste Data

Table S2. Food loss and waste (million Mtons) by country/region and reference year.

Region	Description	2004	2014
CHN	China	390.6	527.4
IND	India	76.8	113.4
USA	United States	175.1	180.4
BRA	Brazil	62.3	99.4
IDN	Indonesia	25.9	36.9
NGA	Nigeria	34.6	43.3
EU27	European Union 27	151.3	146.4
EUR_NOEU	Europe non-EU	94.2	99.9
NAMO	North America & Oceania	32.7	34.5
HI-ASIA	High-Income Asia	59.5	60.5
CENTRAL ASIA	Central Asia	20.2	28.9
MENA	Middle East & North Africa	146.1	183.1
LAC	Latin America & Caribbean	110.2	122.8
SEA	Southeast Asia	85.1	115.3
SSA	Sub-Saharan Africa	90.5	135.7

Methods

Tracing Food Loss & Waste along global food supply chains

To trace flows of food loss and waste (FLW) along global food supply chains (FSC) we adopt a full supply-chain approach, linking FLW estimates to the supply chain stages of countries where food is produced, processed and/or finally consumed (Figure S1).

From the constructed FLW database (Gatto and Chepeliev, 2023) we derive commodity- and country-specific shares of lost and discarded food along the FSC and define the following coefficient

$$FLW\_SHR_{c,d}^{r,g} \tag{1}$$

where *r* represents the country where losses or waste are generated, *g* represents a stage of the food supply chain at which the losses/waste are occurring,[11] *c* represents a primary food commodity being lost or wasted and *d* represents a dummy variable that has a value of "1" when a commodity enters the manufacturing stage (i.e. is finally consumed as a processed food product) and a value of "0" when it does not (i.e. is finally consumed as a fresh food product). To quantify physical (Tonnes) food supply we retrieve information from the Global Trade Analysis Project Food Balance Sheets (GTAP-FBS) database (Chepeliev, 2022) defining a food supply coefficient as following

[11] As discussed below, we consider the following FLW stages: (1) Agricultural production; (2) Post-harvest handling and storage; (3) Manufacturing; (4) Distribution and retail and (5) Consumption.

$$FOOD_{r,s,t}^{c,f,k} \quad (2)$$

where *c* represents a primary food commodity flowing into primary food, processed food or food services which provides information on the primary composition of non-primary foods, f represents the final food product (primary, processed or from food services) consumed by households, *k* represents a metric category on which the food supply is specified i.e. metric tons, calories, proteins, fats, or carbohydrates, *r* and *s* represent regional source (*r*) and destination (*s*) of the food supply (if $r = s$, food is produced and consumed domestically within a country), and *t* represents a reference year of food supply i.e. 2004, 2007, 2011 or 2014. The computation of equation (2) is available in (Chepeliev, 2022) and is briefly illustrated on the left side of Figure S1 below. The information provided in coefficient (2) is developed to match the physical and nutritional food supply estimates from the FAO Food Balance Sheets. Table S3 below provides a listing of sectors represented in the GTAP-FBS database and their classification into primary agricultural activities, processed food sectors, food-supplying service sectors and sectors that correspond to other (non-food) uses.

To quantify physical flows of FLW, we multiply the FLW coefficient (1) by the physical food flows represented by a coefficient (2), tracing FLW along global food supply chains as following

$$FLW\_FSC_{a,f,t}^{r,s,d} = FLW\_SHR_{c,d}^{r,g} * FOOD_{r,s,t}^{c,f,k} \quad (3)$$

where *r* represents the region where primary commodity *a* is produced (source region), hence where losses from Agricultural Production up to Distribution & Retail stages occur, *s* represents the region where final consumption occurs (destination region) hence where Consumption waste is generated, *f* represents the food commodity or food service consumed by final consumers in region *s* and to which primary food flows *a* are flowing to, t represents the stage of the supply chain at which losses are occurring and *k* represents a metric category i.e. metric tons, calories, proteins, fats, or carbohydrates.

The five stages of the food supply chain defined from the developed FLW database in coefficient (1) are combined with the information obtained from coefficient (2). Agricultural Production and Post-Harvest Handling & Storage stages are associated with primary production, while Manufacturing and Consumption stages are linked to the intermediate/final food production and final demand, respectively. As a Distribution & Retail stage is not explicitly available from the material flows of equation (2) we allocate Distribution & Retail losses to food flowing from the Manufacturing to Consumption stage.

Since FLW data is mainly available in primary equivalents, we define the food supply within coefficient (2) in primary equivalents, applying (1) to primary food commodities as they flow to the point of final consumption (primary food, processed food or food service sectors). This allows us to avoid the double counting of losses/waste when a processed commodity is employed in the production of another processed commodity or food service along the supply chain. FLW data are from the perspective that the physical supply of a food commodity decreases after each supply chain stage, entering the next stage net of losses that occurred in previous stages. The definition of a dummy variable in (1) allows us to divide between products consumed as processed and fresh, applying manufacturing losses only to the processed foods.

In cases where $r = d$ (the food commodity is produced and consumed in the same country/region), FLW is entirely generated domestically within a country. Differently, when $r \neq d$ food is produced in country *r* and consumed in country *s* hence FLW are attributed differently. If food is imported by *s* as fresh, farm-level losses i.e. Agricultural Production and Post-Harvest Handling & Storage losses are attributed to exporting country *r* (and not to the importing country *s*). If food is imported by *s* as processed, Manufacturing losses are also attributed to exporting country *r* (and not to the importing country *s*). Differently, if a product is imported by *s* as fresh and successively domestically processed, Manufacturing losses are attributed to the importing country *s.* As Distribution & Retail and Consumption stages are by definition linked to the point of consumption, waste generated at these stages is always attributed to the country where food is finally consumed. An attribution discussed above is used to link the country/region-specific FLW shares across stages (as estimated within the coefficient (1)) with the food flows along the global FSC. From the FLW tracing point of view, either consumption (attribution to the point of final consumption) or production (attribution to the point of production) approaches can be implemented for quantifying the related flows (of FLW and/or environmental impacts).

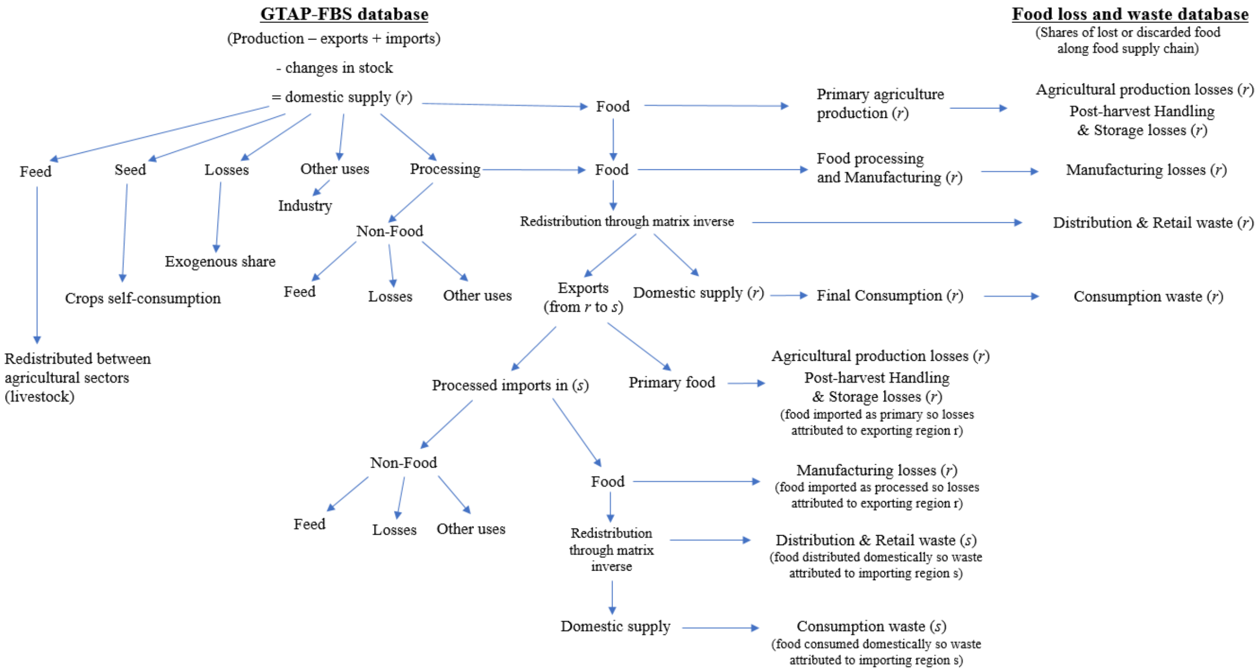

Figure S1. Methodological framework for tracing food loss and waste along global food supply chains. The left-side of the figure provides an overview of the GTAP-FBS database (Chepeliev, 2022) illustrating the approach toward tracing of the primary domestic and imported commodities between GTAP Data Base categories. The right-side of the figure illustrates the merging of a global food loss and waste database in the GTAP-FBS database following the approach of Gatto & Chepeliev (2023). This figure has been adapted from Chepeliev, M. (2022). CC BY 3.0.

Table S3. Mapping between GTAP-FBS sectors and food-supplying instances

No.	Code	Description	Primary agriculture	Processed food	Food-supplying service sectors	Other uses
1	pdr	Paddy rice	+			
2	wht	Wheat	+			
3	gro	Other grains	+			
4	v_f	Vegetables, fruit and nuts	+			
5	osd	Oil Seeds	+			
6	c_b	Cane and beet	+			
7	pfb	Fiber crops				+
8	ocr	Other Crops	+			
9	ctl	Cattle	+			
10	oap	Other Animal Products	+			
11	rmk	Raw milk	+			
12	wol	Wool				+
13	frs	Forestry				+
14	fsh	Fishing	+			
15	coa	Coal mining				+
16	oil	Extraction of crude petroleum				+
17	gas	Extraction of natural gas				+
18	oxt	Other mining extraction				+
19	cmt	Cattle meat		+		
20	omt	Other meat		+		
21	vol	Vegetable oils		+		
22	mil	Milk: dairy products		+		
23	pcr	Processed rice		+		
24	sgr	Sugar and molasses		+		
25	ofd	Other food		+		
26	b_t	Beverages and tobacco products		+		
27	tex	Textiles				+
28	wap	Wearing apparel				+
29	lea	Leather and related products				+
30	lum	Lumber				+
31	ppp	Paper and paper products				+
32	p_c	Petroleum and coke				+
33	chm	Chemicals and chemical products				+
34	bph	Pharmaceuticals products				+
35	rpp	Rubber and plastics products				+
36	nmm	Other non-metallic mineral products				+
37	i_s	Iron and steel				+
38	nfm	Non-ferrous metals				+
39	fmp	Fabricated metal products				+
40	ele	Computer, electronic and optical products				+
41	eeq	Electrical equipment				+
42	ome	Machinery and equipment n.e.c.				+
43	mvh	Motor vehicles, trailers and semi-trailers				+
44	otn	Other transport equipment				+
45	omf	Other Manufacturing				+
46	ely	Electricity, steam and air conditioning supply				+
47	gdt	Gas manufacture, distribution				+
48	wtr	Water supply				+
49	cns	Construction				+
50	trd	Wholesale and retail trade				+
51	afs	Accommodation, food and service activities			+	

No.	Code	Description	Primary agriculture	Processed food	Food-supplying service sectors	Other uses
52	otp	Land transport and transport via pipelines				+
53	wtp	Water transport				+
54	atp	Air transport				+
55	whs	Warehousing and support activities				+
56	cmn	Information and communication				+
57	ofi	Other financial intermediation				+
58	ins	Insurance				+
59	rsa	Real estate activities				+
60	obs	Other business services nec				+
61	ros	Recreation and other services			+	
62	osg	Other services (government)			+	
63	edu	Education			+	
64	hht	Human health and social work			+	
65	dwe	Dwellings				+
		Total number of sectors	**11**	**8**	**5**	**41**

Tracing emissions in the multi-region input-output (MRIO) framework

The relationship between the demand and supply sides in the global MRIO framework can be represented by the following equation:

$X = AX + (Y\mathbf{1})$,

where *X* is the vector of the output of commodity *i* in region *s* (with elements $x_{s,i}$); *A* is the matrix of technological coefficients with elements $a_{si,rj}$, which represent the cost share of commodity *i* supplied by region *s* used in the production process of commodity *j* produced in region *r*; *Y* is the matrix of final demand with elements $y_{s,i,r}$ corresponding to the direct final consumption of commodity *i* produced in region *s* and consumed in region *r*; **1** is the vector of “1” with a dimension *r*.

Solving for *X* we obtain the following:

$X = (I-A)^{-1}(Y\mathbf{1})$,

Where *I* is the identity matrix and $(I-A)^{-1}$ is the Leontief inverse, which represents the aggregate amount of direct and indirect inputs that are required to satisfy the one unit of final demand.

Assuming that the emission intensity of the output of commodity *i* in region *s* is given by $e_{s,i}$ and E is the vector of the corresponding emission intensities with the dimension of s x i, one can estimate the complete emission coefficient or the emission intensity of final consumption as follows:

$E_P = E(I-A)^{-1}$,

The (indirect) emission footprint of the final consumption (C) can then be estimated as follows:

$C_I = E_P Y$,

To calculate the total emissions embodied in final consumption one also needs to take into account direct emissions produced by final users, such as emissions from burning natural gas during the cooking process. Adding direct (C_D) and indirect (C_I) consumption emissions completes the consumption-based tracing of all emissions. With such an approach the consumption-based emission total ($C_D + C_I$) exactly matches the production-based (or territorial) emissions at the global level.

Monetization of the health co-benefits

To value the risks to life we follow a conventional approach that estimates the willingness-to-pay (WTP) to secure the health risk reduction associated with a specific policy or measure (e.g. OECD, 2018). The WTP estimates can be used to estimate the Value of a Statistical Life (VSL), which corresponds to a rate at which people are willing to trade off income to reduce their risk of dying (Alberini, 2004). VSL, in turn, are widely used to monetize the health-related co-benefits of mortality changes (e.g. Markandya et al., 2018; Vandyck et al., 2018) using the so called "unit value transfer approach", which adjusts VSL estimates of the OECD countries to other countries based on the differences in GDP per capita. Values of the VSL for OECD countries used in this study vary from 1.8 million USD per capita and 4.5 million USD per capita measured for 2005 reference year following Holland et al. (2014). Considering that the reference year of our assessment is 2014, we first convert the $2005 price valuations to $2014 price valuations using the U.S. consumer price index as a proxy for price inflation. We further rely on the following formula to transfer the VSL estimates from a group of OECD countries to other countries and regions following World Bank (2016):

$VSL_i = VSL_{OECD} \times (Y_i / Y_{OECD})^b$,

where VSL_i is the Value of Statistical Life in the country of interest; VSL_{OECD} is the average value of VSL in the OECD countries; Y_i is the level of per-capita GDP in the country of interest; Y_{OECD} is the level of per-capita GDP in the average of OECD countries; and *b* is the income elasticity of *VSL,* indicating how *VSL* varies with per capita income levels. Literature suggests that the value of *b* is in a range of 0.8 to 1.2. In this study, following Markandya et al. (2018) we use a value of 0.8.

Additional figures and tables

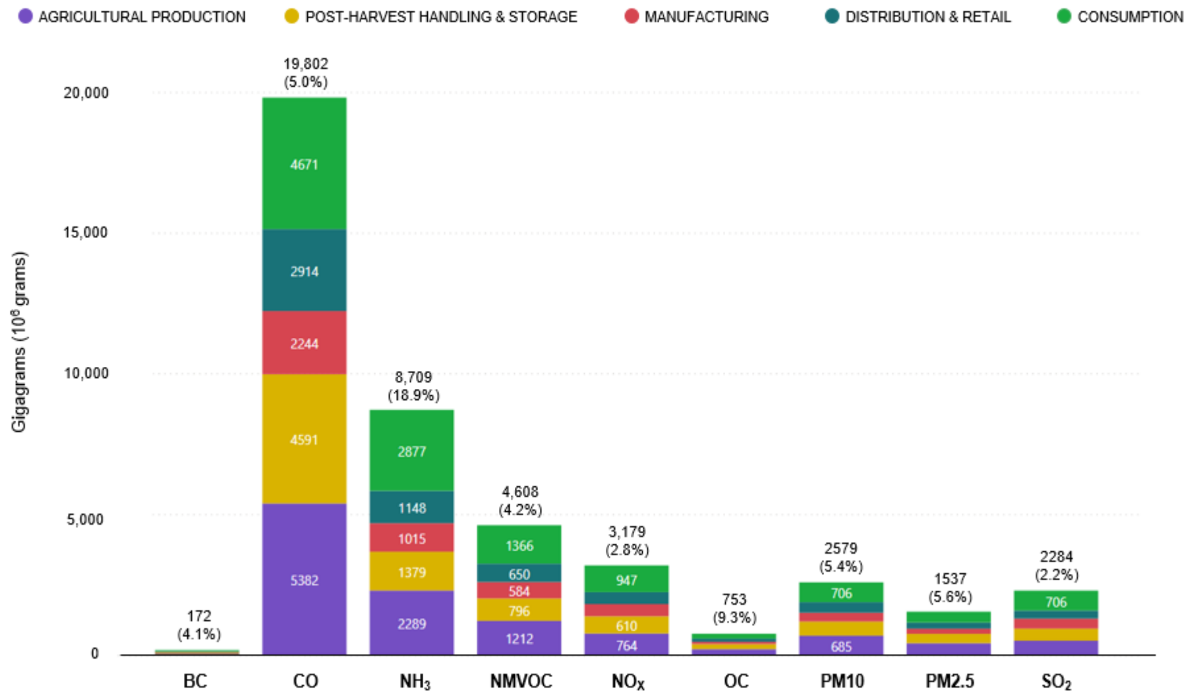

Figure S2. Air pollutants embedded into food loss and waste (along different stages of the food supply chain in 2014. Estimates refer to gigagrams (106 grams) of non-greenhouse gases embedded in the amount of lost and discarded food generated along stages of global food supply chains. BC refers to black carbon; CO refers to carbon monoxide; NH3 refers to ammonia; NMVOC refers to non-methane volatile organic compounds; NOX refers to nitrogen oxides; OC refers to organic carbon; PM10 refers to particle matters with a diameter of 10 microns or less; PM2.5 refers to particle matters with a diameter of 2.5 microns or less; SO2 refers to sulfur dioxide.

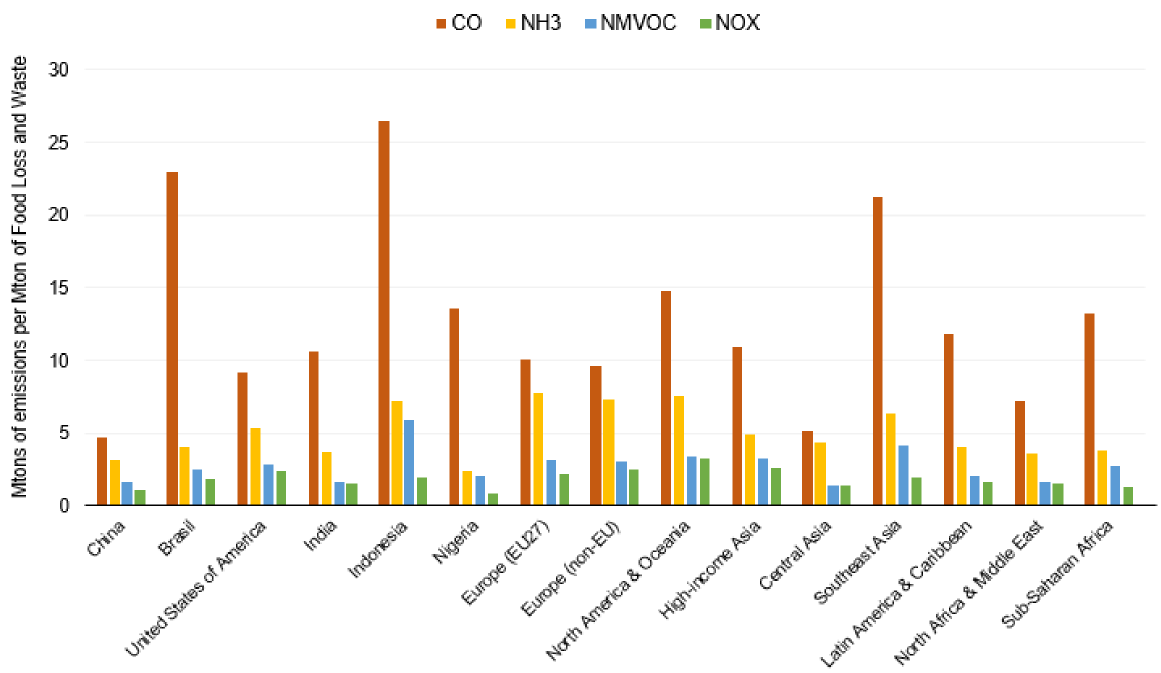

Figure S3. The emission intensity of Food Loss and Waste across global countries. Estimates refer to Mtons of Carbon Oxide (CO), Ammonia (NH_3), Non-Methane Volatile Organic Compounds (NMVOC), and Nitrogen Oxides (NO_X) emitted by the generation of 1 Mton of Food loss and waste along global food supply chains.

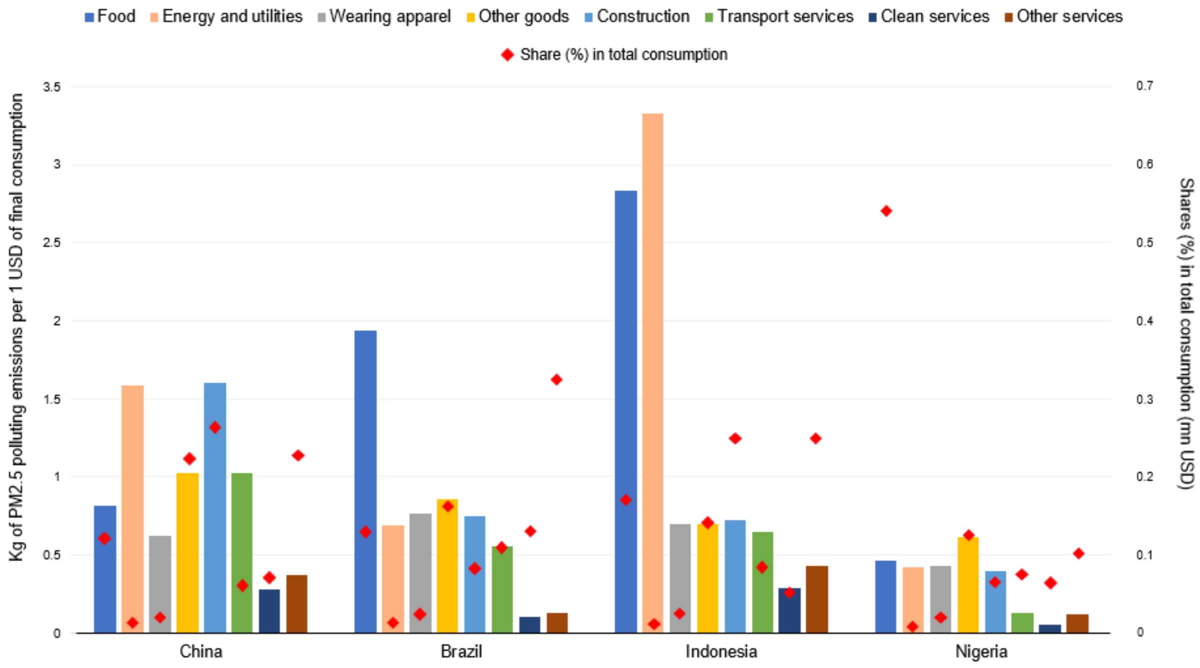

Figure S4. The emission intensity of Food Loss and Waste across global countries. Estimates refer to Mtons of Particulate Matter 10 (PM10), Particulate Matter 2.5 (PM2.5) and Sulfur Dioxide (SO_2) emitted by the generation of 1 Mton of Food loss and waste along global food supply chains.

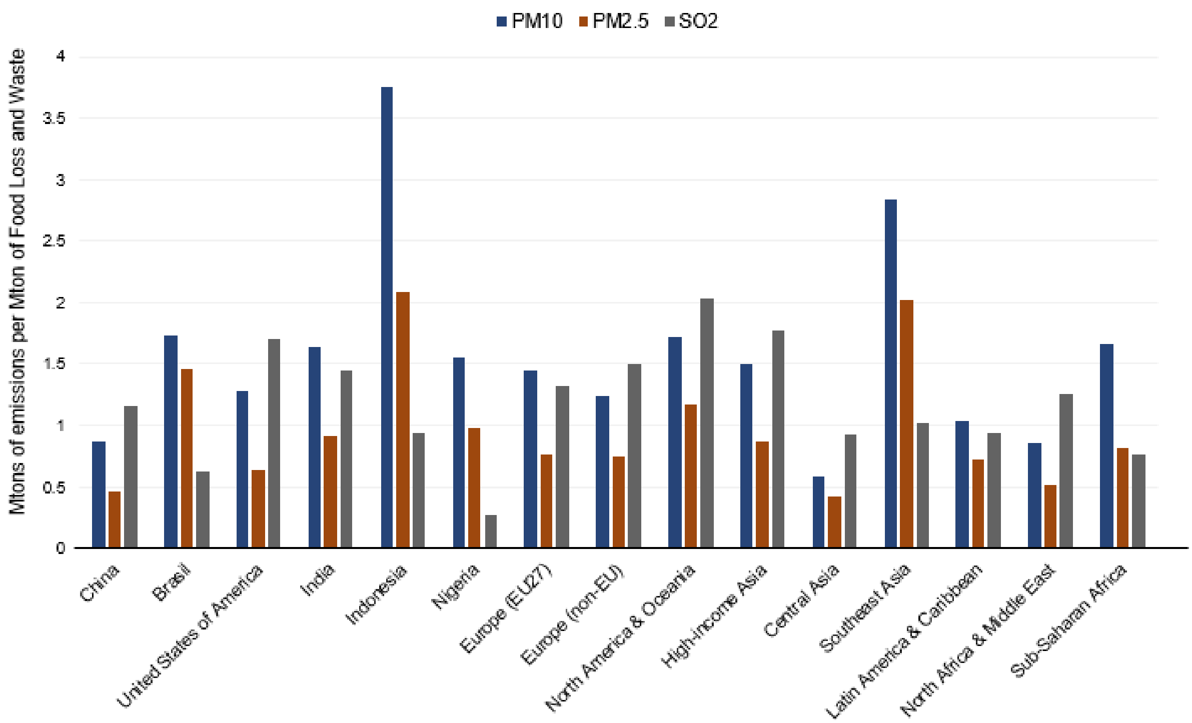

Figure S5. PM2.5 pollution intensity across main commodity groups consumed by households in 2014 in baseline. Estimates illustrated on the left axis refer to kilograms of PM2.5 emissions generated per 1 USD of final consumption. Estimates reported on the right axis refer to the share (%) of a specific commodity group in final consumption (million USD) in a specific region.

Table S3. Black carbon (BC) emissions by region and scenario in 2030.

	Scenario	Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
		Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE
Black Carbon (BC)	CHN	1074.1	1057.4	1078.3	1064.6	10.7%	9.3%	9.1%	9.2%	89.3%	90.7%	90.9%	90.8%
	BRA	202.8	195.9	198.7	196.7	26.4%	23.8%	23.4%	23.7%	73.6%	76.2%	76.6%	76.3%
	USA	290.1	283.0	287.4	284.7	12.3%	10.1%	9.9%	10.0%	87.7%	89.9%	90.1%	90.0%
	IND	538.7	531.1	538.2	532.6	20.6%	19.4%	19.2%	19.4%	79.4%	80.6%	80.8%	80.6%
	IDN	113.3	108.8	110.3	109.9	37.6%	35.0%	34.5%	34.7%	62.4%	65.0%	65.5%	65.3%
	NGA	163.1	159.7	184.2	194.8	16.2%	14.4%	12.5%	11.8%	83.8%	85.6%	87.5%	88.2%
	EU27	348.4	339.5	345.6	341.6	17.1%	14.9%	14.6%	14.8%	82.9%	85.1%	85.4%	85.2%
	EUR_NOEU	159.8	155.3	158.1	156.4	18.1%	15.7%	15.4%	15.6%	81.9%	84.3%	84.6%	84.4%
	NAMO	82.2	79.7	81.2	80.3	15.3%	12.6%	12.3%	12.5%	84.7%	87.4%	87.7%	87.5%
	INDA	203.8	199.9	203.6	201.1	11.8%	10.1%	9.9%	10.0%	88.2%	89.9%	90.1%	90.0%
	CENTRAL ASIA	17.3	16.8	17.3	17.0	24.5%	21.9%	21.3%	21.6%	75.5%	78.1%	78.7%	78.4%
	SEA	320.1	308.5	316.1	313.7	34.2%	31.7%	30.9%	31.1%	65.8%	68.3%	69.1%	68.9%
	LAC	172.5	167.3	170.9	168.8	24.0%	21.6%	21.2%	21.4%	76.0%	78.4%	78.8%	78.6%
	MENA	192.0	186.4	190.6	187.7	21.3%	18.9%	18.5%	18.8%	78.7%	81.1%	81.5%	81.2%
	SSA	305.6	297.1	310.4	311.7	24.7%	22.6%	21.6%	21.5%	75.3%	77.4%	78.4%	78.5%
	GLOBAL	4184.4	4086.5	4190.9	4161.7	18.8%	16.8%	16.4%	16.5%	81.2%	83.2%	83.6%	83.5%

Table S4. Carbon Oxide (CO) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE
Carbon Oxide (CO)	CHN	92587.0	91076.7	92868.0	91867.2	11.2%	9.7%	9.5%	9.6%	88.8%	90.3%	90.5%	90.4%
	BRA	18027.6	16965.3	17146.5	17025.6	45.7%	42.3%	41.9%	42.2%	54.3%	57.7%	58.1%	57.8%
	USA	35889.2	34973.3	35519.4	35206.0	12.8%	10.5%	10.4%	10.5%	87.2%	89.5%	89.6%	89.5%
	IND	46302.9	45451.6	46011.6	45629.2	26.7%	25.3%	25.0%	25.2%	73.3%	74.7%	75.0%	74.8%
	IDN	12053.8	11536.6	11695.0	11660.4	40.2%	37.5%	37.0%	37.1%	59.8%	62.5%	63.0%	62.9%
	NGA	17059.8	16661.5	19165.5	20333.3	18.0%	16.0%	13.9%	13.1%	82.0%	84.0%	86.1%	86.9%
	EU27	25324.5	24368.5	24780.0	24576.7	25.0%	22.1%	21.7%	21.9%	75.0%	77.9%	78.3%	78.1%
	EUR_NOEU	14588.8	14055.0	14339.7	14183.8	23.3%	20.4%	20.0%	20.2%	76.7%	79.6%	80.0%	79.8%
	NAMO	7251.8	6957.0	7084.4	7018.0	19.7%	16.3%	16.0%	16.2%	80.3%	83.7%	84.0%	83.8%
	INDA	15656.6	15252.1	15517.0	15357.7	15.9%	13.6%	13.4%	13.5%	84.1%	86.4%	86.6%	86.5%
	CENTRAL ASIA	2279.0	2206.2	2266.7	2233.8	23.7%	21.2%	20.6%	20.9%	76.3%	78.8%	79.4%	79.1%
	SEA	32302.9	31037.2	31782.4	31647.5	36.8%	34.2%	33.4%	33.6%	63.2%	65.8%	66.6%	66.4%
	LAC	23281.5	22529.4	22984.3	22708.7	25.9%	23.5%	23.0%	23.3%	74.1%	76.5%	77.0%	76.7%
	MENA	21648.9	20940.1	21418.9	21097.8	23.7%	21.1%	20.6%	20.9%	76.3%	78.9%	79.4%	79.1%
	SSA	32293.5	31320.8	32712.0	33004.2	26.4%	24.1%	23.1%	22.9%	73.6%	75.9%	76.9%	77.1%
	GLOBAL	396547.6	385331.1	395291.4	393550.1	22.6%	20.4%	19.9%	20.0%	77.4%	79.6%	80.1%	80.0%

Table S5. Ammonia (NH_3) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE
Ammonia (NH_3)	CHN	8258.8	7377.3	7426.8	7411.1	73.2%	70.0%	69.5%	69.7%	26.8%	30.0%	30.5%	30.3%
	BRA	2302.9	2062.1	2070.2	2064.8	81.1%	78.9%	78.6%	78.8%	18.9%	21.1%	21.4%	21.2%
	USA	3906.4	3413.2	3437.9	3421.8	63.4%	58.2%	57.7%	58.0%	36.6%	41.8%	42.3%	42.0%
	IND	4570.8	4312.3	4325.9	4315.7	82.2%	81.1%	80.9%	81.0%	17.8%	18.9%	19.1%	19.0%
	IDN	1364.0	1244.5	1249.9	1250.5	82.1%	80.4%	80.0%	80.0%	17.9%	19.6%	20.0%	20.0%
	NGA	815.3	761.4	832.9	867.0	50.9%	47.4%	43.3%	41.6%	49.1%	52.6%	56.7%	58.4%
	EU27	5148.1	4537.3	4560.9	4548.4	78.5%	75.6%	75.2%	75.4%	21.5%	24.4%	24.8%	24.6%
	EUR_NOEU	2919.2	2545.4	2557.9	2553.0	81.7%	79.0%	78.6%	78.8%	18.3%	21.0%	21.4%	21.2%
	NAMO	920.1	785.7	791.5	788.7	70.9%	66.0%	65.5%	65.7%	29.1%	34.0%	34.5%	34.3%
	INDA	1499.5	1323.5	1331.9	1328.0	72.7%	69.1%	68.7%	68.9%	27.3%	30.9%	31.3%	31.1%
	CENTRAL ASIA	686.9	614.0	617.9	615.5	83.7%	81.7%	81.2%	81.5%	16.3%	18.3%	18.8%	18.5%
	SEA	4207.1	3875.1	3916.6	3899.1	74.4%	72.2%	71.5%	71.8%	25.6%	27.8%	28.5%	28.2%
	LAC	2959.4	2642.8	2654.1	2648.6	85.8%	84.1%	83.8%	83.9%	14.2%	15.9%	16.2%	16.1%
	MENA	3208.3	2845.3	2864.5	2854.6	80.8%	78.4%	77.9%	78.1%	19.2%	21.6%	22.1%	21.9%
	SSA	3302.9	3011.0	3062.2	3067.1	74.5%	72.1%	70.9%	70.8%	25.5%	27.9%	29.1%	29.2%
	GLOBAL	46069.6	41350.8	41701.3	41633.6	77.1%	74.4%	73.9%	73.9%	22.9%	25.6%	26.1%	26.1%

Table S6. Non-Methane Volatile Organic Compound (NMVOC) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE
Non-Methane Volatile Organic Compound (NMVOC)	CHN	23827.4	23324.9	23767.7	23542.5	14.5%	12.6%	12.4%	12.5%	85.5%	87.4%	87.6%	87.5%
	BRA	3986.7	3851.3	3904.7	3868.0	26.4%	23.8%	23.5%	23.7%	73.6%	76.2%	76.5%	76.3%
	USA	11260.5	10952.3	11122.9	11019.8	13.8%	11.3%	11.2%	11.3%	86.2%	88.7%	88.8%	88.7%
	IND	9417.1	9275.0	9396.5	9315.8	21.9%	20.7%	20.5%	20.6%	78.1%	79.3%	79.5%	79.4%
	IDN	2532.9	2433.6	2468.0	2458.0	36.7%	34.2%	33.7%	33.8%	63.3%	65.8%	66.3%	66.2%
	NGA	2889.0	2828.1	3255.4	3415.2	16.2%	14.4%	12.5%	11.9%	83.8%	85.6%	87.5%	88.1%
	EU27	10992.4	10680.1	10874.2	10753.3	18.8%	16.5%	16.2%	16.4%	81.2%	83.5%	83.8%	83.6%
	EUR_ NOEU	6202.6	6013.6	6137.6	6061.7	19.4%	16.8%	16.5%	16.7%	80.6%	83.2%	83.5%	83.3%
	NAMO	2361.6	2286.4	2331.1	2305.4	15.5%	12.7%	12.5%	12.6%	84.5%	87.3%	87.5%	87.4%
	INDA	6091.5	5953.4	6056.4	5994.7	14.1%	12.1%	11.9%	12.0%	85.9%	87.9%	88.1%	88.0%
	CENTRAL ASIA	882.1	853.8	879.7	864.5	23.9%	21.4%	20.8%	21.2%	76.1%	78.6%	79.2%	78.8%
	SEA	7451.7	7220.3	7402.4	7352.8	29.1%	26.9%	26.2%	26.4%	70.9%	73.1%	73.8%	73.6%
	LAC	6059.3	5893.6	6016.2	5938.8	22.0%	19.8%	19.4%	19.6%	78.0%	80.2%	80.6%	80.4%
	MENA	7765.5	7566.8	7742.6	7624.1	18.6%	16.4%	16.0%	16.3%	81.4%	83.6%	84.0%	83.7%
	SSA	8480.2	8280.2	8683.8	8635.6	20.4%	18.5%	17.6%	17.7%	79.6%	81.5%	82.4%	82.3%
	GLOBAL	110200.6	107413.3	110039.3	109150.4	19.0%	16.9%	16.5%	16.7%	81.0%	83.1%	83.5%	83.3%

Table S7. Nitrogen Oxides (NO_X) emissions by region and scenario in 2030.

	Scenario	Total emissions (Gigagrams) Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Food-related emissions (share of total, %) Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Non-food related emissions (share of total, %) Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE
Nitrogen Oxides (NO_X)	CHN	21887.7	21564.6	21991.3	21700.4	10.1%	8.8%	8.6%	8.7%	89.9%	91.2%	91.4%	91.3%
	BRA	4115.1	4018.3	4078.2	4035.1	18.3%	16.3%	16.1%	16.2%	81.7%	83.7%	83.9%	83.8%
	USA	14453.7	14172.2	14400.3	14270.2	9.8%	8.0%	7.9%	7.9%	90.2%	92.0%	92.1%	92.1%
	IND	8646.5	8539.1	8655.5	8564.7	18.1%	17.0%	16.8%	17.0%	81.9%	83.0%	83.2%	83.0%
	IDN	1998.7	1959.0	1994.6	1977.3	18.6%	17.0%	16.7%	16.8%	81.4%	83.0%	83.3%	83.2%
	NGA	612.3	593.5	665.1	653.8	23.7%	21.2%	19.0%	19.3%	76.3%	78.8%	81.0%	80.7%
	EU27	13558.9	13317.5	13561.3	13391.8	11.8%	10.2%	10.1%	10.2%	88.2%	89.8%	89.9%	89.8%
	EUR_ NOEU	8581.1	8425.2	8611.3	8494.8	11.6%	9.9%	9.7%	9.9%	88.4%	90.1%	90.3%	90.1%
	NAMO	3450.9	3371.4	3440.7	3398.9	11.2%	9.1%	8.9%	9.0%	88.8%	90.9%	91.1%	91.0%
	INDA	8402.2	8284.7	8435.6	8327.7	8.6%	7.3%	7.1%	7.2%	91.4%	92.7%	92.9%	92.8%
	CENTRAL ASIA	1063.4	1039.8	1070.2	1056.5	16.9%	15.1%	14.6%	14.8%	83.1%	84.9%	85.4%	85.2%
	SEA	5658.2	5540.6	5692.5	5586.5	19.6%	17.9%	17.4%	17.7%	80.4%	82.1%	82.6%	82.3%
	LAC	6385.9	6265.1	6406.0	6309.4	15.1%	13.5%	13.2%	13.4%	84.9%	86.5%	86.8%	86.6%
	MENA	10152.3	9985.7	10218.6	10061.2	11.8%	10.4%	10.1%	10.3%	88.2%	89.6%	89.9%	89.7%
	SSA	3288.6	3193.3	3297.4	3244.1	24.1%	21.8%	21.1%	21.4%	75.9%	78.2%	78.9%	78.6%
	GLOBAL	112255.6	110269.9	112518.5	111072.5	12.9%	11.4%	11.1%	11.3%	87.1%	88.6%	88.9%	88.7%

Table S8. Organic Carbon (OC) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE
Organic Carbon (OC)	CHN	1742.2	1691.8	1722.3	1708.6	19.8%	17.4%	17.1%	17.3%	80.2%	82.6%	82.9%	82.7%
	BRA	400.8	366.3	368.8	367.2	66.8%	63.7%	63.3%	63.5%	33.2%	36.3%	36.7%	36.5%
	USA	456.8	431.5	437.2	434.4	27.8%	23.6%	23.3%	23.4%	72.2%	76.4%	76.7%	76.6%
	IND	1072.4	1039.3	1049.0	1042.5	44.9%	43.1%	42.7%	43.0%	55.1%	56.9%	57.3%	57.0%
	IDN	355.4	330.2	332.8	333.0	66.6%	64.0%	63.5%	63.5%	33.4%	36.0%	36.5%	36.5%
	NGA	557.8	542.7	622.5	666.6	20.9%	18.7%	16.3%	15.2%	79.1%	81.3%	83.7%	84.8%
	EU27	506.7	474.2	480.3	477.9	42.5%	38.6%	38.1%	38.3%	57.5%	61.4%	61.9%	61.7%
	EUR_ NOEU	261.7	243.2	246.4	245.2	45.0%	40.8%	40.3%	40.5%	55.0%	59.2%	59.7%	59.5%
	NAMO	123.0	113.4	115.1	114.4	37.8%	32.5%	32.0%	32.2%	62.2%	67.5%	68.0%	67.8%
	INDA	243.3	230.2	233.6	231.9	32.7%	28.9%	28.5%	28.7%	67.3%	71.1%	71.5%	71.3%
	CENTRAL ASIA	45.4	42.5	43.3	43.0	46.4%	42.8%	42.0%	42.3%	53.6%	57.2%	58.0%	57.7%
	SEA	904.3	845.0	858.6	860.2	61.6%	58.9%	58.0%	57.9%	38.4%	41.1%	42.0%	42.1%
	LAC	326.1	304.1	308.2	307.2	54.1%	50.8%	50.1%	50.2%	45.9%	49.2%	49.9%	49.8%
	MENA	342.2	317.7	322.2	319.9	52.2%	48.5%	47.8%	48.2%	47.8%	51.5%	52.2%	51.8%
	SSA	750.1	714.5	738.0	762.7	41.7%	38.8%	37.5%	36.3%	58.3%	61.2%	62.5%	63.7%
	GLOBAL	8088.3	7686.6	7878.4	7914.6	40.8%	37.8%	36.9%	36.7%	59.2%	62.2%	63.1%	63.3%

Table S9. Particulate Matter 10 (PM10) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE
Particulate Matter 10 (PM10)	CHN	12547.1	12287.7	12522.3	12372.4	14.2%	12.4%	12.1%	12.3%	85.8%	87.6%	87.9%	87.7%
	BRA	2053.4	1966.6	1992.2	1974.7	32.8%	29.9%	29.5%	29.7%	67.2%	70.1%	70.5%	70.3%
	USA	3276.5	3148.6	3194.7	3168.9	19.6%	16.4%	16.1%	16.3%	80.4%	83.6%	83.9%	83.7%
	IND	6172.1	6052.2	6125.4	6074.5	28.2%	26.8%	26.5%	26.7%	71.8%	73.2%	73.5%	73.3%
	IDN	1266.2	1199.6	1213.7	1212.8	49.3%	46.5%	45.9%	46.0%	50.7%	53.5%	54.1%	54.0%
	NGA	2384.8	2334.5	2693.5	2883.1	16.2%	14.4%	12.5%	11.7%	83.8%	85.6%	87.5%	88.3%
	EU27	3387.1	3256.1	3311.2	3280.0	25.6%	22.6%	22.3%	22.5%	74.4%	77.4%	77.7%	77.5%
	EUR_ NOEU	1677.3	1608.5	1636.4	1621.6	26.2%	23.0%	22.6%	22.8%	73.8%	77.0%	77.4%	77.2%
	NAMO	780.8	746.8	760.2	753.1	21.2%	17.6%	17.3%	17.5%	78.8%	82.4%	82.7%	82.5%
	INDA	1913.7	1855.7	1887.8	1868.5	18.5%	15.9%	15.7%	15.8%	81.5%	84.1%	84.3%	84.2%
	CENTRAL ASIA	236.2	227.0	232.9	229.7	28.8%	26.0%	25.3%	25.7%	71.2%	74.0%	74.7%	74.3%
	SEA	3756.9	3595.5	3677.3	3671.0	40.3%	37.7%	36.8%	36.9%	59.7%	62.3%	63.2%	63.1%
	LAC	1809.3	1734.9	1767.7	1753.1	32.9%	30.0%	29.5%	29.7%	67.1%	70.0%	70.5%	70.3%
	MENA	2054.0	1967.0	2006.6	1982.0	30.4%	27.4%	26.8%	27.2%	69.6%	72.6%	73.2%	72.8%
	SSA	4446.7	4321.2	4514.2	4552.6	25.1%	22.9%	21.9%	21.7%	74.9%	77.1%	78.1%	78.3%
	GLOBAL	47762.2	46301.8	47535.8	47398.1	24.4%	22.0%	21.5%	21.5%	75.6%	78.0%	78.5%	78.5%

Table S10. Particulate Matter 2.5 (PM2.5) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_QUO	ENV_AWARE
Particulate Matter 2.5 (PM2.5)	CHN	8446.6	8295.6	8456.3	8342.5	12.3%	10.7%	10.5%	10.6%	87.7%	89.3%	89.5%	89.4%
	BRA	1344.2	1274.1	1288.8	1277.9	40.5%	37.2%	36.8%	37.1%	59.5%	62.8%	63.2%	62.9%
	USA	2006.9	1942.4	1970.8	1952.9	16.2%	13.4%	13.2%	13.3%	83.8%	86.6%	86.8%	86.7%
	IND	3438.2	3374.1	3415.3	3382.5	27.1%	25.7%	25.4%	25.7%	72.9%	74.3%	74.6%	74.3%
	IDN	821.3	779.6	789.0	783.8	47.6%	44.8%	44.3%	44.6%	52.4%	55.2%	55.7%	55.4%
	NGA	213.3	194.8	204.0	196.8	66.7%	63.6%	60.7%	62.9%	33.3%	36.4%	39.3%	37.1%
	EU27	2158.7	2084.3	2118.1	2095.5	22.9%	20.1%	19.8%	20.0%	77.1%	79.9%	80.2%	80.0%
	EUR_NOEU	1107.6	1064.3	1082.2	1071.3	24.8%	21.8%	21.4%	21.6%	75.2%	78.2%	78.6%	78.4%
	NAMO	555.3	531.1	540.5	534.5	21.4%	17.8%	17.5%	17.7%	78.6%	82.2%	82.5%	82.3%
	INDA	1282.3	1248.7	1270.4	1255.3	15.9%	13.7%	13.4%	13.6%	84.1%	86.3%	86.6%	86.4%
	CENTRAL ASIA	152.1	145.9	149.2	147.5	30.3%	27.4%	26.8%	27.1%	69.7%	72.6%	73.2%	72.9%
	SEA	2221.7	2104.6	2146.9	2118.4	49.5%	46.7%	45.7%	46.4%	50.5%	53.3%	54.3%	53.6%
	LAC	1072.3	1024.2	1041.0	1029.5	36.0%	33.0%	32.5%	32.8%	64.0%	67.0%	67.5%	67.2%
	MENA	1275.1	1224.7	1249.0	1231.3	28.7%	25.7%	25.2%	25.6%	71.3%	74.3%	74.8%	74.4%
	SSA	1247.2	1183.8	1218.2	1199.0	42.3%	39.2%	38.1%	38.7%	57.7%	60.8%	61.9%	61.3%
	GLOBAL	27343.1	26472.2	26939.7	26618.7	25.3%	22.9%	22.5%	22.7%	74.7%	77.1%	77.5%	77.3%

Table S11. Sulphur Dioxide (SO_2) emissions by region and scenario in 2030.

		Total emissions (Gigagrams)				Food-related emissions (share of total, %)				Non-food related emissions (share of total, %)			
	Scenario	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE	Baseline	NO_REBOUND	STATUS_ QUO	ENV_AWARE
Sulphur Dioxide (SO_2)	CHN	26026.3	25687.7	26199.2	25853.1	8.9%	7.7%	7.6%	7.7%	91.1%	92.3%	92.4%	92.3%
	BRA	2176.5	2140.9	2174.2	2151.2	12.7%	11.2%	11.1%	11.2%	87.3%	88.8%	88.9%	88.8%
	USA	12344.4	12114.0	12307.3	12200.9	9.4%	7.7%	7.5%	7.6%	90.6%	92.3%	92.5%	92.4%
	IND	10226.7	10114.0	10255.1	10152.2	16.0%	15.1%	14.9%	15.0%	84.0%	84.9%	85.1%	85.0%
	IDN	2203.8	2182.0	2225.6	2208.5	9.3%	8.4%	8.2%	8.3%	90.7%	91.6%	91.8%	91.7%
	NGA	307.0	300.7	332.5	330.4	16.0%	14.2%	12.9%	12.9%	84.0%	85.8%	87.1%	87.1%
	EU27	9503.7	9353.0	9531.1	9414.7	10.6%	9.1%	8.9%	9.1%	89.4%	90.9%	91.1%	90.9%
	EUR_ NOEU	6251.9	6153.6	6289.8	6208.2	10.0%	8.5%	8.3%	8.5%	90.0%	91.5%	91.7%	91.5%
	NAMO	2473.8	2420.3	2468.8	2440.1	10.5%	8.5%	8.4%	8.5%	89.5%	91.5%	91.6%	91.5%
	INDA	6057.9	5973.9	6084.0	6008.9	8.3%	7.0%	6.9%	7.0%	91.7%	93.0%	93.1%	93.0%
	CENTRAL ASIA	1357.5	1337.2	1372.5	1361.3	10.6%	9.3%	9.1%	9.1%	89.4%	90.7%	90.9%	90.9%
	SEA	5021.9	4952.6	5095.8	5006.3	13.0%	11.8%	11.4%	11.6%	87.0%	88.2%	88.6%	88.4%
	LAC	4899.9	4824.3	4933.1	4870.1	12.3%	10.9%	10.7%	10.8%	87.7%	89.1%	89.3%	89.2%
	MENA	11605.4	11447.9	11713.7	11557.8	10.0%	8.8%	8.6%	8.7%	90.0%	91.2%	91.4%	91.3%
	SSA	3268.9	3212.7	3307.6	3260.2	14.3%	12.8%	12.4%	12.6%	85.7%	87.2%	87.6%	87.4%
	GLOBAL	103725.6	102214.9	104290.4	103023.8	10.7%	9.4%	9.2%	9.3%	89.3%	90.6%	90.8%	90.7%

Chapter 4

Economic, social, and environmental spillovers decrease the benefits of a global dietary shift

Abstract

Dietary shifts are key for enhancing the sustainability of current food systems, but need to account for potential economic, social, and environmental indirect effects as well. By tracing physical quantities of biomass along supply chains in a global economic model, we investigate the benefits of adopting the EAT-Lancet diet as well as other social, economic, and environmental spillovers to the wider economy. We find that decreased global food demand reduces global biomass production, food prices, trade, land use and food loss and waste (FLW), but also reduces food affordability for low-income agricultural households. In Sub-Saharan Africa, increased food demand and higher prices decrease food affordability also for non-agricultural households. Economic spillovers into non-food sectors limit agricultural land and GHG reductions as cheaper biomass is demanded more for non-food use. From an environmental perspective, economy-wide greenhouse gas emissions increase as lower global food demand at lower prices frees income subsequently spent on non-food items.

This chapter is based on:

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4.1 Main

Shifting to a healthy and sustainable diet is key for enhancing the sustainability of current food systems, but needs to account for potential economic, social, and environmental indirect effects or spillovers as well. Transitioning to a more sustainable food system lies at the core of the Sustainable Development Goals (SDGs) (U.N., 2019). Current food systems generate substantial environmental, social and health costs while failing to provide affordable healthy food to all (FAO et al., 2020). Direct health and sustainability benefits of a diet shift are increasingly recognised following the publication of the EAT-Lancet diet (Springmann et al., 2016; Willet et al., 2019). But in keeping with the core of the SDGs, economic, social and environmental goals need to be achieved in an integrated manner (United Nations, 2015, p1). EAT-Lancet diet changes lead to substantial changes in consumption and production and therefore food prices, which on their turn alter incentives for consumers and producers. Insight in these indirect or spillover effects in economic, social, and environmental terms alongside direct impacts is thus key for steering the future transition of global food systems.

The EAT-Lancet diet is designed to simultaneously improve health and sustainability through a substantial transformation of current global food systems. In all but low-income regions with substantial prevalence of hunger, calories need to be reduced, while increasing plant-based products and limiting animal-sourced foods (ASF) (Willet et al., 2019). The diet shift is designed to reduce mortality from overweight and obesity, low fruit and vegetable consumption, and high red meat consumption (Springmann et al., 2018a). The EAT-Lancet diet simultaneously aims to improve sustainability by reducing global agricultural greenhouse gas (GHG) emissions, land and water use, biodiversity losses, and nitrogen and phosphorus pollution (Willet et al., 2019; Laine et al., 2021; Tilman & Clark, 2014). In the Willet et al. (2019) central EAT-Lancet study the baseline is based on outputs of the partial equilibrium IMPACT model but the impacts of the diet changes are based on a static input-output model ignoring any price impacts and therefore indirect effects.

Indirect effects or spillovers are likely given the extent of the food system transformation implied by the EAT-Lancet diet. First, food affordability is key for social acceptance of the dietary shift and thus for reaching the intended health benefits. Affordability is determined by the combined impact of price and income changes (Swinnen, 2011). Recent studies only outline first effects of dietary changes on food prices. Using empirical data of retail prices and income, Hirvonen et al. (2020) find the EAT-Lancet diet costing only a small fraction of income in high-income regions, while exceeding household per capita income for at least 1.6 billion of the world's poor. Springmann et al. (2021) combine empirical data on food prices with current and simulated diet patterns looking at affordability compared to current diets as well as computing healthcare and climate damage costs. They find healthy diets cheaper in higher-income regions but more expensive than current diets in lower-income regions. While Hirvonen et al. (2020) find food affordability problems for the poor, it does not capture income changes from a global shift in the food systems, which may alter the conclusions. Springmann et al. (2021) do not address income nor prices changes from a global shift in diets. While pointing to regionalised affordability concerns, these studies thus only partially capture social spillovers via food affordability.

Second, the food system transformation affects the wider economy as changing household spending patterns creates economic spillovers in non-food sectors. Reducing agricultural land area and emissions by reducing global food consumption are two key environmental benefits of the EAT-Lancet diet (Willet et al., 2019; Springmann et al. 2018a, Springmann et al., 2018b). Being based on static models without price changes or agricultural sector models, these studies, however, cannot account for changes in non-food demand and thus production when diets shift. Non-food sectors use biomass and thus require land which may reduce the impact of diet changes on land use. While agriculture is the main source of non-CO_2 emissions (Frank et al., 2019), total GHG emissions from the food system (including processing, retail, transport and consumption) are a third of global emissions (Crippa et al., 2021). Shifting consumption from food to non-food could thus generate more GHG emissions outside the food system. Economic spillovers to non-food sectors could alter the initial EAT-Lancet diet impacts in terms of non-food production, land use and GHG emissions.

Third, the substantial change in diet affects the composition and global flows of food loss and waste (FLW) creating environmental spillovers in terms of reuse possibilities. A reduction in total FLW generation is generally associated with a more sustainable diet (Willet et al., 2019; Springmann et al., 2018). Increased demand for plant-based foods commonly associated with high FLW shares (FAO, 2019), may increase FLW along global food supply chains (FSC). These studies however provide no insight in changing types nor geographical location of FLW when transitioning to a healthier diet. The dietary shift will induce changes in FLW composition and geographical production locations, creating environmental spillovers by affecting the scope for FLW reuse.

This study investigates benefits and economic, social, and environmental spillovers of a global transition towards a healthier and sustainable EAT-Lancet diet (Willett et al., 2019) in 2030. We address three main research questions focused on indirect effects or spillovers missing in existing studies, one for each of the domains integral to the SDGs. First, what are the economic spillovers into non-food sectors not targeted by the diet shift and do these thwart the environmental gains in terms of land use and GHG emissions? Second, what are social spillovers in terms of food affordability if we account for changes in food prices and wages that provide the main income for most and especially poor households? Third, what are environmental spillovers in terms of FLW amount, composition, and location?

We contribute to the existing literature on moving within planetary boundaries through a diet shift by simultaneously addressing future non-food, income and FLW direct and indirect impacts through an enhanced economy-wide general equilibrium (GE) model, moving beyond static and partial agricultural equilibrium economic models used in previous studies. The GE model enhancements build a bridge between economic and technical modelling of biomass and FLW. It improves tracing of food and non-food use of biomass in physical quantities along global FSC in a GE model including behavioural responses of producers and consumers lacking in technical studies. Previous studies have extended global GE models with physical data on land use (Van Meijl et al., 2006) and selected biomass flows (Britz & van der Mensbrugghe, 2018; Chepeliev, 2022), but none explicitly addresses the changes of physical biomass flows in the context of a global dietary transition and FLW. Our FLW amounts evolve with changing production and consumption patterns driven by the economic dynamics of the model and are based on best available estimates collected from literature, compiling a new global database to quantify lost or discarded food by region, commodity, and supply chain stage. We align with U.N. (2019) defining FLW as *"food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses, and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products"*.

We simulate the transition towards the EAT-Lancet diet by changing global consumption patterns in line with these healthy and sustainable dietary guidelines and compare it to a business-as-usual (BAU) scenario for 2030 without dietary shifts. While existing studies provide results for the complete EAT-Lancet diet, we also run separate scenarios for commodity targets and total calorie intake. This allows us to identify which components of the diet have the strongest impact. This decomposition also has policy relevance, providing guidance on which diet component to focus on if a complete diet shift is infeasible. We model a partial transition towards the EAT-Lancet diet in all regions, based on the unaffordability of a full diet shift for households in low-income regions (Hirvonen et al, 2020). Applying a a homogenous dietary shift across countries allows comparisons with existing global EAT-Lancet studies. The gap with the EAT-Lancet target is reduced with one third in all regions.

The paper is structured as follows. First, we provide an overview of how the diet scenario changes food demand compared to the BAU as this drives all other results. Second, we analyse results for biomass production, trade, land use and GHG emissions, including economic spillovers in non-food sectors. Third, we present the implications of the diet change for food prices and wages, identifying negative social spillover effects for specific households and regions. Fourth, changes in FLW amounts, composition and geographical location are analysed to identify additional environmental spillovers from changes in FLW generation. We conclude with a discussion, placing our findings in context and deriving policy implications. The methods section and Supplementary Information (SI) provide our methodological contributions to simulate the EAT-Lancet diet in a global economic model and for tracing physical biomass flows and FLW across global supply chains in a more consistent manner.

4.2 Results

Changing food consumption patterns towards a healthier and more sustainable diet

To analyse how a future healthy and sustainable diet may transform the food system we use two scenarios. The BAU scenario provides a "without" situation where diets are endogenously determined in response to two main drivers: population and GDP changes. "*The BAU scenario does not provide a forecast of the future* e, but a plausible future state of the economy if past trends in these two main drivers continue, capturing the expected responses in terms of production, consumption and trade. The "with" situation then simulates a counterfactual breaking with historical dietary developments by imposing a healthier and more sustainable diet on top of the BAU drivers. In addition to a complete diet scenario we run scenarios for commodity group and calorie restriction separately. This provides insight in the contributions of different targets. It also offers a first insight into the effects of a diet better tailored to region-specific circumstances than the global EAT-Lancet reference diet as these commodity groups cover the items generally included in national food-based dietary guidelines. Instead of the BAU endogenous consumption, all diet scenarios consider (part of) consumption exogenous. We use an endogenous shifter variable modifying consumer food preferences such that they adhere to the imposed diet while still taking into account income and price changes.

A summary of our scenario assumptions and impacts on GDP is provided in Table 4.1 to support interpretation of results. Details on scenario implementation and limitations posed by the commodity detail in our model are provided in the methods section and SI. For all regions GDP growth from 2020 to 2030 exceeds population growth so income per capita rises. Moving towards the EAT-Lancet diet only marginally changes GDP. Our preference shifts do not impose any cost on the economies while reducing the size of the agricultural sector which in most regions receives substantial subsidies. As a result economies restructure in response to the diet shift, but do not change in size. In general, our results show that the EAT-Lancet diet reduces intake substantially in most high-income regions. For low-income regions such as Sub-Saharan Africa (SSA) and to a lesser extent Southeast Asia (SEA), changes in the intake of some commodities have to decrease less or even have to increase substantially (e.g., non-ruminant meat and dairy consumption in SSA).

Table 4.1. Overview of investigated dietary scenarios and magnitude of implemented regional diet shocks in net consumption (grams/cap/day) by scenario.

		REGION-SPECIFIC SHOCK (% change in driver or final net consumption)							
		EU27	**SEA**	**INDA**	**NAMO**	**LAC**	**REUCA**	**MENA**	**SSA**
Macro drivers (% change from 2020-2030)+	Population	1.2	8.4	-3.9	8.3	11.4	3.4	21.8	39.1
	BAU GDP	24.7	69.7	18.6	26.3	30.5	17.9	42.5	48.6
	TOWARDS EAT-LANCET GDP	24.7	70.6	18.4	26.7	30.8	17.9	42.4	48.4
Agricultural share in GDP in 2030 (%)	BAU	1.4	5.0	0.6	0.9	5.1	1.9	3.4	14.7
	TOWARDS EAT-LANCET	1.3	4.6	0.9	0.7	4.5	1.4	3.0	18.9
EAT-Lancet targets (grams/cap/day)		**Diet scenarios towards the EAT-Lancet (reducing the gap with targets by a third):**							
232	CEREALS	-26.2	-22.3	-25.8	-28	-21.7	-22.9	-24.6	-15.2
675	HORTICULTURE*	-4.1	-1.4	0.7	9.2	13.9	-3.0	3.6	-9.3
51.8	FATS	-26.9	-26.1	-24.8	-23.5	-24.1	-22.7	-20.7	-14.8
31	SUGARS	-31.4	-30.3	-30.5	-31.5	-32.6	-30.7	-30.6	-27.7
7	MEAT - ruminants**	-24.8	-12.4	-23.8	-29.7	-29.1	-27.3	-23.5	-15.7
49	MEAT - non-ruminants***	-21.6	-5.6	-23.6	-24.6	-22.2	-21.0	-10.3	57.3
250	DAIRIES	-20.7	24.1	15.3	-17.4	-3.6	-17.3	6.9	93.9
28	FISH	-9.0	-20.0	-24.9	-11.1	-16.2	-11.2	3.7	42.5
2500 (kcal/cap/day)	CALORIES	-23.1	-13.0	-20.9	-24.4	-18.4	-18.9	-18.2	-1.7
TOWARDS EAT-LANCET		**combination of all shocks reported above for each region**							

Notes: +Population and BAU GDP projections from IMF (2022) covering the period between 2020-2030. These are used to calibrate a BAU total factor productivity change that replicates the IMF GDP growth. In the diet scenarios this BAU factor productivity is maintained while GDP can adjust, reflecting the average income effects of the diet change. Population growth is exogenous and identical in BAU and diet scenarios.
EU27 = European Union-27; SEA = Southeast Asia; INDA=Industrialised Asia; NAMO = North America & Oceania; LAC = Latin America & Caribbean; REUCA = Rest of Europe & Central Asia; MENA = Middle East & North Africa; SSA = Sub-Saharan Africa.
*Horticulture includes fruits, vegetables, roots, tubers, pulses, starchy vegetables, and nuts.
**Red meat (ruminant meat, mostly beef).
***Other meats and animal products (mostly pork and poultry).

Transitioning to a healthier and sustainable diet results in reduced global food consumption (and thus production) by one fifth in 2030 compared to BAU developments (Figure 4.1). The per capita income increase projected for 2030 results in higher global average food intake when past trends continue as in the BAU. Given the scenario set-up detailed in Table 1, global intake across all commodity groups decreases in the EAT-Lancet scenario. Total intake is 20% lower than in the BAU and 17% lower than in 2020, implying a substantial global reduction in food production. This global average hides regional differences like the increase in food intake in low-income regions such as SSA (11.4%).

The reduction in quantities consumed is not proportional across commodities with diets transitioning towards horticultural products and away from cereals, sugars, meat, and dairy. Compared with the BAU, horticultural intake in 2030 remains the same. While fruit and vegetable consumption needs to increase globally, the horticultural commodity in MAGNET also includes roots and tubers which need to decrease. These opposing shifts cancel each other at global level and lead to targeted reductions for horticultural products in several regions (see Table 1). Consumption of other crops decreases substantially compared to the BAU, ranging from -26% for cereals to -34% for sugar crops. Animal-sourced foods (ASF) also decrease substantially, ranging from a 32% reduction for red meat to a 10% reduction in dairy intake. The dietary shift brings intakes below 2020 levels for all but horticultural products, implying a contraction of current food production instead of the BAU expansion.

Although total food intake reduction can be reached by targeting calories alone, the resulting diet would have too much meat and sugar while lacking in horticultural products and dairy. Targeting calories without side constraints on the composition of the diet about matches the total intake measured in grams (2261 versus 2233 grams/capita/day). But the composition only matches for other meat (85 grams, includes eggs as well). Intake of horticultural products would be much lower (525 grams/capita/day, 22% lower than in the EAT-Lancet diet), as would dairy (16% lower). All other commodity groups would be higher, most notably sugar crops (45%) and red meat (11%).

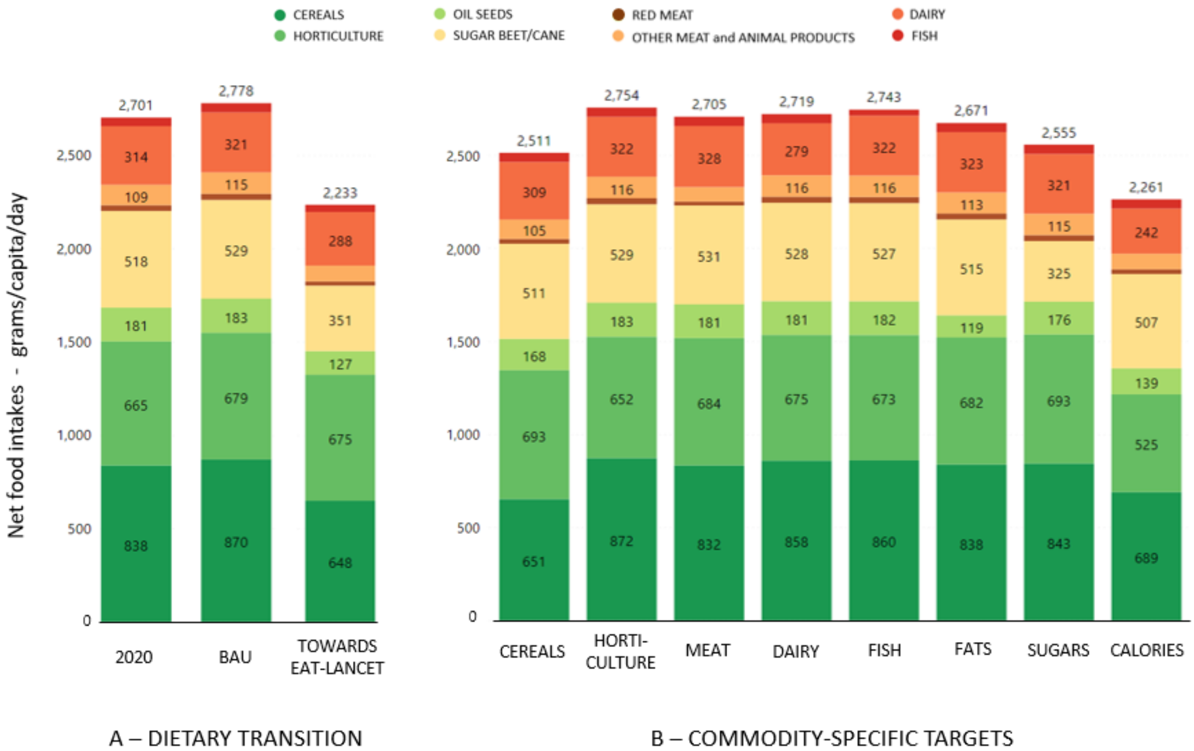

Figure 4.1. Average global net food intakes in 2020 and in 2030 with "Business-as-Usual" (BAU) and diet scenarios (grams/capita/day). Panel A shows average net food intake in 2020 (starting point of our simulation) and in 2030 for the BAU and transition towards the EAT-Lancet diets. Panel B shows the impact of commodity group and calorie targets constituting the EAT-Lancet diet. See Table 1 for a description of the scenario set-up by region. Intake estimates exclude FLW discussed in more detail in the last results section. The reported global averages hide impacts on single supply chain stages as well as regional variation.

Economic spillovers into non-food sectors induced by the dietary transition mitigate reductions of global land use and increase greenhouse gas emissions

To analyse economic spillover effects we investigate how changes in global biomass production, trade and non-agricultural sectors affect global land use and greenhouse gas emissions.

By reducing food demand, the transition towards the EAT-Lancet diet reduces global biomass production for food, but there is no one-to-one link for all commodities. While still increasing from 2020 levels, total biomass production is 79% lower than in the BAU (Panel A – Figure 4.2). The diet transformation reduces cereal, oil seed, sugar crop, meat, and fish production below 2020 levels. Despite a comparable intake of horticultural products (Figure 4.1) the increase in horticultural production with the diet transformation is 14% less than in the BAU. By contrast, average dairy intake decreases below 2020 levels with the dietary transition (Figure 4.1), while dairy production increases compared to 2020 levels (Panel A – Figure 4.2), showing the increase in dairy production in locations (mainly low-income regions) associated with higher rates of FLW. As with food intake, restricting calories is the main driver of decreasing food biomass production, which also shifts production towards meat and sugar crop production. Commodity-specific targets have limited impact on the biomass production pattern, apart from a change in the targeted commodities.

In addition to reducing biomass demand and therefore production for food, we find that the lower food demand imposed with the EAT-Lancet diet induces the economic adjustments leading to lower agricultural prices which stimulates biomass demand and therefore production for non-food use. Production of other crops used as non-food (including for example products such as natural rubber, forage plants, and plants used primarily in perfumery, pharmacy, or textiles) increases substantially compared to 2020 levels (191%), while increases are negligible in the BAU. In our model simulations the production of non-food crops and non-food use of all biomass is stimulated by lower agricultural prices, resulting from the decreased demand for food (illustrated by decreased food prices in most regions, see panel A and B in Figure 4.4). Lower prices make food biomass more competitive relative to non-biomass-based alternatives (e.g. fossil sources) in non-food sectors. Single commodity-specific targets nor calorie reduction have a strong impact on non-food biomass production.

Similar to production, global biomass trade shows a more moderate increase in volume with a changing diet than in the BAU, but the non-food shift is much stronger with trade for food use declining below 2020 levels (Panel B - Figure 4.2). Biomass traded for use as food in primary, processed or service products decreases compared to 2020 by 234 million tonnes (-15%). This is more than compensated by the increase in trade for non-food use of 243 million tonnes (117%). As food biomass production increases (Panel A – Figure 4.2) and especially trade for processed food declines, this signals shorter supply chains (i.e. fewer stages) oriented towards fresh products. Trade of non-food biomass increases under all single commodity-specific targets but most with the calorie target. The 158 million tonnes (or 28%) reduction in biomass trade for processed foods compared to 2020 levels with the EAT-Lancet is principally due to targets on calories, sugars, cereals, and fats. Only the calorie target also leads to a decrease in primary food and food service biomass trade, making it the main driver of changing global biomass trade.

Our results illustrate that transitioning to the EAT-Lancet diet generates an economic spillover effect in non-food sectors, visible in biomass production and trade and by a declining share of agriculture in GDP. The production and trade patterns in Figure 4.2 already show the stimulus of non-food sectors by the diet transition. The impact of the diet extends beyond biomass as shown by lower shares of agriculture in GDP than in the BAU, while GDP growth remains the same (Table 1). With the global transition to a healthier and sustainable diet thus comes a shift towards consumption of non-food commodities made possible by the combined effect of lower food prices (see panel A and B in Figure 4.4) and lower food consumption levels (Figure 4.1). The notable exception is Sub-Saharan Africa where food consumption does not need to decrease and shifts to higher cost for animal-sourced foods (see diet shocks in Table 4.1). As a result, here the already high share of agriculture in GDP in the BAU (15%) increases to 19% with the diet transition.

In our simulations, the economic spillovers into non-food sectors reduce the benefits of the EAT-Lancet diet by mitigating the reduction in global agricultural land use compared to the BAU (Panel C - Figure 4.2). Globally transitioning to the EAT Lancet diet still mitigates the BAU trend of increasing agricultural land use, reducing the 3.8% expansion in the BAU to 3.2%. While rising consumption of primary fresh plant-based products increases global land use for primary biomass by 66 million hectares (4%), reductions from lower consumption of processed foods (317 million hectares) and food services (74 million hectares) result in substantially less land used for food (325 million hectares globally). Lower demand for food reduces land prices, inducing both extensification and land taken out of production. Lower land prices also reduce biomass prices, increasing their competitiveness in non-food use, which also keeps land in production: land use for non-food biomass increases by 163 million hectares (+38%). Globally this implies that the benefit of the EAT-Lancet diet in terms of reducing land use is halved from 325 million hectares from reduced food use to 162 million when accounting for increased non-food land use as well. Linked to this, the global use of chemical fertilisers declines only by a 2% as the decrease in the application of chemical fertilisers for food crops (-20.5%) is almost erased by a parallel increase in fertiliser use for non-food crops (+128.1%).

Regional developments differ from the global pattern with land use in Sub-Saharan Africa and Industrialised Asia increasing more than in the BAU, and similar trends in land use being driven by different commodity targets in high- and mid-income regions. In Sub-Saharan Africa the EAT-Lancet diet increases land demand by 100 million hectares (2.4%) due to a combination of additional land for food (fresh biomass 76, seed and feed 5 million hectares) and non-food biomass (35 million hectares). Being Sub-Saharan Africa relatively land abundant, land prices in Sub-Saharan Africa are also relatively low, stimulating land expansion. Land for non-food biomass production drives the 10 million additional hectares brought into production in Industrialised Asia compared to the BAU. In all other regions land use decreases compared to the BAU, dominated by reductions in land use for processed foods. In high-income regions this is linked to commodity targets on meat and dairy, and thus reductions are mainly pasture land. In mid-income regions targets for cereals and sugars result in less land for processed food, thus reducing land used for crops. Even with similar trends there are thus differences in drivers and types of land hidden in these aggregate numbers.

Economic spillovers into non-food sectors reverse lower food system emissions when transitioning to the EAT-Lancet diet (1195 million tonnes of CO_2 equivalents), resulting in a net increase of GHG emissions by 1.7% compared to the BAU (equal to 961 million tonnes of CO_2 equivalents, Panel D – Figure 4.2). The total reduction in food system emissions is dominated by lower consumption of ruminant meat (739 million tonnes of CO_2 equivalents) and cereals (notably rice, 331 million tonnes of CO_2 equivalents). The stimulus of non-food consumption, as a smaller share of income is spent on food due to lower quantities and prices, the diet transition increases emissions compared to the BAU from non-food primary sectors food (135%), industrial and service sectors (2.3%) and from household consumption (9.9%). Despite lower percentage changes, higher 2020 emission levels have adjustments outside of the agricultural sector (industrial and service sectors, household consumption) that drive the net increase in GHG emissions when transitioning to the EAT-Lancet diet.

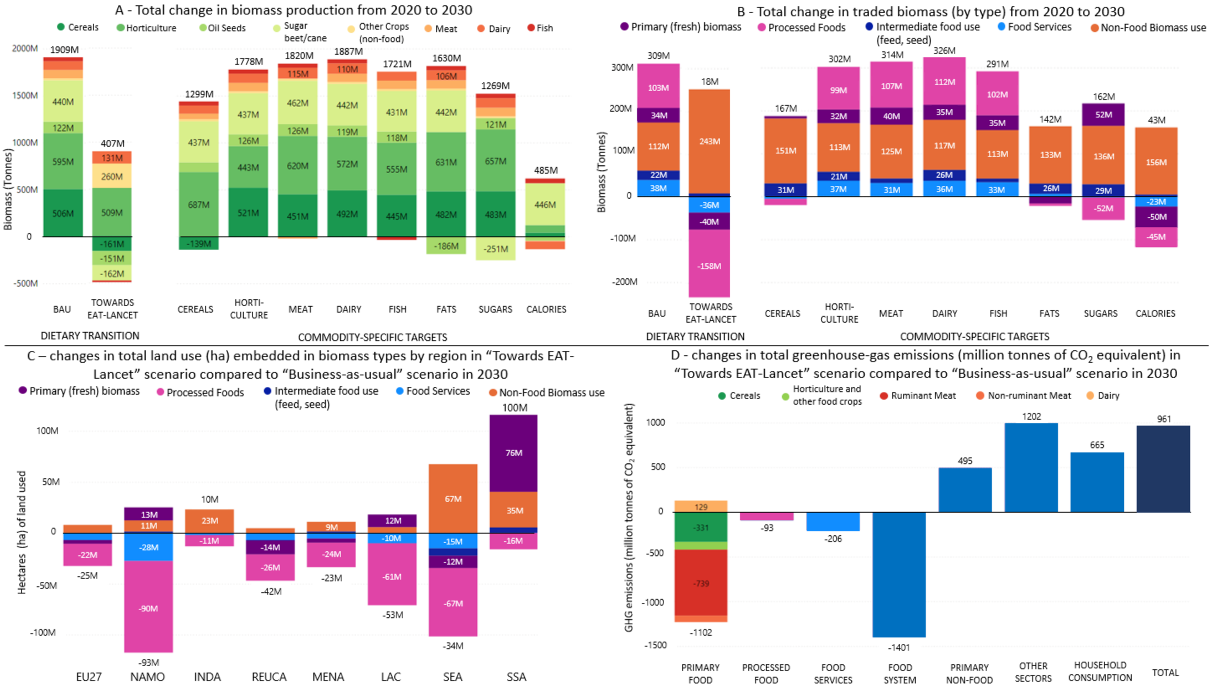

Figure 4.2. Changes in biomass production and international trade with a healthy and sustainable diet.
Panel A shows changes in total biomass production. Estimates refer to change production of total global biomass suitable as food summed over all uses (food, feed, seed, and other non-food) and all sectors (primary sectors, manufacturing, and services) from 2020 to 2030 by scenario and measured in tonnes. To highlight the shift towards non-food use we also report biomass from non-food crops (such as plant-based fibres) that are easily substituted with food crops. "BAU" refers to the baseline Business-As-Usual scenario. "Towards EAT-Lancet" scenario refers to a combination of all commodity-specific scenarios and the "Calories" scenario of which the individual impacts are shown in between the "Sugars" and "Towards Eat-Lancet" scenarios. Panel B shows changes in total global biomass trade volumes by type of biomass from 2020 to 2030 by scenario. Estimates refer to change in trade of biomass categorised through different channels of use. Intermediate food use refers to primary food biomass serving as intermediate input (in the form of feed or seed) for the production of other food commodities (such as meat). Non-food biomass use refers to food biomass used for non-food purposes such as industrial and non-food services. Panel C illustrates changes in land use (hectares) by region and biomass types comparing the "Towards EAT-Lancet" scenario" with our BAU scenario (baseline) in 2030. Finally, Panel D reports total changes in greenhouse gas (GHG) emissions (million tonnes of carbon-dioxide (CO_2) equivalents) in the "Towards EAT-Lancet" scenario" compared to our BAU scenario (baseline) in 2030. The first column of panel D is split by food categories to illustrate the major impact of the dietary transition in reducing GHG emissions from ruminant meat and cereals (mainly rice) production. The "Primary non-food" column refers to GHG emissions related to non-food agricultural sectors. The sum of GHG emissions in the "Primary food" and "Processed food" columns constitutes the "Food system" column, illustrating changes in GHG for the entire food system (i.e. primary food, processed food and food services). The "Other sectors" column refers to changes in GHG emissions produced by non-agricultural sectors. "Household consumption" refers to emissions related to purchases of food and non-food products by households. Finally, the last column of panel D reports the total changes in GHG emissions in the whole economy.

Social spillovers enlarge the income gap between agricultural and non-agricultural low-skilled workers, decreasing food affordability for workers employed in agriculture

To analyse social spillovers we investigate how the dietary transition affects food affordability through changes in food prices and low-skilled wages which provide the main source of income for low-income households in all regions. We analyse prices of two types of food baskets. First, we analyse a healthy food basket defined in accordance with the EAT-Lancet dietary targets to assess if the imposed diet would be affordable and thus more likely to be adopted. Second, we analyse staple foods composed of different cereals which provide the main source of calories for the poor (Clements & Si, 2018). Decreased staple food affordability signals that hunger among the poorest households may increase when transitioning to an EAT-Lancet diet. Prices only tell half the story of affordability and are therefore compared to changes in income for two types of low-skilled workers, those in agriculture and non-agriculture. This distinction is relevant due to the persistent much lower wages in agriculture, and because of the stimulus from economic spillovers to non-agricultural sectors.

We find the diet transition improves affordability of an EAT-Lancet diet for all non-agricultural low-skilled workers except those in Sub-Saharan Africa, but only for agricultural workers in high-income regions and South-East Asia (Panel A and B – Figure 4.3). Prices of an EAT-Lancet diet decrease in all regions apart from Sub-Saharan Africa (Panel A – Figure 4.4). The reduced affordability of an EAT-Lancet diet for low-skilled agricultural workers in all but high-income regions and South-East Asia is thus due to their wages decreasing even more than the drop in food prices (Panel C – Figure 4.4). While affordability of an EAT-Lancet diet for non-agricultural workers in Latin America, EU and Industrialised Asia increases, our results show that the gain is mitigated by a decrease in non-agricultural low-skilled wages (Panel D – Figure 4.4), despite the boost of the non-food economy. In Sub-Saharan Africa, EAT-Lancet targets imply an increase in food demand. Although consumers benefit from lower world market prices and Sub-Saharan Africa turns into a net food importer, part of the foods is still produced domestically at a higher cost. However, the higher food prices also increase wages of agricultural unskilled workers (8.8%, Panel C – Figure 4.4), mitigating most of the 10.1% food price increase for agricultural low-income households. Low-skilled workers in non-agricultural sectors benefit much less from the boost of the non-food sectors: their wages increase by only 0.2% (Panel D – Figure 4.4).

Staple food affordability worsens for all low-skilled agricultural workers apart from those in Industrialised Asia and South-East Asia, while improving for non-agricultural households apart from those in Sub-Saharan Africa and EU. Staple foods are key for the lowest-income households, making the worsening for both agricultural (-3.1%) and non-agricultural households (-11.7%) in Sub-Saharan Africa a concern. As with the price of an EAT-Lancet diet the increase in staple food prices of 11.9% is mostly buffered by agricultural wage increases (8.8%), while non-agricultural households get a minimal increase income from the economic spillovers to non-food sectors (0.2%). Our results show that the global shift towards healthier and sustainable diets may increase hunger in a region where it is already a major worry. For the other regions, except Industrialised Asia and South-East Asia, there is a clear dichotomy. Staple foods become less affordable for poor agricultural households as wages drop more than prices. By contrast, non-agricultural poor households benefit from the economic spillover effects to non-food with their wages increasing (most regions) or decreasing less than staple food prices (notably Latin America).

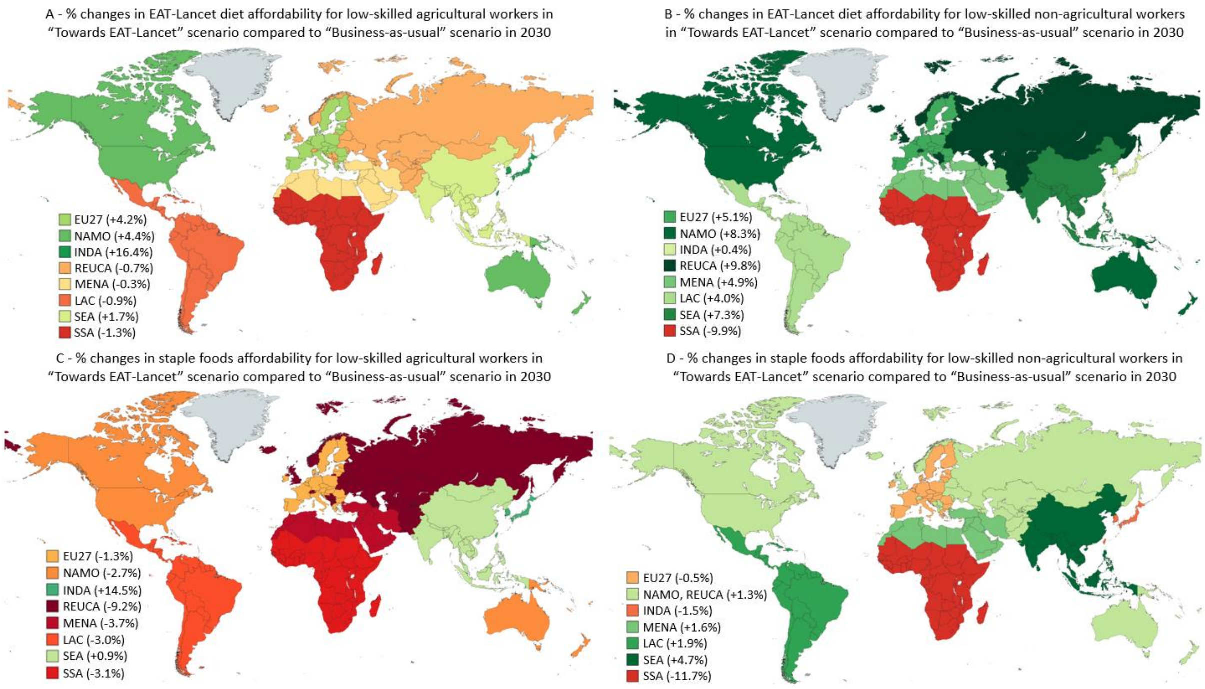

Figure 4.3. Change in healthy foods and staple foods affordability for low-skilled workers (i.e. low-income households) employed in agricultural and non-agricultural sectors. Estimates refer to a comparison the "Towards EAT-Lancet" scenario with the "Business-as-usual" scenario in 2030. Affordability is defined comparing prices of food commodities with labour wages of low-skilled workers. Panel A reports percentage changes in affordability of a "healthy foods" basket defined in accordance with the EAT-Lancet dietary targets for low-skilled workers employed in agricultural sectors across global regions in 2030. Panel B reports percentage changes in affordability of "healthy foods" for low-skilled workers employed in non-agricultural sectors across global regions in 2030. Panel C shows percentage changes in "staple foods" affordability for low-skilled agricultural workers across global regions in 2030. Finally, Panel D illustrates percentage changes in "staple foods" affordability for low-skilled workers employed outside agriculture across global regions in 2030.

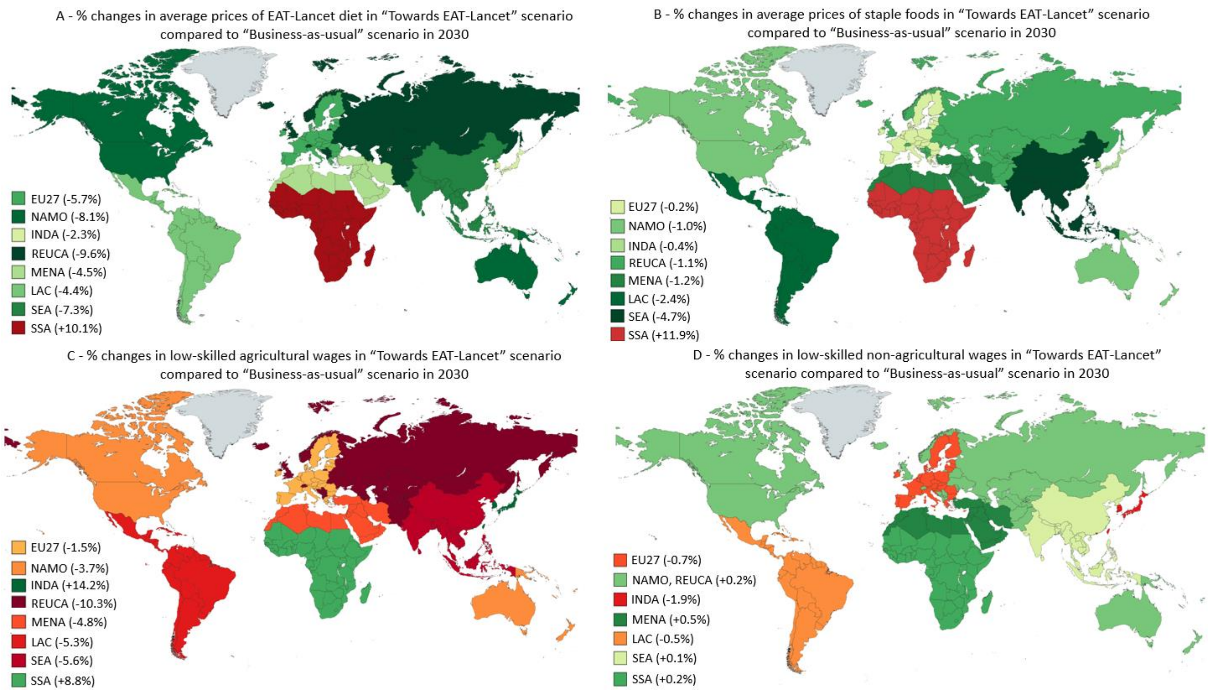

Figure 4.4. Drivers of changes in affordability of healthy foods and staple foods. Estimates refer to a comparison the "Towards EAT-Lancet" scenario with the "Business-as-usual" scenario in 2030. Panel A shows percentage changes in average prices of a healthy food basket defined as the EAT-Lancet dietary targets across global regions. Panel B shows the percentage change in average staple foods prices across global regions in 2030. Panel C shows percentage changes in low-skilled agricultural wages across global regions, while Panel D shows percentage changes in low-skilled non-agricultural wages (i.e. wages of unskilled workers employed in sectors outside agriculture) across global regions in 2030.

Global food loss and waste decrease with healthy diets but environmental spillovers indicate that large losses linked to food consumption in high-income regions are located in lower income regions

We find ,moving towards the EAT-Lancet diet decreases average global food demand, reducing FLW to 1.8 billion tonnes (-18.9% - Panel A – Figure 4.5). With a global shift from processed foods to fresh plant-based products, manufacturing losses have the highest relative decrease (-29.2%). But in absolute terms lower food demand and decreasing trade reduces farm-level losses (around -249.5 million tonnes) and consumption waste (around -94.1 million tonnes) most. The calorie reduction is crucial for the global FLW reduction as most individual targets provide very minor FLW reductions. Apart from calories, a lower demand for cereals, sugar beet/cane, and oil seeds decreases FLW in Middle East and North Africa (MENA, 17.1%), Latin America (LAC, 23.8%) and Rest of Europe and Central Asia (REUCA, 19.2%), mostly at Agricultural Production and Post-Harvest Handling and Storage stages. At the other end of the supply chain, a reduction in ASF consumption is key for decreasing total FLW in high-income North America and Oceania (NAMO, 20.2%), European Union (EU27, 20.5%) and Industrialised Asia (INDA, 18.6%). The same meat and dairy targets increase Agricultural Production losses in Sub-Saharan Africa (SSA), resulting in an overall rise in FLW generation with the diet (3.9%).

Our results illustrate that shifting consumption towards the EAT-Lancet diet enlarges the global share of plant-based products within global FLW (6.3% - Panel B – Figure 4.4). This primarily occurs in higher-income regions (1.3%) and in REUCA (0.3%) where current ASF overconsumption decreases in favour of increasing plant-based product consumption. By contrast, a shift towards ASF in lower-income regions results in lower amounts of plant-based products embedded in total FLW. Plant-based FLW decreases mainly in SSA (10.6%) and South-East Asia (SEA, 2.3%), where cereals and horticulture are replaced by dairy and meat products. Similarly, lower exports of plant-based foods result in lower amounts of plant-based FLW in LAC (0.7%) and MENA (1.2%). Overall dairy targets increase shares of dairy FLW by an average +2.8%, while targets on fats and sugars reduce shares of oil seeds (-1.6%) and sugar beet/cane (-4.4%). In NAMO and EU27, lower ASF intakes reduce shares of meat FLW at the last stages of the FSC (-1.4%). Dairy shares expand particularly in SEA and SSA (4.7%), at Agricultural Production and Consumption production stages, replacing decreasing shares of sugar crops (-3.5%) and oil seeds (-2.9%). Decreasing global food trade with the EAT-Lancet diet in our model simulations reduces amounts of food losses related to food imports (i.e. generated outside of the region where final food consumption occurs) by an average 21.2% (Panel C – Figure 4.5). Main reductions are observed in SEA (-33.2%), INDA (-29.5%) and NAMO (-31.1%) and to a lesser extent in MENA (-18.7%) and EU27 (-25.8%). By contrast, the increasing food demand observed in SSA results in higher food imports, increasing losses generated abroad (16.4%).

Despite import-related food losses decreasing on average across regions, our results show that large shares of losses generated abroad remain, mainly located in lower-income regions (Panel D – Figure 4.4). Such environmental spillover effects are largest in SSA, SEA, and LAC, where exports of perishable fresh foods generate considerable losses at Agricultural Production and Post-Harvest Handling and Storage. Around 67.5% (50 million tonnes) of food losses generated abroad by consumption in higher-income regions (NAMO, EU27 and INDA) are located in lower-income regions. This share is significantly lower for mid- and lower-income regions, where shares of losses generated abroad are more equally distributed between higher-income and lower-income regions. Despite the EAT-Lancet diet decreasing the environmental impact in terms of total amount of FLW, food consumption in high-income regions represents a main driver of FLW at early stages of the supply chain in low-income regions.

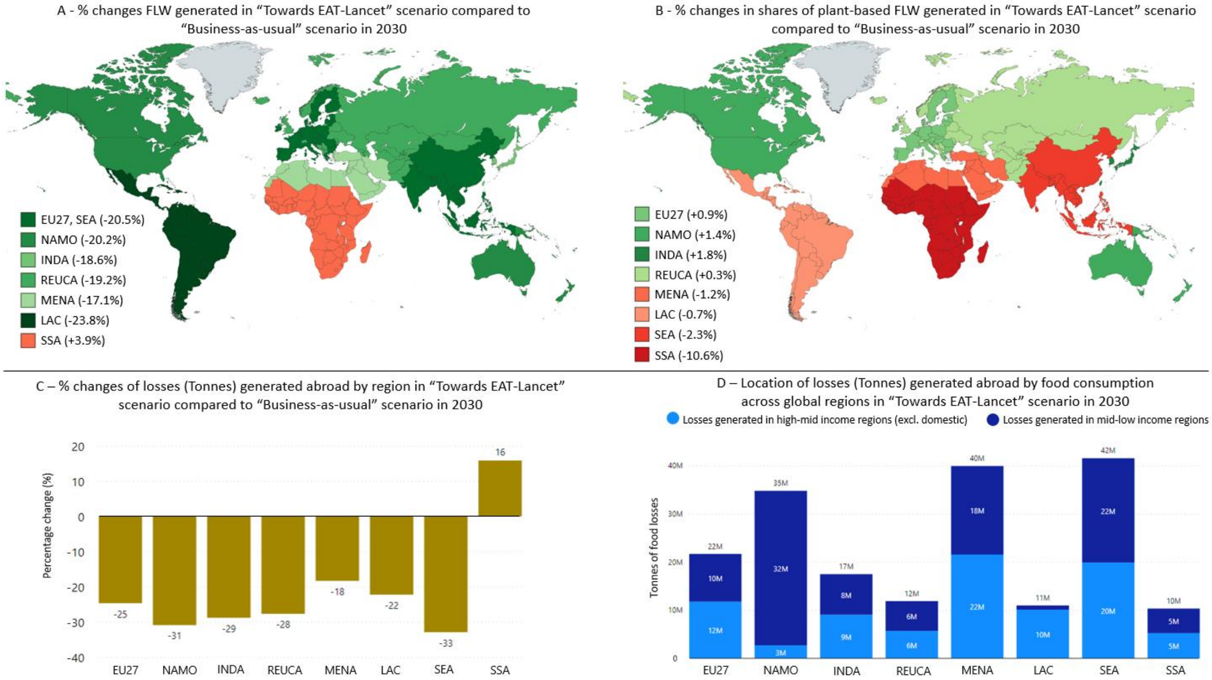

Figure 4.5. Magnitude, composition, and geographical location of global FLW generation in the transition towards the EAT-Lancet diet. Panel A illustrates changes (%) in total FLW amounts generated by region in the "Towards the EAT-Lancet" scenario compared to a "Business-as-usual" scenario in 2030. Panel B reports an overview of the changing composition of FLW with the EAT-Lancet diet, illustrating changing shares of plant-based FLW by regions in comparison to a "Business-as-usual" scenario in 2030. Panel C reports changes (%) in total amounts (tonnes) of food losses generated abroad by region in the "Towards the EAT-Lancet" scenario compared to a "Business-as-usual" scenario in 2030. Finally, Panel D illustrates the total amount of food losses (million tonnes) generated abroad in the "Towards the EAT-Lancet" scenario by source, enlarging the information reported in Panel C.

4.3 Discussion

We investigate benefits and economic, social, and environmental spillover effects of a global transition towards a healthier and more sustainable diet using a global GE model enhanced to trace material flows along global supply chains. Calibrated on national statistics the model captures the response of the current global economy, accounting for presence of trade barriers, regional patterns and volumes of global trade along food supply chains and responses of producers and consumers to price changes. Our improved tracing of physical biomass and FLW material flows in a monetary GE model, addresses one of the key weaknesses of these models (Pyka et al. 2022). Methods for preserving physical quantities in model simulations have been previously developed (van der Mensbrugghe & Peters, 2020; Horridge, 2019). We present an alternative that respects initial material balances in physical units in the model database and shows only minor violations of material balances in counterfactual simulations. Our approach maintains Constant Elasticities of Substitution (CES) functions typical of GE models easing joint economic and biophysical analyses. It permits analysis of the impact of the EAT-Lancet diet on global physical biomass flows while accounting for economic variables key to assess the affordability of dietary shifts. Covering global FSC while collecting best available physical FLW estimates from literature we expand existing monetary analyses of FLW (Britz et al., 2019; Okawa, 2015; Campoy-Muñoz et al., 2021), providing a first quantification of physical FLW in a global GE framework. The large reduction in total food demand and shift between food groups induced by a shift toward the EAT-Lancet diet induces price changes which impact sectoral demand and supply in the rest of the economy and result in land rent, wage, and income changes. Our method adds these direct and indirect (price induced) effects to other EAT-Lancet studies such as Willet et al. (2019).

Our results illustrate that transitioning towards the EAT-Lancet diet improves the sustainability of global food systems, decreasing global food demand and thus global biomass production mostly by reducing calorie intakes in all but the poorest countries. Reduced global land use in 2030 confirms the positive impact of dietary changes in previous studies (Springmann et al., 2016; Willet et al., 2019; Laine et al., 2021). Less land use is crucial to support biodiversity (Leclere et al., 2020). The EAT-Lancet diet additionally reduces GHG emissions from global food systems. We model the transition towards the EAT-Lancet diet imposing one-third of the dietary targets outlined in Willet et al. (2019), and our food-related GHG emissions decrease by 16.1%. A three times higher full dietary transition is projected to decrease food-related GHG emissions by 29-54% (Willet et al., 2019; Springmann et al., 2016; Springmann et al., 2018; Laine et al., 2021), placing our finding within the expected range. Reduced biomass production also reduces global FLW. Agricultural Production and Consumption stages are current global hotspots for FLW generation (Parfitt, 2021; UNEP, 2021). We find the EAT-Lancet diet reduces losses at both these stages, benefitting mainly high-income regions where reduced ASF intakes decrease FLW. The focus on fresh and plant-based foods reduces losses from food manufacturing as well as reducing shares of sugar crops and ASF in total FLW. The change in composition also reduces calorie losses embedded in FLW, as decreasing ASF lowers nutrient losses along each stage of global FSC. Lower ASF shares in high-income regions additionally increase reuse potential of FLW, as plant-based losses have more reuse possibilities as feed (van Hal et al., 2019) or fertiliser (de Boer & van Ittersum, 2018).

While benefits of the EAT-Lancet diet from other studies are confirmed, we find several spillover effects related to a global dietary change missing from previous static and partial equilibrium studies. Economic spillovers to non-food sectors alter the initial EAT-Lancet diet impact in terms of non-food production, land use and GHG emissions. A first negative economic spillover effect occurs through reduced demand for food reducing biomass prices increasing its competitiveness relative to non-biomass substitutes in non-food use. This mitigates the initial biomass production and thus land use reduction from the diet shift. A second negative economic spillover effect of the reduced food demand is lower demand for land, reducing land prices. This, in turn, promotes extensification. Using more land for the same amount of biomass further mitigates the reduction in land use. This extensification process also reduces demand for relatively more expensive labour and capital in production, generating a third negative spillover in the shape of lower wages. Land, however, can also be substituted for fertilisers (and other chemicals) in production. This generates a positive spillover effect by reducing chemical input-related emissions (e.g. N_2O) and pollution. In contrast to the global pattern, land use in Sub-Saharan Africa increases due to rising demand for fresh biomass. The resulting higher land prices result in intensification with a negative spillover in terms of increased chemical inputs and a positive externality in terms of rising wages.

We find economic spillovers into non-food sectors have major implications for total GHG emissions, with increased emissions linked to non-food demand outweighing decreased GHG emissions from the food system. First, the increase in biomass production for non-food use erases almost half of the reduction in emissions achieved by the reduction in biomass demand for food with the diet. Second, reduced food expenditures free income for non-food commodities. Especially consumers in higher-income regions consume less food which is available at lower prices, hence expenditures on non-food items increase. This is a strong stimulus for non-food sectors given the zero-cost consumer preference shift combined with a constant GDP per capita. The resulting stimulus of the non-food sectors increases global economy-wide emissions in 2030 compared to the BAU scenario with no diet shifts.

Our use of a global GE model captures substitutions in food production between land and other production factors (e.g. labour, capital) and inputs (e.g. chemicals) also accounted for in partial equilibrium (PE) assessments (e.g. Springmann et al., 2021) while adding an assessment of changes in non-food sectors. The economic spillovers in non-food sectors dampen the benefits of the diet shift in terms of global biomass production and land use found in previous studies (Springmann et al., 2016; Willet et al., 2019; Poore & Nemecek, 2018). Our economy-wide perspective reverses the impact in terms of GHG emissions. While GHG reductions in the food system are comparable to those in earlier PE assessments, increased non-agricultural emissions result in a net increase in GHG emissions when diets shift.

Our modelling results show that social spillovers enlarge the income gap between agricultural and non-agricultural low-skilled workers, while decreasing food affordability for workers employed in agricultural sectors. The first negative social spillover results from lower global food demand with the EAT-Lancet diet exerting different impacts on agricultural and non-agricultural wages. Labour markets are modelled as segmented between agricultural and non-agricultural sectors to capture observed persistent lower agricultural wages (e.g. Gollin et al., 2014) signalling the presence of barriers for lower paid agricultural workers to move to higher paid non-agricultural jobs. Less demand for agricultural products then leads to lower wages in agriculture relative to the rest of the economy as the skills of agricultural workers are not in line with those demanded by other sectors. This forces workers to remain in agriculture and accept a lower wage. The stimulus of non-food production simultaneously increases non-agricultural wages. The diets shift, thereby increasing the existing income inequality between agricultural and non-agricultural workers.

Social spillover effects on affordability of a healthy food basket derived from the EAT-Lancet diet recommendations vary across regions and nuance the findings of Hirvonen et al. (2020) and Springmann et al. (2021). Our economy-wide results capturing income and price effects not accounted for in these studies confirm positive impacts in high-income regions. Here healthy diet affordability improves for both agricultural and non-agricultural workers, suggesting that the affordability at currently observed prices is further improved. For non-agricultural workers in all regions but Sub-Saharan Africa affordability of healthy diets also improves. This may reduce concerns on the affordability of healthy diets in lower-income regions expressed in these previous studies for at least part of the population. At the same time the negative impact on agricultural wages in lower-income regions worsens healthy food affordability for those employed in agriculture despite lower food prices. For these households current unaffordability of healthy food thus becomes worse. Sub-Saharan Africa is the negative exception with the strongest decrease in healthy food affordability for both agricultural and non-agricultural workers. Here non-agricultural workers are worse off as they do not benefit as much from higher wages.

A third negative social spillover not addressed in Hirvonen et al. (2020) and Springmann et al. (2021) is on staple food affordability in all regions but Industrialised Asia resulting from the combination of diverging wage developments and lower staple prices. Globally for non-agricultural workers gains from the lower staple prices are amplified by the income gains from higher wages, making staples more affordable. While agricultural workers benefit from the lower staple prices as well, the negative income effect from lower agricultural wages reduces affordability of staple foods. Sub-Saharan Africa stands out as the EAT-Lancet diet induces higher consumption levels and thus food prices. While this generates a positive income effect from rising agricultural low-skilled wages, it does not compensate the negative price effect from rising food prices. This region with high hunger and malnutrition rates thus faces decreasing affordability of a main source of cheap calories for both agricultural and non-agricultural low-skilled workers.

Finally, although the transition towards the EAT-Lancet diet decreases FLW by decreasing both biomass production and traded volumes, our findings illustrate that high-income food consumption continues to generate large primary losses in mid- to lower- income regions. This not only continues local environmental pressures. It also hampers FLW reuse due to lack of proper infrastructures and technologies in mid- to low-income regions (Kaza et al., 2018). Environmental impacts of the EAT-Lancet diet in terms of changes in FLW are thus mixed. On the one hand lower levels of FLW mean less calorie and nutrient losses, while increasing shares of fresh plant-based FLW increases options for reuse. On the other hand, increasing plant-based FLW shares can lead to higher pollution rates (Delgado et al., 2021). Given the geographical mismatch between the location of FLW and recycling facilities, this may reduce anticipated environmental benefits of a dietary transition.

Our findings have several policy implications. First, the findings for high-income regions suggest that the adoption of healthy and sustainable diets can help consumers in those countries reduce food expenditures while making a positive environmental impact by decreasing land use and FLW generation both domestically and abroad. However, food affordability for workers within agriculture might deteriorate as wages within agriculture decline due to lower demand and segmented factor markets affecting especially large food exporting countries such as Latin America and Central Asia. To prevent an increase in rural poverty when shifting to a healthier diet low paid agricultural workers could be temporary compensated by income support while lowering barriers to better paid non-agricultural jobs through education or retraining programs. Second, we find the target on calories being most effective in reducing biomass production, notably in reducing ruminant livestock biomass. However, steering consumer behaviour in terms of calorie contents is difficult as calories cannot be directly observed. A focus on calories alone may also result in an unbalanced diet from a nutritional point of view. Steering consumption in terms of food items, easily observable by consumers, may be a more feasible option despite a less clear link to total calorie intake.

By using a preference shift to implement the diet, we dodge the question on the policy instruments used to reach the diet. Consumers are assumed to change their preference to the EAT-Lancet diet overnight with no effort or cost explicitly modelled. This preference shift approach is similar to key publications of the EAT-Lancet (Willett et al., 2019; Springmann et al., 2018). Shifting preferences also resembles the revealed policy preferences for education and information campaigns: most countries have national dietary guidelines and require labelling of foods so consumers can make informed food consumption decisions with more stringent regulation (such as expiration dates) limited to food safety concerns. While appealing for policymakers, our results show that even if information alone would succeed in shifting preferences, health objectives would be reached, but total GHG emissions would increase. This rebound effect through the non-food sectors may be (partially) avoided by taxing consumption in line with the diet recommendations. Measures such as health- or environmentally-related taxes might redirect consumer behaviour, decreasing overconsumption and health-related problems while reducing domestic FLW and farm-level losses in exporting mid- and low-income regions. However, using taxes to steer food consumption can have regressive effects as lower income households spend a relatively large share on food (Latka et al., 2021). Alternatively, the diet transition could be accompanied by economy-wide GHG taxes to reduce the rebound effect. The assessment of individual diet components cautions against selective focus on a few food items in the EAT-Lancet diet when designing policy interventions, as several components have little to no impact on biomass production nor FLW generation. Rising staple and healthy food prices limiting food affordability in Sub-Saharan Africa remain a major concern in transitioning to a healthier and sustainable diet. Subsidies could assist dietary affordability, but our analysis points to the need to not only target healthy food items as staple food affordability declines as well. Supporting access to cheap calories for the poorest households should thus not be abandoned when shifting policies towards supporting healthy diets. In terms of FLW, policies should continue to focus on decreasing farm-level losses through improvements in agricultural production efficiency while simultaneously facilitating the reuse of FLW as feed aiming at lower ASF food production costs and hence food prices.

As always, findings are subject to the uncertainties and limitations of our study. Tracing material flows in a global economy remains a complex and challenging task. In the absence of better data we used value-based shares to split physical flows of biomass across global supply chains implicitly ignoring product quality differences along the supply chains which would be reflected in different prices (and thus different quantity shares) Our method thus serves as a first step towards integrating physical and economic data in a multidisciplinary modelling framework that closely mirrors real-world economic dynamics and provides key insights for exploring global dietary transitions. Additionally, we model a partial transition towards the EAT-Lancet diet, obtaining relatively moderate effects in comparison to a full transition where dietary targets are fully met. Moreover, the high sectoral aggregation chosen because of FLW data availability impedes a proper match of the commodity-specific dietary recommendations of the EAT-Lancet diet with our modelling framework. This is particularly evident in the case of horticulture. By considering a single horticultural sector comprised of fruit and vegetables, pulses, nuts, roots, and tubers, we omit dietary directions concerning specific commodities. For certain regions the general increase in fruit and vegetables is outweighed by a decrease in consumption of starchy vegetables. An additional limitation concerns our modelling of FLW. FLW data is rather weak at a global scale but remains key for devising trade-offs when changing global dietary patterns towards a more sustainable consumption. Monitoring FLW remains a priority to enhance the empirical models. As we keep FLW rates constant over time, we do not investigate how FLW rates may respond to changes in economic structure or income across our scenarios.

This study may represent a starting point for bridging economic and technical models, supporting future multidisciplinary investigations on global biomass, interlinked food and non-food demand, FLW, in support of policies towards a more sustainable and more inclusive global food system. Future work could enhance non-FLW aspects of the Eat-Lancet diet by including additional detail on fruit and vegetable sectors. Expanding the modelling framework with within-country income distributions and purchasing power differences, related social and fiscal policies could be introduced to further enrich distributional analyses. The scope of the environmental impact could be enhanced by including water and more detailed modelling of fertiliser and other chemical use. Finally, the economy-wide spillover effects in this study not only show unintended effects, most notably on GHG emissions, but also highlight the importance of policy design as spillovers could be less when the diet shift is achieved through taxes instead of a costless preference shift. Simultaneously addressing economic, social and environmental economy-wide impacts is key when designing operational policies to steer the food system towards a healthier and more sustainable future.

4.4 Methodology and scenarios

To assess the benefits and spillover effects of the diet change we use the global GE model called MAGNET (Modular Applied GeNeral Equilibrium Tool, www.magnet-model.eu), developed with a focus on agri-food sectors, land use as well as on non-food biomass demand by the rest of the bioeconomy (Van Meijl et al., 2006; Woltjer et al., 2014), implications on food security including food affordability (Van Meijl et al., 2020), greenhouse gas emissions (Perez-Dominguez et al., 2021), and biodiversity (Leclere et al., 2020). It is an advanced recursive dynamic variant of the well-known Global Trade Analysis Project (GTAP) model (Corong et al., 2017). MAGNET cooperates with the integrated assessment model called IMAGE to enhance the representation of the land market (Van Meijl et al. 2006) and quantifies, for example, the IPCC scenarios in an integrated MAGNET-IMAGE modelling approach (Van Vuuren et al. 2017), identifying the trade-off effects of afforestation for climate change mitigation (Doelman, et al. 2019). Food, biomass and related FLW and production factor (various types of labour, capital, land) demand is endogenously determined by income changes, relative prices, preference shifts and dynamic income elasticities. As factor markets are segmented between agricultural and non-agriculture markets for two types of labour (skilled and unskilled), wage developments will differ between the types and sectorial use of labour. Food affordability relates to people's food purchasing power and therefore to food prices, dietary patterns, and income developments (Lele et al., 2016; Van Meijl et al., 2020). We use a food affordability indicator relating price developments of a specific food consumption basket to income developments of a particular income group. For the food basket, we use consumption of cereals (including paddy rice, wheat and 'other grains') as a proxy for the diet of people potentially in poverty, as rice is an important food component for poor people in Asia, while grains are important in Africa. We use changes in the wages of unskilled workers as a proxy for the income component of poor people working in different sectors of the economy. In this paper we improve on existing value-based tracing in GTAP-based GE models (Rutten et al., 2013; Britz, 2020; Chepeliev, 2022) by enhancing the standard GTAP 10 database (Aguiar et al., 2019) with regionalised material balances to get closer to material flows. Furthermore, we integrate primary food biomass flows in tonnes derived from FAOSTAT into MAGNET using weight-based FLW estimates to compute the biomass amounts contained in final demand, respecting material balances in both monetary and physical units. These material balances have a regional dimension with each stage (production, processing, consumption) possibly located in a different region. Deriving the Leontief Inverse (Leontief, 1970) from the regionalised material balances we can trace all direct and indirect material flows throughout the entire global economic system. This tracing is key for processed and imported goods where biomass from various locations can be combined through multiple processing and trading steps before finally being consumed. Additional model details are available in the Supplementary Information.

Healthier and more sustainable dietary scenario

We analyse how a transition to a healthier and more sustainable diet affects global biomass production, economy and FLW generation. Starting from 2020, we define our business-as-usual (BAU) scenario from the IMF-World Economic Outlook projections for GDP and population (IMF, 2022) to project the global economy and associated biomass flows in 2030. As a counterfactual we define a set of diet scenarios moving towards the EAT-Lancet dietary recommendations by 2030 (Willett et al., 2019). We decompose the EAT-Lancet diet in (sub-)diet scenarios linked to nutritional targets for commodity groups as available in the MAGNET model. A summary of our scenario assumptions is provided in Table 4.1.

Supplementary Information for

Economic, social, and environmental spillovers decrease the benefits of a global dietary shift

Contents

Model definition

We used the Modular Applied General Equilibrium Tool (MAGNET) for our analysis. MAGNET is a multi-regional, multi-sectoral applied computable general equilibrium (CGE) model. It is an advanced recursive dynamic version of the Global Trade Analysis Project (GTAP) model (Corong et al., 2017) which has been extended to allow integrated assessments focussing mainly on food and biomass production. As a CGE model, MAGNET solves through adjusting prices such that all markets for factors (land, labour, capital, natural resources) and commodities (good and services) simultaneously clear. Producers (one for each sector-region combination) respond to changing prices for inputs (factors and intermediates) based on profit maximization. With constant returns to scale production, producers operate under zero-profit conditions. Representative private households (one for each region) respond to changing incomes earned with factor sales and changing prices of commodities for consumption based on utility maximization limited by the household's income constraint. International trade flows are modelled bilaterally between all regions with regional sourcing of imports governed by the Armington assumption which allows two-way trade flows. Figure S1 outlines the structure of MAGNET with the interactions between production, trade, and consumption.

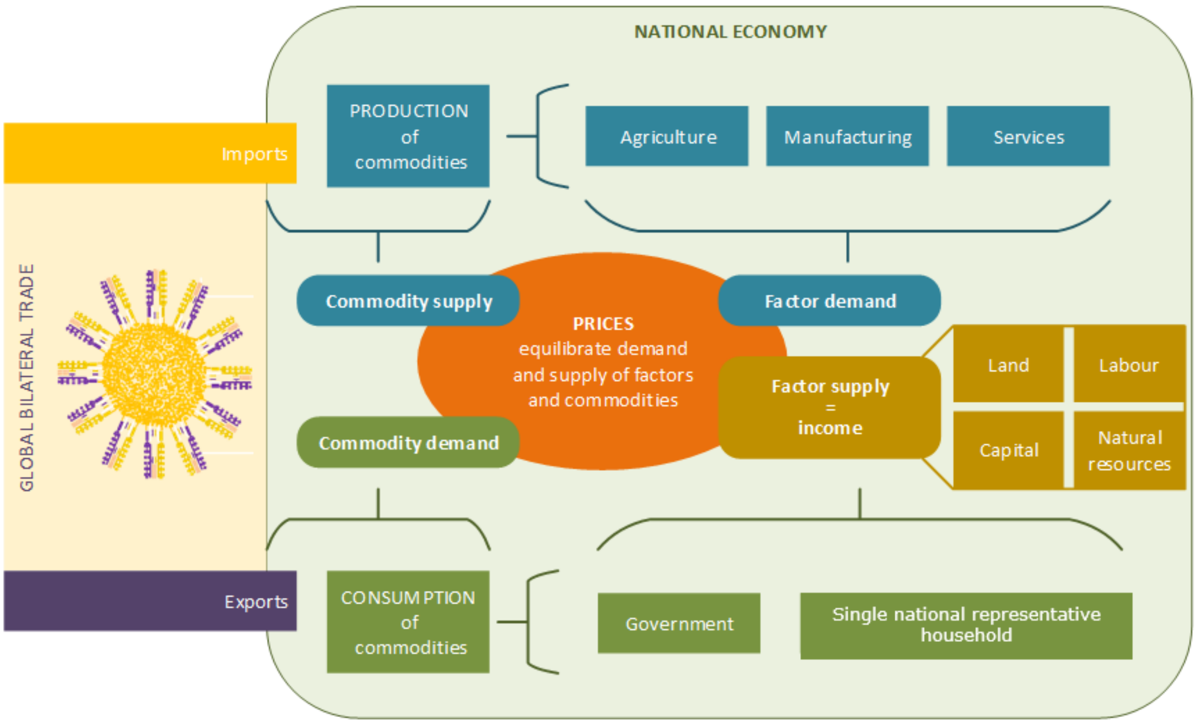

Figure S1. Schematic outline of the structure of MAGNET and the circular flow of money and commodities through the global economy.

A distinguishing feature of MAGNET is its modular structure, allowing the model to be easily tailored to specific research questions, regions, and products of interest. As a global CGE model MAGNET covers the entire global economy, with extensions adding detail on food and biomass production and use not available from other CGE models. Modules relevant for the current study are the flexible nested CES production trees (allowing for more substitution possibilities than in the standard GTAP model), endogenous land supply (allowing land areas to expand and contract depending on demand), flexible nested CET land allocation (governing the movement of sluggish land across sectors depending on the ease of switching between different types of land use), purchasing power adjusted CDE demand function (adjusting income elasticities in baseline projections to attain a more plausible pattern in food demand when incomes rise substantially), and segmented factor markets (capturing diverging labour and capital price developments in agricultural and non-agricultural sectors).

A key MAGNET extension for the current study is improved tracing of biophysical quantities through the global economic system by computing “dollar-based physical quantities” from the standard dollar-based GTAP database values by subtracting taxes and international trade margins for imports (see section “Methodology for tracing FLW along global food supply chains” below) . These dollar-based quantities satisfy the material balance constraints with minor divergences in longer run projections originating in the value-based CES functions governing production. Regionalized material balances can be computed from changes in these dollar-based quantities provided by the MAGNET model. In the case of biomass these flows allow consistent tracing of flows through the global economy including use for feed, food, and non-food products. As MAGNET traces bilateral trade flows between regions, the impact of changing trade patterns is captured as well.

The model aggregation adopted for this study involves 8 regions (Table S1), each comprising 39 production sectors (Table S2). Sectors demanding and supplying biomass are represented as explicitly as possible given the data provided by the GTAP 10 database (Aguiar et al., 2019). The food system is represented by 11 agricultural sectors including livestock and crops production, 8 food processing sectors producing meat, dairies, processed vegetables, and processed foods, and 5 food services. To ease model running time and interpretation of results, we aggregate the remaining sectors (industries and other services) into two categories, namely “other industries” and “other services”, in line with the focus of our study on biomass flows.

Table S1 - Regional model aggregation

Region	Description	Countries
EU27	Europe 27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
NAMO	North America and Oceania	Australia, New Zealand, Rest of Oceania, Canada, United States of America, Rest of North America, Rest of the World
INDA	Industrialised Asia	Hong Kong, Japan, South Korea, Taiwan, Singapore
LAC	Latin America and Caribbean	Mexico, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Belize, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean
MENA	North Africa and Middle East	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Iraq, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic (Syria), Yemen, Egypt, Morocco, Tunisia, Algeria, Libya, Western Sahara
REUCA	Rest of Europe and Central Asia	United Kingdom, Switzerland, Norway, Iceland, Liechtenstein, Albania, Belarus, Russian Federation, Ukraine, Moldova, Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Holy See (Vatican City State), Isle of Man, Jersey, Macedonia, Republic of, Monaco, Montenegro, San Marino, Serbia, Kazakhstan, Kyrgyzstan, Tajikistan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia
SEA	South-East Asia	China, Mongolia, Democratic People's Republic of Korea, Macao, Brunei Darussalam, Cambodia, Indonesia, People's Democratic Republic of Lao, Malaysia, Philippines, Thailand, Viet Nam, India, Nepal, Pakistan, Sri Lanka, Bangladesh, Myanmar, Timor-Leste, Afghanistan, Bhutan, Maldives
SSA	Sub-Saharan Africa	Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone, Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, South Central Africa, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Angola, Congo, Democratic Republic of the, Botswana, Namibia, South Africa, Burundi, Comoros, Djibouti, Ethiopia, Eritrea, Mayotte, Seychelles, Somalia, Sudan, Lesotho, Swaziland

Table S2 - Sectoral model aggregation

MAGNET aggregate	Description	GTAP sectors	Aggregation used for figures and analysis in main text
pdr	Paddy rice	pdr	Cereals
wht	Wheat	wht	Cereals
gro	Cereal grains	gro	Cereals
hort	Vegetables, fruit, nuts	v_f	Horticulture
osd	Oil seeds	osd	Oil seeds
c_b	Sugar cane, sugar beet	c_b	Sugar beet/cane
pfb	Plant-based fibers	pfb	Textiles
ocrops	Other Crops	ocr	Other Crops (non-food)
ctl	Bovine cattle, sheep and goats	ctl	Red Meat (ruminants)
oap	Animal products	oap	Other Meat and animal products
rmk	Raw milk	rmk	Dairy
wol	Wool, silk-worm cocoons	wol	-
frs	Forestry	frs	-
fsh	Fishing	fsh	Fish
coa	Coal	coa	-
c_oil	Crude Oil	oil	-
gas	Gas	gas	-
othind	Other Industry	oxt, tex, wap, lea, lum, ppp, bph, rpp, nmm, i_s, nfm, fmp, ele, eeq, ome, mvh, otn, omf, wtr, cns	-
cmt	Bovine meat products	cmt	Animal sourced foods
omt	Meat products	omt	Animal sourced foods
vol	Vegetable oils and fats	vol	Processed foods
mil	Dairy products	mil	Dairy
pcr	Processed rice	pcr	Cereals
sugar	Refined Sugar	sgr	Sugars
ofd	Processed Food	ofd	Processed Foods
b_t	Beverages and tobacco products	b_t	Processed Foods
petro	Petroleum, coal products	p_c	-
chem	Chemical products	chm	Chemicals
ely	Electricity	ely	-
gas_dist	Gas manufacture, distribution	gdt	-
othsvcs	Other services	cmn, ofi, ins, rsa, obs, dwe	-
trd	Trade	trd	-
afs	Accommodation, Food, and service	afs	Food Services
trans	Transportation, Water transport, Air transport	opt, wtp, atp	-
whs	Warehousing and support activities	whs	-
ros	Recreational and other service	ros	Food Services
osg	Public Administration and defence	osg	Food Services
edu	Education	edu	Food Services
hht	Human health and social work	hht	Food Services

* A detailed description of the GTAP sectors is available at https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

Methodology for tracing FLW along global food supply chains

The following section provides an analytical description of the methodology adopted for tracing FLW along global FSC consisting of two main parts: (i) preparing MAGNET for tracing physical flows; (ii) compute changes in FLW quantities in physical terms.

Preparing MAGNET for tracing physical flows

Use of GE models based on GTAP data for analysing changes in physical quantities is not new. The most recent example is the GTAP nutrition database also providing an overview of different existing approaches to tracing physical quantities of nutrition (Chepeliev, 2022) To our knowledge these approaches, among which a nutrition module in MAGNET, use value-based shares in their calculations that do not account for non-material components like tariffs in transport costs. For example, if the consumer expenditures on domestic and imported commodities are used without adjustments imports will get a higher weight than warranted based on their material content, as they include tariffs, export subsidies and transport costs. These non-material components in expenditures become visible when checking material balances from the GTAP data where production quantities should equal intermediate demand by sectors and final demand by the private household, government, and investment.

To assure a balanced starting point for the tracing of physical flows we compute the components of the material balance equations (production and demand categories) in what we call “dollar-based quantities”. They are as close as we can get to material flows using the information in the MAGNET (or GTAP) database. The reference year material balance will hold for each commodity measured in dollar-based quantities. If output is then known, for example the production of wheat in tons, we can convert this balanced dollar-quantity equation to one in physical units.

The computation of the dollar-based quantities proceeds as follows. We compute production, domestic demand and exports without output taxes. These are levied on producers and then implicit in before-tax demand and trade values. Lacking data on regional sourcing of imports by sectors or for final demand we use a proportionality assumption. This allows us to remove tariffs, export subsidies and transport costs (all of which vary by import source region) from the values of import demand for intermediate demand by sectors and for final demand (household, government and investment). Finally the supply of transport services to the global pool is adjusted to reflect the removal of taxes and subsidies on the demand for transport services. As we lack bilateral data on transport service trade we again use a proportionality assumption lowering all supplies to the global pool of transport service by the amount needed to match total demand. The adjustments to the starting database are checked by constructing material balances where production of commodity *i* in region *p* needs to match the sum over all regions of intermediate demand for *i* by all sectors *j* plus final demand.

A new material balance module is added to MAGNET which adds variables initialized with the dollar-based quantities of production, intermediate and final demand of commodities and trade services. These variables are connected with existing variables measuring percentage changes in quantities in the MAGNET model. This allows us to recompute the material balances in dollar-based quantities after each model run.

The last step in the tracing procedure is to derive the Leontief inverse. From the new variables expressed in dollar-based quantities we construct regionalized material balances:

$$QO_i^p = \sum_{c,d} QI_{i,c}^{p,d} + \sum_{a,d} QF_i^{a,p,d}$$

Where QO_i^p is the production of commodity *i* in region *p*, $QI_{i,c}^{p,d}$ is the intermediate demand for commodity *i* from region *p* by production of *c* in region *d*, and $QF_i^{a,p,d}$ is the final demand for commodity *i* from region *p* by agent (household, government, investment) in region d. This equation describes the direct flows of commodity *i* from region *p* to domestic (*p =d*) and foreign (*p ≠ d*) intermediate demand next to the flows for domestic and foreign final demand. Final demand, however, also generates an indirect flow of commodity *i* from region *p* to final demand in region *d* through the final demand from commodity *j* which uses commodity *i* in its production process. These direct and indirect flows can be computed through the Leontief inverse. Dividing intermediate demand by total production provides a matrix with Leontief input-output coefficients. Inverting this matrix yields the global Leontief inverse (or multiplier) matrix concisely describing all inputs that are directly or indirectly needed from either domestic or foreign origin for one unit of final consumption ($LI_{i,c}^{p,s}$).

Next to deriving the Leontief Inverse the regionalized material balances also allows us to compute any imbalances appearing in simulations due to value-based aggregations in the CES production functions. While volume preserving additive CES or ACES functions have been developed (van der Mensbrugghe and Peters 2020) these require physical shares. In MAGNET such volume preserving functions are used for energy blending sectors where all inputs are measured in the same physical unit (amount of energy delivered as electricity) and meaningful physical shares can be computed. In general meaningful physical measures of inputs are, however, not available as sectors use a wide variety of inputs ranging from primary products (generally measured in tons), land (measured in km2) and services (no obvious definition of unit). Van der Mensbrugghe and Peters (2020) also report that the divergence in results of additive and regular specifications varies depending on the elasticities. As the dollar-based-quantities computed for the material balances only correct for a small part of the difference between dollar values and quantities, using these for ACES quantity share calculations is unlikely to make a large difference in model response. As there are only small imbalances when starting from balanced equations that correct for taxes, subsidies and transport costs (see Tables S3, S4) there does not appear a reason to replace value shares by dollar-based-quantity shares.

Compute changes in FLW quantities in physical terms

Tracing of physical quantities of FLW then starts by defining dollar-based quantity flows of production included (directly and indirectly) in final demand:

$$QFD_{i,c}^{p,s,d} = LI_{i,c}^{p,s} * F_c^{s,d}, \qquad (1)$$

where $QFD_{i,c}^{p,s,d}$ represents the production of primary commodity *i,* in region *p,* produced to satisfy final demand of commodity *c*, that is demanded by region *d* from region *s*. The first term on the right-hand side of the equation represents the Leontief inverse matrix (LI) which specifies the amount of production of commodity *i* from region *p* needed for production of commodity *c* in region *s.* This term thus traces intra-industry flows of intermediate inputs from producer region *p* needed to produce commodities for final consumption (F) in region *s*. The second term represents final demand and reports for region *d,* how much final product *c* is demanded from region *s*. This term thus captures trade in final products, allowing products to be produced in region *s* to be consumed in a region *d*. In case *s* and *d* are the same this refers to consumption of domestically produced commodities, in case *s* and *d* are different regions it refers to imports from *s* to region *d*. Equation (1) provides a complete description of how production of *i* in region *p* flows to final consumers in region *d*. Based on the Leontief inverse it reports all direct and indirect flows of all commodities within the global economy. To ensure consistency of scenario results, we check that the summing of all commodities *c*, in all regions *s* and *d* equals the production of commodity *i* in region *p,* preserving material balances such that (direct and indirect) demand equals total production when expressed in dollar-based quantities.

As our focus in this study is on FLW we take a subset from the material flow tracing limiting the production of input *a* to primary food products (*primary agriculture*) and final demand *f* to all food commodities supplied to final consumers as primary, processed or via food services (*food*). To integrate physical material flows, we divide equation (1) by total production, specifying how a single unit of output flows through the global economy through its share contained in food products consumed by households ($SH\_QFD_{a,f}^{p,s,d}$):

$$SH\_QFD_{a,f}^{p,s,d} = \frac{QFD_{a,f}^{p,s,d}}{Q_a^p} \quad \text{where } a = \text{primary agricultural inputs and } f = \text{food commodities.} \tag{2}$$

The numerator is given by equation (1) while the denominator Q_a^p represents total primary agricultural production of commodity *a* in region *p,* reported in dollar-based quantities. We then extend the dollar-based approach by linking these flows to physical production of global biomass (Tons), defined as $Q\_mt_a^p$, where *a* represents the biomass of agricultural output *a* produced in region *p*. Multiplying the (dimensionless) share of primary product directly or indirectly included in each food commodity f with total primary production in tons then yields the agricultural biomass from region p contained in food produced in region s and consumed in region d ($QFD\_mt_{a,f}^{p,s,d}$):

$$QFD\_mt_{a,f}^{p,s,d} = Q\_mt_a^p * SH\_QFD_{a,f}^{p,s,d} \tag{3}$$

For consistency, as done for equation (1), we check for the counterfactual scenarios that material balances are indeed preserved in physical units. The circular flow of money in the CGE framework depicted in Figure S1 assures that balances are always preserved in dollar values units. Equation (3) describes the global flow of food biomass from farm to fork through global supply chains. It provides a first glance on different stages of global FSC, illustrating how food consumption is linked to primary food production through various stages of processing. Moreover, it captures international trade dynamics, quantifying food production, processing, and consumption in different regions.

We then integrate information on FLW by defining a coefficient reporting physical shares of FLW, $FLW_{a,g}^{p,s}$, where *p* represents the region where the loss is occurring, *s* represents the stage of the supply chain at which the loss is occurring, *a* represents the primary food commodity being lost and *g* represents a dummy variable that has value 1 when a specific commodity goes to manufacturing (processed food consumption) and 0 when it does not (fresh food consumption). As FLW data is mainly available in primary equivalents, we apply $FLW_{a,g}^{p,s}$ only to primary food commodities successively flowing to consumed (primary, processed and food service) commodities. With this we avoid double counting losses when a processed commodity is employed in the production of another processed commodity or food service along the supply chain. We merge $FLW_{a,g}^{p,s}$ such that the physical supply of a food commodity decreases after each supply chain stage, entering the next stage net of losses occurred in previous stages. For primary products freshly consumed by final consumers (e.g. oranges) losses occurring at manufacturing stages are not applied. Moreover, a special treatment is applied to commodities consumed through food services (i.e. food from restaurants, hotels, etc). As commodities flow into food services both as processed and non-processed (e.g. an orange can be consumed from a restaurant both as an orange or as an orange juice), we split the food supply from food services in two different flows, with a share of supply entering manufacturing stage (i.e. consumed from food services as processed thus reporting manufacturing losses), while the remaining share goes directly to distribution and retail (i.e. consumed from food services as fresh therefore not incurring manufacturing losses).

To quantify physical flows of FLW, we multiply our FLW coefficient with the physical food flows derived from equation (3), tracing FLW along global food supply chains as

$$FLW\_FSC_{a,f,t}^{p,s,d} = \mathrm{FLW}_{f,g}^{p,s} * QFD\_mt_{a,f}^{p,s,d} \tag{4}$$

where *p* represents the region where primary commodity *a* is produced, hence where losses from Agricultural Production up to Distribution & Retail occur, *d* represents the region where final consumption occurs hence where Consumption waste is generated, s represents the region through which food flows are linked from *p* to *d*, f represents the food commodity or service consumed by final consumers in region *d* and to which primary food flows *a* are flowing to and t represents the stage of the supply chain at which losses are occurring. The five stages of the food supply chain obtained from our FLW database (see the Data section below) need to be aligned with the information obtained from the Leontief Inverse (equation 3). Agricultural Production and Post-Harvest Handling & Storage stage are associated with primary production ($Q\_mt_a^p$), while Manufacturing and Consumption stage are linked to intermediate/final food production and final demand ($QFD\_mt_{a,f}^{p,s,d}$), respectively. As a Distribution & Retail stage is not explicitly available from the material flows of equation (3) we allocate Distribution & Retail losses to food flowing from Manufacturing to Consumption stage. In the case of $p \neq s, d$ we further attribute trade losses by assigning Distribution & Retail FLW rates to traded food flows, assuming that from a production region to a consumption region some food is lost during transportation. We attribute trade losses to importing regions, assuming food spoiled or damaged during transportation will be physically available in the importing region. Finally, equation (4) allows to quantify, for each stage of the supply chain, how much FLW is generated in a region when a product is consumed domestically or abroad.

Material Balances

The modelling approach adopted in this study allows to trace physical flows of biomass and FLW along global FSC respecting physical material balances within the limitations of a dollar value-based CGE model. We find only minor material imbalances in our calculation of physical material flows. Table S3 and S4 below report the level of imbalances by commodity and region in our main scenarios in 2030.

Table S3. Material imbalances as percentage (%) of total production (Tons) in Business-as-usual (BAU) scenario in 2030.

	EU27	**SEA**	**INDA**	**NAMO**	**LAC**	**REUCA**	**MENA**	**SSA**
pdr	0.0002	0	-0.0001	0.0002	0.001	0.0003	0.0011	0.0083
wht	0.001	0	-0.0001	0.0008	0.0007	0.0009	0.0007	0.006
gro	0.0004	0.0001	0	0.0005	0.0006	0.0003	0.0008	0.0047
hort	0.0003	0.0001	0	0.0002	0.0004	0.0001	0.0006	0.0031
osd	0.0005	-0.0001	0	0.0003	0.0006	0.0003	0.0009	0.0068
c_b	0.0007	0.0001	0.0001	0.0001	0.0012	0.0002	0.0007	0.0069
pfb	0.0012	0.0015	0.0003	0.0006	0.0011	0.001	0.0013	0.0085
ocrops	0.0004	0.0004	0.0003	0.0002	0.0007	0.0005	0.0012	0.0041
ctl	0.0002	-0.0003	-0.0002	0.0002	0.001	0.0001	0.0009	0.0306
oap	0.0002	0.0019	-0.0002	0.0003	0.0014	0.0002	0.001	0.0175
rmk	0.0002	-0.0004	0.0001	0.0001	0.0005	0.0001	0.0007	0.0088
wol	0.0013	-0.0018	0.0006	0.0008	0.0022	0.0021	0.0023	0.0057
frs	0.0011	-0.0003	-0.0003	0.0007	0.0019	0.001	0.0013	0.0135
fsh	0.0002	-0.0004	-0.0001	0.0001	0.0005	0.0002	0.0004	0.0045
cmt	0.0001	-0.0003	-0.0002	0.0002	0.001	0.0001	0.0014	0.0592
omt	0.0002	0.0002	-0.0003	0.0003	0.0022	0.0001	0.0021	0.0325
vol	0.0007	-0.0002	-0.0001	0.0003	0.001	0.0003	0.0007	0.0102
mil	0.0003	-0.0003	-0.0002	0.0002	0.0007	0.0001	0.0008	0.0076
pcr	0.0001	-0.0001	-0.0001	0.0003	0.001	0.0001	0.0011	0.008
sugar	0.0002	-0.0001	-0.0002	0.0001	0.001	0.0001	0.0009	0.0079
ofd	0	-0.0001	-0.0003	0	0.0004	-0.0001	0.0008	0.0104
b_t	0.0001	-0.0001	-0.0002	0.0001	0.0008	0.0002	0.0007	0.0066
trd	0	-0.0021	-0.0017	0.0001	0.0027	0.0006	0.0034	0.0217
afs	0	-0.0001	-0.0006	0.0001	0.0019	0.0002	0.0026	0.0372
ros	0.0005	-0.0026	-0.001	0.0002	0.0055	0.0006	0.0039	0.0457
osg	-0.0002	-0.0004	-0.0004	0	0.0008	0	0.0011	0.0116
edu	-0.0008	-0.002	-0.0024	-0.0001	0.005	0.0001	0.0049	0.0832
hht	-0.0001	-0.0005	-0.0002	0	0.0016	0	0.002	0.0178
whs	0.0072	0.0003	0.0062	0.0012	0.0032	0.0037	0.0046	0.0159
trans	0.0135	0.0016	0.0176	0.0025	0.0049	0.0101	0.0073	0.0167
coa	0.0015	0.0006	0.0004	0.0008	0.0022	0.0019	0.0019	0.0135
c_oil	0.006	0.0012	0.0039	0.0017	0.0025	0.005	0.0031	0.0047
gas	0.0016	0.0006	-0.0004	0.0011	0.0021	0.0017	0.002	0.0061
petro	0.0065	0.0011	0.004	0.0017	0.0027	0.0048	0.0038	0.0148
chem	0.0008	0.0007	0.0005	0.0006	0.0016	0.0008	0.002	0.0121
ely	0.0009	0.0002	0	0.0003	0.0017	0.0011	0.0018	0.0161
gas_dist	0.0003	0	-0.0015	0.0003	0.0016	0.0009	0.0022	0.0102
othind	0.0012	0.0016	0.0008	0.0007	0.0014	0.001	0.0019	0.0145
othsvcs	0	-0.0014	-0.0019	0.0001	0.0042	0.0004	0.0037	0.0384

Table S4. Material imbalances as percentage (%) of total production (Tons) in the "Towards EAT-Lancet" scenario in 2030.

	EU27	SEA	INDA	NAMO	LAC	REUCA	MENA	SSA
pdr	0.0117	-0.0037	-0.0077	0.0023	0.0029	0.0014	0.0051	0.0058
wht	0.019	0.002	-0.0009	0.0036	0.0028	0.0068	0.0048	0.0072
gro	0.0079	0.0024	-0.0008	0.0018	0.0025	0.0027	0.0048	0.0083
hort	0.0053	0.0015	0.0035	0.007	0.004	0.0027	0.0028	0.0031
osd	0.004	0.0021	-0.0028	0.0015	0.0032	0.0023	0.0033	0.009
c_b	0.0042	0.0021	0.0034	0.004	0.0047	0.0027	0.0054	0.0071
pfb	0.0029	0.0013	-0.001	0.0023	0.0021	0.0035	0.0016	0.0042
ocrops	0.0793	-0.2456	-0.2312	-0.0017	0.0413	0.0423	0.0301	-0.1717
ctl	0.0039	-0.0014	-0.0035	0.0016	0.0044	0.0022	0.0035	0.0154
oap	0.0018	0.0058	-0.0009	0.0008	0.0029	0.0015	0.0017	0.0095
rmk	0.0034	-0.0011	-0.0039	0.0024	0.0019	0.0027	0.0037	0.0052
wol	0.0103	0.0024	0.0021	0.0029	0.0034	0.0088	0.0024	0.0085
frs	0.0014	-0.001	-0.0014	0.0008	0.0026	0.001	0.0013	0.0157
fsh	0.0037	0.0054	0.0073	0.0031	0.0057	0.005	0.0008	-0.0291
cmt	0.0008	0.0003	-0.0004	0.0012	0.0045	0.0003	0.0025	0.0233
omt	0.0007	0.0009	-0.0005	0.0004	0.0036	0.0003	0.003	0.0073
vol	0.0036	0.0016	-0.0005	0.0015	0.0029	0.0012	0.003	0.0099
mil	0.002	-0.0002	-0.0007	0.0026	0.0019	0.0006	0.0029	0.0014
pcr	0.0044	0.0002	0.0002	0.0014	0.0028	0.0011	0.0055	0.0069
sugar	0.0019	0.0025	-0.0007	0.0008	0.0035	0.0012	0.0042	0.0113
ofd	0.001	0.0017	-0.0004	0.0003	0.0016	0.0006	0.0027	0.0109
b_t	0.0007	-0.0002	-0.0009	0.0002	0.0046	0.0006	0.0014	0.0054
trd	-0.0005	-0.0034	-0.0046	-0.0002	0.0034	0.0004	0.0033	0.0148
afs	-0.0004	-0.0001	-0.0008	-0.0001	0.0055	0.0002	0.0044	0.0252
ros	-0.0005	-0.0025	-0.0043	0.0003	0.0092	0.0006	0.0049	0.0384
osg	-0.0008	-0.0005	-0.0038	-0.0005	0.0008	0	0.0016	0.0102
edu	-0.0028	-0.0032	-0.0098	-0.0022	0.0067	-0.0004	0.0061	0.0745
hht	-0.0013	-0.0012	-0.0047	-0.0007	0.004	-0.0001	0.003	0.0155
whs	0.0058	-0.0005	0.0032	0.0009	0.0035	0.003	0.0038	0.0131
trans	0.011	0.0003	0.0128	0.002	0.0047	0.0082	0.0061	0.0131
coa	0.0016	-0.0007	-0.0014	-0.0001	0.0023	0.0012	0.0019	0.0101
c_oil	0.0053	-0.0004	0.001	0.0012	0.0023	0.004	0.0015	0.003
gas	0.0016	-0.0011	-0.0025	0.0007	0.0027	0.0014	0.0012	0.0036
petro	0.0058	-0.0004	0.0011	0.0012	0.0029	0.0039	0.0027	0.0109
chem	0.0011	-0.0017	-0.0028	0.0004	0.0038	0.0006	0	0.0018
ely	0.0011	-0.0015	-0.0021	-0.0001	0.0025	0.001	0.0018	0.0129
gas_dist	0.0009	-0.0011	-0.0038	0	0.0022	0.0007	0.0018	0.0092
othind	0.0014	0.0014	0.0003	0.001	0.0021	0.0009	0.0018	0.0124
othsvcs	-0.0002	-0.0016	-0.0032	-0.0002	0.0048	0.0003	0.0036	0.0387

Data

Biomass data

To quantify total physical flows of biomass through the global economy, we use primary production data (Tons) from FAOSTAT (FAO, 2020a). We integrate additional data from the FAO–Food Balance Sheets (FAO, 2020a), including primary production of food not covered in standard FAO production data. We only require food production data for primary agricultural products as all processing is computed using the GTAP data on intra-industry transactions. Data on non-primary commodities available from the FAO database are thus excluded to avoid double-counting. Table S5 reports the regional mappings between FAO countries and our MAGNET regions, while Table S6 reports the commodity mappings between FAO commodities and MAGNET sectors. We further report in Table S7 the commodities that have been excluded being reported by FAO as non-primary food commodities.

Table S5 – Region mappings between FAO countries and MAGNET regions

FAO country code	FAO country description	FBS country description	GTAP country	MAGNET aggregate
AFG	Afghanistan	Afghanistan	xsa	SEA
AGO	Angola	Angola	xac	SSA
ALB	Albania	Albania	alb	REUCA
ARE	United Arab Emirates	United Arab Emirates	are	MENA
ARG	Argentina	Argentina	arg	LAC
ARM	Armenia	Armenia	arm	REUCA
ATG	Antigua and Barbuda	Antigua and Barbuda	xcb	LAC
AUS	Australia	Australia	aus	NAMO
AUT	Austria	Austria	aut	EU27
AZE	Azerbaijan	Azerbaijan	aze	REUCA
BDI	Burundi	N.A.	xec	SSA
BEL	Belgium	Belgium	bel	EU27
BEN	Benin	Benin	ben	SSA
BFA	Burkina Faso	Burkina Faso	bfa	SSA
BGD	Bangladesh	Bangladesh	bgd	SEA
BGR	Bulgaria	Bulgaria	bgr	EU27
BHR	Bahrain	N.A.	bhr	MENA
BHS	Bahamas	Bahamas	xcb	LAC
BIH	Bosnia and Herzegovina	Bosnia and Herzegovina	xer	REUCA
BLR	Belarus	Belarus	blr	REUCA
BLZ	Belize	Belize	xca	LAC
BOL	Bolivia, Plurinational State of	Bolivia, Plurinational State of	bol	LAC
BRA	Brazil	Brazil	bra	LAC
BRB	Barbados	Barbados	xcb	LAC
BRN	Brunei Darussalam	N.A.	brn	SEA
BTN	Bhutan	N.A.	xsa	SEA
BWA	Botswana	Botswana	bwa	SSA
CAF	Central African Republic	Central African Republic	xcf	SSA
CAN	Canada	Canada	can	NAMO
CHE	Switzerland	Switzerland	che	REUCA
CHL	Chile	Chile	chl	LAC
CHN	China	China	chn	SEA
CIV	Côte d'Ivoire	Côte d'Ivoire	civ	SSA
CMR	Cameroon	Cameroon	cmr	SSA
COD	Congo, the Democratic Republic of the	N.A.	xac	SSA
COG	Congo	Congo	xcf	SSA
COK	Cook Islands	N.A.	xoc	NAMO
COL	Colombia	Colombia	col	LAC
COM	Comoros	Comoros	xec	SSA
CPV	Cape Verde	Cape Verde	xwf	SSA
CRI	Costa Rica	Costa Rica	cri	LAC
CUB	Cuba	Cuba	xcb	LAC
CYP	Cyprus	Cyprus	cyp	EU27
CZE	Czech Republic	Czech Republic	cze	EU27
DEU	Germany	Germany	deu	EU27
DJI	Djibouti	Djibouti	xec	SSA
DMA	Dominica	Dominica	xcb	LAC
DNK	Denmark	Denmark	dnk	EU27
DOM	Dominican Republic	Dominican Republic	dom	LAC
DZA	Algeria	Algeria	xnf	MENA
ECU	Ecuador	Ecuador	ecu	LAC

EGY	Egypt	Egypt	egy	MENA
ERI	Eritrea	N.A.	xec	SSA
ESP	Spain	Spain	esp	EU27
EST	Estonia	Estonia	est	EU27
ETH	Ethiopia	Ethiopia	eth	SSA
FIN	Finland	Finland	fin	EU27
FJI	Fiji	Fiji	xoc	NAMO
FRA	France	France	fra	EU27
FRO	Faroe Islands	N.A.	xer	REUCA
FSM	Micronesia, Federated States of	N.A.	xoc	NAMO
GAB	Gabon	Gabon	xcf	SSA
GBR	United Kingdom	United Kingdom	gbr	REUCA
GEO	Georgia	Georgia	geo	REUCA
GHA	Ghana	Ghana	gha	SSA
GIN	Guinea	Guinea	gin	SSA
GMB	Gambia	Gambia	xwf	SSA
GNB	Guinea-Bissau	Guinea-Bissau	xwf	SSA
GNQ	Equatorial Guinea	N.A.	xcf	SSA
GRC	Greece	Greece	grc	EU27
GRD	Grenada	Grenada	xcb	LAC
GTM	Guatemala	Guatemala	gtm	LAC
GUY	Guyana	Guyana	xsm	LAC
HKG	Hong Kong	Hong Kong	hkg	INDA
HND	Honduras	Honduras	hnd	LAC
HRV	Croatia	Croatia	hrv	EU27
HTI	Haiti	Haiti	xcb	LAC
HUN	Hungary	Hungary	hun	EU27
IDN	Indonesia	Indonesia	idn	SEA
IND	India	India	ind	SEA
IRL	Ireland	Ireland	irl	EU27
IRN	Iran, Islamic Republic of	Iran, Islamic Republic of	irn	MENA
IRQ	Iraq	Iraq	xws	MENA
ISL	Iceland	Iceland	xef	REUCA
ISR	Israel	Israel	isr	MENA
ITA	Italy	Italy	ita	EU27
JAM	Jamaica	Jamaica	jam	LAC
JOR	Jordan	Jordan	jor	MENA
JPN	Japan	Japan	jpn	INDA
KAZ	Kazakhstan	Kazakhstan	kaz	REUCA
KEN	Kenya	Kenya	ken	SSA
KGZ	Kyrgyzstan	Kyrgyzstan	kgz	REUCA
KHM	Cambodia	Cambodia	khm	SEA
KIR	Kiribati	Kiribati	xoc	NAMO
KNA	Saint Kitts and Nevis	Saint Kitts and Nevis	xcb	LAC
KOR	Korea, Republic of	Korea, Republic of	kor	INDA
KWT	Kuwait	Kuwait	kwt	MENA
LAO	Lao People's Democratic Republic	Lao People's Democratic Republic	lao	SEA
LBN	Lebanon	Lebanon	xws	MENA
LBR	Liberia	Liberia	xwf	SSA
LBY	Libyan Arab Jamahiriya	N.A.	xnf	MENA
LCA	Saint Lucia	Saint Lucia	xcb	LAC
LKA	Sri Lanka	Sri Lanka	lka	SEA
LSO	Lesotho	Lesotho	xsc	SSA
LTU	Lithuania	Lithuania	ltu	EU27
LUX	Luxembourg	N.A.	lux	EU27
LVA	Latvia	Latvia	lva	EU27
MAC	Macao	Macao	xea	SEA
MAR	Morocco	Morocco	mar	MENA
MDA	Moldova, Republic of	Moldova, Republic of	xee	REUCA
MDG	Madagascar	Madagascar	mdg	SSA
MDV	Maldives	Maldives	xsa	SEA
MEX	Mexico	Mexico	mex	LAC
MHL	Marshall Islands	N.A.	xoc	NAMO
MKD	Macedonia, the former Yugoslav Republic of	Macedonia, the former Yugoslav Republic of	xer	REUCA
MLI	Mali	Mali	xwf	SSA
MLT	Malta	Malta	mlt	EU27
MMR	Myanmar	Myanmar	xse	SEA
MNE	Montenegro	Montenegro	xer	REUCA
MNG	Mongolia	Mongolia	mng	SEA
MOZ	Mozambique	Mozambique	moz	SSA
MRT	Mauritania	Mauritania	xwf	SSA
MUS	Mauritius	Mauritius	mus	SSA
MWI	Malawi	Malawi	mwi	SSA
MYS	Malaysia	Malaysia	mys	SEA
NAM	Namibia	Namibia	nam	SSA
NCL	New Caledonia	New Caledonia	xoc	NAMO
NER	Niger	Niger	xwf	SSA
NGA	Nigeria	Nigeria	nga	SSA
NIC	Nicaragua	Nicaragua	nic	LAC

NIU	Niue	N.A.	xoc	NAMO
NLD	Netherlands	Netherlands	nld	EU27
NOR	Norway	Norway	nor	REUCA
NPL	Nepal	Nepal	npl	SEA
NRU	Nauru	N.A.	xoc	NAMO
NZL	New Zealand	New Zealand	nzl	NAMO
OMN	Oman	Oman	omn	MENA
PAK	Pakistan	Pakistan	pak	SEA
PAN	Panama	Panama	pan	LAC
PER	Peru	Peru	per	LAC
PHL	Philippines	Philippines	phl	SEA
PNG	Papua New Guinea	Papua New Guinea	xoc	NAMO
POL	Poland	Poland	pol	EU27
PRI	Puerto Rico	N.A.	pri	LAC
PRK	Korea, Democratic People's Republic of	Korea, Democratic People's Republic of	xea	SEA
PRT	Portugal	Portugal	prt	EU27
PRY	Paraguay	Paraguay	pry	LAC
PSE	Palestinian Territory, Occupied	N.A	xws	MENA
PYF	French Polynesia	French Polynesia	xoc	NAMO
QAT	Qatar	N.A	qat	MENA
ROU	Romania	Romania	rou	EU27
RUS	Russian Federation	Russian Federation	rus	REUCA
RWA	Rwanda	Rwanda	rwa	SSA
SAU	Saudi Arabia	Saudi Arabia	sau	MENA
SDN	Sudan	Sudan	xec	SSA
SEN	Senegal	Senegal	sen	SSA
SGP	Singapore	N.A	sgp	INDA
SLB	Solomon Islands	Solomon Islands	xoc	NAMO
SLE	Sierra Leone	Sierra Leone	xwf	SSA
SLV	El Salvador	El Salvador	slv	LAC
SOM	Somalia	N.A	xec	SSA
SRB	Serbia	Serbia	xer	REUCA
SSD	South Sudan	N.A	xec	SSA
STP	Sao Tome and Principe	Sao Tome and Principe	xcf	SSA
SUR	Suriname	Suriname	xsm	LAC
SVK	Slovakia	Slovakia	svk	EU27
SVN	Slovenia	Slovenia	svn	EU27
SWE	Sweden	Sweden	swe	EU27
SWZ	Swaziland	Swaziland	xsc	SSA
SYC	Seychelles	Seychelles	xec	SSA
SYR	Syrian Arab Republic	N.A	xws	MENA
TCD	Chad	Chad	xcf	SSA
TGO	Togo	Togo	tgo	SSA
THA	Thailand	Thailand	tha	SEA
TJK	Tajikistan	Tajikistan	tjk	REUCA
TKL	Tokelau	N.A	xoc	NAMO
TKM	Turkmenistan	Turkmenistan	xsu	REUCA
TLS	Timor-Leste	Timor-Leste	xse	SEA
TON	Tonga	N.A	xoc	NAMO
TTO	Trinidad and Tobago	Trinidad and Tobago	tto	LAC
TUN	Tunisia	Tunisia	tun	MENA
TUR	Turkey	Turkey	tur	MENA
TUV	Tuvalu	N.A	xoc	NAMO
TWN	Taiwan, Province of China	Taiwan, Province of China	twn	INDA
TZA	Tanzania, United Republic of	Tanzania, United Republic of	tza	SSA
UGA	Uganda	Uganda	uga	SSA
UKR	Ukraine	Ukraine	ukr	REUCA
URY	Uruguay	Uruguay	ury	LAC
USA	United States	United States	usa	NAMO
UZB	Uzbekistan	Uzbekistan	xsu	REUCA
VCT	Saint Vincent and the Grenadines	Saint Vincent and the Grenadines	xcb	LAC
VEN	Venezuela, Bolivarian Republic of	Venezuela, Bolivarian Republic of	ven	LAC
VNM	Viet Nam	Viet Nam	vnm	SEA
VUT	Vanuatu	Vanuatu	xoc	NAMO
WSM	Samoa	Samoa	xoc	NAMO
YEM	Yemen	Yemen	xws	MENA
ZAF	South Africa	South Africa	zaf	SSA
ZMB	Zambia	Zambia	zmb	SSA
ZWE	Zimbabwe	Zimbabwe	zwe	SSA

Table S6 – Commodity mappings between FAO commodities and MAGNET sectors

FAO commodity code (CPC code)	FAO commodity description	GTAP sector	MAGNET aggregate
101	Canary seed	osd	osd
1017	Meat, goat	ctl	ctl
1018	Offals, edible, goats	ctl	ctl
1019	Fat, goats	ctl	ctl
1020	Milk, whole fresh goat	rmk	rmk
1025	Skins, goat, fresh	ctl	ctl
103	Grain, mixed	gro	gro
1035	Meat, pig	oap	oap
1036	Offals, pigs, edible	oap	oap
1037	Fat, pigs	oap	oap
1058	Meat, chicken	oap	oap
1062	Eggs, hen, in shell	oap	oap
1067	Eggs, hen, in shell (number)	oap	oap
1069	Meat, duck	oap	oap
1073	Meat, goose, and guinea fowl	oap	oap
108	Cereals nes	gro	gro
1080	Meat, turkey	oap	oap
1089	Meat, bird nes	oap	oap
1091	Eggs, other bird, in shell	oap	oap
1092	Eggs, other bird, in shell (number)	oap	oap
1097	Meat, horse	ctl	ctl
1098	Offals, horses	ctl	ctl
1108	Meat, ass	ctl	ctl
1111	Meat, mule	ctl	ctl
1127	Meat, camel	ctl	ctl
1128	Offals, edible, camels	ctl	ctl
1129	Fat, camels	ctl	ctl
1130	Milk, whole fresh camel	rmk	rmk
1141	Meat, rabbit	oap	oap
1151	Meat, other rodents	oap	oap
1158	Meat, other camelids	ctl	ctl
116	Potatoes	v_f	hort
1163	Meat, game	ctl	ctl
1166	Meat nes	oap	oap
1176	Snails, not sea	oap	oap
1182	Honey, natural	oap	oap
1183	Beeswax	oap	oap
1185	Silk-worm cocoons, reelable	wol	wol
122	Sweet potatoes	v_f	hort
125	Cassava	v_f	hort
135	Yautia (cocoyam)	v_f	hort
136	Taro (cocoyam)	v_f	hort
137	Yams	v_f	hort
149	Roots and tubers nes	v_f	hort
15	Wheat	wht	wht
156	Sugar cane	c_b	c_b
157	Sugar beet	c_b	c_b
161	Sugar crops nes	c_b	c_b
176	Beans, dry	v_f	hort
181	Broad beans, horse beans, dry	v_f	hort
187	Peas, dry	v_f	hort
191	Chickpeas	v_f	hort
195	Cow peas, dry	v_f	hort
197	Pigeon peas	v_f	hort
201	Lentils	v_f	hort
203	Bambara beans	v_f	hort
205	Vetches	v_f	hort
210	Lupins	v_f	hort
211	Pulses nes	v_f	hort
216	Brazil nuts, with shell	v_f	hort
217	Cashew nuts, with shell	v_f	hort
220	Chestnut	v_f	hort
221	Almonds, with shell	v_f	hort
222	Walnuts, with shell	v_f	hort
223	Pistachios	v_f	hort
224	Kola nuts	v_f	hort
225	Hazelnuts, with shell	v_f	hort
226	Areca nuts	v_f	hort
234	Nuts nes	v_f	hort
236	Soybeans	v_f	hort
242	Groundnuts, with shell	v_f	hort
249	Coconuts	v_f	hort
260	Olives	v_f	hort
263	Karite nuts (sheanuts)	v_f	hort
265	Castor oil seed	osd	osd
267	Sunflower seed	osd	osd
27	Rice, paddy	pdr	pdr
270	Rapeseed	osd	osd

275	Tung nuts	v_f	hort
277	Jojoba seed	osd	osd
280	Safflower seed	osd	osd
289	Sesame seed	osd	osd
292	Mustard seed	osd	osd
296	Poppy seed	osd	osd
299	Melonseed	osd	osd
30	Rice, paddy (rice milled equivalent)	pdr	pdr
305	Tallowtree seed	osd	osd
310	Kapok fruit	v_f	hort
328	Seed cotton	osd	osd
333	Linseed	osd	osd
336	Hempseed	osd	osd
339	Oilseeds nes	osd	osd
358	Cabbages and other brassicas	v_f	hort
366	Artichokes	v_f	hort
367	Asparagus	v_f	hort
372	Lettuce and chicory	v_f	hort
373	Spinach	v_f	hort
378	Cassava leaves	v_f	hort
388	Tomatoes	v_f	hort
393	Cauliflowers and broccoli	v_f	hort
394	Pumpkins, squash, and gourds	v_f	hort
397	Cucumbers and gherkins	v_f	hort
399	Eggplants (aubergines)	v_f	hort
401	Chillies and peppers, green	v_f	hort
402	Onions, shallots, green	v_f	hort
403	Onions, dry	v_f	hort
406	Garlic	v_f	hort
407	Leeks, other alliaceous vegetables	v_f	hort
414	Beans, green	v_f	hort
417	Peas, green	v_f	hort
420	Vegetables, leguminous nes	v_f	hort
423	String beans	v_f	hort
426	Carrots and turnips	v_f	hort
430	Okra	v_f	hort
44	Barley	gro	gro
446	Maize, green	gro	gro
449	Mushrooms and truffles	v_f	hort
459	Chicory roots	v_f	hort
461	Carobs	v_f	hort
463	Vegetables, fresh nes	v_f	hort
486	Bananas	v_f	hort
489	Plantains and others	v_f	hort
490	Oranges	v_f	hort
495	Tangerines, mandarins, clementines, satsumas	v_f	hort
497	Lemons and limes	v_f	hort
507	Grapefruit (inc. pomelos)	v_f	hort
512	Fruit, citrus nes	v_f	hort
515	Apples	v_f	hort
521	Pears	v_f	hort
523	Quinces	v_f	hort
526	Apricots	v_f	hort
530	Cherries, sour	v_f	hort
531	Cherries	v_f	hort
534	Peaches and nectarines	v_f	hort
536	Plums and sloes	v_f	hort
541	Fruit, stone nes	v_f	hort
542	Fruit, pome nes	v_f	hort
544	Strawberries	v_f	hort
547	Raspberries	v_f	hort
549	Gooseberries	v_f	hort
550	Currants	v_f	hort
552	Blueberries	v_f	hort
554	Cranberries	v_f	hort
558	Berries nes	v_f	hort
56	Maize	gro	gro
560	Grapes	v_f	hort
567	Watermelons	v_f	hort
568	Melons, other (inc.cantaloupes)	v_f	hort
569	Figs	v_f	hort
571	Mangoes, mangosteens, guavas	v_f	hort
572	Avocados	v_f	hort
574	Pineapples	v_f	hort
577	Dates	v_f	hort
587	Persimmons	v_f	hort
591	Cashewapple	v_f	hort
592	Kiwi fruit	v_f	hort
600	Papayas	v_f	hort
603	Fruit, tropical fresh nes	v_f	hort
619	Fruit, fresh nes	v_f	hort

656	Coffee, green	ocr	ocrops
661	Cocoa, beans	ocr	ocrops
667	Tea	ocr	ocrops
671	Maté	ocr	ocrops
677	Hops	ocr	ocrops
687	Pepper (piper spp.)	ocr	ocrops
689	Chillies and peppers, dry	ocr	ocrops
692	Vanilla	ocr	ocrops
693	Cinnamon (cannella)	ocr	ocrops
698	Cloves	ocr	ocrops
702	Nutmeg, mace and cardamoms	ocr	ocrops
71	Rye	gro	gro
711	Anise, badian, fennel, coriander	ocr	ocrops
720	Ginger	ocr	ocrops
723	Spices nes	ocr	ocrops
748	Peppermint	ocr	ocrops
75	Oats	gro	gro
754	Pyrethrum, dried	ocr	ocrops
767	Cotton lint	pfb	pfb
773	Flax fibre and tow	pfb	pfb
777	Hemp tow waste	pfb	pfb
780	Jute	pfb	pfb
782	Bastfibres, other	pfb	pfb
788	Ramie	pfb	pfb
789	Sisal	pfb	pfb
79	Millet	gro	gro
800	Agave fibres nes	pfb	pfb
809	Manila fibre (abaca)	pfb	pfb
813	Coir	pfb	pfb
821	Fibre crops nes	pfb	pfb
826	Tobacco, unmanufactured	ocr	ocrops
83	Sorghum	gro	gro
836	Rubber, natural	ocr	ocrops
867	Meat, cattle	ctl	ctl
868	Offals, edible, cattle	ctl	ctl
869	Fat, cattle	ctl	ctl
882	Milk, whole fresh cow	rmk	rmk
89	Buckwheat	gro	gro
919	Hides, cattle, fresh	ctl	ctl
92	Quinoa	gro	gro
94	Fonio	gro	gro
947	Meat, buffalo	ctl	ctl
948	Offals, edible, buffaloes	ctl	ctl
949	Fat, buffaloes	ctl	ctl
951	Milk, whole fresh buffalo	rmk	rmk
957	Hides, buffalo, fresh	ctl	ctl
97	Triticale	gro	gro
977	Meat, sheep	ctl	ctl
978	Offals, sheep,edible	ctl	ctl
979	Fat, sheep	ctl	ctl
982	Milk, whole fresh sheep	rmk	rmk
987	Wool, greasy	wol	wol
995	Skins, sheep, fresh	ctl	ctl

FBS commodity code (CPC code)	FBS commodity description	GTAP sector	MAGNET aggregate
2761	Freshwater Fish	fsh	fsh
2762	Demersal Fish	fsh	fsh
2763	Pelagic Fish	fsh	fsh
2764	Marine Fish, Other	fsh	fsh
2765	Crustaceans	fsh	fsh
2766	Cephalopods	fsh	fsh
2767	Molluscs, Other	fsh	fsh

Table S7 – FAO commodities excluded as reported as non-primary commodities

FAO commodity code (CPC code)	FAO commodity description	FAO commodity code (CPC code)	FAO commodity description
237	Oil, soybean	271	Oil, rapeseed
252	Oil, coconut (copra)	281	Oil, safflower
254	Oil palm fruit	290	Oil, sesame
258	Oil, palm kernel	331	Oil, cottonseed
261	Oil, olive, virgin	334	Oil, linseed
268	Oil, sunflower	60	Oil, maize
244	Oil, groundnut		

Food Loss and Waste data

Definitions

We define FLW as "*food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses, and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products"*. With this classification, we align with SDG12.3 considering only food produced for human consumption, including all food types, disposal routes and stages of the FSC. We consider the entirety of food products including inedible foods parts as the definition of inedible parts vary by country or culture. Including this (unavoidable) type of FLW we overcome a broadly debated (Delgado et al., 2021) methodological limitation of the FLW estimates in Gustavsson et al. (FAO, 2011). Moreover, we exclude from FLW food produced for other purposes than human consumption, to avoid counting biomass for feed and seed or for use in non-food industrial products as FLW. Finally, we report data as percentage losses of total food weight as percentage estimates are more stable across years (Fabi and English, 2018).

Database

The core of our FLW database is the FAO–FLW database (FAO, 2019). Within the FAO–FLW database we use the standard data computation method building on edible and inedible shares of commodities, excluding other non-food biomass flows (i.e. feed, seed, etc.) from FLW[12]. To assure consistent FLW estimates we restrict additional data merged with the FAO-FLW data to sources using the same method. We group FAO-FLW data in seven global regions, defining seven commodity groups produced along five macro-stages of the FSC. While this aggregation procedure influences detail in the final estimates it is necessary due to unavailability of data at single country/commodity level.

The FAO–FLW database mainly covers low-income regions. Data is mostly available for sub-Saharan Africa, South-East Asia and North Africa & Middle East, while for high-income regions such as Europe and North America & Oceania observations are limited. This geographical focus influences overall data availability for commodities and supply chain stages. Most reported losses occur at early stages of the supply chain, i.e. Agriculture Production and Post-Harvest Handling & Storage and involve horticultural commodities and cereals, usually prevailing in low-income regions' diets. Data is mostly unavailable for animal-sourced products, particularly in the final stages of the supply chain such as Distribution & Retail and Consumption. Despite the broad temporal coverage of the database (1945-2021), observations are concentrated between 2000 and 2017, with peaks between 2009 and 2011.

To address the coverage limitations of the FAO-FLW database we perform a literature review, building on previous reviews (Xue et al., 2017; Porter et al., 2016; Affognon et al., 2015; OECD, 2021). We only collect data computed consistently with our FLW definition, enhancing data availability mainly for Europe, North America & Oceania and North Africa & Middle East. To achieve a global data coverage, we complete our database by replacing non-available data with a consistent gap-filling methodology based on FLW in comparable regions, commodities, and stages of the FSC. This gap-filing implies a careful utilization and interpretation of final estimates as data assumptions and aggregations may influence the magnitude of estimates. Moreover, as we aggregate data through physical mass, our methodology does not allow a direct assessment of SDG12.3, for which an indicator based on economic weights (Fabi and English, 2018) is adopted as measurement methodology. Estimates on percentage losses and waste of total food weight, and respective sources, are reported in Tables A-G.

[12] SDG12.3 - Food Loss Index (FLI) and Food Waste Index (FWI) – see Fabi and English, 2018. For an integral explanation see FAO, 2019, p. 32-34.

Table A – Europe	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	8.6[1]	1.4 – 1.5[2,3]	3.2[2]	2.2[2]	28.0[1]
Oilseed, Pulses and Nuts (incl. sugar)	11.1[1]	2.5 – 3[2,3]	6.0[1]	0.3[2]	4.0 – 4.8[2,10]
Roots and Tubers	3.5[1]	4.0[1]	11.2[1]	1.1[1]	28.0[1]
Fruits and Vegetables	12.8[1]	6.4[1]	10.6[1]	4.1[1]	12.2[1]
Dairy products	0.3[2,3]	0.1 – 0.3[2,4,5]	0.7[2]	0.2 – 0.8[2,7,8]	3.2 – 12.1[2,7,10,11]
Meat	0.8[2,3]	0.1[4,5]	4.7[2]	2.7 – 3.8[2,9]	8.0 – 50.3[2,7,10,11]
Fish and Seafood	0.0 –0.7[2,3]	0.1[4,5]	37.8[2]	2.4 – 3.6[2,7]	9.7 – 22.3[2,7,10]
Other animal products	3.6 – 3.8[2,3,4]	1.0[4,5]	1.6[2]	1.4 – 1.6[2,7]	22.6 – 36[2,7,10]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).

[2] calculated from Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011

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Table B – North America & Oceania	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	7.2[2]	4[4]	3.2[13]	15.0[7]	18.5[6] – 23.8[7]
Oilseed, Pulses and Nuts (incl. sugar)	12.0[10]	3.0[12]	6.0[13]	11.0[1]	18.0[1]
Roots and Tubers	20.0[11]	7.1[4]	1.4 – 2.6[8] or 11.2[12]	13.9[1]	17.6[4]
Fruits and Vegetables	8.8[1]	19.8[4]	14.2 – 14.8[8]	12.9[1]	17.0[1]
Dairy products	3.5[11]	0.4[4]	0.7[13]	12.0[1]	18.0[1]
Meat	3.5[11]	1.0[11]	4.7[13]	4.0[1]	34.0[1]
Fish and Seafood	12.0[11]	0.5[11]	37.8[13]	2.7[5] - 8.0[6]	31.6[6]
Other animal products	4.0[3]	1.0[13]	1.6[13]	9.0[6]	20.9[9]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).

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[4] calculated from USDA ERS - food availability (per capita) data system; Available from: http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx. (calculated on whole commodity, including inedible food parts)

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[7] calculated from Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States. SSRN Electron. J.https://doi.org/10.2139/ssrn.2501659 (calculated on whole commodity, including inedible food parts)

[8] World Wide Fund for Nature. 2018. Maximizing farm resources and edible food rescue. Specialty Crop Loss Report. https://c402277.ssl.cf1.rackcdn.com/publications/1243/files/original/WWF_Farm_Loss_Technical_Report_Redacted_0619.pdf?1560175295

[9] OECD (2021), "Waste: Food Waste", OECD Environment Statistics (database), https://doi.org/10.1787/ba9da2b7-en (accessed on 1 January 2023).

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[11] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.

[12] Assumption made by taking the higher boundry of the interval reported for Europe.

[13] Assumption based on values for Europe.

Table C – Industrialized Asia	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	5.6[1]	7.9[1]	2.7[1]	1.1[1]	13.8[1]
Oilseed, Pulses and Nuts (incl. sugar)	6.0[5]	2.5[6]	6.0[7]	0.3[7]	16.55[4]
Roots and Tubers	2.2[1]	11.0[1]	1.4 – 2.6[8] or 11.2[7]	2.0[1]	7.1[4]
Fruits and Vegetables	10.7[1]	22.0[1]	15.9[1]	8.2[1]	17.2[2]
Dairy products	3.5[5]	0.1[6]	4.7[7]	0.2[6]	2.6[4]
Meat	8.7[2]	2.0 - 3.6[2]	1.3[2]	3.5[2]	16.3[2]
Fish and Seafood	3.6[2]	7.3[2]	37.8[7]	5.8[2]	26.1[2]
Other animal products	6.0[3]	1.0[7]	1.6[7]	1.4[6]	13.5[2]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).
[2] calculated from Liu, G., 2014. Food Losses and Food Waste in China: A First Estimate. https://doi.org/10.1787/5jz5sq5173lq-en (calculated on whole commodity, including inedible food parts)
[3] Aerni V., Brinkhof, M.W.G., Wechsler, B., Oester, H., Fröhlich, E. 2005. Productivity and mortality of laying hens in aviaries: A systematic review. World's Poultry Science Journal 2005; 61(01):13
[4] calculated from Song, G., Li, M., Semakula, H.M., Zhang, S. 2015. Food consumption and waste and the embedded carbon, water and ecological footprints of households in China. Sci Total Environ 2015, Oct 1; 529:191-7. http://dx.doi.org/10.1016/j.scitotenv.2015.05.068
[5] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes end Prevention. Rome: FAO.
[6] Assumption made by taking the lower boundry of the interval reported for Europe.
[7] Assumption based on values for Europe.
[8] Assumption based on values for North America & Oceania.

Table D – North Africa & Middle East	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	14.0[1]	18.3[1]	2.0[2]	1.0[2]	5.0[2]
Oilseed, Pulses and Nuts iIncl. sugar)	15.0[2,3]	5.0[2]	7.0[2]	1.0[2]	4.0[2]
Roots and Tubers	14.8[1]	8.3[1]	4.0[1]	5.3[1]	10.0[1]
Fruits and Vegetables	9.3[1]	6.2[1]	10.0[2]	10.7[1]	34.1 – 35.4[3]
Dairy products	10.0[2]	1.0[2]	1.5[2]	6.0[2]	5.5[3]
Meat	10.0[2]	0.2[2]	5.0[2]	0.5[2]	7.4[3]
Fish and Seafood	10.0[2]	0.05[2]	0.04[2]	0.1[2]	4.8[3]
Other animal products	6.0[2]	1.0[2]	2.0[2]	1.0[2]	2.0[3]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).
[2] Koester, U., Empen, J., Holm, T. 2013. Food Losses and Waste in Europe and Central Asia. Draft synthesis report. FAO – Regional Office for Europe and Central Asia. http://www.fao.org/3/a-au843e.pdf
[3] OECD (2021), "Waste: Food Waste", OECD Environment Statistics (database), https://doi.org/10.1787/ba9da2b7-en (accessed on 1 January 2023).

Table E – Latin America & Caribbean	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	8.7[1]	15.2[1]	3.3[1]	1.2[1]	5.0[3]
Oilseed, Pulses and Nuts (incl. sugar)	14.8[1]	15.3[1]	6.6[1]	0.8[1]	4.0[3]
Roots and Tubers	6.3[1]	26.4[1]	3.6[1]	4.0[1]	10.0[3]
Fruits and Vegetables	13.3[1]	10.4[1]	4.0[1]	10.9[1]	3.4[1]
Dairy products	3.5[2]	1.0[3]	1.5[3]	6.0[3]	5.5[3]
Meat	5.6[2]	1.1[2]	5.0[3]	0.5[3]	7.4[3]
Fish and Seafood	5.7[2]	5.0[2]	0.04[3]	0.1[3]	4.8[3]
Other animal products	6.0[2,3]	1.0[3]	2.0[3]	1.0[3]	2.0[3]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).

[2] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.

[3] Assumption based on values for North Africa & Middle East.

Table F – South-East Asia	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	3.7[1]	4.6[1]	3.2[1]	1.5[1]	4.0[3]
Oilseed, Pulses and Nuts (incl. sugar)	0.8[1]	1.2[1]	7.8[1]	1.0[1]	4.0[7]
Roots and Tubers	3.2[1]	4.5[1]	3.2[1]	3.5[1]	4.0[7]
Fruits and Vegetables	4.0[1]	4.2[1]	14.2[1]	8.5[1]	3.4[1]
Dairy products	3.5[4]	3.4[5]	1.5[6]	6.0[6]	5.5[6]
Meat	5.6[4]	0.3[4]	5.0[6]	0.5[6]	7.4[6]
Fish and Seafood	8.2[4]	6.0[4]	0.04[6]	12.3[2]	4.8[6]
Other animal products	34.7[1]	1.0[6]	2.0[6]	7.4[1]	2.0[6]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).

[2] Hossain, M.M., Rahman, M., Hassan, M.N., Nowsad, A.A. 2013. Post-harvest loss of farm raised Indian and Chinese major carps in the distribution channel from Mymensingh to Rangpur of Bangladesh. Pak J Biol Sci 2013, Jun 15; 16(12):564-9.

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[4] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.

[5] Assumption based on FAOSTAT, 2020 and on values for North Africa & Middle East.

[6] Assumption based on values for North Africa & Middle East.

[7] Assumption based on Cereals.

Table G – Sub-Saharan Africa	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
Cereals	3.3[1]	3.25[1]	3.7[1]	1.8[1]	4.0[7]
Oilseed, Pulses and Nuts (incl. sugar)	7.7[1]	17.0[1]	8.0[1]	24.1[1]	4.0[8]
Roots and Tubers	12.8[1]	25.5[1]	4.1[1]	16.5[1]	4.0[8]
Fruits and Vegetables	18.1[1]	3.3[1]	8.7[1]	17.0[1]	3.4[7]
Dairy products	6.0[4]	8.2[2]	1.5[5]	13.8[3]	5.5[5]
Meat	19.0[4]	3.0[2]	5.0[5]	0.5[5]	7.4[5]
Fish and Seafood	5.7[4]	14.3 - 27.3[2]	9.0[6]	12.3[7]	4.8[5]
Other animal products	1.8[1]	1.0[5]	2.0[5]	7.4[7]	2.0[5]

[1] FAO, 2019. Food Loss and Waste Database. Food Agric. Organ. U. N. URL http://www.fao.org/platform-food-loss-waste/flw-data/en/ (accessed 1.01.23).
[2] Affognon, H., Mutungi, C., Sanginga, P., Borgemeister, C. 2015. Unpacking postharvest losses in sub-Saharan Africa: A meta-analysis. World Development 2015, Feb; 66:49-68. http://dx.doi.org/10.1016/j.worlddev.2014.08.002
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[4] FAO (Food and Agriculture Organization of the United Nations). 2011. Global Food Losses and Food Waste. Extent, Causes and Prevention. Rome: FAO.
[5] Assumption based on values for North Africa & Central-West Asia.
[6] Davies, R. M., Davies, O.A. 2009. "Traditional and Improved Fish Processing Technologies in Bayelsa State, Nigeria." European Journal of Scientific Research 26: 539-548.
[7] Assumption based on values for South & South-East Asia.
[8] Assumption based on Cereals.

Combining FLW data with the MAGNET model

To integrate our FLW data into our analysis we map FLW estimates to primary food commodities in MAGNET. The definition of primary commodities in MAGNET may differ from the commodity groups reported in our FLW database. For example, the primary commodity “hort” (horticulture) comprehends fruit and vegetables, as well as pulses, starchy vegetables, nuts, roots, and tubers. As we map FLW estimates from FAO (2019) directly to MAGNET commodities, estimates for horticulture, cereals and other crops may vary according to commodity-specific data available in FAO data. From Table S8 to S15 we report the FLW (%) estimates applied to commodities across our model regions. In the case of estimates reporting a range in Tables A-G, the mean between lower and upper boundaries has been taken as reference estimate.

Table S8 – EU27	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.042	0.014	0.032	0.022	0.28
wht	0.094	0.014	0.032	0.022	0.137
gro	0.042	0.014	0.032	0.022	0.137
hort	0.121	0.063	0.101	0.037	0.154
osd	0.025	0.025	0.282	0.003	0.048
c_b	0.026	0.03	0	0.003	0.013
ocrops	0.042	0.014	0.032	0.022	0.137
ctl	0.008	0.001	0.047	0.032	0.292
oap	0.037	0.01	0.016	0.015	0.293
rmk	0.003	0.002	0.007	0.005	0.076
fsh	0.004	0.001	0.378	0.03	0.16

Table S9 – SEA	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.038	0.041	0.033	0.011	0.04
wht	0.043	0.066	0.03	0.033	0.04
gro	0.024	0.041	0.03	0.067	0.04
hort	0.038	0.035	0.078	0.087	0.04
osd	0.009	0.013	0.13	0.01	0.04
c_b	0.012	0.004	0.03	0.067	0.04
ocrops	0.006	0.012	0.03	0.054	0.04
ctl	0.056	0.003	0.05	0.005	0.074
oap	0.347	0.01	0.02	0.074	0.02
rmk	0.035	0.034	0.015	0.06	0.055
fsh	0.082	0.06	0.0004	0.123	0.048

Table S10– INDA	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.037	0.076	0.027	0.011	0.166
wht	0.088	0.066	0.027	0.011	0.111
gro	0.126	0.097	0.027	0.011	0.111
hort	0.103	0.205	0.159	0.08	0.172
osd	0.06	0.025	0.06	0.003	0.048
c_b	0.126	0.097	0.027	0.011	0.111
ocrops	0.126	0.097	0.027	0.011	0.111
ctl	0.087	0.028	0.013	0.035	0.163
oap	0.06	0.01	0.016	0.014	0.135
rmk	0.035	0.001	0.047	0.002	0.026
fsh	0.036	0.073	0.378	0.058	0.261

Table S11 – NAMO	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.072	0.04	0.032	0.15	0.207
wht	0.072	0.04	0.032	0.15	0.207
gro	0.072	0.04	0.032	0.15	0.207
hort	0.088	0.198	0.145	0.13	0.17
osd	0.12	0.03	0.06	0.15	0.207
c_b	0.072	0.04	0.032	0.11	0.18
ocrops	0.072	0.04	0.032	0.15	0.207
ctl	0.035	0.01	0.047	0.04	0.34
oap	0.04	0.01	0.016	0.09	0.209
rmk	0.035	0.004	0.007	0.12	0.18
fsh	0.12	0.005	0.378	0.054	0.316

Table S12 – LAC	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.036	0.076	0.034	0.012	0.05
wht	0.03	0.099	0.03	0.012	0.05
gro	0.122	0.182	0.034	0.012	0.05
hort	0.112	0.166	0.043	0.074	0.034
osd	0.15	0.15	0.07	0.01	0.04
c_b	0.122	0.182	0.034	0.012	0.05
ocrops	0.122	0.182	0.034	0.012	0.05
ctl	0.056	0.011	0.05	0.005	0.074
oap	0.06	0.01	0.02	0.01	0.02
rmk	0.035	0.01	0.015	0.06	0.055
fsh	0.057	0.05	0.004	0.001	0.048

Table S13 – REUCA	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.14	0.293	0.02	0.01	0.05
wht	0.14	0.129	0.02	0.01	0.05
gro	0.14	0.293	0.02	0.01	0.05
hort	0.056	0.1	0.113	0.04	0.227
osd	0.15	0.05	0.07	0.01	0.04
c_b	0.14	0.293	0.02	0.01	0.05
ocrops	0.14	0.293	0.02	0.01	0.05
ctl	0.1	0.002	0.05	0.005	0.074
oap	0.06	0.01	0.02	0.01	0.02
rmk	0.1	0.01	0.015	0.06	0.055
fsh	0.1	0.0005	0.004	0.001	0.048

Table S14 – MENA	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.14	0.293	0.02	0.01	0.05
wht	0.14	0.129	0.02	0.01	0.05
gro	0.14	0.293	0.02	0.01	0.05
hort	0.056	0.1	0.113	0.04	0.227
osd	0.15	0.05	0.07	0.01	0.04
c_b	0.14	0.293	0.02	0.01	0.05
ocrops	0.14	0.293	0.02	0.01	0.05
ctl	0.1	0.002	0.05	0.005	0.074
oap	0.06	0.01	0.02	0.01	0.02
rmk	0.1	0.01	0.015	0.06	0.055
fsh	0.1	0.0005	0.004	0.001	0.048

Table S15 – SSA	Agricultural Production	Post-Harvest Handling & Storage	Manufacturing	Distribution & Retailing	Consumption
pdr	0.031	0.012	0.045	0.018	0.04
wht	0.037	0.045	0.035	0.017	0.04
gro	0.033	0.036	0.035	0.019	0.04
hort	0.17	0.208	0.05	0.18	0.04
osd	0.06	0.131	0.095	0.166	0.04
c_b	0.033	0.036	0.035	0.019	0.04
ocrops	0.111	0.036	0.035	0.108	0.04
ctl	0.19	0.03	0.05	0.005	0.074
oap	0.018	0.01	0.02	0.074	0.02
rmk	0.06	0.082	0.015	0.138	0.055
fsh	0.057	0.208	0.09	0.123	0.048

EAT-Lancet diet scenario

The challenge for modelling the EAT-Lancet scenario in a global GE model like MAGNET is its definition in terms of (mostly) primary food items. While PE models tend to define household demand in primary equivalents only, MAGNET like all GTAP-based global GE models includes food processing and food service sectors through which primary products can reach the consumer. In a previous MAGNET study (Kuiper and Van den Bos Verma 2021) a rather strong assumption was used. Primary content of commodities was computed after which the household demand pattern was defined exogenous such that the specified combination of primary products, processed food and food services matches the EAT-Lancet diet.

In this study we developed a new approach exploiting the tracing of commodities with the Leontief inverse. We compute for 2020 data (from which the diet scenario starts) the primary product content of each food commodity. As we cannot invert the Leontief matrix inside the simulation, we have to keep the primary content composition of food fixed. We can only update primary contents with the percent change in food consumed, so the quantities change in the same amount as the demand for the final commodity. While not perfect this approach allows us to impose a diet in terms of primary content avoiding imposing a fixed diet in terms of primary, processed and food service demand. Instead the model can adjust the demand for different types of food as long as the diet constraint is met. For example, for fruit and vegetables there is a significant flow via other processed food as preserved items (like canned tomatoes) are included under processed food. In the current set-up the model can adjust direct primary flows of fruit and vegetables in response to changes in processed food and food service demand which have implications for the total fruit and vegetable intake.

This new approach tackles the problem of multiple diet items entering food processing or food services using a weighted change of intermediate inputs. In the EAT-Lancet diet red meat consumption needs to decrease while fruit and vegetable consumption needs to increase, both of which are partly consumed via processed food. The change in processed food consumption is now computed by weighing the downward shifts in meat and upward shift in fruit and vegetables with their primary content in processed food to get the change in processed food consumption that gets as close as possible to satisfying both diet constraints.

Table S16 below illustrates the primary commodities available in MAGNET and used in our diet scenarios. Following, Table S17 reports the size of the shock implemented to simulate the application of EAT-Lancet dietary guidelines in our modelling scenarios. The magnitude of the shock is computed on food intakes net of FLW along FSC. From our model baseline we derive households' intakes in 2030 and apply our FLW shares to obtain physical net food supply (grams per capita per day) by region. From this intake estimate we calculate the required change in consumption necessary to advance towards the EAT-Lancet dietary recommendations. An important note has to be made with regards to the shock applied to the consumption of horticulture. In MAGNET the "hort" commodity comprehends fruit and vegetables but also nuts, pulses, starchy vegetables, roots and tubers. Such level of aggregation impedes targeting the intakes of such specific commodities available in the EAT-Lancet. As a result our shock on horticulture consumption might result negative for regions where the decrease in consumption of for example starchy vegetables overruns the increase in consumption in fruit and vegetables. In the "calories" scenario we do not impose commodity specific targets (shocks) but compute a required change in total net calorie intake of households, simulating a transition to the EAT-Lancet calorie target. Finally, our "Towards EAT-Lancet" scenario is defined by a simultaneous application of commodity-specific shocks and calorie shock, obtaining the closest representation of a full dietary transition in which the consumption of all commodities is changing simultaneously. Finally, as we model the transition towards the EAT-Lancet diet, Table S18 below illustrates the distance of our “Towards EAT-Lancet” scenario with respect to the full EAT-Lancet dietary targets.

Table S16. Primary commodities included in dietary scenarios implemented in this study.

MAGNET PRIMARY COMMODITIES	CEREALS	HORTICULTURE	MEAT	MILK	FISH	FATS	SUGARS	CALORIES	TOWARDS EAT-LANCET
pdr	1	0	0	0	0	0	0	1	1
wht	1	0	0	0	0	0	0	1	1
gro	1	0	0	0	0	0	0	1	1
hort	0	1	0	0	0	0	0	1	1
osd	0	0	0	0	0	1	0	1	1
c_b	0	0	0	0	0	0	1	1	1
ctl	0	0	1	0	0	0	0	1	1
oap	0	0	1	0	0	0	0	1	1
rmk	0	0	0	1	0	0	0	1	1
fsh	0	0	0	0	1	0	0	1	1

Table S17. Applied shock (% changes) to private per-capita household demand for each commodity in different global regions, under different dietary scenarios.

MAGNET PRIMARY COMMODITIES	SCENARIO	REGION SPECIFIC SHOCK							
		EU27	SEA	INDA	NAMO	LAC	REUCA	MENA	SSA
pdr, wht, gro	CEREALS	-26.2	-22.0	-25.8	-28.0	-21.7	-22.9	-24.6	-15.2
hort	HORTICULTURE	-4.1	-1.4	0.7	9.2	13.9	-3.0	3.6	-9.3
osd	FATS	-26.9	-26.1	-24.8	-23.5	-24.0	-22.7	-20.7	-14.8
c_b	SUGARS	-31.4	-30.3	-30.5	-31.5	-32.6	-30.7	-30.6	-27.7
ctl	MEAT	-24.8	-12.4	-23.8	-29.7	-29.1	-27.3	-23.5	-15.7
oap	MEAT	-21.6	-5.6	-23.6	-24.6	-22.2	-21.0	-10.3	57.3
rmk	MILK	-20.7	24.1	15.3	-17.4	-3.6	-17.3	6.9	93.9
fsh	FISH	-9.0	-20.0	-24.9	-11.0	-16.2	-11.2	3.7	42.5
all primary commodities	CALORIES	-23.1	-13.0	-20.9	-24.4	-18.4	-18.9	-18.2	-1.7
all primary commodities	TOWARDS EAT-LANCET	combination of all shocks reported above for each region							

Table S18. Difference in net intakes (grams/capita/day) of our "Towards EAT-Lancet" scenario with respect to the full implementation of the EAT-Lancet dietary targets on net food intakes in 2030.

	FULL EAT-LANCET TARGET	TOWARDS EAT-LANCET scenario							
		EU27		SEA		INDA		NAMO	
	g/c/d	g/c/d	abs. diff.	g/c/d	abs. diff.	g/c/d	abs. diff.	g/c/d	abs. diff.
Cereals	232	792	-560	503	-271	722	-490	1070	-838
Horticulture	675	722	-47	660	15	683	-8	628	47
Red meat	7	20	-13	9	-2	15	-8	42	-35
Other meats and ASF	49	103	-54	48	1	106	-57	130	-81
Dairy	250	495	-245	180	70	200	50	405	-155
Fish	28	33	-5	45	-17	67	-39	38	-10
Oils/Fats	51.8	169	-118	148	-96	144	-92	126	-74
Sugars	31	328	-297	217	-186	305	-274	353	-322
Total	1323.8	2662	-1338	1810	-486	2242	-918	2791	-1468
		LAC		REUCA		MENA		SSA	
	g/c/d	g/c/d	abs. diff.	g/c/d	abs. diff.	g/c/d	abs. diff.	g/c/d	abs. diff.
Cereals	232	499	-267	569	-337	644	-412	387	-155
Horticulture	675	539	136	707	-32	618	57	843	-168
Red meat	7	36	-29	27	-20	17	-10	11	-4
Other meats and ASF	49	106	-57	98	-49	59	-10	28	21
Dairy	250	264	-14	416	-166	215	35	127	123
Fish	28	42	-14	36	-8	25	3	19	9
Oils/Fats	51.8	129	-77	117	-66	100	-48	81	-29
Sugars	31	954	-923	248	-217	262	-231	139	-108
Total	1323.8	2567	-1244	2218	-894	1939	-615	1636	-313

Sensitivity Analysis

With the aim of increasing the robustness of our results, the following section provides an illustration of our results under different modelling assumptions key for our model outcomes. We compare our results on net intakes and FLW generation with different scenarios in which different estimates for baseline drivers, trade elasticities (Armington elasticities) and FLW shares are adopted. Additionally, we compare our FLW estimates with estimates derived from different assumptions on FLW imputation. Our FLW imputation approach entails a mixed producer-consumer perspective as FLW shares are assigned to both, according to the stage of the FSC. For this we compare our estimates with cases in which a “producer perspective” and a “consumer perspective” are adopted. Finally, we provide a comparison of some of our final estimates with data available from FAO Food-Balance-Sheets (FBS), showing both similarities and divergences.

Baseline and model parametrisation.

The following section provides an overview of estimates of net food intakes and FLW generation under different assumptions on baseline trends and model parameters. Figure S1 reports average net intakes and FLW generation under different baselines. We compare our baseline calibrated on estimates derived from IMF World Economic Outlook with two alternative baselines defined in relation to the U.N. Shared Socioeconomic Pathways (SSP) (O’Neill et al., 2017). We proportionally adjust the IMF World Economic Outlook guidelines to the SSP1 (sustainability – taking the Green Road (Low challenges to mitigation and adaptation)) and the SSP3 (Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)) development pathways to illustrate changes in 2030 under different trends of GDP and population growth. Table S19 reports the estimates adopted for each baseline definition.

Table S19. Region-specific estimates adopted for each baseline development.

		2020-2030	
		GDP growth (%)	**Population growth (%)**
BAU (Business-as-Usual)	EU27	24.7	1.2
	SEA	69.7	8.4
	INDA	18.6	-3.9
	NAMO	26.3	8.3
	LAC	30.5	11.4
	REUCA	17.9	3.4
	MENA	42.5	21.8
	SSA	48.6	39.1
IMF - SSP1	EU27	28.7	2.2
	SEA	89.7	6.4
	INDA	23.6	-3.9
	NAMO	31.3	9.3
	LAC	37.5	9.4
	REUCA	23.9	2.4
	MENA	47.2	18.8
	SSA	64.6	35.1
IMF - SSP3	EU27	18.7	-2.2
	SEA	58.7	11.4
	INDA	13.6	-6.9
	NAMO	20.3	3.3
	LAC	25.5	15.4
	REUCA	11.9	3.4
	MENA	38.5	24.8
	SSA	36.6	44.9

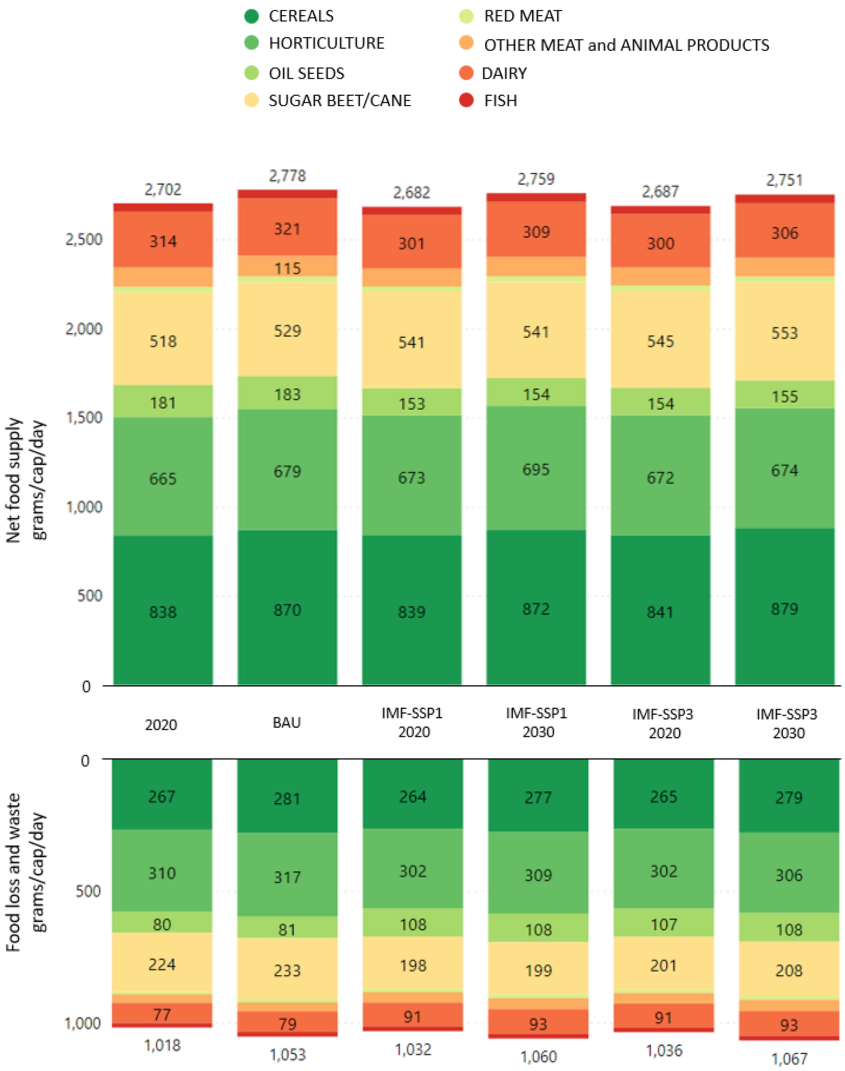

Figure S1. Global average net intakes and FLW generation under different baseline assumptions. Estimates reported in this figure illustrate a global average. FLW amounts refer to total amount of lost or discarded food generated along each stage of global FSC by the final consumption domestic and imported food products. The BAU scenario refers to our Business-as-usual scenario in 2030. The "IMF-SSP1" scenario refers to a baseline in which baseline parameters for GDP and population growth from the IMF-World Economic Outlook have been proportionally adapted to the U.N. SSP1 pathway. Similarly, the "IMF-SSP3" refers to a baseline in which estimates of IMF-World Economic Outlook have been proportionally adapted to the U.N. SSP3 pathway. As is possible to observe from the figure, different assumptions on baseline parameters do not drastically affect our final outcomes. Differences of final estimates for net intakes and FLW generation with respect to our baseline in 2030 are found to be 0.68% and 0.97% for the "IMF-SSP1" and 0.66% and 1.33% for the "IMF-SSP3".

In GE models, the parametrisation of the applied modelling framework plays a key role in defining potential modelling results. As trade constitutes a central aspect of our results, we provide an overview of baseline results adopting different trade elasticities. Figure S2 illustrates average net intakes and FLW generation in cases where trade elasticities i.e. Armington elasticities are increased and decreased by a 50%.

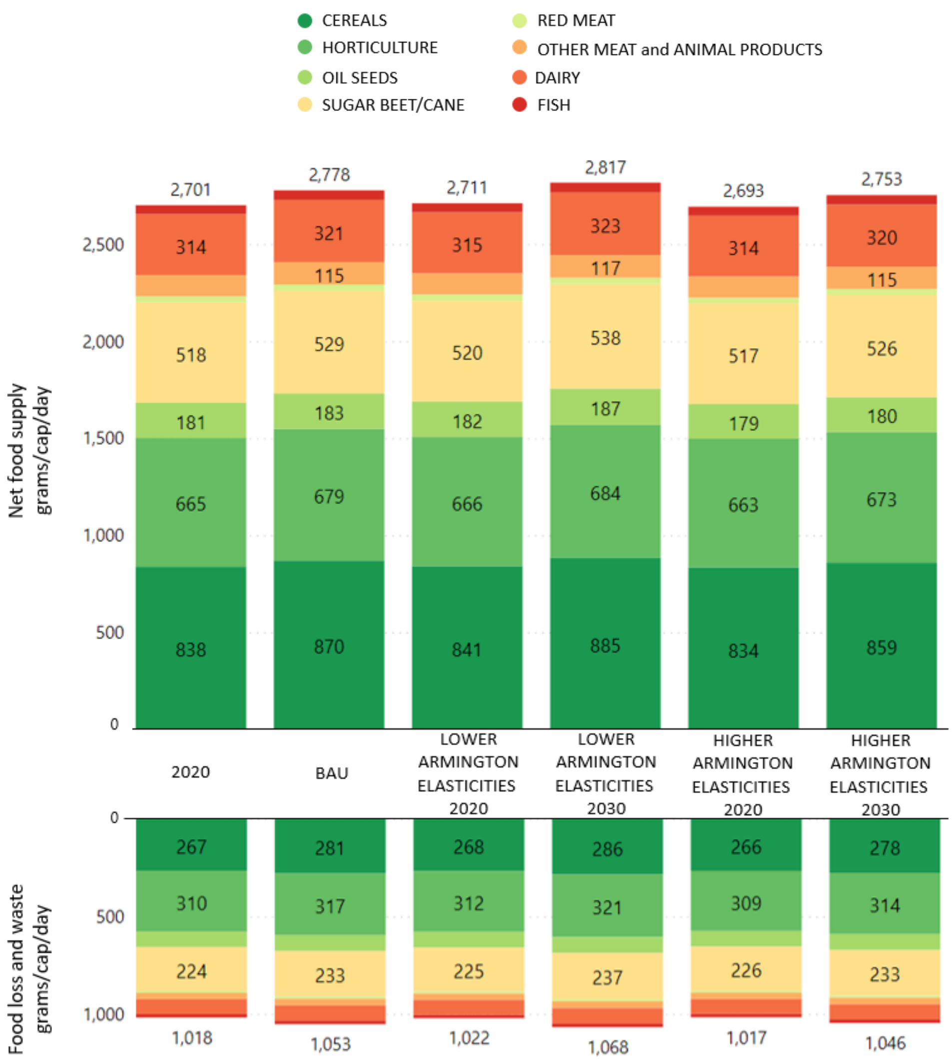

Figure S2. Global average net intakes and FLW generation under different Armington elasticities. Estimates reported in this figure illustrate a global average. FLW amounts refer to total amount of lost or discarded food generated along each stage of global FSC by the final consumption domestic and imported food products. The BAU scenario refers to our Business-as-usual scenario in 2030. In the “lower Armington elasticities” scenario, baseline elasticities have been decreased by 50%. In the “higher Armington elasticities” scenario, baseline elasticities have been increased by 50%. As it is possible to observe, changing trade elasticities does not drastically change our results. Differences of final estimates for net intakes and FLW generation with respect to our baseline elasticities in 2030 are found to be 1.44% and 1.42% for the “lower Armington elasticities” scenario and 0.90% and 0.66% for the “higher Armington elasticities ” scenario.

FLW estimates

Given the underlying uncertainty of our FLW estimates, figure S4 below reports average net intakes and FLW generation in the case of FLW estimates computed on lower and upper bounds of intervals reported in Tables A-G.

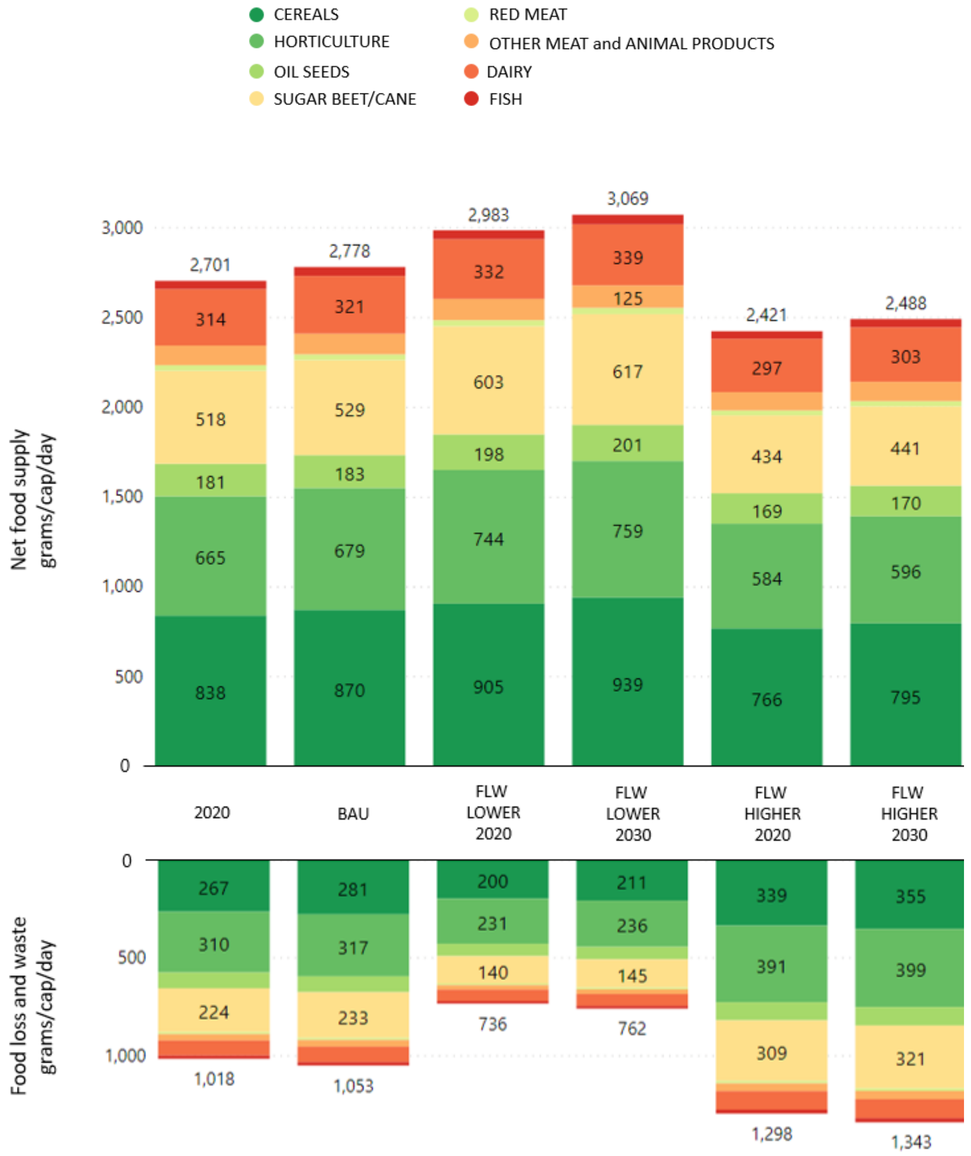

Figure S4. Global average net intakes and FLW generation under different estimation of shares of FLW along FSC. Estimates reported in this figure illustrate a global average. FLW amounts refer to total amount of lost or discarded food generated along each stage of global FSC by the final consumption domestic and imported food products. The BAU scenario refers to our Business-as-usual scenario in 2030. Increasing or decreasing applied FLW shares has direct impact on magnitude of FLW. For this, the choice of taking the mean of the reported intervals in Tables A-G is in line with our baseline assumption of a business-as-usual scenario. Differently, if we were to take different assumptions on baseline, assuming for example a more/less sustainable pathway to 2030 (SSP1/SSP3), the adoption of lower/upper bounds of our reported intervals would have been more representative of the narrative behind different baseline definitions.

Producer vs Consumer FLW

The FLW reported in our study are computed by assigning production losses to producing countries and consumption waste to consuming countries. This means that while final consumers are the main drivers of FLW generation, shares of FLW are assigned to countries based on the stages of the FSC. To illustrate how this choice affects our final estimates, Figures S5-S7 report a comparison of FLW generation from different imputation perspectives. We compare our approach to a “producer perspective” in which all FLW along global FSC is assigned to food production countries, and to a “consumer perspective” in which all FLW along global FSC is assigned to countries where food is consumed at household level.

FLW magnitude

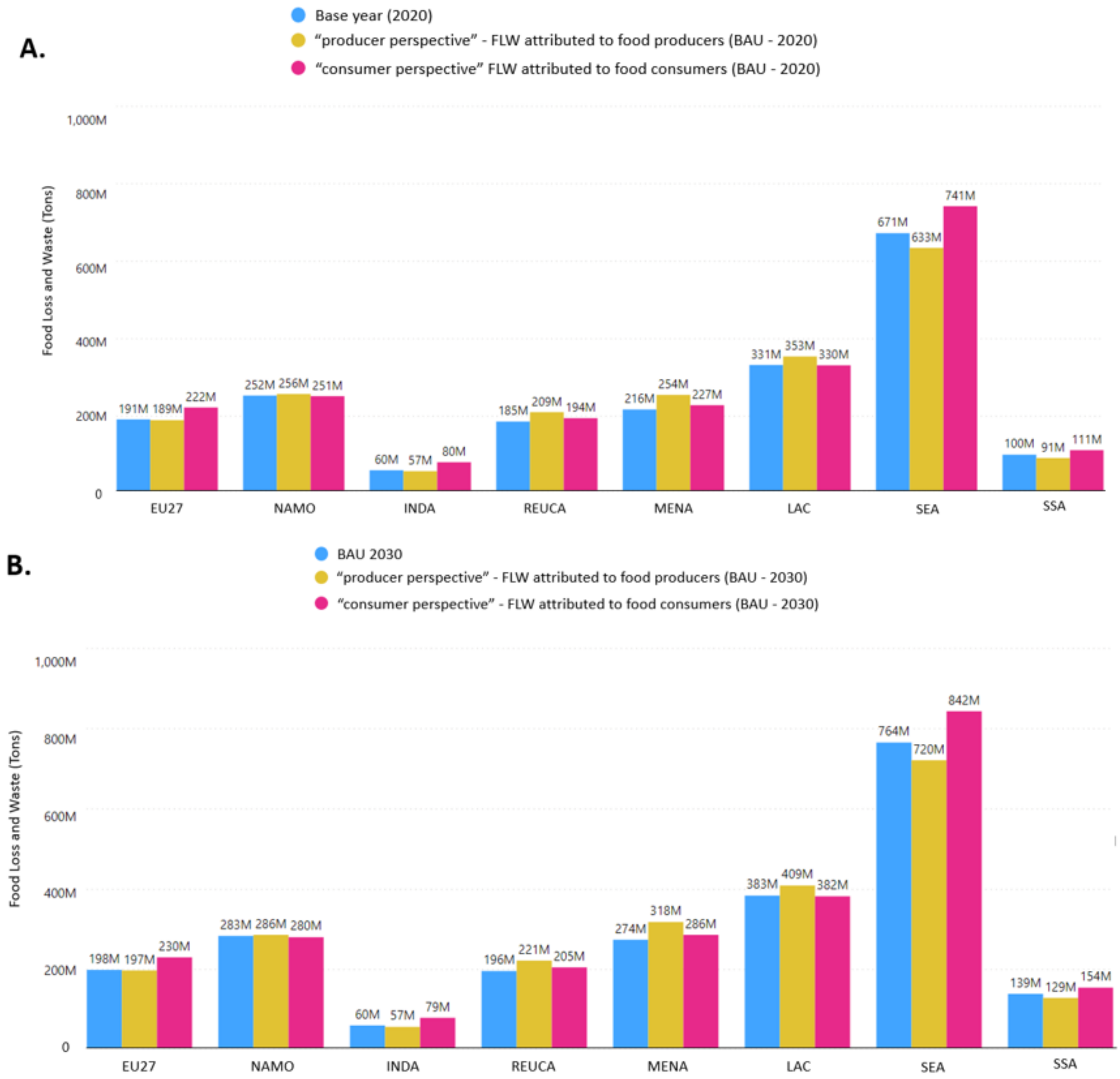

Figure S5: Magnitude (tons) of FLW by region generated under different FLW imputation perspectives. Figure A represents tons of FLW by region generated under different FLW imputation perspectives in 2020. Figure B represents tons of FLW by region generated under different FLW imputation perspectives in our business-as-usual (BAU) scenario in 2030. Different imputation perspectives do not drastically affect overall FLW magnitude by regions. Highest differences are observed in SEA where a “consumer perspective” results in an increase in total FLW generation compared to our baseline and BAU scenario +70 million tons in 2020; +78 million tons in 2030).

FLW composition

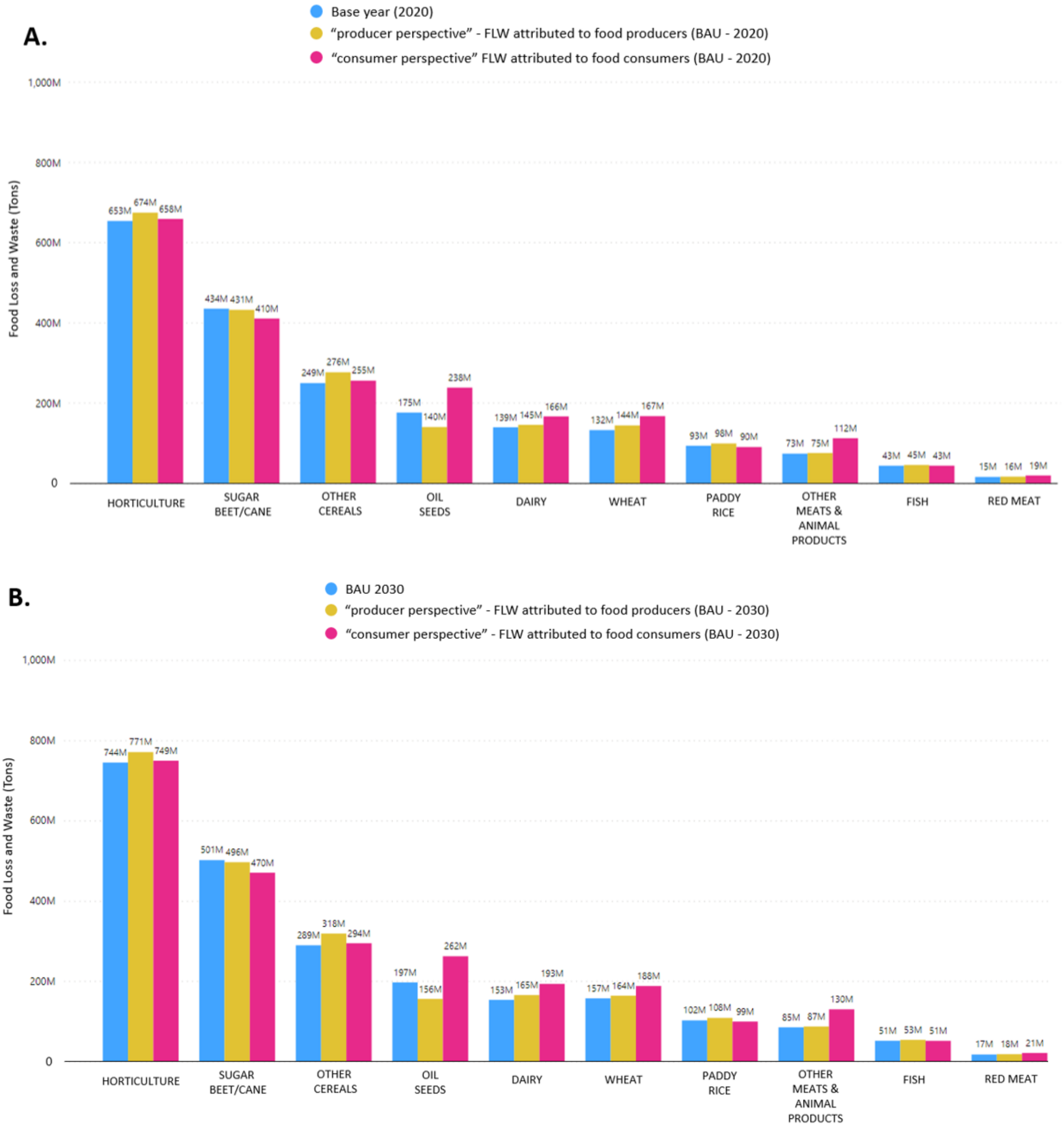

Figure S6: Composition (tons) of FLW by commodity generated under different FLW imputation perspectives. Figure A represents tons of FLW by region generated under different FLW imputation perspectives in 2020. Figure B represents tons of FLW by region generated under different FLW imputation perspectives in our business-as-usual (BAU) scenario in 2030. Different imputation perspectives do not drastically affect overall FLW magnitude by regions. Highest differences are observed for Oil seeds where a "consumer perspective" results in an increase in total FLW generation compared to our baseline and BAU scenario +63 million tons in 2020; +65 million tons in 2030).

Results comparison

This section provides a comparison between gross food supply estimates presented in this study and estimates available from literature. As we adopt different data sources to derive physical flows of food and non-food biomass and associated FLW, comparing our estimates with available data from FAO Food Balance Sheets (FBS) might result in large differences.

To provide a clarification of similarity and divergence with FAO-FBS data, Table S21 reports a comparison of our estimates of gross food supply (grams/capita/day) in primary equivalents with the estimates provided by FAO-FBS. In the interpretation of Table S21 the following differences between the two databases should be taken into account. First, FAO-FBS estimates are provided for 2019 while MAGNET estimates are defined for 2020 (model base year). While a single year difference does non critically influence estimates, some divergencies may be linked to the adoption of different time frames. Second, estimates from the MAGNET model concern physical weight in primary equivalents. This means that in the case of sugar beet/cane (c_b), our food supply will be significantly higher as reported estimates concern the weight of sugar beet and canes which, due to the inclusion of water before processing into raw sugars are much heavier. Third, FAO-FBS provide estimates for non-primary commodities such as beer, wine or infant food. While such commodities are reported separately in FAO-FBS, estimates in MAGNET already include such non-primary commodities in primary equivalents. For this, while we do not report an explicit comparison for such commodities, they must be included in the calculation of total food supply from the FAO-FBS estimates. Finally, as reported in Table S20 below, the differences between commodities listed in FAO-FBS and MAGNET do not allow a perfect mapping, influencing the comparison of estimates. This is particularly relevant in the case of oils from FBS-FAO and osd (oil seeds) from MAGNET. As oil intakes in MAGNET are represented in primary equivalents, the average weight of oil seeds is likely to be higher as product intakes are defined gross of kernels, hence heavier than processed oils (net of kernels) reported in FAO-FBS. With regards to differences in grains (gro) intakes, MAGNET estimates are significantly higher as intakes of grains are indirectly accounted for in the consumption of processed foods (on average grains constitute 17.4% of processed foods), and in beverages (alcoholic and non-alcoholic). The FAO-FBS framework covers a more restricted set of commodities under “grains” including only flour and cereal germs. This can result in average lower amounts of grains consumed, especially in higher income regions such as NAMO and EU27 where consumption of processed foods is relatively large.

Table S20. Mapping between FAO-FBS food commodities and MAGNET commodities for estimates comparisons.

FAO-FBS commodity	CPC code	MAGNET commodity	FAO-FBS commodity	CPC code	MAGNET commodity
Wheat and products	2511	wht	Sesame seed	2561	osd
Rice and products	2807	pdr	Olives (including preserved)	2563	osd
Barley and products	2513	gro	Soyabean Oil	2571	osd
Maize and products	2514	gro	Groundnut Oil	2572	osd
Rye and products	2515	gro	Sunflower seed Oil	2573	osd
Oats	2516	gro	Rape and Mustard Oil	2574	osd
Millet and products	2517	gro	Cottonseed Oil	2575	osd
Sorghum and products	2518	gro	Palm kernel Oil	2576	osd
Cereals, Other	2520	gro	Palm Oil	2577	osd
Cassava and products	2532	hort	Coconut Oil	2578	osd
Potatoes and products	2531	hort	Sesame seed Oil	2579	osd
Sweet potatoes	2533	hort	Olive Oil	2580	osd
Roots, Other	2534	hort	Rice bran Oil	2581	osd
Sugar cane	2536	c_b	Maize Germ Oil	2582	osd
Sugar (Raw Equivalent)	2542	c_b	Oil crops Oil, Other	2586	osd
Sweeteners, Other	2543	c_b	Tomatoes and products	2601	hort
Honey	2745	oap	Onions	2602	hort
Beans	2546	hort	Vegetables, other	2605	hort
Peas	2547	hort	Oranges, Mandarines	2611	hort
Pulses, Other and products	2549	hort	Lemons, Limes, and products	2612	hort
Nuts and products	2551	hort	Grapefruit and products	2613	hort
Soyabeans	2555	gro	Citrus, Other	2614	hort
Groundnuts	2552	hort	Bananas	2615	hort
Rape and Mustard seed	2558	osd	Plantains	2616	hort
Coconuts - Incl Copra	2560	hort	Apples and products	2617	hort
Pineapples and products	2618	hort	Freshwater Fish	2761	fsh
Dates	2619	hort	Infant food	2680	ofd
Grapes and products (excl. wine)	2620	hort	Miscellaneous	2899	ofd
Fruits, other	2625	hort	Pimento	2641	hort
Coffee and products	2630	hort	Fish, Body Oil	2781	fsh
Cocoa Beans and products	2633	hort	Fish, Liver Oil	2782	fsh
Tea (including mate)	2635	hort	Demersal Fish	2762	fsh
Pepper	2640	hort	Pelagic Fish	2763	fsh
Cloves	2642	hort	Marine Fish, Other	2764	fsh
Spices, Other	2645	hort	Crustaceans	2765	fsh
Wine	2655	b_t	Cephalopods	2766	fsh
Beer	2656	b_t	Molluscs, Other	2767	fsh
Beverages, Fermented	2657	b_t	Aquatic Animals, Others	2769	oap
Beverages, Alcoholic	2658	b_t	Aquatic Plants	2775	fsh
Bovine Meat	2731	ctl	Sugar beet	2537	c_b
Mutton & Goat Meat	2732	oap	Oil crops, Other	2570	osd
Pig meat	2733	oap	Yams	2535	hort
Poultry Meat	2734	oap	Sunflower seed	2557	osd
Meat, Other	2735	oap	Sugar non-centrifugal	2541	c_b
Offals, Edible	2736	oap	Meat, Aquatic Mammals	2768	oap
Butter, Ghee	2740	rmk	Palm kernels	2562	osd
Cream	2743	rmk	Cottonseed	2559	osd
Fats, Animals, Raw	2737	rmk	Alcohol, Non-Food	2659	ofd
Eggs	2744	oap			
Milk - Excluding Butter	2848	rmk			

Table S21. Gross food supply (grams/capita/day) from FAO-FBS (2019) compared to MAGNET estimates (base year, 2020) by region.

	EU27 grams/capita/day		INDA grams/capita/day		LAC grams/capita/day		MENA grams/capita/day	
	FAO-FBS	**MAGNET**	**FAO-FBS**	**MAGNET**	**FAO-FBS**	**MAGNET**	**FAO-FBS**	**MAGNET**
c_b	114	615	91	460	141	2143	109	599
ctl	38	42	31	27	63	63	21	27
fsh	65	51	154	151	28	59	32	28
gro	51	800	62	722	144	604	78	487
hort	736	1166	550	840	633	706	823	965
oap	221	209	206	182	190	154	95	74
osd	55	388	52	293	45	271	53	190
pdr	19	36	214	267	94	105	83	91
rmk	536	715	99	173	299	328	174	258
wht	291	546	128	288	136	156	403	663
ofd	4	-	7	-	2	-	4	-
b_t	270	-	122	-	151	-	10	-
Total	**2405**	**4571**	**1722**	**3408**	**1931**	**4594**	**1890**	**3386**

	NAMO grams/capita/day		REUCA grams/capita/day		SEA grams/capita/day		SSA grams/capita/day	
	FAO-FBS	**MAGNET**	**FAO-FBS**	**MAGNET**	**FAO-FBS**	**MAGNET**	**FAO-FBS**	**MAGNET**
c_b	167	889	126	613	67	405	45	211
ctl	94	96	39	47	11	11	13	14
fsh	61	63	36	48	79	81	22	14
gro	50	1459	42	538	46	205	210	298
hort	788	1001	788	1216	910	855	831	1045
oap	286	266	169	144	112	78	37	21
osd	58	324	35	226	25	286	26	105
pdr	33	78	21	25	356	386	98	83
rmk	602	740	458	648	124	171	61	91
wht	214	234	359	510	155	164	70	82
ofd	4	-	10	-	0.7	-	2	-
b_t	238	-	149	-	44	-	78	-
Total	**2600**	**5154**	**2237**	**4019**	**1934**	**2648**	**1497**	**1969**

Supplementary figures

Biomass

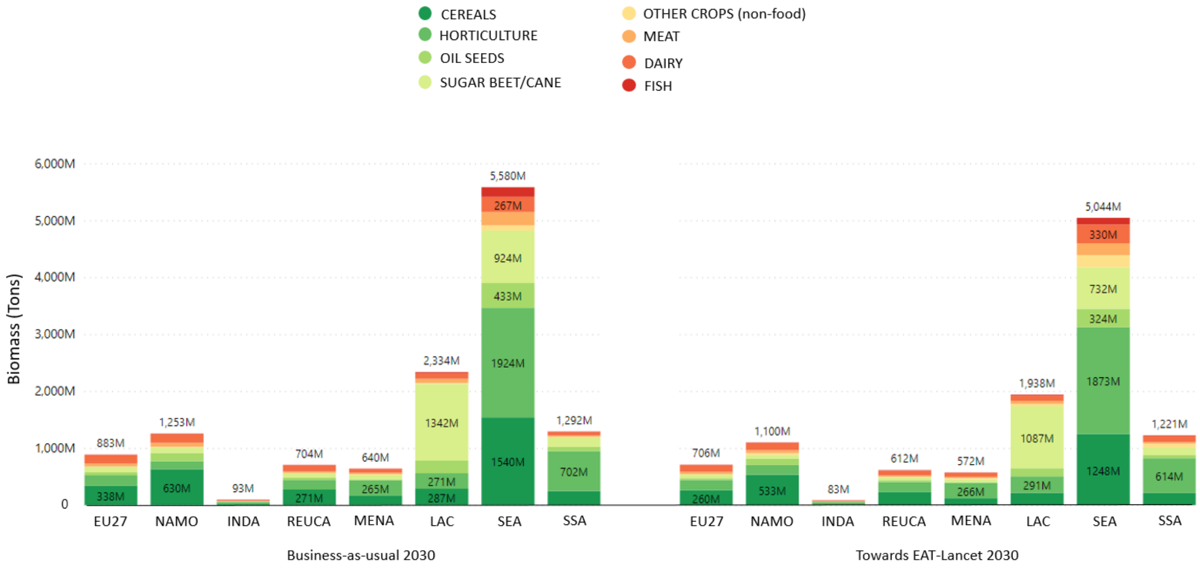

Figure S7. Tons of biomass production by region (2030, by scenario). Estimates refer to the total amount of biomass produced domestically in each region. In both scenarios SEA accounts for highest amount of biomass production, particularly for cereals and horticulture. Relevant amounts of biomass are produced in LAC (sugar beet/cane) and in SSA and NAMO where cereals and horticulture represent the largest shares of produced biomass.

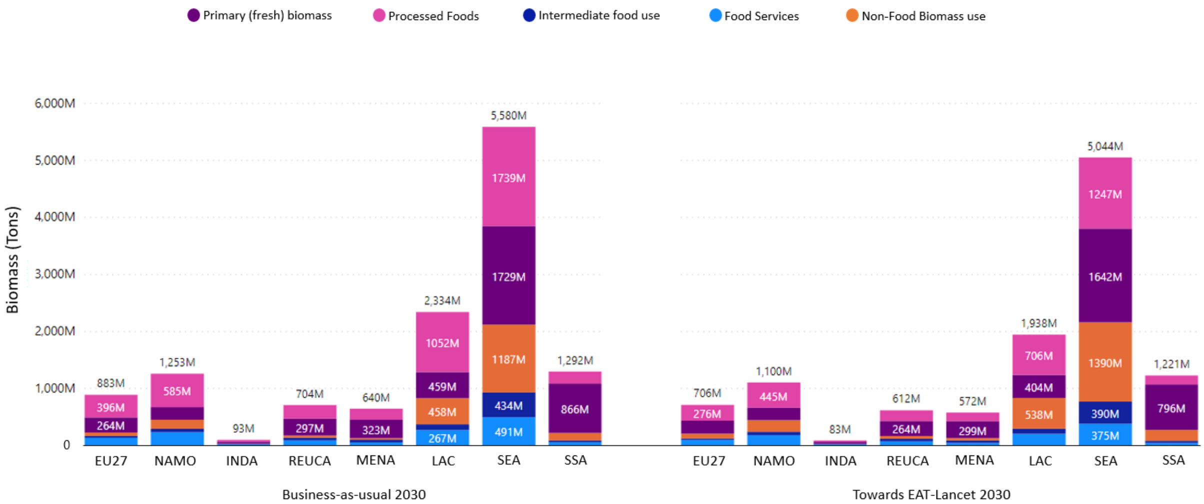

Figure S8. Total global biomass production by type (2030, by scenario). Estimates refer to the total amount of biomass (categorised by type) produced domestically in each region. In both scenarios, SEA represents the largest producer of processed foods, primary (fresh biomass) and non-food biomass use. SSA mainly produces primary (fresh) biomass, while large amounts of processed foods are produced in LAC.

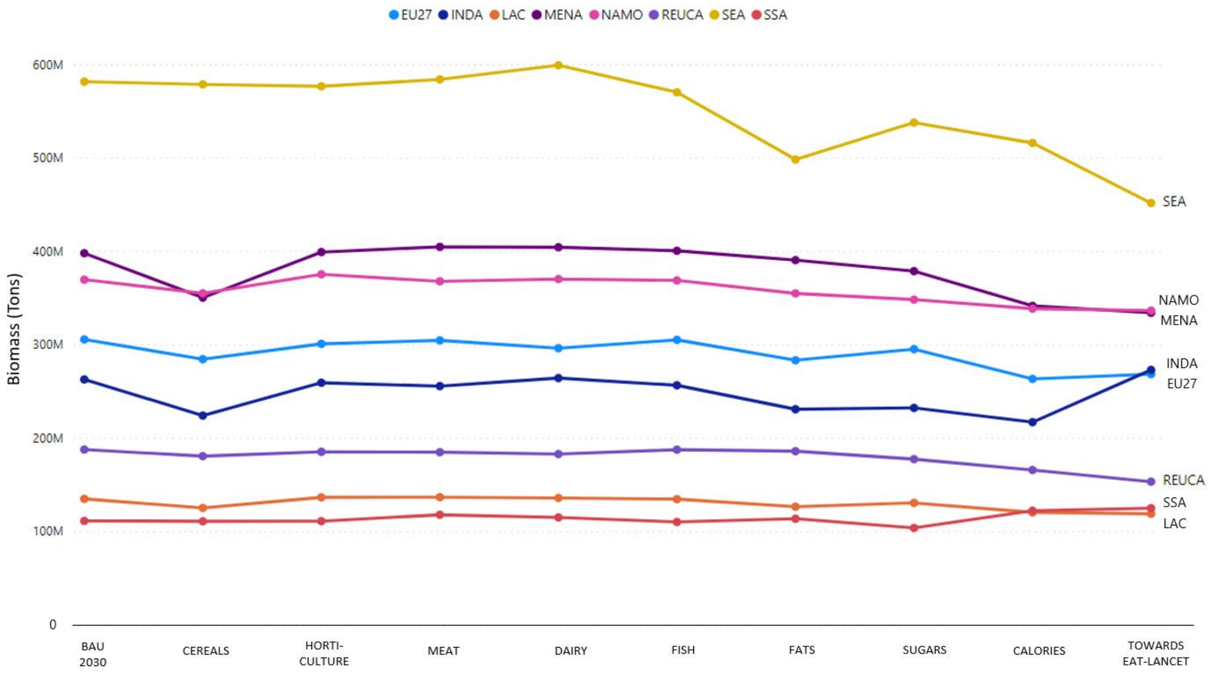

Figure S9. Total global biomass imports by region (2030, by scenario). Estimates refer to total amount of biomass imported by region across investigated scenarios representing different dietary targets. SEA is the largest global importer of biomass, although such amounts decrease in the "Towards the EAT-Lancet" scenario. Dairy targets increase average imports, mainly in lower income regions such as SSA and SEA. Differently, Cereal and Calorie targets decrease average imports of biomass, particularly affecting higher-income regions such as EU27 and NAMO.

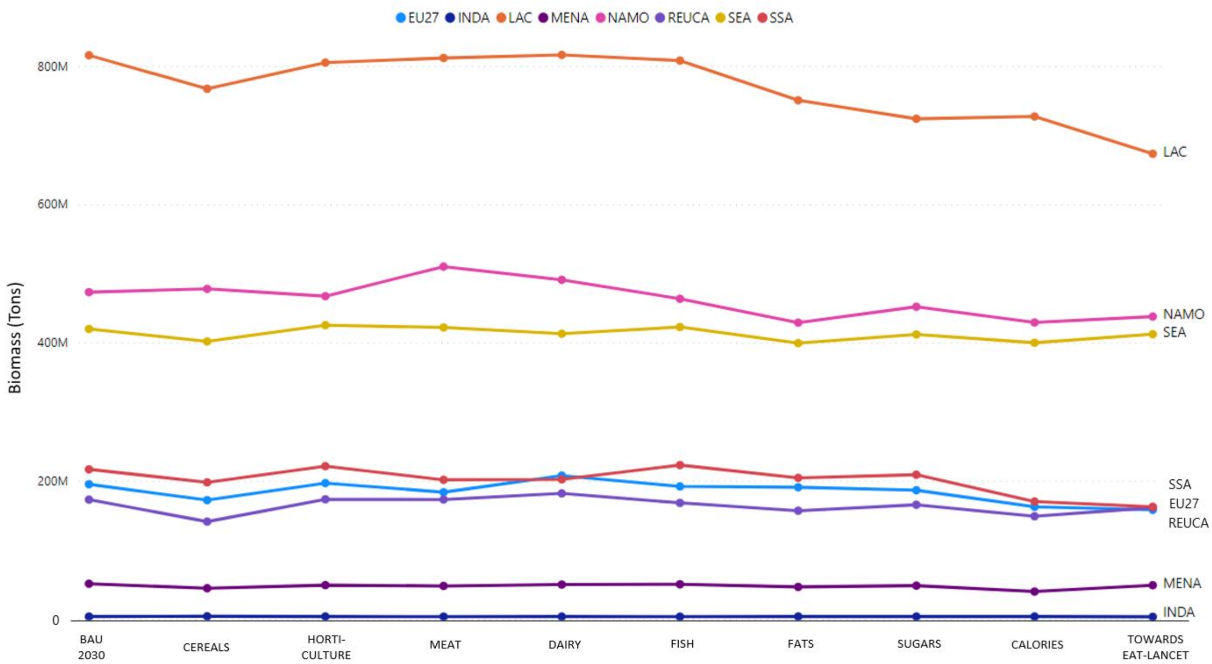

Figure S10. Total global biomass exports by region (2030, by scenario). Estimates refer to total amount of biomass exported by region across investigated scenarios representing different dietary targets. LAC is the largest global exporter of biomass, although such amounts decrease in the "Towards the EAT-Lancet" scenario. Cereal targets and Calorie targets mainly decrease exports across regions, particularly in LAC, SSA and REUCA. Meat targets benefits exports in NAMO, while targets on fish increase exports in SSA.

Food Loss and Waste

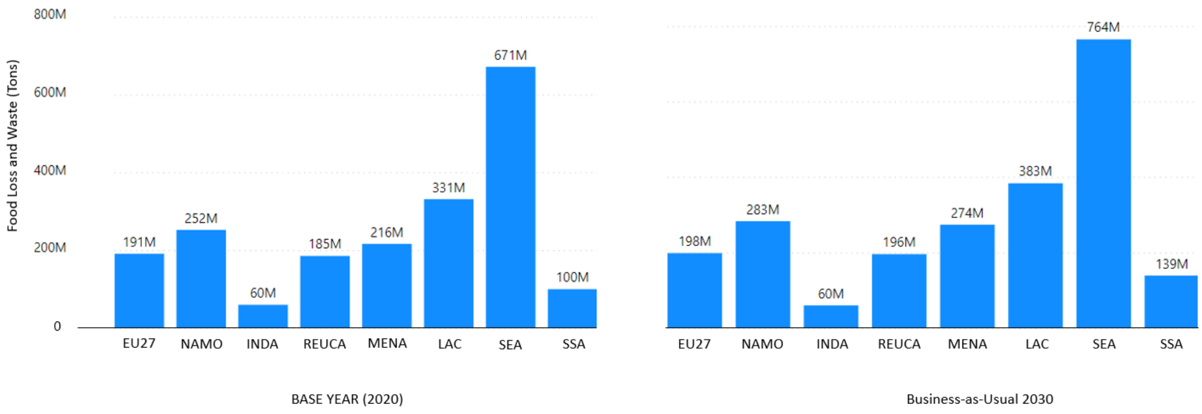

Figure S11. Tons of globally generated FLW (global total) by region (baseline, by year). Across regions, SSA experience the highest relative increase in total FLW in 2030 (39.2%). In absolute terms, the highest increase is observed in SEA where FLW increase by 93 million tons in 2030.

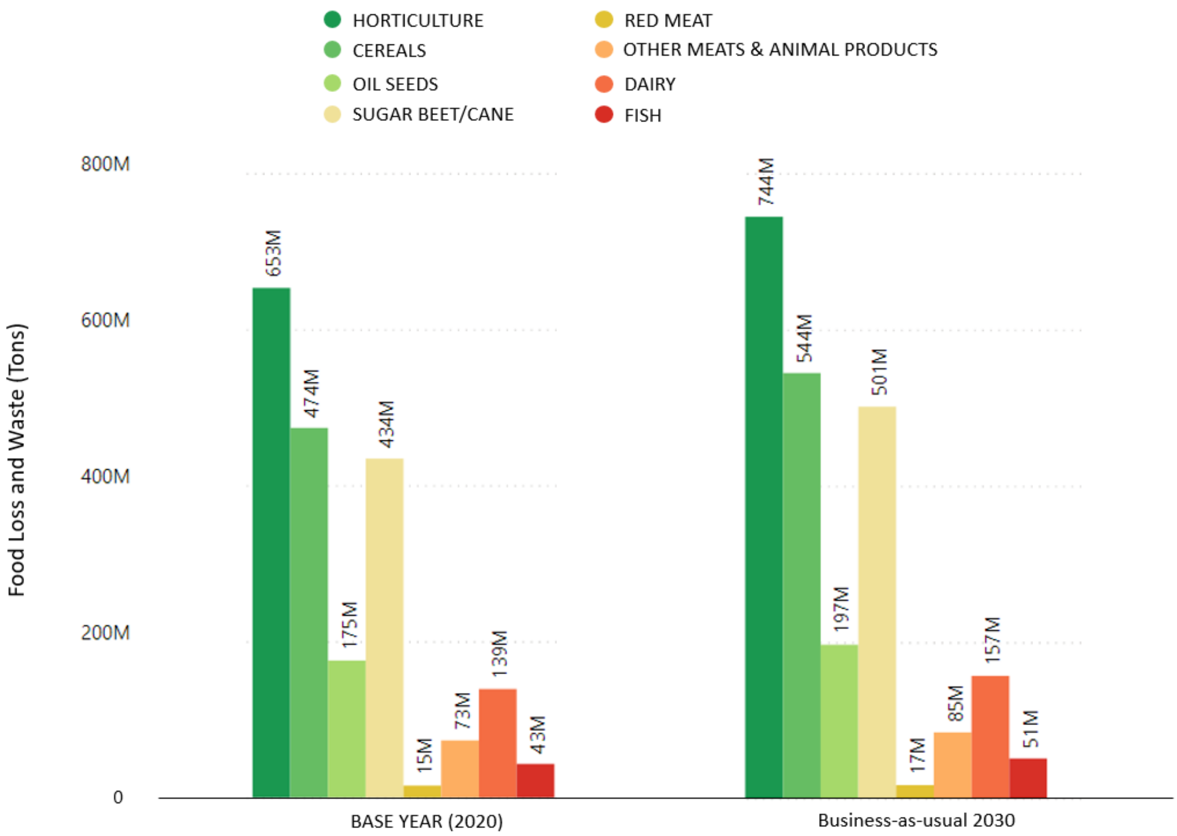

Figure S12. Tons of globally generated FLW (global total) by commodity (baseline, by year). Across different primary food commodities, the main relative increase from 2020 to 2030 is observed for fish (19.2%). In absolute terms, the highest increase in FLW is observed for horticulture, increasing by 91 million tons in 2030.

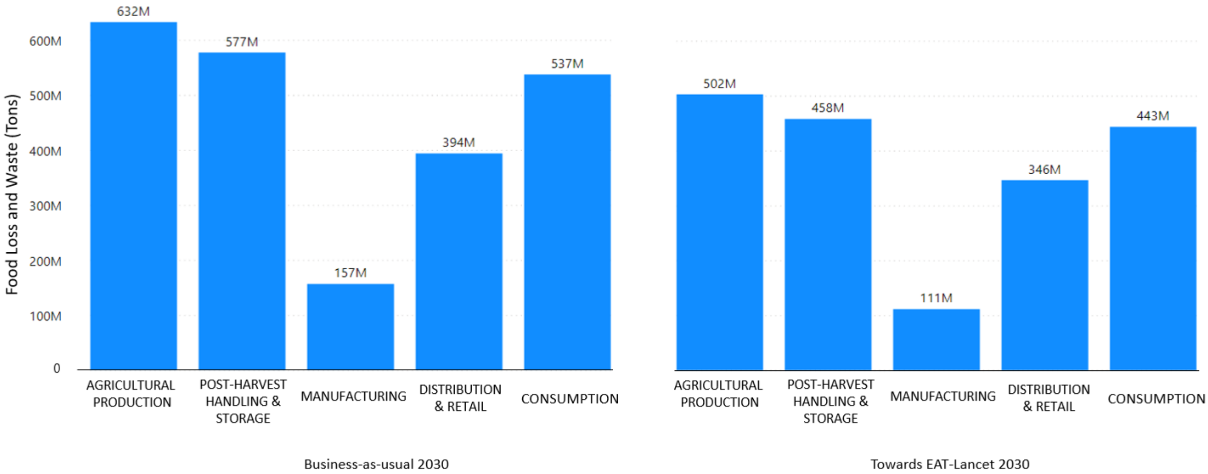

Figure S13. Tons of globally generated FLW (global total) along each stage of the FSC (2030, by scenario). Estimates refer to the sum of FLW generated in different global regions. Figure S9 illustrates the key global hotspots for FLW generation along global FSC. In the baseline scenario in 2030 farm-level losses i.e. Agricultural Production and Post-Harvest Handling & Storage, and Consumption waste account for the largest shares of FLW. Similarly, shifting to the EAT-Lancet diet generates largest amounts of losses at farm-level production and waste at final consumption.

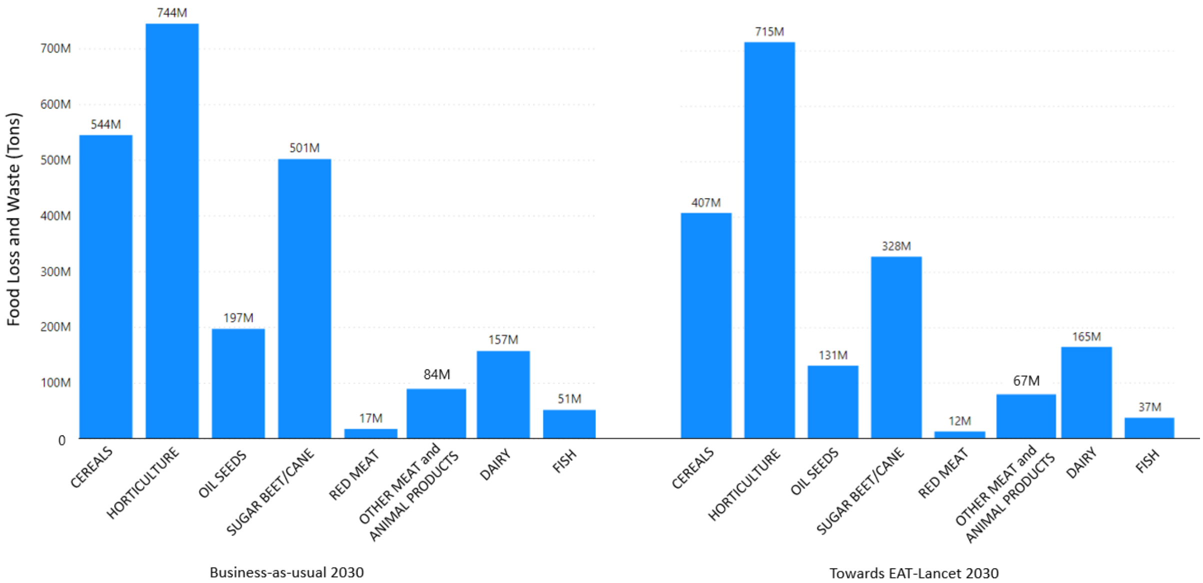

Figure S14. Tons of globally generated FLW (global total) by commodity, along each stage of the FSC (2030, by scenario). Primary equivalent composition of tons of FLW generated (2030, by scenario). Estimates refer to the sum of FLW generated in all regions along global FSC. Fruit & vegetables associate with highest shares of FLW per tons of commodity produced and consumed, resulting in largest amounts of total FLW. As the EAT-Lancet diet is by design a plant-based food diet, the dietary shift reduces total horticulture FLW relatively less, mainly decreasing cereals, sugar beet/cane, and other meat and animal products. Differently, FLW of dairy increase reflecting current consumption of such commodities on average below the EAT-Lancet dietary recommendations.

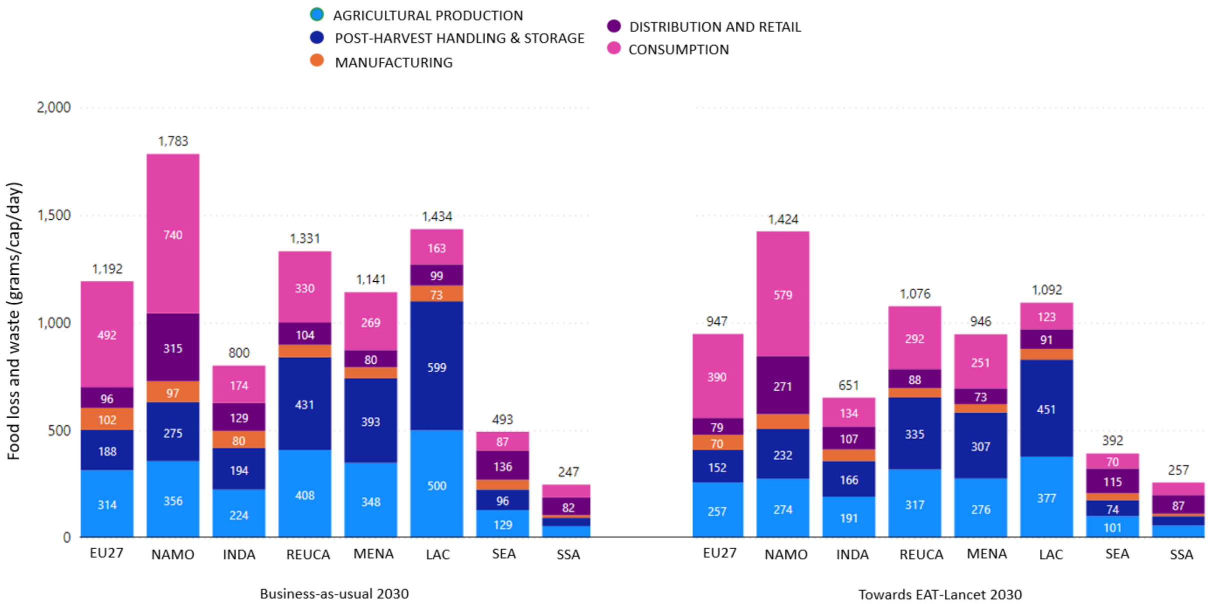

Figure S15. Grams of FLW generated per-capita/day along FSC stages in different regions (2030, by scenario). FLW amounts refer to total final consumption of food excluding biomass losses in non-food biomass use, including both domestic and FLW embedded in imported food. Note we attribute FLW in imports to the location of final consumption but depending on the FSC where FLW occurs the FLW may not be physically present in the location of final consumption.

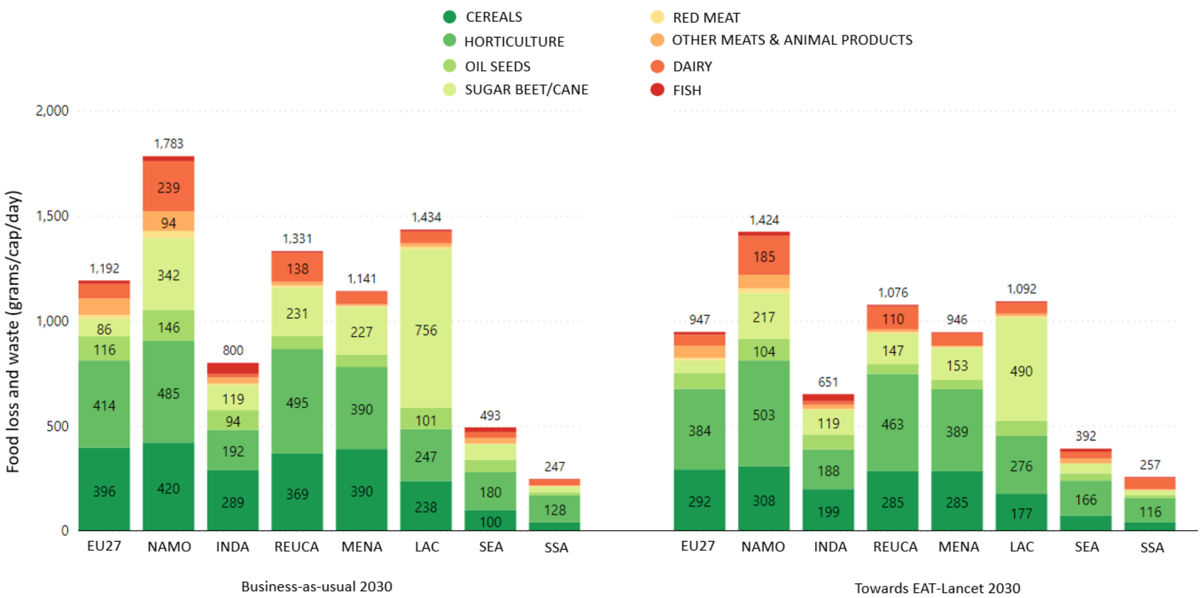

Figure S16. **Composition of grams of FLW generated per-capita/day in different regions (2030, by scenario).** FLW composition refers to different types of FLW generated by the final consumption of listed food products, domestically or embedded in imports.

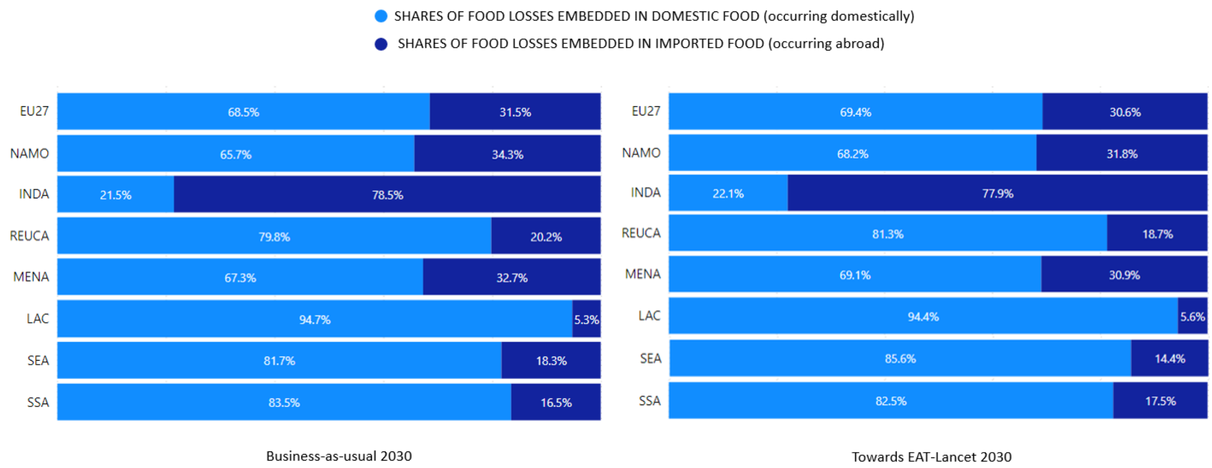

Figure S17. Shares of source of grams of food losses (thus excluding consumption waste) generated per-capita/day in different regions (2030, by scenario). Amounts indicate if losses are generated from domestically produced food products (i.e. all stages from farm to fork are in the same region), or from products that have been imported at one or more stages of the FSC and then consumed domestically. Figure S17 shows that transitioning to the EAT-Lancet diet affects the source shares of generated losses mainly in higher-income regions such as the Europe-27, and North America & Oceania. This is mainly due to decreasing imports of plant-based foods generating farm-level losses in exporting low- and mid-income regions. For this, as the EAT-Lancet diet decreases food trade, shares of losses generated domestically simultaneously increase.

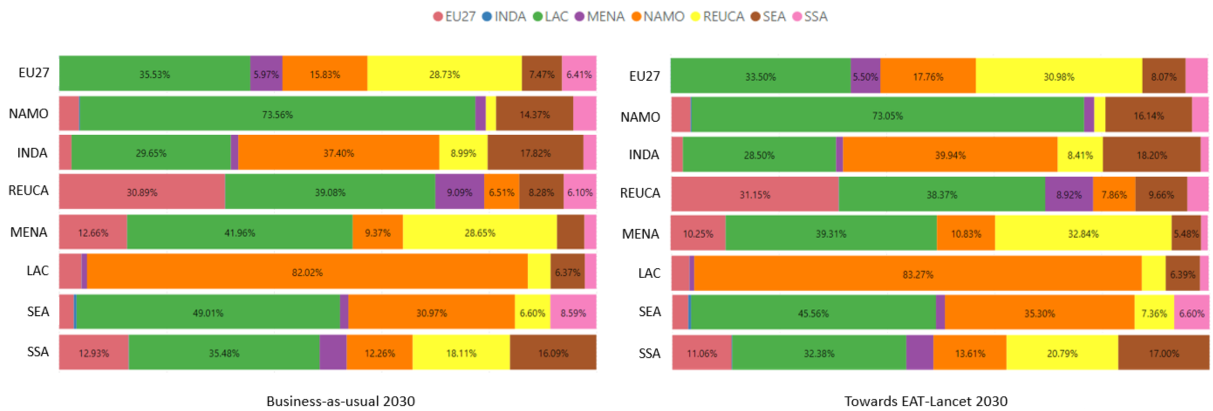

Figure S18. Regional source shares of food losses per-capita/day (excl. consumption waste) generated abroad hence embedded in food imports in different regions (2030, by scenario). Amounts refer to food losses generated by products that have been imported from the regions indicated in the legend at one or more stages of the FSC and then consumed domestically. Figure S18 decomposes the imports shares reported in figure S17, illustrating regional sources of import-embedded food losses.

Chapter 5

Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system

Abstract

Feeding animals with low-opportunity-cost feed (LCF) such as agricultural residues and by-products, and better use of local feed resources are discussed as strategies for transitioning towards more circular food systems. This study incorporates technical characteristics of livestock production into a global economic model to investigate the economic and environmental effects of these circular food system transitions in the European Union (EU27) in relation to the policies used to reach them. We compare the impact of LCF stimulating subsidies, budget-neutrality and import tariffs stimulating domestic sourcing. Providing only subsidies increases circularity and agricultural wages (0.1 to 0.3%), but also animal production (0.1 to 1.5%) with negative indirect effects on land use (0.3 to 1.1%) and emissions (1.3 to 8.0%). Promoting the use of LCF through budget-neutral subsidies and domestic feed sourcing through import tariffs, decreases animal production (-0.1 to -1.6%) and GHG emissions in agriculture (-0.4 to -6.0%). Synergy effects from subsidising DDGS, a biofuel by-product used as feed, increase biofuel production, positively contributing to lower GHG emissions (-0.3 to -0.6%) in 2030. However, budget-neutrality drives land use up (0.1 to 0.5%) while decreasing agricultural wages (-0.1 to -0.3%). This calls for complementary policies to mitigate drawbacks and enhance benefits of a more circular agri-food system in the EU27 in 2030.

This chapter is based on:

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5.1 Introduction

Animal-sourced foods (ASF) dominate the environmental impacts of our food system (ASF) (Hilborn et al., 2018; Herrero et al., 2015; Poore & Nemecek, 2018; Steinfeld et al., 2006). Animal feed plays a major role (Salami et al., 2019), accounting for 45% of greenhouse gas (GHG) emissions from the livestock sector (Gerber et al., 2013), occupying 70% of the global agricultural land (Steinfeld et al., 2006) and utilising 30-40% of human-edible feed crops (Erb et al., 2012). As historically ASF demand increases with rising incomes (Cole & McCoskey, 2013; Schader et al., 2015), expected global population and prosperity growth cause serious environmental concerns. To tackle this challenge, current studies identify solutions in more circular agri-food systems with a particular role for livestock (Röös et al., 2017; van Hal et al., 2019; Van Zanten et al., 2019; De Boer & van Ittersum, 2018). Low-opportunity-cost feed (LCF) such as discarded biomass, plant residues, by-products, and food loss and waste, typically compete less for land or natural resources and represent an important human-inedible feed resource for livestock production (Salami et al., 2019). Upcycling LCF to replace human-edible feed crops in animal diets represents a first strategy for transitioning towards a more circular food system as it mitigates food-feed competition and could contribute to reducing the environmental impacts of global livestock production (van Hal et al., 2019). On top of this, a second strategy for circularity consists in feeding livestock through a better use of local resources (De Schutter, 2017; Stephens et al., 2020; European Commission, 2020). Decreasing feed imports in EU27 can reduce the negative environmental externalities associated with feed production and trade (IPES-Food, 2022), simultaneously increasing the availability and reuse of domestic LCF (Van Zanten et al., 2019).

Despite the recognized environmental benefits of circular agri-food systems (Röös et al., 2017; van Hal et al., 2019; Van Zanten et al., 2019; De Boer & van Ittersum, 2018), limited knowledge exists on the economic implications of policy interventions that foster this transition when market mechanism are taken into account (Ominski et al., 2021). Increasing the reuse of LCF while simultaneously decreasing feed imports alters demand for agricultural residues and industrial by-products (such as oilcakes, distillers' dried grains (DDGS) or molasses) suitable as animal feed, affecting agricultural and industrial production systems. Substituting compound feed and feed crops with LCF may jeopardise the income of stakeholders in the agricultural sector, including livestock and animal feed producers. A higher demand for domestic resources and agricultural residues may drive up crop production, intensifying demand for land, chemical fertilizers use, and GHG emissions. Similarly, a higher use of industrial by-products (e.g. from biofuels) as animal feed risks to increase production and supply of primary commodities generating by-products, increasing GHG emissions. In the absence of a parallel increase in demand this may reduce sectoral revenues and in turn affect wages. Effective design of policies thus requires an economy-wide assessment of the potential consequences of transitioning towards a circular food system.

The EU27 stands actively as global promoter of circular policies (European Commission, 2020; 2021c), but no official policy has yet been established to achieve circularity within agri-food systems. Policies such as tax incentives for reused products, environmentally-motivated subsidies on loss/waste reuse, and recycled content requirements can promote resource efficiency (European Commission, 2020), incentivizing more sustainable material reuse (OECD-G20, 2021). However, devising policies for circular food systems transitions requires an interdisciplinary understanding of its technical and socioeconomic consequences.

Technical studies (van Hal et al., 2019; van Selm et al., 2022; Van Zanten et al., 2019) outline the possibilities of using LCF as feed or closing nutrient cycles through circular systems (Wiel et al., 2019). However, biophysical optimization models (Muscat et al., 2021; Frehner et al., 2022; van Zanten et al., 2023; Van Selm et al., 2023) frequently employed to explore the effects of adopting circularity, ignore opportunity costs, price changes, and other market responses crucial for devising the effect that policy interventions could have in practice. On the other hand, economic assessments of circular food systems (Pagotto & Halog, 2016; Winning et al., 2017; Donati et al., 2020; Donner et al., 2020) are rather scarce, and often overlook biophysical and technical constraints of circularity as they often rely on economic money-based frameworks. Bridging disciplines, additional studies (Salemdeeb et al., 2017; Tarifouris & Martin, 2021; Awasthi et al., 2022) linked economic optimization procedures or life-cycle assessments (LCA) to technical inquiries on circularity. Several economywide models (Godzinski, 2015; Fujimori et al., 2017; Winning et al., 2017; Stadler et al., 2018) include waste management and material recovery but primarily focus on the upcycling of discarded metals, providing no inquiry on biomass reuse. Van Meijl et al. (2018) incorporate various biobased residues into a global economic framework to formulate policies that promote the use of secondary biomass for bioenergy, but such framework does not account for the potential reuse of these residues as animal feed.

Global general equilibrium (GE) models are useful for analysing circular economy policies that involve multiple agents, countries, and integrated sectors within a market environment (McCarthy et al., 2018; Winning et al., 2017). GE models depict interactions among producers along global supply chains and consumer responses to changing prices and incomes, analysing endogenous economic-wide price effects and socioeconomic and environmental impacts crucial for assessing the consequences of circularity measures. However, GE models do not fully account for biophysical or nutritional balances (Pauliuk et al., 2017; Pyka et al. 2022) nor livestock feeding constraints necessary for quantifying the implications of circular policies targeting livestock production. As GE models might misrepresent biophysical flows during simulations (Delzeit et al., 2020, Pyka et al., 2022), their standard framework impedes the accounting of technical features and dietary constrains of different types of livestock when policies changing feed supply and livestock production are applied. While previous studies (Britz & van der Mensbrugghe, 2018; Chepeliev, 2022; Gatto et al., 2023) have integrated physical biomass data into GE models, none has investigated circular food system solutions including a detailed technical modelling of livestock systems.

In this study, we combine economic and technical modelling of circularity in livestock production to evaluate the impact of circular agri-food policies in the EU27. A novelty of this research is the enhancement of a global GE model with physical biomass tracing and improved modelling of the technical requirements of livestock production and feeding. This extension of existing work aims to account for the dietary constraints and nutritional requirements of various livestock species while capturing the behavioural responses of economic actors along global supply chains when policies promote LCF use as feed. In substituting primary feed with LCF we verify feed-conversion-ratios (FCR) and energy supply in animal diets, describing and contextualising cases where energy supply and livestock requirements are imbalanced. This makes a first step towards integrating biophysical balances and livestock feeding constraints into GE models, which is crucial for evaluating circular agri-food system policies.

5.2 Methods

Modelling circular flows in livestock production systems

To investigate the impact of policies towards more circular livestock systems in EU27, we use a global GE model. GE models provide economy-wide coverage, offering a detailed representation of value flows throughout the economy which allows an in-depth understanding of economic adjustments when policies favouring the use of LCF are implemented. For this study we use MAGNET[13] (Modular Applied GeNeral Equilibrium Tool), a recursive dynamic variant of the well-known Global Trade Analysis Project (GTAP) model (Corong et al. 2017), with a specific focus on agri-food sectors and the rest of the bioeconomy (Van Meijl et al., 2006, Woltjer et al., 2014. Van Meijl et al. 2020a; 2020b, Leclere et al., 2020, Gatto et al., 2023). The version of MAGNET utilised for this study is based on the GTAP 10 database (Aguiar et al., 2019). We extended the model with livestock and feed specific parameters to capture the dietary constraints and nutritional requirements of various livestock species while modelling the implications of policies to promote the use of LCF and domestic feed sources.

As a first step towards including aforementioned biophysical constraints we distinguished four different feed sectors supplying animal-specific feed based on the suitability of each feed type per livestock category. Livestock type specific feed needs are generally glossed-over by GE models. The additional feed details allow us to calculate the feed-conversion-ratios (FCR), defined as a ratio between feed inputs (Mtons) and livestock production (Mtons), and the energy requirements (gross energy and crude protein) for each livestock sector before and after policies change (detailed calculations are reported in the Supplementary Information). To foster a circular agri-food system, we focus on partly replacing primary feed (i.e. feeding crops and compound feed) with LCF derived from by-products and agricultural residues. By-products comprise oilcakes, molasses, and distillers' dried grains (DDGS) respectively generated from the production of vegetable oils, refined sugars and biofuels, and fishmeal, already largely used as animal feed. Agricultural residues are obtained from agricultural production of several cereals and horticulture commodities. More detailed information on model changes and feed sources in MAGNET is provided in the Supplementary information.

In the integration of physical quantities, we preserve the consistency of a GE framework, while better representing biophysical balances and technical input substitution possibilities. We follow the approach of Gatto et al. (2023) manipulating the standard GTAP-based MAGNET database to obtain a closer representation of material flows. For primary commodities we convert dollar-based quantities to physical units (Mtons) derived from FAOSTAT and World Bank (2014), allowing a complete tracing of physical flows through the global economy. To address nutritional balances in livestock diets we verify our results by calculating FCRs (on the basis of physical quantity, protein, and energy) and compare those to values reported in literature (see Supplementary Information). First, we quantify the production output (Mtons) of livestock sectors in MAGNET, and define the nutritional supply required to produce this output of live animals, in terms of physical quantities, energy, and protein. Then the composition of total feed supplied to each livestock sector is specified, indicating the type of products and their energy and protein content. We then verify that in the processes of substituting primary feed with LCF the overall nutritional supply required for healthy feed remains preserved across model simulations. As we do not fully represent livestock diets by omitting grass, hey, and other types of animal-based by-products and residues, feed-conversion-ratios from literature for certain livestock have been adjusted accordingly. Further model details, nutritional balance calculations, and detailed composition of animals' diets are available in the Supplementary information.

Towards more circular livestock system scenarios

We use 2020 as base year and define our business-as-usual (BAU) scenario from the IMF-World Economic Outlook projections for GDP and population (IMF, 2022), projecting changes in the global economy towards 2030 (Table 5.1). We compare our BAU scenario with scenarios simulating different circular policies. To promote higher use of

[13] For more detailed information visit www.magnet-model.eu

LCF (first strategy) and increase use of domestic feed sources (second strategy) we examine subsidies on LCF use, import tariffs on primary feed (compound feed and feed crops), and combinations of both strategies.

Table 5.1. Overview of regional macro drivers in our model from 2020 to 2030.

		REGION SPECIFIC SHOCK (% change)	
		Population growth	GDP growth
Macro drivers in BAU scenario[+]	EU27	0.6	39.1
	BRA	4.8	60.8
	CHN	-0.5	82.8
	USA	3.1	42.9
	SEA	7.2	77.6
	INDA	-2.1	29.0
	NAMO	8.3	58.6
	LAC	7.5	52.4
	REUCA	3.2	48.3
	MENA	11.6	72.5
	SSA	19.4	76.0

Notes: [+]Population and GDP projections from the International Monetary Fund (IMF, 2022) covering the period between 2020-2030.
EU27 = European Union-27; BRA = Brazil; CHN = China; USA = United States of America; SEA = Southeast Asia; INDA=Industrialised Asia; NAMO = North America & Oceania; LAC = Latin America & Caribbean; REUCA = Rest of Europe & Central Asia; MENA = Middle East & North Africa; SSA = Sub-Saharan Africa.

In the base year LCF makes up 10.2% of the total feed supply, while 88.8% of feed is sourced domestically within the EU27. Subsidies can be budget-neutral or non-budget-neutral. Budget-neutral subsidies, in line with the first strategy, are financed through endogenous ad-valorem taxes on domestic non-LCF feed use by livestock sectors in EU27. Non-budget-neutral subsidies are funded from the general government budget, i.e. are non-specific in terms of where the funds are coming from. In the case of budget-neutral subsidies, taxes are levied on domestic compound feed and feed crops. This first of all addresses the fiscal implications of the subsidy, raising the required funds from the livestock sectors benefiting from the subsidy instead of putting this burden on the broader economy. Secondly, by taxing the feed inputs that the circular policy intends to replace, budget-neutrality strengthens the impact of the LCF subsidies. To address the second strategy for circularity we introduce import tariffs to stimulate the use of more local resources of animal feed. Tariffs are levied on imported compound feed and feed crops (cereals and horticultural products) demanded by livestock sectors. Finally, we investigate the combination of LCF subsidies and import tariffs at different levels, addressing two main pillars of circularity: promoting LCF use and stimulating domestic sourcing of animal feed.

First, we investigate which combination of instruments and magnitude of interventions presents the best option for promoting a circular agri-food system without generating significant spillover effects. Following, we analyse the impact of two prototypical policy scenarios in non-food sectors, delving deeper into the economy-wide synergies and trade-offs of circular policies beyond agrifood sectors.

5.3 Results

To address our first research question we test the impact of policies promoting different levels of LCF subsidies, import tariffs, and combinations of both interventions on variables key for a circular agri-food system transition, such as livestock and feed production, land use and GHG emissions. Based on the model's response to different magnitudes of interventions (see Supplementary Information, section "Enhanced modelling of livestock systems and circularity"), we introduce a range of subsidies (both non-budget neutral and budget neutral) varying between 20% and 70% to investigate the first strategy for circularity, and a stand-alone import tariff of 60% to investigate the second strategy. The chosen policy scale is determined by the negligible impact smaller policy changes exert on the analysed variables, and on the fact that stronger policies do not provide additional insights into the interaction between key variables.

The Economic impacts of policies promoting animal feed for a circular food system

Financing subsidies on LCF through general government spending (non-budget-neutral subsidies – blue bars in Figure 5.1) increases feed use as livestock production expands in response to the subsidy stimulus (Panel A and D - Figure 5.1). The subsidy reduces average LCF costs, increasing its share in total feed (10.2% in baseline) from 12.0% (with a 20% non-budget neutral subsidy) up to a 33.6% (with a 70% non-budget-neutral subsidy) (Panel B - Figure 5.1). Regardless of the subsidy level, subsidies to LCF stimulate production of primary crops generating agricultural residues which, due to the expansion of livestock production and thus feed demand, results in a stronger increase in crop production (Panel E - figure 5.1), positively influencing labour demand and average low-skilled wages in agriculture (Panel F – Figure 5.1).

Financing LCF subsidies by imposing taxes on compound feed and feed crops (budget-neutral subsidies – orange bars in Figure 5.1) decreases livestock feed demand, total feed supply (Panel A - Figure 5.1), and livestock production (Panel D - Figure 5.1). Taxes increase costs of primary feed inputs, encouraging their replacement with subsidized LCF which increase within total feed supply from a 12.2% (with a 20% subsidy) up to a 40.5% (with a 70% subsidy) (Panel B - Figure 5.1). As taxes reduce demand for crops from livestock and compound feed sectors, average unskilled wages in agriculture decline as demand for agricultural products decreases in response to higher prices (+0.1% with a 20% subsidy to +0.7% with a 70% subsidy), and workers transition from relatively more labour-intensive livestock sectors to the crop sectors, which on average rely more on land.

Imposing a high tariff (TAR 60%) on imported feed stimulates the use of domestic feed (Panel C - Figure 5.1) while having a small negative impact on livestock production levels (Panel D - Figure 5.1). A stand-alone import tariff mainly reduces compound feed due to its relatively large import volume compared to other feed. A lower demand for imported compound feed indirectly increases domestic feed crops demand, resulting in a small increase in total feed use (Panel A – Figure 5.1). While not severely affecting livestock production levels (Panel D – Figure 5.1) or shares of LCF within total feed (Panel B – Figure 5.1), such shift in feed demand can contribute to a circular food system as it promotes domestic feed sourcing. Nonetheless, negative wage effects additionally occur when a stand-alone import tariff is imposed as agri-food prices increase, lowering demand.

Combining subsidies with import tariffs has varying impacts on LCF use and domestic feed production. When subsidies are not budget-neutral, adding a 20% or 60% import tariff boosts domestic feed (crop) and livestock production (Panel C, D and E – Figure 5.1). In contrast, combining any import tariff with budget-neutral subsidies further decreases total feed demand and livestock production (Panel A and D – Figure 5.1). Here, a rise in budget-neutral subsidies results in a stronger decrease in livestock production compared to rising import tariffs (Panel D - Figure 5.1) as budget-neutral subsidies increase costs of domestic primary feed more. Finally, while combining tariffs with budget-neutral subsidies leads to a stronger decrease in agricultural low skilled wages, coupling any level of import tariffs with non-budget-neutral subsidies partially contains the increase in agricultural wages.

As changes by livestock type follow the same pattern we focus the main text on the impact on the total livestock sector, providing in the Supplementary Information detailed results on changing livestock-specific production volumes, diets, feed-conversion-ratios, and energy supply.

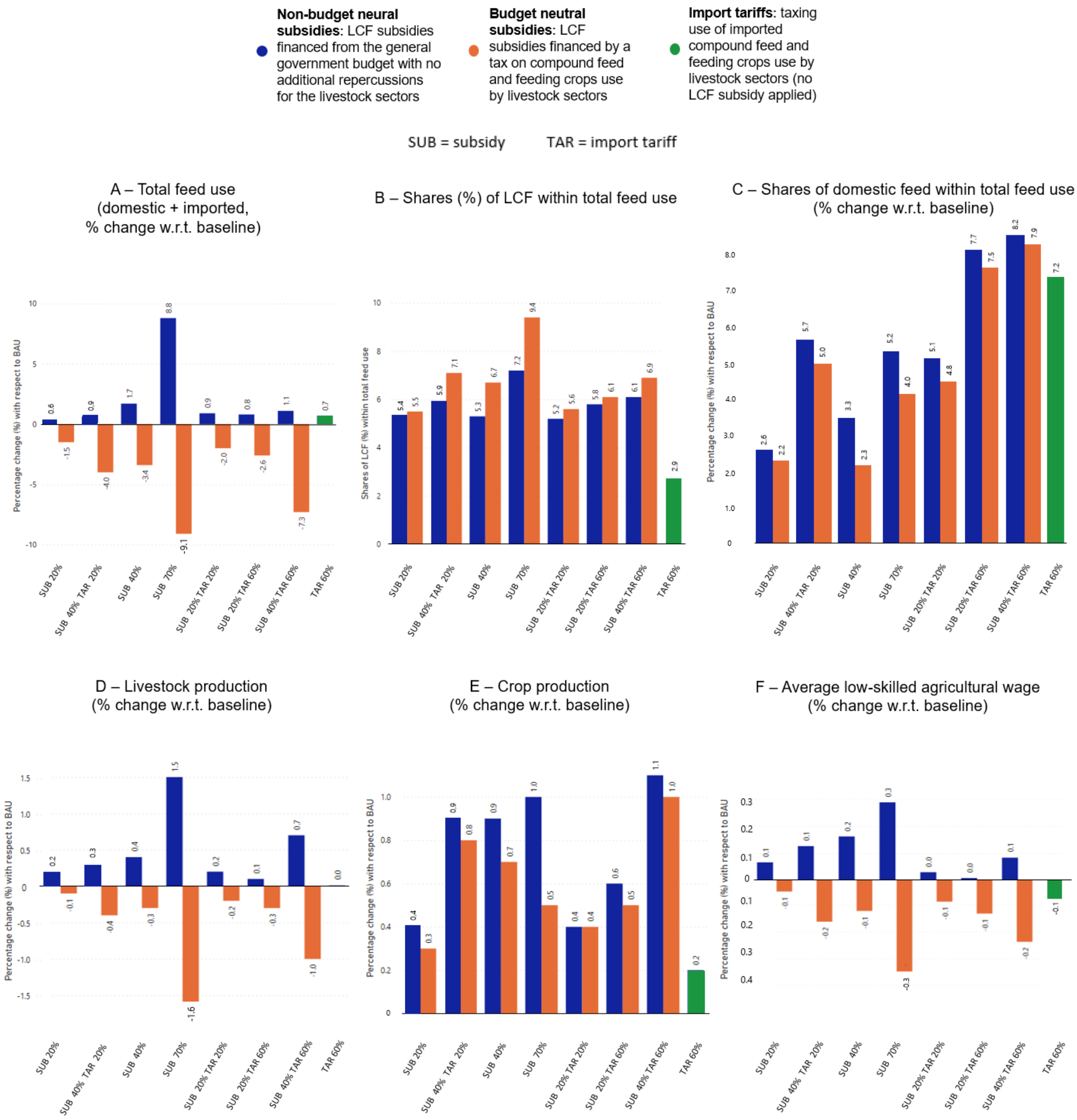

Figure 5.1. Overview of the economic impact of policy instruments promoting a circular livestock system in EU27 in 2030. Estimates illustrated in the figure report changes (%) with respect to our business-as-usual (BAU) scenario in 2030. The only exception regards Panel B, where estimates refer to shares of low-cost-opportunity feeds (LCF) i.e. agricultural residues and by-products, within total feed use (domestic and imported) by livestock sectors in the EU27. Panel A illustrates how different policies affect total feed use (domestic and imported) in the EU27. Panel B reports the shares of LCF within total feed supply, illustrating the degree of circularity achievable under each policy combination. Panel C reports the impact of policies on the shares of domestic feed within total feed use by livestock sectors in the EU27. Paned D reports changes of livestock production under different policy combinations. Panel E illustrates changes in crop production under different policy combinations. Panel F illustrates changes in average low-skilled wages in agricultural sectors (crops and livestock) in the EU27 under different policy combinations.

The environmental impacts of policies promoting animal feed for a circular food system

Rising non-budget neutral subsidies from 20% to 70% proportionally leads to a higher increase in crop and pastureland within the EU27 (Panel A and B – Figure 5.2) due to an expansion of livestock and crop production which parallelly drives GHG emissions from agriculture (Panels D, E, and F – Figure 5.2).

Differently, applying budget-neutral subsidies limits the increase in crop production and crop land use within the EU27 (Panel E – Figure 5.1 and Panel B – Figure 5.2) as taxes shrink demand for feeding crops from livestock and compound feed sectors. Despite budget-neutral subsidies reduce livestock production, the use of pastureland from livestock sectors decreases at a lower rate (Panel A – Figure 5.2). This is because financing subsidies through taxes on primary feed indirectly stimulates the use of pastureland for ruminants sectors, maintaining land into production. As a result total land use increases under both subsidy schemes, being higher under non-budget-neutral subsidies given the expansion of both crop and livestock production (Panel C – Figure 5.2). Nonetheless, as budget-neutral subsidies reduce livestock production and related GHG emissions (Panel D – Figure 5.2), total agricultural emissions in the EU27 decrease (Panel F – Figure 5.2). This is primarily driven by decreased livestock emissions which, in the case of budget-neutral subsidies, offsets the increase in crop-related emissions linked to higher crop production volumes (Panel E – Figure 5.1 and Panel E – Figure 5.2).

While standalone tariffs affect crop production, land use, and emissions (Panels B and E – Figure 5.2), these effects intensify when tariffs are combined with any type of subsidy. Particularly, when tariffs accompany non-budget neutral subsidies, there are sharper increases in total land use and agricultural emissions (Panels C and F – Figure 5.2) as increasing non-budget neutral subsidies boost the demand for domestic feed and livestock production, exacerbating related environmental impacts. On the contrary, when budget-neutral subsidies are combined with tariffs, there's a more significant reduction in total agricultural emissions (Panel F – Figure 5.2). This effect occurs because higher budget-neutral subsidies reduce livestock production to a greater extent, compensating for the emissions increase resulting from expanded crop production.

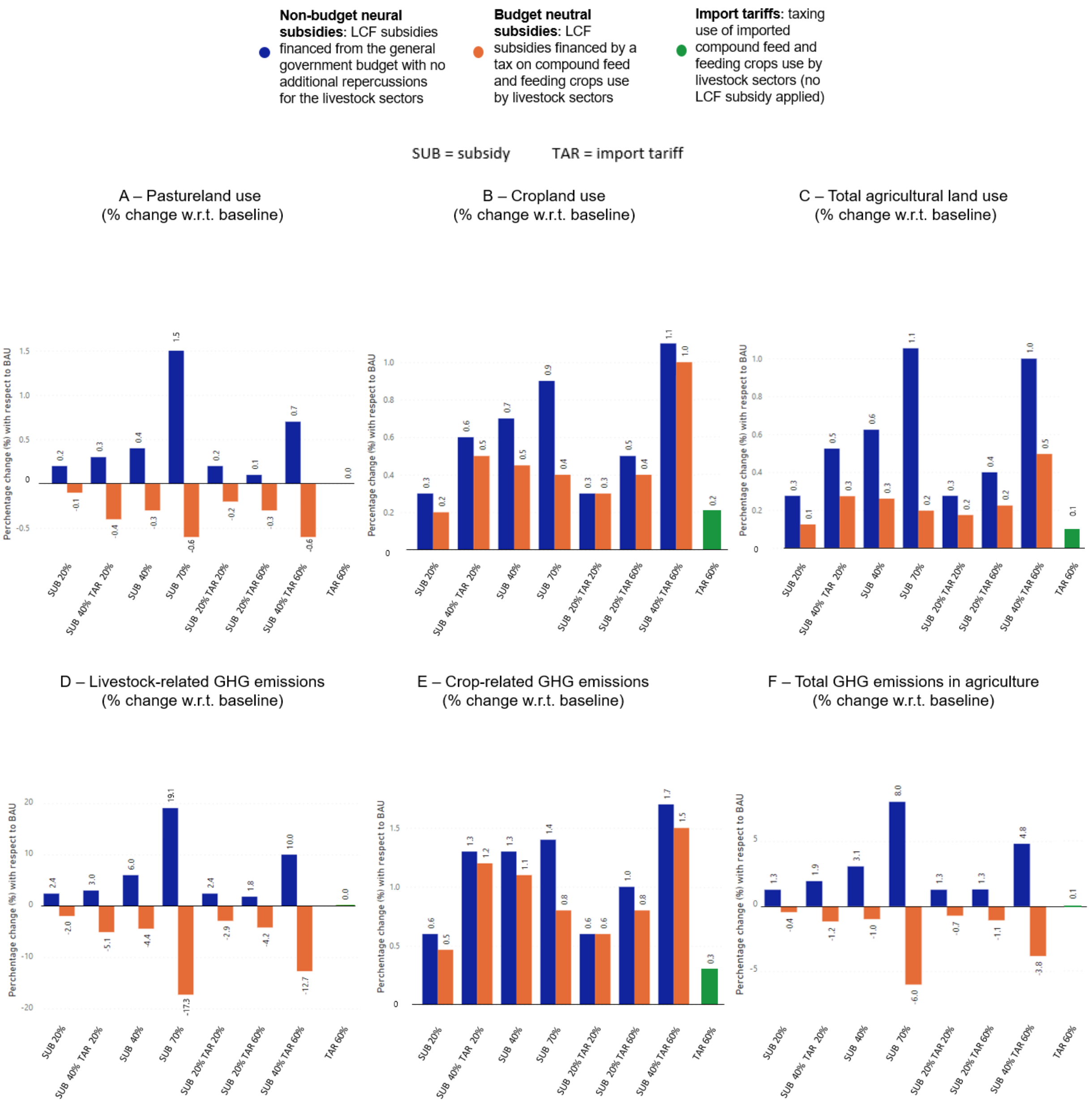

Figure 5.2. Overview of the environmental impact of policy instruments promoting a circular livestock system in EU27 in 2030. Estimates illustrated in the figure report changes (%) with respect to our business-as-usual (BAU) scenario in 2030. Panel A reports changes in total pastureland (demanded by livestock sectors) under different policy combinations. Panel B reports the changes in total crop-land (demanded by crop sectors) under different policy combinations. Panel C reports changes in total agricultural land (crop land and pastureland) under different policy combinations. Panel D reports changes in livestock-related emissions (generated by livestock production) under different policy combinations. Panel E reports changes in crop-related GHG emissions (generated by crop production) under different policy combinations. Finally, panel F illustrates changes in total GHG emissions in agriculture (from crops and livestock sectors) associated with different policy combinations.

5.3.3 A Weak and Strong Circular Economy Scenario

From our policy instrument analysis we observe that while budget-neutral subsidies have a slightly negative effect on agricultural wages, they are preferrable to non-budget-neutral subsidies as the budget-neutral subsidies lead to higher levels of LCF within total feed, without increasing feed and livestock production and thus avoiding an increases in GHG emissions. In this section we select two prototypical policy scenarios from the interventions discussed above to illustrate their impacts on biomass trade and non-agricultural sectors. We use these scenarios to showcase impacts on different livestock productions, diet composition, FCRs, and energy requirements, reporting more detailed results in the Supplementary Information. Our prototypical scenarios consist of a “weak circular economy” (WCE) scenario, where a 20% budget-neutral subsidy on LCF use is provided to livestock sectors, and a “strong circular economy” (SCE) scenario where a 40% budget-neutral subsidy on LCF use as feed and an 20% import tariff on compound feed and feed crops is imposed in the EU27. A detailed scenario description is provided in Table 5.2 below. The WCE scenario is equal to the SUB 20% and the SCE scenario is equal to SUB 40% TAR20% in the section above and impacts on production, land use, low skilled wages and emissions can be found in Figure 5.2. The next section discusses additional economy wide impacts beyond agriculture.

Table 5.2. Overview of magnitude of selected policy interventions to promote a circular agri-food system in the in EU27 in 2030.

		Weak Circular Economy scenario (WCE)		Strong Circular Economy scenario (SCE)	
Source of input	**Feed inputs demanded by livestock sectors**	**TAX (%) (budget-neutral tax rate)**	**SUBSIDY (%) (budget-neutral)**	**TAX (%) (budget-neutral tax rate)**	**SUBSIDY (%) (budget-neutral)**
Domestic	CEREALS	2.7*		6.6*	
	HORTICULTURE	2.7*		6.6*	
	COMPOUND FEED	2.7*		6.6*	
	AGRICULTURAL RESIDUES		20.0		40.0
	BY-PRODUCTS		20.0		40.0
Imported	CEREALS			20.0**	
	HORTICULTURE			20.0**	
	COMPOUND FEED			20.0**	
	AGRICULTURAL RESIDUES				
	BY-PRODUCTS				

*Size of the ad-valorem tax levied to finance the subsidy (endogenously computed in the model based on the response to the LCF subsidy).
**Import tariff levied to crops and horticultural products demanded by livestock sectors. Import tariffs do not apply to imported crops and horticultural products demanded by other sectors in the economy.

The impacts of policies promoting animal feed for a circular food system on industrial by-products, biomass competition, trade, and economywide GHG emissions

Both the WCE and the SCE scenarios increase demand for by-products as animal feed, leading to an increase in demand and production of the main commodities generating them (Panel A - Figure 5.3) as the overall profitability of sectors improves with higher demand and thus prices for by-products. In the WCE scenario, production primarily increases for biofuels generating distillers' dried grains (DDGS) (+15.5%), and processed fish generating fishmeal (+1.1%). The production of molasses (a by-product of refined sugars) increases relatively less (+0.4%) due to the high use of molasses in other production processes (i.e., processed foods) which limits its use as animal feed. In the SCE scenario, we find a more significant increase in the production of biofuels (DDGS, +45.2%), processed fish (fishmeal, +2.6%), and vegetable oils (oilcakes, +1.1%) with again a relatively minor impact on the production of refined sugars (molasses, +0.7%).

Expanding biofuel production drives demand for domestic and imported energy crops (WCE +30.1%; SCE +46.5%), contributing to the increase in cropland. The subsidy leads to a higher demand for DDGS (and biofuel), while the tax imposed for financing the subsidy reduces demand for feed, making it more advantageous to cultivate crops for energy production rather than for animal feed. As a result, domestic biomass is redirected towards other uses (including energy), reducing its availability for food and feed production (Panel B – Figure 5.3). Compared to BAU, policies in the WCE scenario slightly increase domestic biomass allocation towards other uses (+0.1%), decreasing biomass use for feed (-0.2%) and food (-0.02%). In the SCE scenario changes are more significant, as biomass allocation to other use increases (+0.4%), while decreasing for feed (-0.4%) and food (-0.03%).

The import tariff primarily impacts main feed-exporting regions such as LAC and Rest of Europe & Central Asia (REUCA), decreasing exports of feeding crops (average -19.2%) towards EU27. However, higher imports of food (+2.3%) and non-food biomass (average +2.2%) counterbalance the negative effects of the tariff and result in expanding crop imports in the EU27 (+1.9%). Imports of ruminant and poultry meat increase by an average of 2.1%, mainly from LAC, REUCA, and Southeast Asia. Similarly, the higher production of biofuels drives imports of energy crops (WCE +2.5% ; SCE +4.1%), particularly increasing imports of sugar beet/cane from SSA, LAC, Brazil, and REUCA. The crop price increase in both scenarios (WCE +0.4%; SCE +0.9%) drives imports of crops (Panel C – Figure 5.3). In WCE, imports increase for primary fresh food (+1.1%) and other non-food uses (average +0.7%), originating primarily from Latin America & Caribbean (LAC) and Sub-Saharan Africa (SSA). Average imports of non-feed crops increase in the SCE scenario (+1.9%) as such crops are not subject to feed tariffs and freeing domestic biomass for feed use. The decrease in imported biomass use for animal feed and the increase in biomass use for food and energy (Panel A - Figure 5.3), result in a decrease of imports of grains in favor of sugar beet/cane and wheat, respectively used for energy production and food consumption. Despite this, the regional sourcing of biomass remains largely unchanged, with REUCA, LAC, and SSA remaining the main primary biomass import sources of the EU27.

On the export side, while the crop price increase reduces feed and food biomass exports (WCE -0.3%; SCE -1.4%), the increasing production of biofuels leads to higher exports (WCE +7.2%; SCE +21.5% - categorized under "other use (energy)" in Panel C – Figure 5.3), primarily towards Brazil, Industrialized Asia, and United States. Increased availability of biofuels also decreases EU27 demand for refined petroleum products from, both from domestic (WCE -0.3%; SCE -0.5%) and imported (WCE -0.02%; SCE -0.05%) sources. The substitution from fossil to biobased sources occurs mainly in transportation and chemical sectors. As a result non-agricultural emissions decrease across scenarios (WCE -0.3%; SCE -0.5%) and lead to lower total GHG emissions (WCE -0.3%; SCE -0.6%) in the EU27 (Panel D – Figure 5.3).

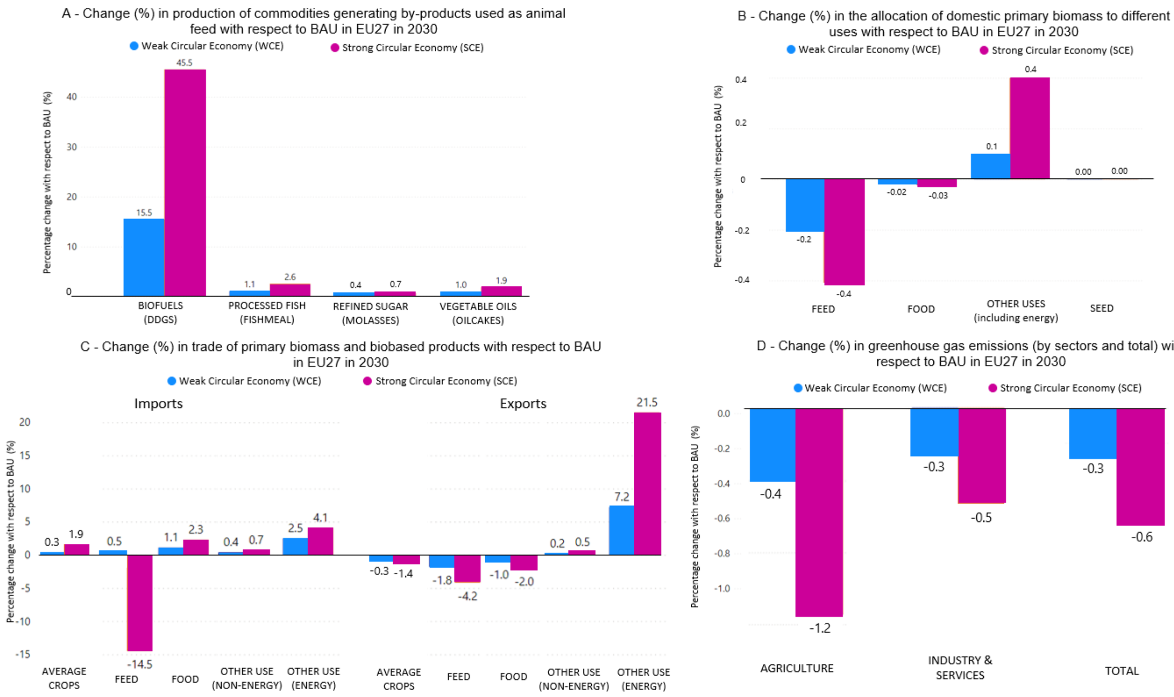

Figure 5.3. Changes in production of by-products, biomass allocation, trade, and greenhouse gas emissions in the EU27 in 2030 (by scenario). Estimates refer to percentage change (%) in our circular policy scenarios with respect to our business-as-usual (BAU) scenario in 2030. Panel A illustrates change (%) in production of commodities generating by-products under our policy scenarios in 2030. Panel B illustrates change (%) in the allocation of domestically produced primary biomass in the EU27 to different uses (feed, food, other uses, and seed) under our policy scenarios in 2030. Here "other uses" refers to the use of biomass in industrial non-food sectors such as textile, chemical, and bioenergy sectors. Panel C reports changes in trade of primary biomass and biobased products under our policy scenarios in 2030. "Average crops" refers to a change in the weighted average of all traded crops (cereals and horticulture) in the EU27. The "feed" category refers to feed crops as well as processed compound feed. Similarly, the "food" category refers to trade of primary fresh agri-food products as well as processed foods. The "other use (non-energy)" category refers to trade of biomass products (fresh and processed) used in industrial non-food non-energy sectors such as textile or chemical sectors. Differently, the "other use (energy)" category refers to trade of biomass products used to produce bioenergy, including trade of energy crops as well as biofuels. Finally, Panel D illustrates changing greenhouse gas emissions by sectors and in total under our policy scenarios in 2030.

5.4 Discussion

This study analyses economywide and environmental impacts of policies promoting a more circular food system with a focus on livestock. We use a global general equilibrium (GE) model to explore subsidies and import tariffs on agriculture and non-agricultural products. The novelty of our study revolves around improved modelling of livestock systems by including livestock specific feed constraints in monetary CGE models, addressing a key limitation of these models (Pauliuk et al., 2017; Pyka et al. 2022). The expansion of our economic model in terms of modelling technical aspects of livestock production provides an understanding of the economic feasibility of strategies aiming to improve circularity in agri-food systems while respecting biophysical constraints on livestock production. Our results show that subsidies on LCF use and import tariffs on compound feed and feed crops are able to increase LCF shares in total feed while promoting a higher use of domestically sourced feed, key in a circular agri-food system.

A core finding is that well-designed budget neutrality of policies is crucial as it turns an expansion of livestock production and total feed use induced by a pure subsidy into a contraction, limiting negative indirect production-related effects, such as increased land use and GHG emissions. This becomes especially relevant for the EU27 policymakers as core agricultural policies in the EU27 (e.g. CAP 2023-27, the New Green Deal) often promote subsidies without well-designed accompanying taxes. This neglect of the indirect production stimulating effect of subsidies risks generating potential environmental drawbacks. However, while budget-neutral policies might be preferred for promoting circularity given their positive impact on GHG emissions and land use, the price increase generated by the taxes decreases agricultural low-skilled wages in the EU27. This supports the inverse correlation between rising agri-food prices and agricultural wages (Swinton and Young, 2001; Sumner et al., 2017; European Commission, 2018), and contributes to ongoing debates on circularity in the EU27 (European Commission, 2020; 2021c) illustrating that a circular agri-food system transition may come at a labour cost often not accounted for by technical studies (De Boer & van Ittersum, 2018; Billen et al., 2021; Karlsson et al., 2021).

We find lower magnitudes of policy interventions do not significantly increase shares of LCF within total feed use but increasing magnitude of interventions can lead to more severe externalities on land use and agricultural wages. The size of the interventions is therefore crucial and becomes especially relevant when envisioning a livestock sector heavily reliant on LCF (van Zanten et al., 2019; Wiel et al., 2019, van Hal et al., 2019, Sandström et al., 2022). While a stand-alone stronger subsidy (e.g. 40% or 70%) increases negative externalities (GHG, land use), a viable option to increase the degree of circularity of the EU27 food system lies in complementing a budget-neutral subsidy with a low import tariff. This policy combination, tested in our prototypical “strong circular economy” (SCE) scenario, allows to promote LCF and domestic feed use, reduces emissions in agriculture and overall economy within the EU27, without severely affecting land use and wages in comparison to other investigated policy options. Additionally, we find a positive contribution to lower GHG emissions through interactions with non-agricultural sectors illustrating the relevance of using a GE model. Positive effects in agriculture are observed only when budget-neutral subsidies are introduced as such interventions directly decrease primary livestock production, an important source of agricultural emissions in the EU. While this contributes to the discussion on practical policy tools for promoting circularity to address GHG emissions, it also emphasizes that the GHG mitigation potential of policies to promote LCF and local feed use in livestock production is limited, underscoring the need for more stringent complementary policies to meet the agricultural emission targets outlined in the New EU Common-Agricultural-Policy (CAP27). The analysis of our prototypical scenarios illustrates furthermore that promoting the use of by-products as animal feed may increase the production of main commodities. In the case of biofuels generating DDGS as a by-product, we find mixed effects. A higher biofuel production increases demand for energy crops, contributing to increasing land demand while diverting domestic biomass towards industrial uses. However, higher biomass imports counterbalance the negative effects of feed tariffs on main EU27 trading partners, compensating potential welfare losses abroad. Parallelly, the higher availability of biofuel reduces demand for refined petroleum products, increasing the use of more sustainable biobased energy sources. The total reduction in GHG emissions in the EU27 reinforces the benefits achieved by policies in agriculture, further contributing to economywide EU27 emission targets in 2030.

Finally, while prior economic research on large-scale livestock-focused circular food systems is rather limited, available technical inquiries provide results largely not comparable to those from our analysis. Technical studies often present a different set-up of scenarios, investigating more explorative extreme scenarios in which e.g. livestock systems entirely rely on secondary feed or domestic feed sources (Van Selm et al., 2023). In contrast, our study presents policy scenarios that closely align with current feeding practices, providing a more accurate representation of real-world conditions. For this, reproducing such scenarios into our economy-wide model would result rather unfeasible as monetary constraints as well as rational economic behaviour of agents within our model contrast by design with the extreme scenarios detectable only with biophysical models. Nonetheless, the different approaches can enrich each other's and assist researchers and decision makers by providing different pieces of the same puzzle. While technical approaches may learn, for example, from the potential rebound effects revealed by an economy-driven approach, economic enquiries may benefit from understanding how a sustainable future would look like when non-monetary objectives become leading. In this study, we aimed to bridge part of the gap between disciplines by enhancing the representation of biological systems (animals, crops) in a GE model for an integrated assessment of circularity.

The mixed impacts found across sectors and indicators show that to increase the effectiveness of a transition towards circular food systems complementary policies should be implemented. Taxation on animal-sourced foods (currently applied or debated in several countries) or changes in regulations to allow and favour the reuse of discarded biomass as animal feed (Zu Ermgassen et al., 2016), may constitute viable solutions for decreasing pressures on land in the EU27. Relaxing regulations for upcycling secondary biomass as animal feed can increase LCF supply, limiting the high increase in crop production linked to the higher demand for agricultural residues. This could additionally avoid increasing land use and prices, limiting the rise in agricultural imports and negative spillovers to agricultural wages.

With regards to wage losses in agriculture, a potential approach is to provide temporary compensation through income subsidies, such as the current direct payment system within the EU, recognising the need to safeguard the welfare of the main actors in the food system when policies for sustainability are implemented. In this, policies should facilitate the transition of workers towards non-agricultural sectors by implementing specialized training and educational programs. These initiatives aim to provide workers with better opportunities to explore alternative employment options, particularly in cases where agricultural wages decrease. Finally, while our policies promote an increase in the domestic sourcing of feed, which benefits material and nutritional cycles, targeting only the feed sector leads to a higher dependency on imports of non-feed biomass. This underscores the risks associated with implementing policies focusing on a single sector and emphasizes the need for more comprehensive and cross-cutting policies to effectively address potential spillover effects on agriculture as a whole and the broader economy. As always, our findings are subject to several limitations. A more detailed distinction between cattle (sheep, horses, others), poultry (broilers, hen, etc) or aquaculture (marine fish, freshwater fish, molluscs, etc) would have provided more specific impacts of circular policy measures. Similarly, the inclusion of additional feed types such as pasture grass, hay, animal by-products, minerals, and additional plants, currently beyond the scope of our current modelling framework, would have enhanced the calculation of nutritional balances, enriching our analysis. This limitation becomes apparent when having a closer look at the diets (Tables S10a-g in Supplementary Information). Across our investigated scenarios, FCRs for each livestock sector are close to reference estimates observed in literature. The only exception is represented by bovine cattle which presents a relatively lower FCR compared to literature as several feed products (i.e. hay, pasture grass) are not integrated in our model and thus omitted from nutritional calculations. However, the differences in FCRs and energy and protein content across scenarios, although small, indicate that livestock productivity might be affected. Further research could therefore improve our economic framework by differentiating livestock by productivity level and including species specific requirements such as maximum inclusion levels for certain ingredients. This becomes especially relevant when investigating scenarios with higher shares of LCF or diets that might compromise the productivity of specific livestock production systems. Moreover, further research could improve the modelling of livestock-related GHG emissions. As we quantify GHG emissions from livestock sectors based on the number of livestock, we ignore changing animal emissions linked to livestock dietary shifts, being already included in the national GHG inventory of some EU27 countries.

5.5 Conclusion

Feeding animals with low-opportunity-cost feed (LCF) such as agricultural residues and by-products, and better use of local feed resources are potential strategies for transitioning towards more circular food systems. We find providing only subsidies increases circularity and agricultural wages but also animal production, exerting negative indirect effects on land use and GHG emissions. Differently, we find promoting the use of LCF through budget-neutral subsidies and domestic feed sourcing through import tariffs, decreases animal production and GHG emissions in agriculture. Relevant synergy effects are found from subsidising DDGS, which indirectly increases biofuel production, positively contributing to lower GHG emissions in 2030. However, we find budget-neutrality drives land use up while decreasing agricultural wages. Thes findings indicate that integrating technical and economic modelling of circularity and adopting an economywide perspective, allows identification of trade-offs of circular policies often overlooked when adopting a technical perspective or focusing solely on the livestock sector. While circularity is an important initial step in mitigating GHG emissions, policymakers need to adopt a multidisciplinary approach to effectively address these trade-offs. This involves implementing complementary policies to tackle negative spillovers and ensure a successful transition towards a sustainable food system in the EU27 by 2030.

Supplementary Information for

Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system

Contents

Model definition

We used the Modular Applied General Equilibrium Tool (MAGNET) for our analysis. MAGNET is a multi-regional, multi-sectoral applied computable general equilibrium (CGE) model. It is an advanced recursive dynamic version of the Global Trade Analysis Project (GTAP) model (Corong et al. 2017) which has been extended to allow integrated assessments focusing mainly on food and biomass production. MAGNET has been used for simulating global policies on agriculture, trade, and the bioeconomy (Francois et al., 2005, Van Meijl et al., 2018), assessing impacts on a wide range of indicators including agricultural markets, food security (Gatto et al., 2023; Van Meijl et al., 2020a; 2020b) and sustainability (Perez-Dominguez et al., 2021; Leclere et al., 2020). Its detailed representation of biobased materials, including by-products and residues from agricultural and forestry sectors, enables modelling circular flows in agriculture, investigating the replacement of primary agricultural inputs with secondary biobased alternatives.

As a CGE model, MAGNET solves through adjusting prices such that all markets for factors (land, labor, capital, natural resources) and commodities (good and services) simultaneously clear. Producers (one for each sector-region combination) respond to changing prices for inputs (factors and intermediates) based on profit maximization. With constant returns to scale production producers operate under zero-profit conditions. Representative private households (one for each region) respond to changing incomes earned with factor sales and changing prices of commodities for consumption based on utility maximization limited by the household's income constraint. International trade flows are modelled bilaterally between all regions with regional sourcing of imports governed by the Armington assumption which allows two-way trade flows. Figure S1 outlines the structure of MAGNET with the interactions between production, trade, and consumption.

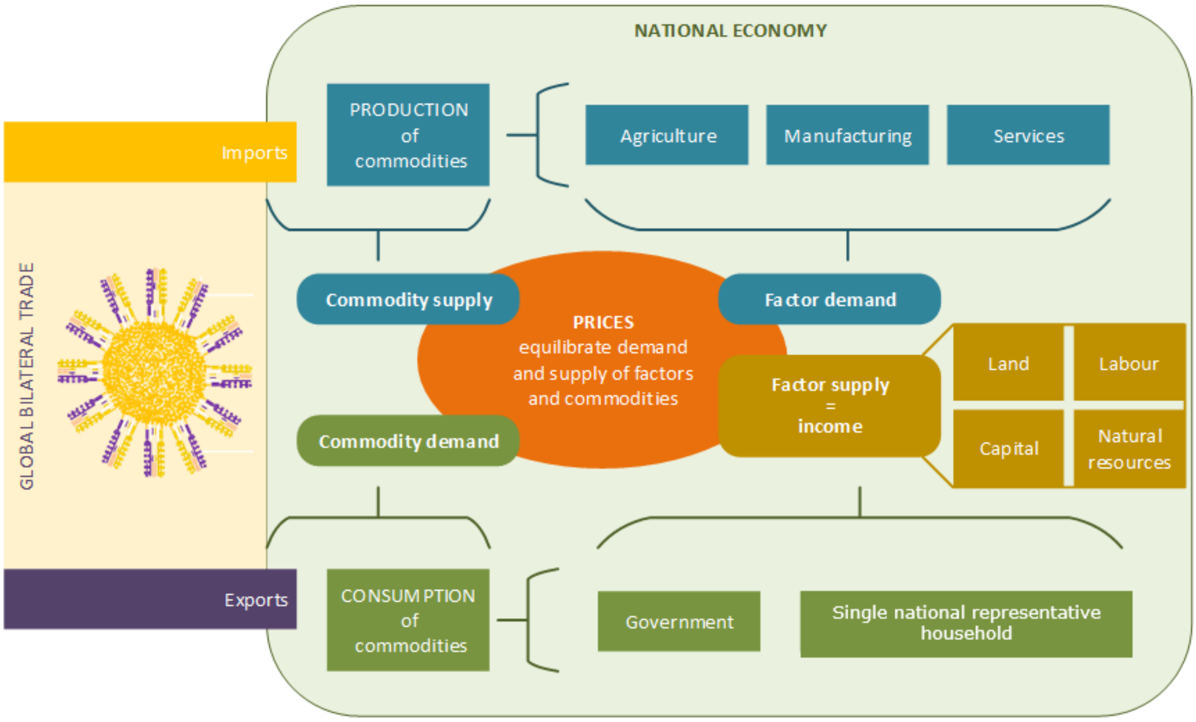

Figure S1. Schematic outline of the structure of MAGNET and the circular flow of money and commodities through the global economy.

A distinguishing feature of MAGNET is its modular structure, allowing the model to be easily tailored to specific research questions, regions, and products of interest. As a global CGE model MAGNET covers the entire global economy, with extensions adding detail on food and biomass production and use not available from other CGE models. Modules relevant for the current study are the flexible nested CES production trees (allowing for more substitution possibilities than in the standard GTAP model), endogenous land supply (allowing land areas to expand and contract depending on demand), flexible nested CET land allocation (governing the movement of sluggish land across sectors depending on the ease of switching between different types of land use), purchasing power adjusted CDE demand function (adjusting income elasticities in baseline projections to attain a more plausible pattern in food demand when incomes rise substantially), and segmented factor markets (capturing diverging labor and capital price developments in agricultural and non-agricultural sectors).

The total agricultural land supply is determined by a land supply curve, which specifies the relation between the real agricultural land rent and agricultural land area in squared kilometers (km^2) (see Figure S2). The general idea underlying the land supply curve specification is that the most productive land is first taken into production. The potential for bringing additional land into agriculture production is limited to the maximum potentially available land. That maximum is defined based on regional data regarding land use (e.g. arable land, forestry, pasture areas, fallow land etc.) and is arranged in order of diminishing productivity. Eickhout et al. (2009) assume that land rents and yields are related in that increasing yields result in lower land rents and vice versa, which gives a land supply curve in which the total amount of land used in production is an increasing function of land rent.

If the gap between the potentially available agricultural land and the land used in the agricultural sector is large, an increase in demand for agricultural land will lead to land being converted to agricultural land and a modest increase in rental rates to compensate for the cost to put this land into production (see left part of Figure S2). Such a situation is illustrated by points situated on the left, flat part of the land supply curve. However, once nearly all agricultural land is in use, an increase in demand for agricultural land will mainly lead to large increases in land rental rates (land becomes scarce, see right part of Figure S2). In this case, land conversion is difficult to achieve and therefore the elasticity of land supply with respect to land rental rates is low as well. Additional land is brought into production until the point where the benefit of the last (additional) hectare of land (hence marginal benefit), measured by its marginal value, equals the cost of making an extra hectare of land suitable for cultivation.

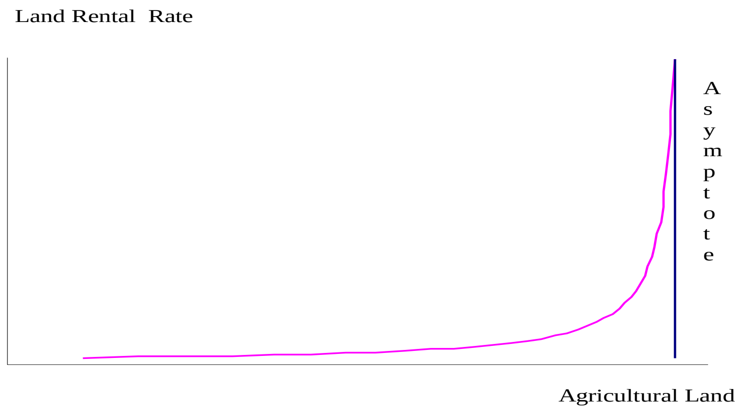

Figure S2. Land supply curve determining land conversion and land rental rate.

Greenhouse Gas (GHG) emissions representation follow the approach of Adams et al. (2015) which in turn is based on material found in Adams and Parmenter (2013). The accounting of Greenhouse Gas (GHG) emissions is expressed in units of CO2-equivalent. Different categories of emissions emanate from:

- the combustion of fossil fuels — the burning of carbon-based fuels derived from coal, oil (burnt in its processed form as petroleum products and other refinery products) and gas; and
- as a consequence or by-product of undertaking specific activities, such as certain agricultural activities and industry processes (non-combustion)

Emissions can be modelled from the quantity of each fossil fuel used (for combustion emissions) and the level of each relevant activity (for non-combustion emissions) by applying the appropriate emissions coefficient. If Q denotes the physical quantity of a particular fossil fuel burnt (such as tons or liters) or activity undertaken (such as cubic meters of gas extracted or the number of cattle) and the corresponding emissions coefficient is C (tons of CO2-e per ton or liter of that fuel burnt or per unit of activity undertaken), CO2-e emissions are defined as:

$$E = C \times Q \qquad (1)$$

With the percentage change form of equation (1) being:

$$e = c + q \qquad (2)$$

A key MAGNET extension for the current study is improved tracing of biophysical quantities through the global economic system by computing “dollar-based physical quantities” from the standard dollar-based GTAP database values by subtracting taxes and international trade margins for imports (Gatto et al., 2023). These dollar-based quantities satisfy the material balance constraints with minor divergences in longer run projections originating in the value-based CES functions governing production. Regionalized material balances can be computed from changes in these dollar-based quantities provided by the MAGNET model. In the case of biomass these flows allow consistent tracing of flows through the global economy including use for feed, food, and non-food products. As MAGNET traces bilateral trade flows between regions, the impact of changing trade patterns is captured as well.

The model aggregation adopted for this study involves 11 regions (Table S1), each comprising 73 production sectors (Table S2). Sectors demanding and supplying biomass are represented as explicitly as possible given the data provided by the GTAP 10 database (Aguiar et al. 2019). Livestock systems (Table S3) are represented by 7 different sectors producing bovine (meat) cattle, other cattle (smaller ruminants), dairy cattle, swine, poultry, wool (sheep), fish and aquaculture. Feed production is represented by 4 sectors producing compound feed for cattle, swine, poultry and fish and aquaculture, and is additionally complemented by feed obtained directly from cereals and horticultural sectors. Secondary feed sources i.e. low cost-opportunity-feed (LCF) are represented by 4 types of by-products including oilcake, distiller’s dried grains (DDGS), molasses and fishmeal, and by agricultural residues obtained from cereals and horticultural sectors. Table S4 reports the different types of primary and secondary feed currently supplied to animals in MAGNET. To ease model running time and interpretation of results, we aggregate the several sectors not relevant to our analysis into two categories, namely “manufacturing” and “services”, in line with the focus of our study on feed, livestock and biomass flows.

Table S1 - Regional model aggregation

Region	Description	Countries
EU27	European Union 27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
BRA	Brazil	Brazil
CHN	China	China
USA	United States of America	United States of America
NAMO	North America and Oceania	Australia, New Zealand, Rest of Oceania, Canada, Rest of North America, Rest of the World
INDA	Industrialised Asia	Hong Kong, Japan, South Korea, Taiwan, Singapore
LAC	Latin America and Caribbean	Mexico, Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Belize, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean
MENA	North Africa and Middle East	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Iraq, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic (Syria), Yemen, Egypt, Morocco, Tunisia, Algeria, Libya, Western Sahara
REUCA	Rest of Europe and Central Asia	United Kingdom, Switzerland, Norway, Iceland, Liechtenstein, Albania, Belarus, Russian Federation, Ukraine, Moldova, Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Holy See (Vatican City State), Isle of Man, Jersey, Macedonia, Republic of, Monaco, Montenegro, San Marino, Serbia, Kazakhstan, Kyrgyzstan, Tajikistan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia
SEA	Southeast Asia	Mongolia, Democratic People's Republic of Korea, Macao, Brunei Darussalam, Cambodia, Indonesia, People's Democratic Republic of Lao, Malaysia, Philippines, Thailand, Viet Nam, India, Nepal, Pakistan, Sri Lanka, Myanmar, Timor-Leste, Afghanistan, Bhutan, Maldives
SSA	Sub-Saharan Africa	Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Cape Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone, Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, South Central Africa, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Angola, Congo, Democratic Republic of the, Botswana, Namibia, South Africa, Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia, Sudan, Lesotho, Swaziland

Table S2 - Sectoral model aggregation

MAGNET aggregate	Description	GTAP sectors	Aggregation used for figures and analysis in main text
pdr	Paddy and processed rice	pdr	Cereals
wht	Wheat	wht	Cereals
grain	Cereal grains	gro	Cereals
veg	Vegetables	v_f	Horticulture
fruit	Fruit	v_f	Horticulture
nuts	Nuts	v_f	Horticulture
roots	Roots and tubers	v_f	Horticulture
pulses	Pulses	v_f	Horticulture
oils	Oil seeds	osd	Horticulture
sug	Sugar cane, sugar beet	c_b	Horticulture
oagr	Other agriculture	pfb	Horticulture
crops	Crops	ocr	Horticulture
pltry	Poultry sector	oap	Horticulture
cattle	Bovine cattle sector	ctl	Poultry
othctl	Sheep, goats, horses, and other ruminants	ctl	Bovine cattle (meat)
pigpls	Pig and other animal products	oap	Other ruminants
wol	Wool, silk-worm cocoons	wol	Swine
milk	Dairy cattle and raw milk	rmk	Other ruminants
frs	Forestry	frs	Bovine cattle (dairy)
wfish	Wild fish	fsh	-
coa	Coal	coa	-
c_oil	Crude oil	oil	-
gas	Gas	gas	-
manu	Manufacturing	oxt, nmm, i_s, nfm, fmp, ele, eeq, ome, mvh, otn, omf	-
othcmt	Meat: other cattle, sheep ,goats, horses and other ruminants	cmt	-
othmt	Other meat product	omt	-
pcr	Processed rice	pcr	-
sugar	Sugar and molasses	sgr	-
pulmt	Poultry meat	omt	-
bfmt	Beef meat	cmt	-
ofd	Processed food	ofd	-
dairy	Dairy products	mil	-
texplus	Textiles, leather and wearing apparel	tex, wap, lea	-
petro	Petroleum, coal products	p_c	-
chm	Chemical products	chm	-
bph	Basic pharmaceutical products	bph	-
rpp	Rubber and plastic products	rpp	-
ely	Electricity	ely	-
gas_dist	Gas manufacture, distribution	gdt	-
ser	Services	wtr, cns, cmn, ofi, ins, rsa, obs, dwe	-
foodserv	Food services	afs, ros, osg, edu, hht	-
trans	Transport sector	otp, wtp, atp	-
vol	Vegetable oils and fats	vol	-
cvol	Crude vegetable oil	N/A	-
biog	Biogasoline	N/A	-
biod	Biodiesel	N/A	-
fert_n	Fertilizer nutrient n	N/A	-
fert_p	Fertilizer nutrient p	N/A	-
fert_k	Fertilizer nutrient k	N/A	-
ftfuel	Ftfuel 2nd gen biofuel	N/A	-
eth	Ethanol 2nd gen biofuels	N/A	-
ely_c	Electricity from coal	N/A	-
ely_g	Electricity from gas	N/A	-
ely_n	Electricty from nuclear	N/A	-
ely_h	Electricty from hydro	N/A	-
ely_w	Electricty from wind and solar	N/A	-
bioe	Bioelectricity 2nd gen	N/A	-

plan	Plantation	N/A	-
pel	Pellet sector	N/A	-
res	Residue sector	N/A	-
aqcltr	Aquaculture	N/A	-
fishp	Fish processing	N/A	Aquaculture
heat	Heat	N/A	-
bioh	Bioheat	N/A	-
wood	Wood products	N/A	-
ppp	Paper products, publishing	ppp	-
bioph	Bio pharmaceuticals	N/A	-
biopl	Bio plastics	N/A	-
bioch	Bio chemicals	N/A	-
fdctl	Compound feed for cattle (suitable for all ruminants)	N/A	Compound feed
fdpig	Compound feed for pigs	N/A	Compound feed
fdpltr	Compound feed for poultry	N/A	Compound feed
fdfsh	Compound feed for aquaculture	N/A	Compound feed

* A detailed description of the GTAP sectors is available at https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

Table S3 – Livestock production sectors in the model

MAGNET aggregate	Description	GTAP sectors	Aggregation used for figures and analysis in main text
cattle	Beef cattle	ctl	Bovine cattle (meat)
othctl	Sheep, goats, and other ruminants	ctl	Other ruminants
milk	Dairy cattle	rmk	Bovine cattle (dairy)
wol	Wool (sheep)	wol	Other ruminants
pltry	Poultry	oap	Poultry
swine	Pigs	oap	Swine
aqcltr	Aquaculture: Diadromous fish, Fresh water fish, Crustaceans, Marin fish, Molluscs	N/A	Aquaculture

Table S4 – Primary and secondary feed production sectors in the model

Primary feed

MAGNET aggregate	Description	GTAP sectors	Aggregation used for figures and analysis in main text
fdctl	Compound feed for cattle (suitable for all ruminants)	N/A	Compound feed
fdpig	Compound feed for pigs	N/A	Compound feed
fdpltr	Compound feed for poultry	N/A	Compound feed
fdfsh	Compound feed for aquaculture	N/A	Compound feed

Secondary feed – Low cost-opportunity feed (LCF)

MAGNET aggregate	Description	GTAP sectors	Aggregation used for figures and analysis in main text
oilcake	Oilcake obtained from production of vegetable oils	N/A	By-products/ Low-opportunity-cost feed (LCF)
ddgs	Distiller's dried grains obtained from production of biogas	N/A	By-products/ Low-opportunity-cost feed (LCF)
mola	Molasses obtained from production of refined sugar	N/A	By-products/ Low-opportunity-cost feed (LCF)
fishm	Fishmeal obtained from processing of fish and aquaculture products	N/A	By-products/ Low-opportunity-cost feed (LCF)
r_pdr	Agricultural residues from paddy rice production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_wht	Agricultural residues from wheat production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_gro	Agricultural residues from grains production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_osd	Agricultural residues from oil seed production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_ocr	Agricultural residues from other crops production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)

r_veg	Agricultural residues from vegetables production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_frt	Agricultural residues from fruit production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_nuts	Agricultural residues from nuts production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_root	Agricultural residues from roots production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)
r_puls	Agricultural residues from pulses production	N/A	Agricultural residues/ Low-opportunity-cost feed (LCF)

Enhanced modelling of livestock systems and circularity

In the assessment of multidisciplinary challenges, value-based economic models are often criticized for their inaccurate representation of technical features and constraints concerning analyzed subjects. Modelling a transition towards a more circular economy requires understanding the technical characteristics of different materials to address how the upcycling of a secondary material may proficiently serve as production input substituting a primary (raw) material in a production process. Transitioning towards a more circular economy for livestock production entails substituting primary feed with low-cost-opportunity feed (LCF) such as agricultural residues and by-products. Modelling this substitution process from a value-based perspective can lead to plausible results but is insufficient to fully grasp if the extent of circular solutions effectively complies with the nutritional requirements of different livestock types. Feeding cattle with animal-based by-products for example may represent a valid economic solution but would result inconsistent and unfeasible from a technical perspective as cattle are vegetarian animals and cannot eat animal-based products. Such dynamics are often disregarded by economic models and are overlooked in general equilibrium (GE) models where value-based flows hamper a consistent assessment of circular policies from a joint economic and technical perspective. For this, the novelty of this study consists of improving the representation of livestock systems in a GE framework. We include dietary constrains and nutritional intakes of different animals to consistently devise policy solutions for transitioning towards a more circular livestock system.

The first step required to enhance the modelling of livestock systems concerns animal feed supply. In the GTAP framework compound animal feed is categorized under "other food" (ofd) sector. We assume that flows of "ofd" demanded by livestock sectors define the amount of animal feed supplied to livestock for production. As "ofd" is composed by several inputs (primary and processed food types and other non-food inputs), livestock demand for feed indirectly includes feed products that specific animals can not intake due to dietary constrains (e.g. animal-based products included in ofd supplied to cattle). To obtain a feed supply that respects the dietary constrains of different livestock we create, based on the type of livestock included in MAGNET, four different feed types consistently with the dietary restrictions of animals. To do so, we receive inputs from experts[14] on dietary characteristics of each livestock type (sector) included in MAGNET. Based on this information, we split the original flow of feed included in the GTAP framework introducing four feed sectors supplying animal feed to cattle (suitable to all ruminants), swine, poultry, and fish (aquaculture). We modify the social-accounting-matrix (SAM) on which the MAGNET model is based in order to assign correct types of input (i.e. products flowing into feed and

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successively supplied to animals), and a specific cost-structure (based on the inputs demanded) to each animal-specific feed sector. The input constrains of each feed sector and the livestock sectors supplied by different feeds are illustrated in Table A below.

In the GTAP framework, inedible inputs reported in Table A can additionally flow directly from a production sector to livestock. For this we detract from the SAM all the flows of products currently supplied to animal sectors that do not comply with different livestock diets. The majority of GE models do not differentiate between different livestock types when defining the production characteristics of livestock sectors. An additional novelty of our approach consists in assigning a specific production tree and cost structure to each livestock type in order to differentiate between animals according to different production (feed inputs) characteristics. This results particularly determinant for the consistency of our policy analysis. For example if in our policies a specific feed would be targeted with an ad-valorem tax, a livestock sector could substitute the taxed feed input with a relatively cheaper feed input. This means that in the current GTAP framework the cattle sector can possibly substitute a feed input with a feed product that may not respect the dietary constraints of cattle. For this, having animal-specific production trees and no flows of inedible products to each livestock ensures that livestock dietary constrains are consistently respected across model simulations.

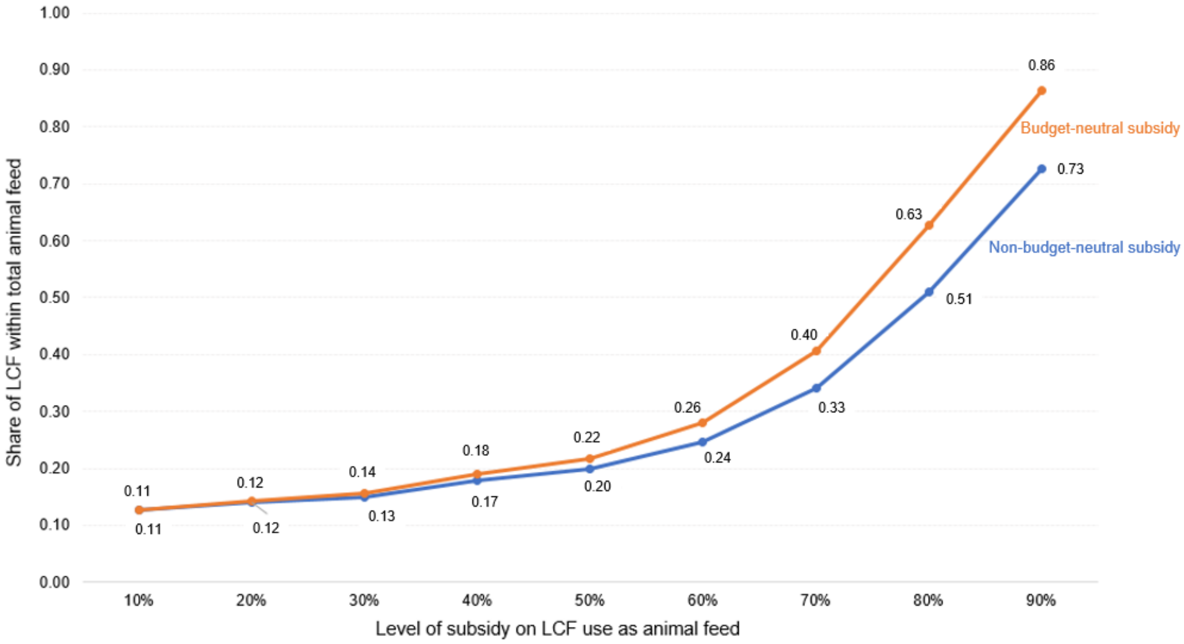
To enhance the modelling of circularity a similar approach is adopted. We analyse livestock circularity from the feed input side. In our framework, a more circular livestock production system entails that primary feed is replaced by secondary low-cost-opportunity feeds (LCF) derived from production process of other commodities. First, based on dietary characteristics of livestock types we define which low-cost-opportunity feeds (LCF) i.e. by-products, agricultural residues, losses and waste, available in MAGNET can be utilized as animal feed. According to the current European Union (EU) regulation (zu Ermgassen et al., 2016) food waste cannot be utilized as animal feed. For this we only include plant-based agricultural residues and food processing by-products such as molasses, distillers' grains with solubles (DDGS), fishmeal, and oilcakes, as potential secondary feed options. Here it is important to note that we treat LCF products as substitutes of primary feed (crops and compound feed), assuming that one unit of primary feed can be replaced by a unit of LCF based on price dynamics derived from our model simulations. A step to further improve our current model framework may entail treating primary feed and LCF as non-perfect substitutes based on different productivity levels of feed and livestock types. As we assess nutritional balances (see "Nutritional Balances" section below) without differentiating livestock or feed by productivity level, we omit potential variations in substitution effects linked to a specific livestock/feed productivity level. Nonetheless, as we address feed-conversion-ratios as well as gross energy and protein requirements, we monitor that in the substitution of primary feed with LCF, the nutritional contents of diets are respected.

Table. A New feed sectors introduced in the MAGNET model

Feed sectors by type	Allowed inputs	Not allowed inputs	Output (livestock sectors supplied)
Feed for cattle (suitable for all ruminants)	Plant-based products and by-products	Animal-based products including by-products and slaughter waste	Bovine cattle (meat & dairy), other ruminants, sheep
Feed for swine	Plant-based and animal-based products including by-products	Swine meat including by-products and swine slaughter waste	Swine
Feed for poultry	Plant-based and animal-based products including by-products	Poultry meat including by-products and poultry slaughter waste	Poultry
Feed for fish (aquaculture)	Plant-based and animal-based products including by-products	Dairy products	Aquaculture

The relationship between policy interventions, LCF use, and feed sourcing in our model is illustrated in figure S3. Panel A illustrates that, from a circularity perspective, our budget-neutral subsidy is preferable to a non-budget-neutral subsidy as for a given subsidy level it to achieves a higher share of LCF within total feed supply. Panel B shows the impact of import tariffs on promoting a domestic feed sourcing in the EU27. The marginal increase in the share of domestic feed decreases as the import tariff level is higher.

Panel A – Impact of subsidising LCF use on shares of LCF within total feed use in EU27 in 2020



Panel B – Impact of import tariffs on compound feed and feed crops on total feed sourcing in EU27 in 2020

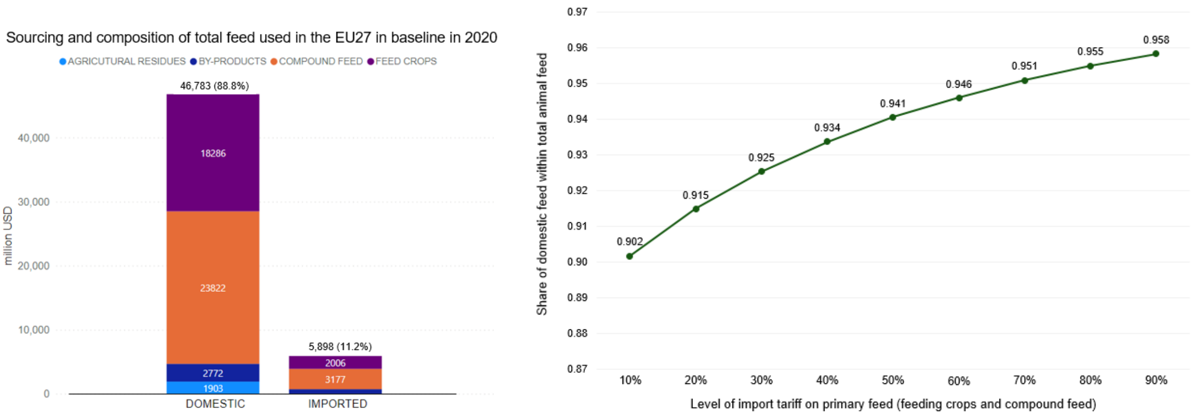


Figure S3. Relationship between policy interventions and shares of LCF within total feed supply. Estimates refer to dollar-based units (USD) in 2020. Panel A illustrates the relationship between subsidies on LCF use (x-axis) and shares of LCF within total feed supply (y-axis) in case of "budget-neutral" subsidies (orange) and "non-budget-neutral" subsidies (blue) in EU27 in 2020. The curve in blue illustrates how the application of different subsidy levels affects the shares of LCF within total feed supply in the case of a "non-budget-neutral" policy where the subsidy is not financed by a dedicated tax but drawn from the general government budget. The orange curve illustrates the effects of different subsidy levels on the shares of LCF within total feed supply in the case of a "budget-neutral policy" where the subsidy is fully financed by a tax levied on domestic primary animal feed use by livestock sectors in EU27. The slope of the orange response curve results becomes steeper after a 30% subsidy, providing a higher share of LCF within total feed supply at a given LCF subsidy level. This is principally due to the tax levied to finance the subsidy which directly increases prices of primary animal feed discouraging its use and thus resulting in a stronger substitution between LCF and primary feed. Panel B illustrates the sourcing and composition of total feed use in EU27 in our baseline (2020), further illustrating the relationship between import tariffs on primary feed (feed crops and compound feed) (x-axis) and shares domestically sourced feed within total feed supply (y-axis). Import tariffs exert a rather weak effect on promoting LCF use as animal feed as the majority (around 89%) of total feed used in the EU27 is domestically sourced. For this, import tariffs have the primary focus to increase domestic sourcing and allow indirectly to increase shares of LCF within total feed use as the primary feed sourced from both domestic and imports becomes more expensive.

Methodology for tracing physical quantities along global food supply chains

The following section provides an analytical description of the methodology adopted for tracing physical quantities in along global FSC in a global general equilibrium framework.

Preparing MAGNET for tracing physical flows

Use of GE models based on GTAP data for analysing changes in physical quantities is not new. The most recent example is the GTAP nutrition database also providing an overview of different existing approaches to tracing physical quantities of nutrition (Chepeliev, 2022). To our knowledge these approaches, among which a nutrition module in MAGNET, use value-based shares in their calculations that do not account for non-material components like tariffs in transport costs. For example, if the consumer expenditures on domestic and imported commodities are used without adjustments imports will get a higher weight than warranted based on their material content, as they include tariffs, export subsidies and transport costs. These non-material components in expenditures become visible when checking material balances from the GTAP data where production quantities should equal intermediate demand by sectors and final demand by the private household, government, and investment.

To assure a balanced starting point for the tracing of physical flows we compute the components of the material balance equations (production and demand categories) in what we call “dollar-based quantities”. They are as close as we can get to material flows using the information in the MAGNET (or GTAP) database. The reference year material balance will hold for each commodity measured in dollar-based quantities. If output is then known, for example the production of wheat in tons, we can convert this balanced dollar-quantity equation to one in physical units.

The computation of the dollar-based quantities proceeds as follows. We compute production, domestic demand and exports without output taxes. These are levied on producers and then implicit in before-tax demand and trade values. Lacking data on regional sourcing of imports by sectors or for final demand we use a proportionality assumption. This allows us to remove tariffs, export subsidies and transport costs (all of which vary by import source region) from the values of import demand for intermediate demand by sectors and for final demand (household, government and investment). Finally the supply of transport services to the global pool is adjusted to reflect the removal of taxes and subsidies on the demand for transport services. As we lack bilateral data on transport service trade we again use a proportionality assumption lowering all supplies to the global pool of transport service by the amount needed to match total demand. The adjustments to the starting database are checked by constructing material balances where production of commodity i in region p needs to match the sum over all regions of intermediate demand for i by all sectors j plus final demand.
A new material balance module is added to MAGNET which adds variables initialized with the dollar-based quantities of production, intermediate and final demand of commodities and trade services. These variables are

connected with existing variables measuring percentage changes in quantities in the MAGNET model. This allows us to recompute the material balances in dollar-based quantities after each model run.
The last step in the tracing procedure is to derive the Leontief inverse. From the new variables expressed in dollar-based quantities we construct regionalized material balances:

$$QO_i^{\,p} = \sum_{c,d} QI_{i,c}^{p,d} + \sum_{a,d} QF_i^{a,p,d}$$

Where $QO_i^{\,p}$ is the production of commodity *i* in region *p*, $QI_{i,c}^{p,d}$ is the intermediate demand for commodity *i* from region *p* by production of *c* in region *d*, and $QF_i^{a,p,d}$ is the final demand for commodity *i* from region *p* by agent (household, government, investment) in region d. This equation describes the direct flows of commodity *i* from region *p* to domestic (*p* =*d*) and foreign (*p* ≠ *d*) intermediate demand next to the flows for domestic and foreign final demand. Final demand, however, also generates an indirect flow of commodity *i* from region *p* to final demand in region *d* through the final demand from commodity *j* which uses commodity *i* in its production process. These direct and indirect flows can be computed through the Leontief inverse. Dividing intermediate demand by total production provides a matrix with Leontief input-output coefficients. Inverting this matrix yields the global Leontief inverse (or multiplier) matrix concisely describing all inputs that are directly or indirectly needed from either domestic or foreign origin for one unit of final consumption ($LI_{i,c}^{p,s}$).

Next to deriving the Leontief Inverse the regionalized material balances also allows us to compute any imbalances appearing in simulations due to value-based aggregations in the CES production functions. While volume preserving additive CES or ACES functions have been developed (van der Mensbrugghe and Peters, 2020) these require physical shares. In MAGNET such volume preserving functions are used for energy blending sectors where all inputs are measured in the same physical unit (amount of energy delivered as electricity) and meaningful physical shares can be computed. In general meaningful physical measures of inputs are, however, not available as sectors use a wide variety of inputs ranging from primary products (generally measured in tons), land (measured in km2) and services (no obvious definition of unit). Van der Mensbrugghe and Peters (2020) also report that the divergence in results of additive and regular specifications varies depending on the elasticities. As the dollar-based-quantities computed for the material balances only correct for a small part of the difference between dollar values and quantities, using these for ACES quantity share calculations is unlikely to make a large difference in model response. As there are only small imbalances when starting from balanced equations that correct for taxes, subsidies and transport costs (see Tables S3, S4) there does not appear a reason to replace value shares by dollar-based-quantity shares.

Compute changes in quantities in physical terms

Tracing of physical quantities of FLW then starts by defining dollar-based quantity flows of production included (directly and indirectly) in final demand:

$$QFD_{i,c}^{p,s,d} = LI_{i,c}^{p,s} * F_c^{s,d}, \qquad (1)$$

where $QFD_{i,c}^{p,s,d}$ represents the production of primary commodity *i,* in region *p,* produced to satisfy final demand of commodity *c*, that is demanded by region *d* from region s. The first term on the right-hand side of the equation represents the Leontief inverse matrix (LI) which specifies the amount of production of commodity *i* from region *p* needed for production of commodity *c* in region *s.* This term thus traces intra-industry flows of intermediate inputs from producer region *p* needed to produce commodities for final consumption (F) in region s. The second term represents final demand and reports for region *d,* how much final product *c* is demanded from region *s*. This term thus captures trade in final products, allowing products to be produced in region *s* to be consumed in a region *d*. In case *s* and *d* are the same this refers to consumption of domestically produced commodities, in case *s* and *d* are different regions it refers to imports from *s* to region *d*. Equation (1) provides a complete description of how production of *i* in region *p* flows to final consumers in region *d*. Based on the Leontief inverse it reports all direct and indirect flows of all commodities within the global economy. To ensure consistency of scenario results, we check that the summing of all commodities *c*, in all regions *s* and *d* equals the production of commodity *i* in region *p*, preserving material balances such that (direct and indirect) demand equals total production when expressed in dollar-based quantities.

As our focus in this study is on FLW we take a subset from the material flow tracing limiting the production of input *a* to primary food products (*primary agriculture*) and final demand *f* to all food commodities supplied to final consumers as primary, processed or via food services (*food*). To integrate physical material flows, we divide equation (1) by total production, specifying how a single unit of output flows through the global economy through its share contained in food products consumed by households ($SH\_QFD_{a,f}^{p,s,d}$):

$$SH\_QFD_{a,f}^{p,s,d} = \frac{QFD_{a,f}^{p,s,d}}{Q_a^p} \quad \text{where } a = \text{primary agricultural inputs and } f = \text{food commodities.} \qquad (2)$$

The numerator is given by equation (1) while the denominator Q_a^p represents total primary agricultural production of commodity *a* in region *p,* reported in dollar-based quantities. We then extend the dollar-based approach by linking these flows to physical production of global biomass (Tons), defined as $Q\_mt_a^p$, where *a* represents the biomass of agricultural output *a* produced in region *p*. Multiplying the (dimensionless) share of primary product directly or indirectly included in each food commodity f with total primary production in tons then yields the agricultural biomass from region p contained in food produced in region s and consumed in region d ($QFD\_mt_{a,f}^{p,s,d}$):

$$QFD\_mt_{a,f}^{p,s,d} = Q\_mt_a^p * SH\_QFD_{a,f}^{p,s,d} \qquad (3)$$

For consistency, as done for equation (1), we check for the counterfactual scenarios that material balances are indeed preserved in physical units. The circular flow of money in the CGE framework depicted in Figure S1 assures that balances are always preserved in dollar values units. Equation (3) describes the global flow of food biomass from farm to fork through global supply chains. It provides a first glance on different stages of global FSC, illustrating how food consumption is linked to primary food production through various stages of processing. Moreover, it captures international trade dynamics, quantifying food production, processing, and consumption in different regions.

Data

Crops and Livestock

To quantify physical biomass production we rely on production data (Mtons) from FAOSTAT (FAO, 2020a). We gather data for livestock and crops production and further integrate additional data from the World Bank[15] for primary production of aquaculture in the European Union-27, not covered in standard FAO production data. Table S5 reports the regional mappings between FAO countries and our MAGNET regions, while Table S6 reports the commodity mappings between FAO commodities and MAGNET sectors. We further report in Table S7 the commodities that have been excluded from the data merging as reported by FAO as non-primary food commodities.

Table S5 – Region mappings between FAO countries and MAGNET regions

FAO country code	FAO country description	FBS country description	GTAP country	MAGNET aggregate
AFG	Afghanistan	Afghanistan	xsa	SEA
AGO	Angola	Angola	xac	SSA
ALB	Albania	Albania	alb	REUCA
ARE	United Arab Emirates	United Arab Emirates	are	MENA
ARG	Argentina	Argentina	arg	LAC
ARM	Armenia	Armenia	arm	REUCA
ATG	Antigua and Barbuda	Antigua and Barbuda	xcb	LAC
AUS	Australia	Australia	aus	NAMO
AUT	Austria	Austria	aut	EU27
AZE	Azerbaijan	Azerbaijan	aze	REUCA
BDI	Burundi	N.A.	xec	SSA
BEL	Belgium	Belgium	bel	EU27
BEN	Benin	Benin	ben	SSA
BFA	Burkina Faso	Burkina Faso	bfa	SSA
BGD	Bangladesh	Bangladesh	bgd	SEA
BGR	Bulgaria	Bulgaria	bgr	EU27
BHR	Bahrain	N.A.	bhr	MENA
BHS	Bahamas	Bahamas	xcb	LAC
BIH	Bosnia and Herzegovina	Bosnia and Herzegovina	xer	REUCA
BLR	Belarus	Belarus	blr	REUCA
BLZ	Belize	Belize	xca	LAC
BOL	Bolivia, Plurinational State of	Bolivia, Plurinational State of	bol	LAC
BRA	Brazil	Brazil	bra	BRA
BRB	Barbados	Barbados	xcb	LAC
BRN	Brunei Darussalam	N.A.	brn	SEA
BTN	Bhutan	N.A.	xsa	SEA
BWA	Botswana	Botswana	bwa	SSA
CAF	Central African Republic	Central African Republic	xcf	SSA
CAN	Canada	Canada	can	NAMO
CHE	Switzerland	Switzerland	che	REUCA
CHL	Chile	Chile	chl	LAC
CHN	China	China	chn	CHN
CIV	Côte d'Ivoire	Côte d'Ivoire	civ	SSA
CMR	Cameroon	Cameroon	cmr	SSA
COD	Congo, the Democratic Republic of the	N.A.	xac	SSA
COG	Congo	Congo	xcf	SSA
COK	Cook Islands	N.A.	xoc	NAMO
COL	Colombia	Colombia	col	LAC
COM	Comoros	Comoros	xec	SSA
CPV	Cape Verde	Cape Verde	xwf	SSA
CRI	Costa Rica	Costa Rica	cri	LAC
CUB	Cuba	Cuba	xcb	LAC
CYP	Cyprus	Cyprus	cyp	EU27
CZE	Czech Republic	Czech Republic	cze	EU27
DEU	Germany	Germany	deu	EU27

[15] https://data.worldbank.org/indicator/ER.FSH.AQUA.MT?end=2014&name_desc=false&start=2014

DJI	Djibouti	Djibouti	xec	SSA
DMA	Dominica	Dominica	xcb	LAC
DNK	Denmark	Denmark	dnk	EU27
DOM	Dominican Republic	Dominican Republic	dom	LAC
DZA	Algeria	Algeria	xnf	MENA
ECU	Ecuador	Ecuador	ecu	LAC
EGY	Egypt	Egypt	egy	MENA
ERI	Eritrea	N.A.	xec	SSA
ESP	Spain	Spain	esp	EU27
EST	Estonia	Estonia	est	EU27
ETH	Ethiopia	Ethiopia	eth	SSA
FIN	Finland	Finland	fin	EU27
FJI	Fiji	Fiji	xoc	NAMO
FRA	France	France	fra	EU27
FRO	Faroe Islands	N.A.	xer	REUCA
FSM	Micronesia, Federated States of	N.A.	xoc	NAMO
GAB	Gabon	Gabon	xcf	SSA
GBR	United Kingdom	United Kingdom	gbr	REUCA
GEO	Georgia	Georgia	geo	REUCA
GHA	Ghana	Ghana	gha	SSA
GIN	Guinea	Guinea	gin	SSA
GMB	Gambia	Gambia	xwf	SSA
GNB	Guinea-Bissau	Guinea-Bissau	xwf	SSA
GNQ	Equatorial Guinea	N.A.	xcf	SSA
GRC	Greece	Greece	grc	EU27
GRD	Grenada	Grenada	xcb	LAC
GTM	Guatemala	Guatemala	gtm	LAC
GUY	Guyana	Guyana	xsm	LAC
HKG	Hong Kong	Hong Kong	hkg	INDA
HND	Honduras	Honduras	hnd	LAC
HRV	Croatia	Croatia	hrv	EU27
HTI	Haiti	Haiti	xcb	LAC
HUN	Hungary	Hungary	hun	EU27
IDN	Indonesia	Indonesia	idn	SEA
IND	India	India	ind	SEA
IRL	Ireland	Ireland	irl	EU27
IRN	Iran, Islamic Republic of	Iran, Islamic Republic of	irn	MENA
IRQ	Iraq	Iraq	xws	MENA
ISL	Iceland	Iceland	xef	REUCA
ISR	Israel	Israel	isr	MENA
ITA	Italy	Italy	ita	EU27
JAM	Jamaica	Jamaica	jam	LAC
JOR	Jordan	Jordan	jor	MENA
JPN	Japan	Japan	jpn	INDA
KAZ	Kazakhstan	Kazakhstan	kaz	REUCA
KEN	Kenya	Kenya	ken	SSA
KGZ	Kyrgyzstan	Kyrgyzstan	kgz	REUCA
KHM	Cambodia	Cambodia	khm	SEA
KIR	Kiribati	Kiribati	xoc	NAMO
KNA	Saint Kitts and Nevis	Saint Kitts and Nevis	xcb	LAC
KOR	Korea, Republic of	Korea, Republic of	kor	INDA
KWT	Kuwait	Kuwait	kwt	MENA
LAO	Lao People's Democratic Republic	Lao People's Democratic Republic	lao	SEA
LBN	Lebanon	Lebanon	xws	MENA
LBR	Liberia	Liberia	xwf	SSA
LBY	Libyan Arab Jamahiriya	N.A.	xnf	MENA
LCA	Saint Lucia	Saint Lucia	xcb	LAC
LKA	Sri Lanka	Sri Lanka	lka	SEA
LSO	Lesotho	Lesotho	xsc	SSA
LTU	Lithuania	Lithuania	ltu	EU27
LUX	Luxembourg	N.A.	lux	EU27
LVA	Latvia	Latvia	lva	EU27
MAC	Macao	Macao	xea	SEA
MAR	Morocco	Morocco	mar	MENA
MDA	Moldova, Republic of	Moldova, Republic of	xee	REUCA
MDG	Madagascar	Madagascar	mdg	SSA
MDV	Maldives	Maldives	xsa	SEA
MEX	Mexico	Mexico	mex	LAC
MHL	Marshall Islands	N.A.	xoc	NAMO
MKD	Macedonia, the former Yugoslav Republic of	Macedonia, the former Yugoslav Republic of	xer	REUCA

MLI	Mali	Mali	xwf	SSA
MLT	Malta	Malta	mlt	EU27
MMR	Myanmar	Myanmar	xse	SEA
MNE	Montenegro	Montenegro	xer	REUCA
MNG	Mongolia	Mongolia	mng	SEA
MOZ	Mozambique	Mozambique	moz	SSA
MRT	Mauritania	Mauritania	xwf	SSA
MUS	Mauritius	Mauritius	mus	SSA
MWI	Malawi	Malawi	mwi	SSA
MYS	Malaysia	Malaysia	mys	SEA
NAM	Namibia	Namibia	nam	SSA
NCL	New Caledonia	New Caledonia	xoc	NAMO
NER	Niger	Niger	xwf	SSA
NGA	Nigeria	Nigeria	nga	SSA
NIC	Nicaragua	Nicaragua	nic	LAC
NIU	Niue	N.A.	xoc	NAMO
NLD	Netherlands	Netherlands	nld	EU27
NOR	Norway	Norway	nor	REUCA
NPL	Nepal	Nepal	npl	SEA
NRU	Nauru	N.A.	xoc	NAMO
NZL	New Zealand	New Zealand	nzl	NAMO
OMN	Oman	Oman	omn	MENA
PAK	Pakistan	Pakistan	pak	SEA
PAN	Panama	Panama	pan	LAC
PER	Peru	Peru	per	LAC
PHL	Philippines	Philippines	phl	SEA
PNG	Papua New Guinea	Papua New Guinea	xoc	NAMO
POL	Poland	Poland	pol	EU27
PRI	Puerto Rico	N.A.	pri	LAC
PRK	Korea, Democratic People's Republic of	Korea, Democratic People's Republic of	xea	SEA
PRT	Portugal	Portugal	prt	EU27
PRY	Paraguay	Paraguay	pry	LAC
PSE	Palestinian Territory, Occupied	N.A	xws	MENA
PYF	French Polynesia	French Polynesia	xoc	NAMO
QAT	Qatar	N.A	qat	MENA
ROU	Romania	Romania	rou	EU27
RUS	Russian Federation	Russian Federation	rus	REUCA
RWA	Rwanda	Rwanda	rwa	SSA
SAU	Saudi Arabia	Saudi Arabia	sau	MENA
SDN	Sudan	Sudan	xec	SSA
SEN	Senegal	Senegal	sen	SSA
SGP	Singapore	N.A	sgp	INDA
SLB	Solomon Islands	Solomon Islands	xoc	NAMO
SLE	Sierra Leone	Sierra Leone	xwf	SSA
SLV	El Salvador	El Salvador	slv	LAC
SOM	Somalia	N.A	xec	SSA
SRB	Serbia	Serbia	xer	REUCA
SSD	South Sudan	N.A	xec	SSA
STP	Sao Tome and Principe	Sao Tome and Principe	xcf	SSA
SUR	Suriname	Suriname	xsm	LAC
SVK	Slovakia	Slovakia	svk	EU27
SVN	Slovenia	Slovenia	svn	EU27
SWE	Sweden	Sweden	swe	EU27
SWZ	Swaziland	Swaziland	xsc	SSA
SYC	Seychelles	Seychelles	xec	SSA
SYR	Syrian Arab Republic	N.A	xws	MENA
TCD	Chad	Chad	xcf	SSA
TGO	Togo	Togo	tgo	SSA
THA	Thailand	Thailand	tha	SEA
TJK	Tajikistan	Tajikistan	tjk	REUCA
TKL	Tokelau	N.A	xoc	NAMO
TKM	Turkmenistan	Turkmenistan	xsu	REUCA
TLS	Timor-Leste	Timor-Leste	xse	SEA
TON	Tonga	N.A	xoc	NAMO
TTO	Trinidad and Tobago	Trinidad and Tobago	tto	LAC
TUN	Tunisia	Tunisia	tun	MENA
TUR	Turkey	Turkey	tur	MENA
TUV	Tuvalu	N.A	xoc	NAMO
TWN	Taiwan, Province of China	Taiwan, Province of China	twn	INDA
TZA	Tanzania, United Republic of	Tanzania, United Republic of	tza	SSA

UGA	Uganda	Uganda	uga	SSA
UKR	Ukraine	Ukraine	ukr	REUCA
URY	Uruguay	Uruguay	ury	LAC
USA	United States	United States	usa	USA
UZB	Uzbekistan	Uzbekistan	xsu	REUCA
VCT	Saint Vincent and the Grenadines	Saint Vincent and the Grenadines	xcb	LAC
VEN	Venezuela, Bolivarian Republic of	Venezuela, Bolivarian Republic of	ven	LAC
VNM	Viet Nam	Viet Nam	vnm	SEA
VUT	Vanuatu	Vanuatu	xoc	NAMO
WSM	Samoa	Samoa	xoc	NAMO
YEM	Yemen	Yemen	xws	MENA
ZAF	South Africa	South Africa	zaf	SSA
ZMB	Zambia	Zambia	zmb	SSA
ZWE	Zimbabwe	Zimbabwe	zwe	SSA

Table S6 – Commodity mappings between FAO commodities and MAGNET sectors

FAO commodity code (CPC code)	FAO commodity description	GTAP sector	MAGNET aggregate
111	Wheat	wht	wht
112	Maize (corn)	gro	grain
113	Rice	pdr	pdr
114	Sorghum	gro	grain
115	Barley	gro	grain
116	Rye	gro	grain
117	Oats	gro	grain
118	Millet	gro	grain
1191	Triticale	gro	grain
1192	Buckwheat	gro	grain
1193	Fonio	gro	grain
1194	Quinoa	ocrops	crops
1195	Canary seed	osd	oils
1199.02	Mixed grain	gro	grain
1199.9	Cereals n.e.c.	gro	grain
1211	Asparagus	v_f	veg
1212	Cabbages	v_f	veg
1213	Cauliflowers and broccoli	v_f	veg
1214	Lettuce and chicory	v_f	veg
1215	Spinach	v_f	veg
1216	Artichokes	v_f	veg
1219.01	Cassava leaves	v_f	roots
1221	Watermelons	v_f	fruit
1229	Cantaloupes and other melons	v_f	fruit
1231	Chillies and peppers, green (Capsicum spp. and Pimenta spp.)	ocrops	crops
1232	Cucumbers and gherkins	v_f	veg
1233	Eggplants (aubergines)	v_f	veg
1234	Tomatoes	v_f	veg
1235	Pumpkins, squash and gourds	v_f	veg
1239.01	Okra	v_f	veg
1241.01	String beans	v_f	pulses
1241.9	Other beans, green	v_f	pulses
1242	Peas, green	v_f	veg
1243	Broad beans and horse beans, green	v_f	veg
1251	Carrots and turnips	v_f	roots
1252	Green garlic	v_f	veg
1253.01	Onions and shallots, green	v_f	veg
1253.02	Onions and shallots, dry (excluding dehydrated)	v_f	veg
1254	Leeks and other alliaceous vegetables	v_f	veg
1270	Mushrooms and truffles	v_f	veg
1290.01	Green corn (maize)	gro	grain
1290.9	Other vegetables, fresh n.e.c.	v_f	veg
1311	Avocados	v_f	fruit
1312	Bananas	v_f	fruit
1313	Plantains and cooking bananas	v_f	fruit
1314	Dates	v_f	veg
1315	Figs	v_f	fruit
1316	Mangoes, guavas and mangosteens	v_f	fruit
1317	Papayas	v_f	fruit
1318	Pineapples	v_f	fruit
1319	Other tropical fruits, n.e.c.	v_f	fruit

1321	Pomelos and grapefruits	v_f	fruit
1322	Lemons and limes	v_f	veg
1323	Oranges	v_f	fruit
1324	Tangerines, mandarins, clementines	v_f	fruit
1329	Other citrus fruit, n.e.c.	v_f	fruit
1330	Grapes	v_f	fruit
1341	Apples	v_f	fruit
1342.01	Pears	v_f	fruit
1342.02	Quinces	v_f	fruit
1343	Apricots	v_f	fruit
1344.01	Sour cherries	v_f	fruit
1344.02	Cherries	v_f	fruit
1345	Peaches and nectarines	v_f	fruit
1346	Plums and sloes	v_f	fruit
1349.1	Other pome fruits	v_f	fruit
1349.2	Other stone fruits	v_f	fruit
1351.01	Currants	v_f	fruit
1351.02	Gooseberries	v_f	fruit
1352	Kiwi fruit	v_f	fruit
1353.01	Raspberries	v_f	fruit
1354	Strawberries	v_f	fruit
1355.01	Blueberries	v_f	fruit
1355.02	Cranberries	v_f	fruit
1355.9	Other berries and fruits of the genus vaccinium n.e.c.	v_f	fruit
1356	Locust beans (carobs)	v_f	fruit
1359.01	Persimmons	v_f	fruit
1359.02	Cashew apple	v_f	nuts
1359.9	Other fruits, n.e.c.	v_f	fruit
1371	Almonds, in shell	v_f	nuts
1372	Cashew nuts, in shell	v_f	nuts
1373	Chestnuts, in shell	v_f	nuts
1374	Hazelnuts, in shell	v_f	nuts
1375	Pistachios, in shell	v_f	nuts
1376	Walnuts, in shell	v_f	nuts
1377	Brazil nuts, in shell	v_f	nuts
1379.01	Areca nuts	v_f	nuts
1379.02	Kola nuts	v_f	nuts
1379.9	Other nuts (excluding wild edible nuts and groundnuts), in shell, n.e.c.	v_f	nuts
141	Soya beans	v_f	pulses
142	Groundnuts, excluding shelled	v_f	nuts
1441	Linseed	osd	oils
1442	Mustard seed	osd	oils
1443	Rape or colza seed	osd	oils
1444	Sesame seed	osd	oils
1445	Sunflower seed	osd	oils
1446	Safflower seed	osd	oils
1447	Castor oil seeds	osd	oils
1448	Poppy seed	osd	oils
1449.01	Melon seed	osd	oils
1449.02	Hempseed	osd	oils
1449.9	Other oil seeds, n.e.c.	osd	oils
1450	Olives	osd	oils
1460	Coconuts, in shell	v_f	fruit
1491.01	Oil palm fruit	osd	oils
1499.01	Karite nuts (sheanuts)	v_f	nuts
1499.02	Tung nuts	v_f	nuts
1499.03	Jojoba seeds	osd	oils
1499.04	Tallowtree seeds	osd	oils
1499.05	Kapok fruit	v_f	fruit
1510	Potatoes	v_f	roots
1520.01	Cassava, fresh	v_f	roots
1530	Sweet potatoes	v_f	roots
1540	Yams	v_f	roots
1550	Taro	v_f	roots
1591	Yautia	v_f	roots
1599.1	Edible roots and tubers with high starch or inulin content, n.e.c., fresh	v_f	roots
1610	Coffee, green	ocrops	crops
1620	Tea leaves	ocrops	crops
1630	Maté leaves	ocrops	crops

1640	Cocoa beans	ocrops	crops
1651	Pepper (Piper spp.), raw	ocrops	crops
1652	Chillies and peppers, dry (Capsicum spp., Pimenta spp.), raw	ocrops	crops
1653	Nutmeg, mace, cardamoms, raw	ocrops	crops
1654	Anise, badian, coriander, cumin, caraway, fennel, and juniper berries, raw	ocrops	crops
1655	Cinnamon and cinnamon-tree flowers, raw	ocrops	crops
1656	Cloves (whole stems), raw	ocrops	crops
1657	Ginger, raw	ocrops	crops
1658	Vanilla, raw	ocrops	crops
1659	Hop cones	ocrops	crops
1691	Chicory roots	v_f	nuts
1699	Other stimulant, spice and aromatic crops, n.e.c.	ocrops	crops
1701	Beans, dry	v_f	pulses
1702	Broad beans and horse beans, dry	v_f	pulses
1703	Chick peas, dry	v_f	pulses
1704	Lentils, dry	v_f	pulses
1705	Peas, dry	v_f	pulses
1706	Cow peas, dry	v_f	pulses
1707	Pigeon peas, dry	v_f	pulses
1708	Bambara beans, dry	v_f	pulses
1709.01	Vetches	ocrops	crops
1709.02	Lupins	v_f	pulses
1709.9	Other pulses n.e.c.	v_f	pulses
1801	Sugar beet	sgr	sug
1802	Sugar cane	sgr	sug
1809	Other sugar crops n.e.c.	sgr	sug
1921.01	Seed cotton, unginned	osd	oils
1922.01	Jute, raw or retted	pfb	oagr
1922.02	Kenaf, and other textile bast fibres, raw or retted	pfb	oagr
1929.02	True hemp, raw or retted	pfb	oagr
1929.04	Ramie, raw or retted	pfb	oagr
1929.05	Sisal, raw	pfb	oagr
1929.06	Agave fibres, raw, n.e.c.	pfb	oagr
1929.07	Abaca, manila hemp, raw	pfb	oagr
1929.08	Coir, raw	pfb	oagr
1929.9	Other fibre crops, raw, n.e.c.	pfb	oagr
1930.01	Peppermint, spearmint	ocrops	crops
1930.02	Pyrethrum, dried flowers	ocrops	crops
1950.01	Natural rubber in primary forms	ocrops	crops
1970	Unmanufactured tobacco	ocrops	crops
21111.01	Meat of cattle with the bone, fresh or chilled	ctl	cattle
21112	Meat of buffalo, fresh or chilled	ctl	othctl
21113.01	Meat of pig with the bone, fresh or chilled	oap	pigpls
21114	Meat of rabbits and hares, fresh or chilled	oap	pigpls
21115	Meat of sheep, fresh or chilled	ctl	othctl
21116	Meat of goat, fresh or chilled	ctl	othctl
21117.01	Meat of camels, fresh or chilled	ctl	othctl
21117.02	Meat of other domestic camelids, fresh or chilled	ctl	othctl
21118.01	Horse meat, fresh or chilled	ctl	othctl
21118.02	Meat of asses, fresh or chilled	ctl	othctl
21118.03	Meat of mules, fresh or chilled	ctl	othctl
21119.01	Meat of other domestic rodents, fresh or chilled	oap	pigpls
21121	Meat of chickens, fresh or chilled	oap	pltry
21122	Meat of ducks, fresh or chilled	oap	pltry
21123	Meat of geese, fresh or chilled	oap	pltry
21124	Meat of turkeys, fresh or chilled	oap	pltry
21151	Edible offal of cattle, fresh, chilled or frozen	ctl	cattle
21152	Edible offal of buffalo, fresh, chilled or frozen	ctl	othctl
21153	Edible offal of pigs, fresh, chilled or frozen	oap	pigpls
21155	Edible offal of sheep, fresh, chilled or frozen	ctl	othctl
21156	Edible offal of goat, fresh, chilled or frozen	ctl	othctl
21159.01	Edible offals of horses and other equines, fresh, chilled or frozen	ctl	othctl
21159.02	Edible offals of camels and other camelids, fresh, chilled or frozen	ctl	othctl
21170.01	Meat of pigeons and other birds n.e.c., fresh, chilled or frozen	oap	pltry
21170.02	Game meat, fresh, chilled or frozen	ctl	othctl
21170.92	Other meat n.e.c. (excluding mammals), fresh, chilled or frozen	oap	pigpls

21511.01	Fat of pigs	oap	pigpls
21512	Cattle fat, unrendered	ctl	cattle
21513	Buffalo fat, unrendered	ctl	othctl
21514	Sheep fat, unrendered	ctl	othctl
21515	Goat fat, unrendered	ctl	othctl
21519.02	Fat of camels	ctl	othctl
2211	Raw milk of cattle	rmk	milk
2212	Raw milk of buffalo	rmk	milk
2291	Raw milk of sheep	rmk	milk
2292	Raw milk of goats	rmk	milk
2293	Raw milk of camel	rmk	milk
231	Hen eggs in shell, fresh	oap	pltry
232	Eggs from other birds in shell, fresh, n.e.c.	oap	pltry
26190.01	Flax, processed but not spun	pfb	oagr
2910	Natural honey	oap	pigpls
2920	Snails, fresh, chilled, frozen, dried, salted or in brine, except sea snails	oap	igpls
2941	Shorn wool, greasy, including fleece-washed shorn wool	wol	wol
2944	Silk-worm cocoons suitable for reeling	wol	wol
2951.01	Raw hides and skins of cattle	ctl	cattle
2951.03	Raw hides and skins of buffaloes	ctl	othctl
2953	Raw hides and skins of sheep or lambs	ctl	othctl
2954	Raw hides and skins of goats or kids	ctl	othctl
2960.01	Beeswax	oap	pigpls

Feed

To quantify feed production across global regions we rely on feed production data from FAO-Food-Balance-Sheets (FAOSTAT, 2020). The regional mapping adopted for feed data is reported in Table S5 while Table S7 illustrates the commodities used for quantifying feed production. As FAO does not report feed data for specific animals, we split feed production by animal based on our dollar-based quantities from the MAGNET model. We define the total physical (Mtons) supply of feed and split it based on feed demand from specific livestock sectors. With this procedure we allocate 46% of total feed supply to ruminants (bovine cattle, sheep, and other ruminants), 29% to swine, 23% to poultry and 2% to aquaculture.

Table S7. Commodity mappings between FAO commodities and MAGNET sectors

FBS commodity	MAGNET commodity	GTAP commodity	FBS commodity	MAGNET commodity	GTAP commodity
Apples and products	fruit	v_f	Rape and Mustard seed	oil	osd
Barley and products	grain	gro	Rice and products	pdr	pdr
Beans	pulses	v_f	Roots, Other	roots	v_f
Cassava and products	roots	v_f	Rye and products	grain	gro
Cereals, Other	grain	gro	Sesame seed	oil	osd
Coconuts – Incl. Copra	oil	osd	Sorghum and products	grain	gro
Cottonseed	oil	osd	Soyabean Oil	oil	osd
Fruits, other	fruit	v_f	Soyabeans	pulses	v_f
Maize and products	grain	gro	Sugar (Raw Equivalent)	sug	sgr
Millet and products	grain	gro	Sugar beet	sug	sgr
Oats	grain	gro	Sugar cane	sug	sgr
Oil crops, Other	oil	osd	Sunflower seed	oil	osd
Onions	veg	v_f	Sweet potatoes	roots	v_f
Peas	pulses	v_f	Sweeteners, Other	sug	v_f
Potatoes and products	roots	v_f	Tomatoes and products	veg	v_f
Pulses, Other and products	pulses	v_f	Vegetables, other	veg	v_f
Rape and Mustard Oil	oil	osd	Wheat and products	wht	wht

Low-cost-opportunity feed (LCF)

By-products

To quantify physical production of by-products we adopt technical-conversion-factors (TCF) derived from FAO[16]. Frist, we derive primary production data (Mtons) for commodities generating by-products. Successively, we apply FAO TCF to quantify the amount of by-products generated in the production process. Table S8 below illustrates data sources utilized to quantify primary production of commodities generating by-products and reports the TCF adopted for the quantification of by-products. For fishmeal production we directly derive production data from (USDA, 2022)[17].

Table S8. Commodities generating by-products and technical-conversion factors adopted for quantifying by-products availability

Main commodity (generating by-products)	Data source (production data – Mtons)	By-product	TCF
Sugar	FAOSTAT	molasses	0.06
Vegetable oils	FAOSTAT	oilcakes	0.53
Biofuel	International Energy Agency	ddgs	0.34

Agricultural Residues

Agricultural residues in the MAGNET model are modelled with a non-linear relationship between the price of residues and the quantity supplied as shown in Figure S4 below. The relationship between price and quantity is assumed to resemble an asymptote: the price of residues is low until the demand approaches the maximum available residues.

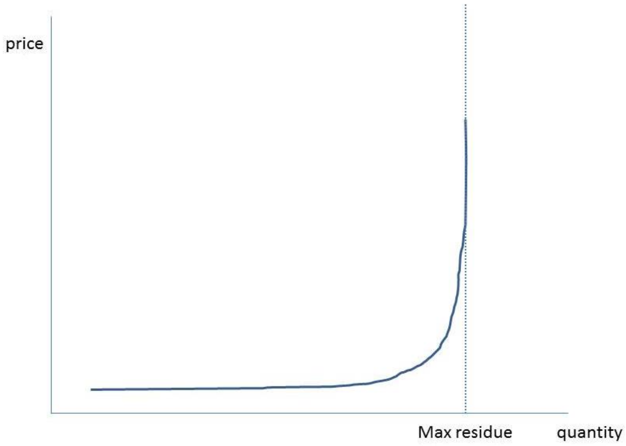


Figure S4. Relationship between price and quantity of residues.

To include this asymptote in MAGNET, we define the ratio of the demand for residues to the maximum supply of residues. The maximum supply of residues is read from data and updated according to the change in the output of the main sector generating residues. The demand for residues is also read from data and is parallelly updated with the change in the residue production. We define a ratio between the use of residue and the potential maximum supply of residues. Such ratio determines the price elasticity of the residue supply. If the ratio is small, the price elasticity is very small; meaning that an increase in demand will hardly raise the price. If the ratio is large, the price

[16] https://www.fao.org/economic/the-statistics-division-ess/methodology/methodology-systems/technical-conversion-factors-for-agricultural-commodities/en/
[17] https://www.indexmundi.com/agriculture/?country=eu&commodity=fish-meal&graph=production

elasticity is also large; meaning that an increase in demand will greatly affect the price of residues. The quantity of residues used, is determined by the supply price of residues, multiplied by the price elasticity, where the price of residues is corrected with a price index. The quantity is also influenced by the size of the sector output. If, for example, the size of the wheat sector grows, the residue production of the wheat sector also grows. However, we allow that residues can grow without the main commodity also having to grow. The use of residues is based on the sustainable potential (Elbersen, pers. comm., 2015; Biomass Policies, 2015; Daioglou et al., 2015) i.e. the amount that is not used for other purposes and can be used without reducing long-term soil fertility. The potential residue supply per individual country per originating sector is calculated based on production shares in value terms in the corresponding regional aggregate.

To quantify physical availability of residues going to livestock we rely on physical shares (%) of lost biomass at agricultural production and post-harvest handling & storage stages of the supply chain. We derive shares for primary agricultural commodities from Gatto et. al. (2023). We apply shares to primary production (Mtons) and quantify the amount of residues available to be reused as animal feed. Table S9 reports for each region the shares adopted for the quantification of residues availability.

Table S9. Shares (%) of primary production generating agricultural residues.

Residue type	EU-27	BRA	CHN	USA	INDA	NAMO	REUCA	MENA	LAC	SEA	SSA
Paddy rice	6.0	4.0	2.0	5.0	1.0	3.0	14.0	14.0	4.0	4.0	1.0
Grains	6.0	11.0	2.0	5.0	13.0	3.0	14.0	14.0	12.0	2.0	1.0
Oil seeds	5.0	15.0	12.0	5.0	6.0	40.0	15.0	15.0	13.0	1.0	2.0
Wheat	11.0	3.0	2.0	5.0	9.0	3.0	14.0	14.0	3.0	2.0	1.0
Other crops	5.0	11.0	2.0	5.0	1.0	3.0	12.0	12.0	12.0	1.0	3.0
Vegetables	18.0	13.0	13.0	5.0	5.0	4.0	6.0	6.0	11.0	4.0	2.0
Fruits	18.0	13.0	13.0	5.0	5.0	4.0	6.0	6.0	11.0	4.0	2.0
Nuts	18.0	15.0	12.0	5.0	6.0	4.0	15.0	15.0	13.0	1.0	2.0
Roots	18.0	15.0	12.0	5.0	6.0	4.0	15.0	15.0	13.0	1.0	2.0
Pulses	18.0	15.0	12.0	5.0	6.0	4.0	15.0	15.0	13.0	1.0	2.0

Additional Results

The Economic impacts of policies promoting livestock diets for a circular food system across different livestock sectors in the EU27

In the following section we showcase the impact of policies promoting a circular agri-food system on different livestock sectors, analysing how different productions respond to policy interventions.

The impact of circular policies varies by type of livestock (Panel A - Figure S5). Other ruminants (small ruminants and sheep) are particularly affected by policies due to their relatively higher shares of domestic compound feed and imported feed crops within total feed consumption. In the "*weak circular economy*" scenario (WCE), these sectors experience a 0.3% decrease in production, which further decreases by 1.4% in the "*strong circular economy*" scenario (SCE) due to the import tariff. Conversely, dairy cattle and swine production result more affected in absolute terms, given their larger reliance on primary feed (i.e. compound feed and feed crops) volumes. In the WCE scenario, dairy cattle production decreases by 0.1% (0.11 million Mtons), further decreasing by 0.3% (0.41

million Mtons) in the SCE scenario. Swine production also decreases by 0.2% (0.04 million Mtons) in the WCE scenario and by 0.8% (0.15 million Mtons) in the SCE scenario. Finally, aquaculture sectors benefit from the policies due to low amounts of imported feeds and higher reliance on LCF such as fishmeal, increasing production by 2.7% and 5.7% in the WCE and SCE scenarios, respectively.

Both policy scenarios lead to a decrease in feed production, but the changes in feed composition vary across livestock sectors (Panel B - Figure S5). The implementation of a low subsidy on LCF use in the EU27 leads to an increase in its use (1.84 million Mtons) principally generated by a partial replacement of primary feed (compound feed and feed crops), which decreases (-2.2% or 6.8 million Mtons) across livestock sectors.

The 20% subsidy lowers domestic prices of by-products (-20.6%) and residues (-16.7%), while increasing compound feed and feed crops prices (average +2.4%), due to the tax imposed to finance the subsidy. Compound feed prices increase relatively more than feed crops, leading to a decrease in its share (-1.5% or 6.54 million Mtons) in favor of feed crops (+0.8% or 0.65 million Mtons). In absolute terms, substitution effects are stronger for dairy cattle and swine, the largest consumers of primary feed and are more incentivized to replace it with LCF when primary feed prices increase. These sectors experience an average 1.4% increase (or 1.16 million Mtons) in the share of LCF within the total feed supply. Poultry and cattle (respectively 0.8% or 0.39 million Mtons and 0.7% or 0.21 million Mtons) also experience an increase in the share of LCF, while aquaculture is relatively less affected (0.5% or 0.08 million Mtons) due to an already higher use of LCF in the business-as-usual (BAU) scenario which results in a less pronounced substitution of primary feed.

In the SCE scenario, increasing subsidies on LCF while imposing an import tariff on primary feed leads to a further increase in the use of LCF within total feed consumption (5.24 million Mtons). The import tariff reduces primary feed imports by an average of 14.5% compared to BAU, resulting in a lower feed supply compared to BAU. The higher price of imported feed incentivizes an increase in LCF use, especially for dairy cattle (+3.1% or 1.6 million Mtons) and swine (+2.4% or 1.65 million Mtons), which rely more on imported feed. The higher taxes levied to finance higher subsidies have exert stronger effects on livestock sectors, reducing total feed demand by 6.0% (15.7 million Mtons).

In a circular food system, increasing dependence on domestic feed sources is crucial for closing nutrient loops. A low subsidy on domestic LCF increases domestic feed use by an average of 1.7% (Panel C - Figure S5) while the imposition of an import tariff and higher subsidies leads to a substantial increase in the use of domestic feed biomass (5.1%). This has relatively weak implications for feed-exporting regions such as Latin America and the Caribbean (LAC) and Rest of Europe & Central Asia (REUCA), where feed exports to the EU27 decrease by an average of 0.2% and 1.8%, respectively, in the WCE and SCE scenarios. Brazil is also affected, with feed exports decreasing by 0.1% and 1.0% in the WCE and SCE scenarios, respectively.

A – Changes (%) in livestock production in reference scenarios compared to BAU in 2030

B – Feed demand (million Mtons) by livestock sectors in reference scenarios in 2030

C – Shares of LCF (%) within total feed use in reference scenarios in 2030

D – Shares (%) of domestic feed sourcing over total feed use in reference scenarios compared to BAU in 2030

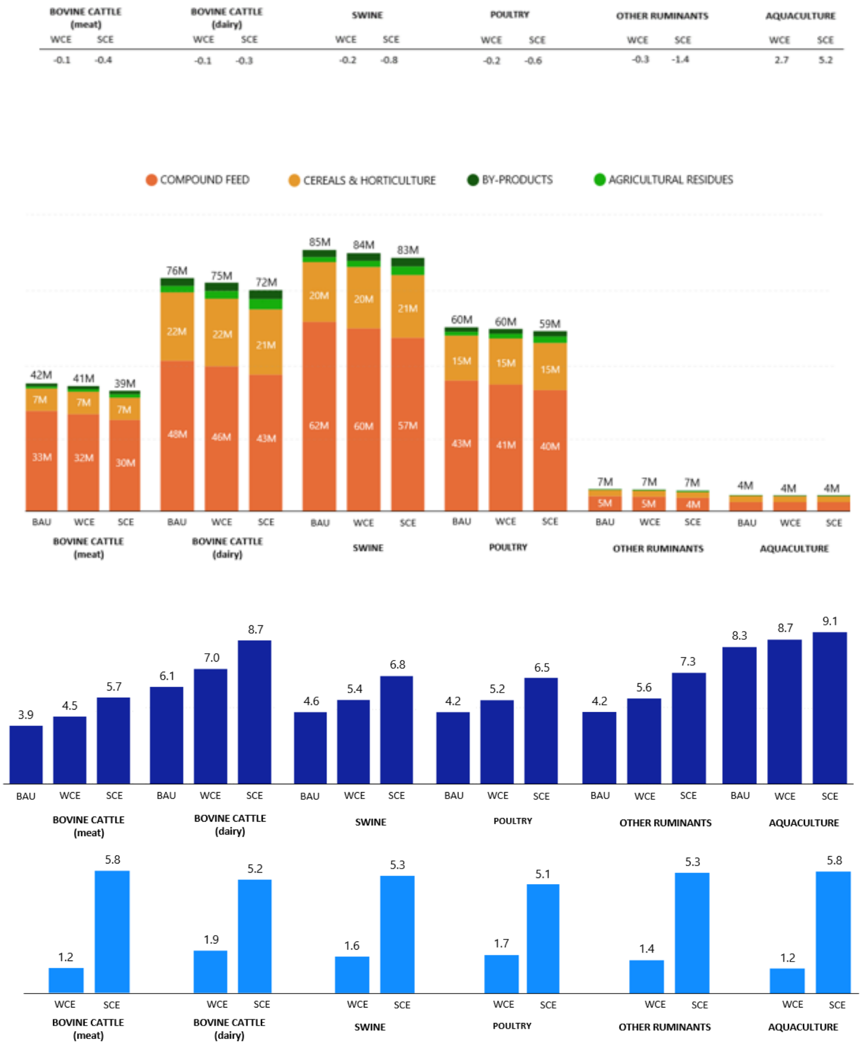


Figure S5. Changes in livestock production, feed supply, composition, and sourcing in EU27 in 2030 (by scenario). Estimates refer to Metric tons. BAU refers to our business-as-usual (baseline) scenario, while WCE and SCE respectively represent the "weak circular economy" and the "strong circular economy" scenario. "Other ruminants" refers to the sum of feed supplied to other cattle (goats, sheep, and other types of small ruminants raised for meat and dairy products) and sheep (raised for wool production). Panel A illustrates changes (%) in total livestock production under different policies compared to our baseline scenario in 2030. Panel B reports total feed demand (million Mtons) by each livestock sector in baseline and under different policies in 2030, illustrating the composition of total feed use. Panel B reports the changing shares of low-cost-feedstuff (LCF) such as agricultural residues and by-products in our reference scenarios in 2030.Finally, Panel C illustrates the changing shares (%) of domestic feed use over total feed use by each livestock type compared to BAU by reference scenario in 2030.

Nutritional balances

Feeding animals under a circular paradigm requires understanding how nutritional balances in livestock diets are preserved in the processes of substituting primary feed with LCF. Often economic policies focus on the economic feasibility of interventions but tend to overlook technical constraints of circularity. To enhance the consistency of our analysis, this section provides an overview on how the application of our policies towards a more circular livestock production system in EU27 affects the nutritional dietary balances of livestock sectors. A core contribution of our study is that in providing and analyzing feasible economic policies for transitioning towards circularity, the nutritional requirements of different animals are respected across our model simulations.

Our procedure to calculate nutritional balances of livestock types consists of several steps. First, we quantify the physical amount (Mtons) of livestock produced as well as the total amount of feed supplied to each livestock type in 2030 across investigated scenarios. Following, based on these estimates we compute the ratio between feed supply and animal production, defining the amount (Mtons) of dry matter intakes (DM) per Mtons of animal produced. We compare our defined ratios with feed-conversion-rations (FCR) available from literature, examining how our circular solutions result consistent with current livestock nutritional requirements. In the case of poultry and dairy cattle we quantify the FCR based on the specific sectoral output (milk, poultry meat, eggs).

Our modelling framework excludes several feed components currently fed to livestock. For this, certain FCR result lower that reference values derived from literature. This is particularly relevant for bovine cattle (meat) as our feed supply excludes hay, grass, and other feed additives which account for large shares in bovine cattle diets. For this our FCR for results below the FCR derived from literature as reference studies include feed types not covered in our modelling framework. Additionally, we compute gross energy (MJ/kg DM) and crude protein (% DM) values of single livestock diets across scenarios and compare such values with reference estimates obtained from literature. Here, it is important to notice that as the average diet across livestock sectors in our model is mainly composed by grains (around 80-85%), with LCF ranging from an average 5% to 7% across scenarios, the high energy content of livestock diets allows to remain consistent with gross energy (MJ/kg DM) and crude protein (% DM) requirements observed in literature (Tables S10a-g). For this, despite our FCR for bovine cattle do not align with literature, the high energy content of livestock diets allows to remain consistent with gross energy (MJ/kg DM) and crude protein (% DM) requirements observed in literature. Tables S10a-S10g below illustrate the composition of livestock diets by livestock type, reporting estimated FCR, gross energy (MJ/kg DM) and crude protein (% DM) requirements in each investigated scenario.

Table S10a – Bovine Cattle (meat)	SCENARIO					
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	124182	0.30%	121718	0.30%	117318	0.30%
wheat	8561740	20.49%	8292993	20.26%	7810624	19.82%
grains	27918978	66.81%	27225374	66.50%	25923871	65.80%
vegetables	265909	0.64%	257670	0.63%	243739	0.62%
fruit	102099	0.24%	100408	0.25%	99798	0.25%
nuts	1508	0.00%	1519	0.00%	1441	0.00%
roots	682670	1.63%	660661	1.61%	625855	1.59%
pulses	703517	1.68%	680535	1.66%	640817	1.63%
oilseeds	487802	1.17%	464050	1.13%	430021	1.09%
sugar beet/cane	495326	1.19%	478587	1.17%	450040	1.14%
other crops	107822	0.26%	107989	0.26%	107529	0.27%
other agric. products	1544	0.00%	1540	0.00%	1537	0.00%
residues paddy rice	4884	0.01%	6276	0.02%	8141	0.02%
residues grains	595529	1.43%	662988	1.62%	739055	1.88%
residues oilseed	1508	0.00%	2261	0.01%	3652	0.01%
residues wheat	59599	0.14%	119495	0.29%	307759	0.78%
residues other crops	6278	0.02%	12583	0.03%	32395	0.08%
residues vegetables	1246	0.00%	2497	0.01%	6430	0.02%
residues fruit	4160	0.01%	8341	0.02%	21483	0.05%
residues nuts	14	0.00%	28	0.00%	72	0.00%
residues roots	3713	0.01%	7446	0.02%	19184	0.05%
residues pulses	700	0.00%	1403	0.00%	3614	0.01%
oilcake	811885	1.94%	880277	2.15%	960917	2.44%
DDGS	0	0.00%	0	0.00%	0	0.00%
molasses	155489	0.37%	155338	0.38%	154792	0.39%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	629129	1.51%	628665	1.54%	626621	1.59%
vegetal oils	32975	0.08%	32935	0.08%	32810	0.08%
other oils	29087	0.07%	29052	0.07%	28942	0.07%
TOTAL	**41789293**	100%	**40942629**	100%	**39398457**	100%
Share main products	96.06%		95.46%		94.27%	
Share by-products	3.94%		4.54%		5.73%	
Gross energy (MJ/kg DM)	18.72		18.72		18.74	
Crude Protein (% DM)	12.89		12.88		12.87	
FCR (kg DM / kg output)	5.7		5.6		5.4	
Reference gross energy[1]	18.0 – 20.0		18.0 – 20.0		18.0 – 20.0	
Reference proteins[1]	16.0 – 18.0		16.0 – 18.0		16.0 – 18.0	
Reference FCR[2]	4.5 – 10.0		4.5 – 10.0		4.5 – 10.0	

[1] National Research Council (NRC). (2001). Nutrient Requirements of Dairy Cattle. 7th rev. ed. Washington, D.C.: National Academy Press.
[2] Smil, V. (2002). Eating Meat: Evolution, Patterns, and Consequences. Population and Development Review, 28(4), 599–639. https://doi.org/10.1111/j.1728-4457.2002.00599. Shike, D.W. (2013). Beef Cattle Feed Efficiency. Driftless Region Beef Conference, University of Illinois at Urbana-Champaign.

Table S10b – Bovine Cattle (dairy)

	SCENARIO					
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	195101	0.26%	190884	0.26%	184532	0.26%
wheat	13237692	17.35%	12733447	17.03%	11940616	16.51%
grains	49541546	64.95%	48134406	64.37%	45668416	63.13%
vegetables	397059	0.52%	382510	0.51%	362448	0.50%
fruit	195342	0.26%	191718	0.26%	190386	0.26%
nuts	1057721	1.39%	1017522	1.36%	971239	1.34%
roots	1000109	1.31%	960404	1.28%	903850	1.25%
pulses	687772	0.90%	647492	0.87%	595848	0.82%
oilseeds	723738	0.95%	694716	0.93%	653195	0.90%
sugar beet/cane	2691	0.00%	2720	0.00%	2512	0.00%
other crops	4620	0.01%	4613	0.01%	4609	0.01%
other agric. products	176017	0.23%	175818	0.24%	173152	0.24%
residues paddy rice	8590	0.01%	10935	0.01%	13689	0.02%
residues grains	1838425	2.41%	2026938	2.71%	2179962	3.01%
residues oilseed	2062	0.00%	3062	0.00%	4773	0.01%
residues wheat	197321	0.26%	391953	0.52%	974800	1.35%
residues other crops	9883	0.01%	19626	0.03%	48788	0.07%
residues vegetables	4241	0.01%	8423	0.01%	20941	0.03%
residues fruit	10304	0.01%	20468	0.03%	50904	0.07%
residues nuts	43	0.00%	86	0.00%	213	0.00%
residues roots	18171	0.02%	36100	0.05%	89807	0.12%
residues pulses	2994	0.00%	5948	0.01%	14796	0.02%
oilcake	2072086	2.72%	2230457	2.98%	2409403	3.33%
DDGS	7121	0.01%	8087	0.01%	9789	0.01%
molasses	494111	0.65%	493755	0.66%	492527	0.68%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	4295068	5.63%	4292349	5.74%	4281898	5.92%
vegetal oils	57353	0.08%	57307	0.08%	57162	0.08%
other oils	40581	0.05%	40549	0.05%	40446	0.06%
TOTAL	**76277762**	100%	**74782293**	100%	**72340701**	100%
Share main products	93.88%		92.97%		91.28%	
Share by-products	6.12%		7.03%		8.72%	
Gross energy (MJ/kg DM)	19.85		19.87		19.92	
Crude Protein (% DM)	13.68		13.68		13.70	
FCR (kg DM / kg output)	0.4		0.4		0.4	
Reference gross energy[1]	17.0 – 19.0		17.0 – 19.0		17.0 – 19.0	
Reference proteins[1]	12.0 – 18.0		12.0 – 18.0		12.0 – 18.0	
Reference FCR[2]	0.7		0.7		0.7	

[1] National Research Council (NRC). (2001). Nutrient Requirements of Dairy Cattle. 7th rev. ed. Washington, D.C.: National Academy Press.

[2] FCR calculations based on production of raw milk (Mtons). Alexander, P., Brown, C., Arneth, A., Finnigan, J., & Rounsevell, M. D. A. (2016). Human appropriation of land for food: The role of diet. Global Environmental Change, 41, 88–98. https://doi.org/10.1016/j.gloenvcha.2016.09.005. Opio, C., Gerber, P., Mottet, A., Falculli, A., et al. (2013). Greenhouse Gas Emissions from Ruminant Supply Chains–A Global Life Cycle Assessment. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Table S10c – Swine			**SCENARIO**			
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	179000	0.21%	174119	0.21%	166995	0.20%
wheat	16823395	19.68%	16344226	19.36%	15609468	18.83%
grains	55221501	64.60%	54274177	64.28%	52649670	63.52%
vegetables	468850	0.55%	453009	0.54%	431476	0.52%
fruit	142502	0.17%	140729	0.17%	141345	0.17%
nuts	1232081	1.44%	1189646	1.41%	1138504	1.37%
roots	1260885	1.48%	1215564	1.44%	1152108	1.39%
pulses	852457	1.00%	813958	0.96%	763269	0.92%
oilseeds	904954	1.06%	870864	1.03%	824306	0.99%
sugar beet/cane	2002	0.00%	2037	0.00%	1928	0.00%
other crops	1857	0.00%	1843	0.00%	1835	0.00%
other agric. products	32937	0.04%	33980	0.04%	35177	0.04%
residues paddy rice	4418	0.01%	5664	0.01%	7213	0.01%
residues grains	1397990	1.64%	1552385	1.84%	1699468	2.05%
residues oilseed	1157	0.00%	1731	0.00%	2744	0.00%
residues wheat	197335	0.23%	394662	0.47%	997761	1.20%
residues other crops	1603	0.00%	3204	0.00%	8097	0.01%
residues vegetables	2005	0.00%	4010	0.00%	10141	0.01%
residues fruit	4532	0.01%	9067	0.01%	22935	0.03%
residues nuts	21	0.00%	43	0.00%	108	0.00%
residues roots	8558	0.01%	17128	0.02%	43336	0.05%
residues pulses	1365	0.00%	2731	0.00%	6909	0.01%
oilcake	1981778	2.32%	2181426	2.58%	2453789	2.96%
DDGS	7480	0.01%	8797	0.01%	11494	0.01%
molasses	341290	0.40%	340719	0.40%	338654	0.41%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	4165739	4.87%	4161059	4.93%	4132648	4.99%
vegetal oils	128901	0.15%	128664	0.15%	127913	0.15%
other oils	109560	0.13%	109359	0.13%	108721	0.13%
TOTAL	**85476153**	100%	**84434801**	100%	**82888012**	100%
Share main products	95.38%		94.64%		93.24%	
Share by-products	4.62%		5.36%		6.76%	
Gross energy (MJ/kg DM)	19.69		19.70		19.72	
Crude Protein (% DM)	13.62		13.62		13.62	
FCR (kg DM / kg output)	3.3		3.3		3.2	
Reference gross energy[1]	19.0 – 21.0		19.0 – 21.0		19.0 – 21.0	
Reference proteins[1]	12.0 – 18.0		12.0 – 18.0		12.0 – 18.0	
Reference FCR[2]	3.3 – 4.1		3.3 – 4.1		3.3 – 4.1	

[1] National Research Council (NRC). (2012). Nutrient Requirements of Swine. 11th rev. ed. Washington, D.C.: The National Academies Press.
[2] Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. P., & Oenema, O. (2011). Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*, *166–167*, 16–28. https://doi.org/10.1016/j.anifeedsci.2011.04.058. Mekonnen, M. M., Neale, C. M. U., Ray, C., Erickson, G. E., & Hoekstra, A. Y. (2019). Water productivity in meat and milk production in the US from 1960 to 2016. *Environment International*, *132*, 105084. https://doi.org/10.1016/j.envint.2019.105084

Table S10d – Poultry			**SCENARIO**			
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	130411	0.22%	127356	0.21%	123106	0.21%
wheat	11582442	19.25%	11286591	18.93%	10848598	18.42%
grains	39421768	65.51%	38895661	65.22%	38034941	64.56%
vegetables	329228	0.55%	319197	0.54%	306393	0.52%
fruit	111492	0.19%	109964	0.18%	110465	0.19%
nuts	860619	1.43%	833308	1.40%	802572	1.36%
roots	875825	1.46%	847558	1.42%	809868	1.37%
pulses	593167	0.99%	567468	0.95%	535648	0.91%
oilseeds	629639	1.05%	607998	1.02%	580256	0.98%
sugar beet/cane	1429	0.00%	1451	0.00%	1372	0.00%
other crops	1199	0.00%	1194	0.00%	1190	0.00%
other agric. products	27833	0.05%	28479	0.05%	29064	0.05%
residues paddy rice	3579	0.01%	4615	0.01%	5899	0.01%
residues grains	1087368	1.81%	1214175	2.04%	1334187	2.26%
residues oilseed	970	0.00%	1459	0.00%	2323	0.00%
residues wheat	134742	0.22%	271017	0.45%	687746	1.17%
residues other crops	1464	0.00%	2944	0.00%	7469	0.01%
residues vegetables	1892	0.00%	3807	0.01%	9665	0.02%
residues fruit	4412	0.01%	8879	0.01%	22548	0.04%
residues nuts	19	0.00%	39	0.00%	99	0.00%
residues roots	6949	0.01%	13990	0.02%	35537	0.06%
residues pulses	1334	0.00%	2685	0.00%	6820	0.01%
oilcake	1243693	2.07%	1359833	2.28%	1506812	2.56%
DDGS	0	0.00%	0	0.00%	0	0.00%
molasses	232791	0.39%	232469	0.39%	231377	0.39%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	2748863	4.57%	2746849	4.61%	2729963	4.63%
vegetal oils	78389	0.13%	78266	0.13%	77930	0.13%
other oils	69370	0.12%	69261	0.12%	68965	0.12%
TOTAL	**60180887**	100%	**59636513**	100%	**58910813**	100%
Share main products	95.48%		94.78%		93.46%	
Share by-products	4.52%		5.22%		6.54%	
Gross energy (MJ/kg DM)	19.61		19.62		19.62	
Crude Protein (% DM)	13.52		13.51		13.50	
FCR (kg DM / kg output)	3.1		3.1		3.1	
Reference gross energy[1]	20.0 – 23.0		20.0 – 23.0		20.0 – 23.0	
Reference proteins[1]	12.0 – 18.0		12.0 – 18.0		12.0 – 18.0	
Reference FCR[2]	1.3 – 3.3		1.3 – 3.3		1.3 – 3.3	

[1] National Research Council (NRC). (1994). Nutrient Requirements of Poultry. 9th rev. ed. Washington, D.C.: National Academy Press.

[2] FCR calculations based on production of poultry and eggs (Mtons). Lesschen, J. P., van den Berg, M., Westhoek, H. J., Witzke, H. P., & Oenema, O. (2011). Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*, *166–167*, 16–28. https://doi.org/10.1016/j.anifeedsci.2011.04.058. Mekonnen, M. M., Neale, C. M. U., Ray, C., Erickson, G. E., & Hoekstra, A. Y. (2019). Water productivity in meat and milk production in the US from 1960 to 2016. *Environment International*, *132*, 105084. https://doi.org/10.1016/j.envint.2019.105084. Eshel, G., Shepon, A., Makov, T. and Milo, R. (2015). Partitioning United States' feed consumption among livestock categories for improved environmental cost assessments J. Agric. Sci. 153 432–45. Peters, C. J., Picardy, J, Darrouzet-Nardi, A. F., Wilkins, J. L., Griffin, T. S. and Fick, G. W. (2016). Carrying capacity of US agricultural land: ten diet scenarios Elem. Sci. Anthr. 4 000116.

Table S10e – Other ruminants SCENARIO

	BAU	Share in total diet	WCE	Share in total diet	SCE	Share in total diet
paddy rice	17505	0.28%	17126	0.29%	16298	0.29%
wheat	1139117	18.51%	1097793	18.29%	1010707	17.79%
grains	4223664	68.64%	4092552	68.17%	3819190	67.23%
vegetables	37527	0.61%	36259	0.60%	33837	0.60%
fruit	17250	0.28%	16883	0.28%	16696	0.29%
nuts	98808	1.61%	95351	1.59%	89433	1.57%
roots	94580	1.54%	91200	1.52%	84257	1.48%
pulses	68256	1.11%	63604	1.06%	56804	1.00%
oilseeds	65912	1.07%	63457	1.06%	58440	1.03%
sugar beet/cane	259	0.00%	262	0.00%	246	0.00%
other crops	222	0.00%	222	0.00%	220	0.00%
other agric. products	17093	0.28%	16972	0.28%	16745	0.29%
residues paddy rice	742	0.01%	949	0.02%	1210	0.02%
residues grains	136093	2.21%	150769	2.51%	165208	2.91%
residues oilseed	485	0.01%	723	0.01%	1148	0.02%
residues wheat	8474	0.14%	16894	0.28%	42766	0.75%
residues other crops	977	0.02%	1948	0.03%	4929	0.09%
residues vegetables	381	0.01%	759	0.01%	1923	0.03%
residues fruit	831	0.01%	1656	0.03%	4193	0.07%
residues nuts	5	0.00%	9	0.00%	23	0.00%
residues roots	1498	0.02%	2987	0.05%	7564	0.13%
residues pulses	233	0.00%	464	0.01%	1174	0.02%
oilcake	110213	1.79%	121739	2.03%	135591	2.39%
DDGS	748	0.01%	842	0.01%	1010	0.02%
molasses	18963	0.31%	18910	0.31%	18698	0.33%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	85970	1.40%	85762	1.43%	84818	1.49%
vegetal oils	3939	0.06%	3926	0.07%	3881	0.07%
other oils	3443	0.06%	3432	0.06%	3392	0.06%
TOTAL	**6153188**	100%	**6003450**	100%	**5680401**	100%
Share main products	95.46%		94.69%		93.21%	
Share by-products	4.54%		5.31%		6.79%	
Gross energy (MJ/kg DM)	18.86		18.87		18.89	
Crude Protein (% DM)	12.88		12.86		12.84	
FCR (kg DM / kg output)	9.8		9.6		9.2	
Reference gross energy[1]	17.0 – 19.0		17.0 – 19.0		17.0 – 19.0	
Reference proteins[1]	12.0 – 16.0		12.0 – 16.0		12.0 – 16.0	
Reference FCR[2]	9.0 – 10.5		9.0 – 10.5		9.0 – 10.5	

[1] National Research Council. (2007). Nutrient requirements of small ruminants. National Academies Press. 362 pp.

[2] FCR calculations based on on average FCR between cattle, goats, and other types of ruminants. Brand, T. S., Cloete, S. W. P. and Franck, F. (1991). Wheat-straw as roughage component in finishing diets of growing lambs. S. Afr. J. Anim. Sci 21: 184-188. Knott, S. A., Leury, M, B. J., Cummins L. J., Brien F. D. and Dunshea, F. R. (2003). Relationship between body composition, net feed intake and gross feed conversion efficiency in composite sire line sheep. In: Souffrant, W. B. and C. C. Metges (eds.). Progress in research on energy and protein metabolism. EAAP publ. no. 109. Wageningen. Mekonnen, M. M., Neale, C. M. U., Ray, C., Erickson, G. E., & Hoekstra, A. Y. (2019). Water productivity in meat and milk production in the US from 1960 to 2016. *Environment International*, *132*, 105084. https://doi.org/10.1016/j.envint.2019.105084 Opio, C., Gerber, P., Mottet, A., Falculli, A., et al. (2013). Greenhouse Gas Emissions from Ruminant Supply Chains–A Global Life Cycle Assessment. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Table S10f – Sheep (wool)

	SCENARIO					
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	8527	0.79%	8406	0.80%	8318	0.80%
wheat	147728	13.72%	141814	13.48%	131129	12.59%
grains	508659	47.25%	489084	46.50%	457409	43.92%
vegetables	17716	1.65%	16369	1.56%	15617	1.50%
fruit	26463	2.46%	23944	2.28%	22800	2.19%
nuts	55178	5.13%	50006	4.75%	49037	4.71%
roots	17711	1.65%	16721	1.59%	16280	1.56%
pulses	72501	6.73%	69526	6.61%	64727	6.22%
oilseeds	134775	12.52%	132282	12.58%	131506	12.63%
sugar beet/cane	404	0.04%	394	0.04%	317	0.03%
other crops	465	0.04%	456	0.04%	456	0.04%
other agric. products	1033	0.10%	1002	0.10%	895	0.09%
residues paddy rice	792	0.07%	1020	0.10%	1305	0.13%
residues grains	21363	1.98%	23849	2.27%	26230	2.52%
residues oilseed	5612	0.52%	8412	0.80%	13389	1.29%
residues wheat	2526	0.23%	5055	0.48%	12801	1.23%
residues other crops	40	0.00%	79	0.01%	200	0.02%
residues vegetables	1166	0.11%	2333	0.22%	5909	0.57%
residues fruit	1816	0.17%	3634	0.35%	9202	0.88%
residues nuts	12	0.00%	24	0.00%	62	0.01%
residues roots	4707	0.44%	9421	0.90%	23857	2.29%
residues pulses	682	0.06%	1366	0.13%	3458	0.33%
oilcake	0	0.00%	0	0.00%	0	0.00%
DDGS	0	0.00%	0	0.00%	0	0.00%
molasses	0	0.00%	0	0.00%	0	0.00%
fishmeal	0	0.00%	0	0.00%	0	0.00%
raw milk	31479	2.92%	31452	2.99%	31385	3.01%
vegetal oils	8020	0.75%	8013	0.76%	7997	0.77%
other oils	7131	0.66%	7126	0.68%	7112	0.68%
TOTAL	**1076506**	100%	**1051788**	100%	**1041398**	100%
Share main products	96.40%		94.75%		90.74%	
Share by-products	3.60%		5.25%		9.26%	
Gross energy (MJ/kg DM)	20.74		20.72		20.70	
Crude Protein (% DM)	14.61		14.56		14.50	
FCR (kg DM / kg output)	4.5		4.4		4.4	
Reference gross energy[1]	17.0 – 19.0		17.0 – 19.0		17.0 – 19.0	
Reference proteins[1]	12.0 – 16.0		12.0 – 16.0		12.0 – 16.0	
Reference FCR[2]	4.0 – 5.0		4.0 – 5.0		4.0 – 5.0	

[1] National Research Council. (2007). Nutrient requirements of small ruminants. National Academies Press. 362 pp.

[2] National Research Council. (2007). Nutrient requirements of small ruminants. National Academies Press. 362 pp. Brand, T. S., Cloete, S. W. P. and Franck, F. (1991). Wheat-straw as roughage component in finishing diets of growing lambs. S. Afr. J. Anim. Sci 21: 184-188. Knott, S. A., Leury, M, B. J., Cummins L. J., Brien F. D. and Dunshea, F. R. (2003). Relationship between body composition, net feed intake and gross feed conversion efficiency in composite sire line sheep. In: Souffrant, W. B. and C. C. Metges (eds.). Progress in research on energy and protein metabolism. EAAP publ. no. 109. Wageningen.

Table S10g – Aquaculture

	SCENARIO					
	BAU	**Share in total diet**	**WCE**	**Share in total diet**	**SCE**	**Share in total diet**
paddy rice	5770	0.14%	5781	0.14%	5736	0.14%
wheat	1290684	31.58%	1289010	31.38%	1304047	31.60%
grains	1596105	39.05%	1597589	38.89%	1591447	38.56%
vegetables	66425	1.63%	66351	1.62%	66214	1.60%
fruit	111612	2.73%	111493	2.71%	111489	2.70%
nuts	100300	2.45%	100196	2.44%	99786	2.42%
roots	53198	1.30%	53184	1.29%	53012	1.28%
pulses	21846	0.53%	21858	0.53%	21736	0.53%
oilseeds	19979	0.49%	19981	0.49%	19898	0.48%
sugar beet/cane	3390	0.08%	3388	0.08%	3281	0.08%
other crops	79	0.00%	80	0.00%	78	0.00%
other agric. products	1041	0.03%	1044	0.03%	1029	0.02%
residues paddy rice	293	0.01%	313	0.01%	323	0.01%
residues grains	47179	1.15%	48718	1.19%	49008	1.19%
residues oilseed	0	0.00%	0	0.00%	0	0.00%
residues wheat	66174	1.62%	78883	1.92%	92878	2.25%
residues other crops	0	0.00%	0	0.00%	0	0.00%
residues vegetables	4867	0.12%	5802	0.14%	6834	0.17%
residues fruit	9390	0.23%	11193	0.27%	13184	0.32%
residues nuts	143	0.00%	170	0.00%	200	0.00%
residues roots	5730	0.14%	6830	0.17%	8046	0.19%
residues pulses	1253	0.03%	1494	0.04%	1759	0.04%
oilcake	0	0.00%	0	0.00%	0	0.00%
DDGS	0	0.00%	0	0.00%	0	0.00%
molasses	0	0.00%	0	0.00%	0	0.00%
fishmeal	205413	5.03%	205575	5.00%	205374	4.98%
raw milk	0	0.00%	0	0.00%	0	0.00%
vegetal oils	36155	0.88%	36280	0.88%	35709	0.87%
other oils	440594	10.78%	442284	10.77%	436088	10.57%
TOTAL	**4087620**	100%	**4107497**	100%	**4127156**	100%
Share main products	91.67%		91.26%		90.85%	
Share by-products	8.33%		8.74%		9.15%	
Gross energy (MJ/kg DM)	19.78		19.78		19.76	
Crude Protein (% DM)	16.11		16.09		16.06	
FCR (kg DM / kg output)	2.9		2.8		2.8	
Reference gross energy[1]	18.0 – 21.0		18.0 – 21.0		18.0 – 21.0	
Reference proteins[1]	20.0 – 35.0		20.0 – 35.0		20.0 – 35.0	
Reference FCR[2]	1.2 – 3.0		1.2 – 3.0		1.2 – 3.0	

[1] Tacon, A. G. J., & Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture*, *285*(1–4), 146–158. https://doi.org/10.1016/j.aquaculture.2008.08.015

[2] Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Feed conversion efficiency in aquaculture: Do we measure it correctly? *Environmental Research Letters*, *13*(2), 024017 https://doi.org/10.1088/17489326/aaa273. Tacon, A. G. J., & Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture*, *285*(1–4), 146–158. https://doi.org/10.1016/j.aquaculture.2008.08.015.

Chapter 6

Discussion and Conclusion

6.1 Main findings

This thesis explores economic, social, and environmental synergy effects and trade-offs of changes in components of the food system commonly analyzed in isolation when studying a transition towards more sustainable food and biomass system. Through the different chapters, this investigation takes a step-by-step approach, expanding the complexity of analyses and methods to address subsequent research questions. This thesis starts with a pure data approach (Chapter 2), followed by a multiregional input-output analysis (MRIO) capturing connections between sectors in a static manner (Chapter 3), and finishing with a general equilibrium (GE) approach including feedback loops and behavioral change inducing adjustments in production and consumption (Chapters 4 and 5).

To begin, Chapter 2 primarily addresses current data gaps on food loss and waste (FLW), providing a new global database and a solid data ground on which the following chapters build. In Chapter 3, a first layer of complexity is added. The FLW database is expanded with air pollution data and used in a MRIO to compare impacts of interventions to achieve FLW reduction. While the MRIO allows using the dataset at is most disaggregated level, and facilitates links to non-economic models due fixed technologies and no behavioral changes, it omits price effects - prices remain unchanged while demand and supply adjust. In the absence of income and substitution effects, the MRIO provides a partial analysis of synergies and trade-offs when reducing FLW. In Chapters 4 and 5, the complexity of the analysis further expands as changes in consumption and production are investigated adopting a GE model. This additional layer of complexity allows to unveil potential new synergy effects and trade-offs of policies for more sustainable food and biomass systems, as changes in prices represent the major driver of direct and indirect economic, social, and environmental impacts.

The main research question addressed in this thesis – "What are the synergy *effects and trade-offs between global food loss and waste reductions, dietary transitions, and a livestock-focused circular food system in terms of economic, social and environmental consequences?"* – underscores the importance of interventions at various stages of the global supply chain to promote sustainability but simultaneously emphasizes that preserving observed synergies requires a multidisciplinary perspective that enables designing cross-sectoral policies apt to mitigate unintended economic, social, and environmental trade-offs.

Synergy effects between FLW reductions, dietary transitions and circular food system policies are several (Table 6.1). First, the second chapter of this thesis has clarified magnitude, composition, and location of global FLW, providing a new database (Gatto & Chepeliev, 2023) key for analyzing FLW impacts of changing food and biomass systems in the rest of the thesis and beyond. From this, Chapter 3 has highlighted the environmental benefits of FLW reductions, illustrating synergy effects in decreasing air pollution, related premature mortality risks, and its associated economic costs. As reducing FLW increases food availability while promoting resource efficiency, such intervention aligns with the overall targets of global dietary transitions and circular biobased strategies. However, the MRIO analysis performed in Chapter 3 limits the potential assessment of substitution effects, possibly overlooking additional indirect synergies and trade-offs. Following, Chapter 4 showed that dietary shifts can reduce FLW and the environmental impact of global food systems, notably by reducing animal-sourced food (ASF) production. However, as ASF remains under-consumed in low-income regions, a regional increase in production is necessary to combat malnutrition. The findings of Chapter 5 showed that enhancing a circular bio-based economy in which livestock are fed low-cost-opportunity feedstuff (LCF) such as residues and by-products, could be a solution for a more sustainable ASF production. In this, circular bioeconomy interventions can complement FLW reductions as reusing secondary biomass inputs along global food supply chains (FSC) indirectly entails decreasing magnitude and spillage of lost and discarded foods into the environment. Integrating such policies has the potential to improve food availability, particularly in food-insecure low-income regions where significant plant-based losses occur at the farm level. Additionally, it can lead to a reduction in total food demand (as shown in Chapters 3 and 4), thereby increasing the prospects of sustaining agricultural production while relying on a higher share of discarded biomass inputs.

Table 6.1. Synergy effects between solutions investigated in this thesis.

<table>
<tr><th></th><th>FLW reduction
(Chapter 3)</th><th>Transition towards a healthier and more sustainable diet
(Chapter 4)</th><th>Transition towards a circular biobased economy with a focus on livestock
(Chapter 5)</th></tr>
<tr><td>FLW quantification (Chapter 2)</td><td colspan="3">New global database containing physical, nutritional, and environmental FLW data for enabling FLW-related analyses in multiple research fields</td></tr>
<tr><td rowspan="2">FLW reduction (Chapter 3)</td><td></td><td colspan="2">A reduction in FLW increases food availability enhancing nutritional security and the adoption of healthier diets;
Parallelly, decreasing lost or discarded foods promotes resource efficiency aligning with the overall targets of global dietary transitions and circular biobased strategies.</td></tr>
<tr><td></td><td></td><td rowspan="2">A reduction in FLW and/or the adoption of healthier and more sustainable diets reduce overall food and biomass demand, increasing the possibility of sustaining livestock production largely relying on discarded and secondary biomass as feed following circular economy principles.</td></tr>
<tr><td>Transition towards a healthier and more sustainable diet (Chapter 4)</td><td>A global shift towards a healthier and more sustainable diet contributes to a reduction in FLW along global supply chains.</td><td></td></tr>
<tr><td>Transition towards a circular biobased economy with a focus on livestock (Chapter 5)</td><td>Circular bioeconomy solutions complement FLW reductions as reusing discarded food biomass along global food supply chains (FSC) as production input decreases the magnitude and spillage of lost and discarded foods into the environment.</td><td>Feeding livestock through low-cost-opportunity feedstuff (LCF) such as residues and by-products, supports a more sustainable increase in livestock production, key for expanding protein supply to achieve healthier diets in food insecure low-income regions.</td><td></td></tr>
</table>

However, the presence of trade-offs must be considered (Table 6.2). Chapters 3 and 4 illustrated that a reduction in food demand in line with dietary recommendations coupled with increased food availability resulting from reduced FLW, could potentially lead to a higher consumption of non-food items. This, in turn, might exacerbate issues related to land use, greenhouse gas (GHG) emissions, and air pollution. While in Chapter 3, changes in demand and associated trade-offs were exogenously introduced in the MRIO based on the assumption that a decrease in food prices might increase consumption of non-food products, the trade-offs illustrated in Chapter 4 were endogenously defined by the GE model simulations. This more sophisticated representation of price mechanisms, income, and substitution effects, allowed to grasp additional trade-offs, not visible in the MRIO used in Chapter 3. From the income side, changes in food demand and biomass production linked to a more sustainable diet decrease average wages of low-skilled workers in agriculture. As food prices decrease relatively less, the food affordability for agricultural workers decreases. This effect is less remarked outside agriculture where low-skilled wages are not severely impacted and food affordability improves, enlarging the income gap between agricultural and non-agricultural workers. Additionally, Chapter 5 showcased that without appropriate policy measures, the shift towards a circular bioeconomy could trigger a rebound effect, potentially resulting in additional adverse environmental consequences.

Table 6.2. Trade-offs between solutions investigated in this thesis.

<table>
<tr><th></th><th>FLW reduction
(Chapter 3)</th><th>Transition towards a healthier and more sustainable diet
(Chapter 4)</th><th>Transition towards a circular biobased economy with a focus on livestock
(Chapter 5)</th></tr>
<tr><td>FLW quantification (Chapter 2)</td><td colspan="3">The magnitude of FLW contributes to an inadequate nutritional supply and dietary intake.
The location of FLW may prevent FLW reduction strategies in certain regions. Its composition can inhibit the reuse of discarded biomass as production input.</td></tr>
<tr><td rowspan="2">FLW reduction (Chapter 3)</td><td></td><td></td><td>Decreasing FLW potentially reduces the scope of circularity as less secondary biomass inputs are available for reuse.</td></tr>
<tr><td colspan="3" rowspan="2">The increasing consumption of non-food products resulting from a decrease in food expenses linked to a higher food availability (FLW reduction) or lower dietary intakes (sustainable diets) risks to increase land use, greenhouse gas (GHG) emissions, and air pollution, compromising the benefit policies promoting the transition towards a more sustainable food and biomass system.</td></tr>
<tr><td rowspan="2">Transition towards a healthier and more sustainable diet (Chapter 4)</td></tr>
<tr><td colspan="2" rowspan="2">A healthier and more sustainable diet at a global level decreases food affordability for workers in agriculture. In lower income countries food affordability decreases also for non-agricultural workers due to a general rise in food prices linked to an increase in food demand necessary to reach a healthy diet. Budget neutral circular bioeconomy policies in livestock sectors also risk to lower wages in agriculture. These effects may exacerbate food security in food insecure regions, compromising the possibility of healthier dietary transitions and the affordability of the increased food availability linked to FLW reductions.</td><td rowspan="2"></td></tr>
<tr><td rowspan="2">Transition towards a circular biobased economy with focus on livestock (Chapter 5)</td></tr>
<tr><td colspan="3">Without appropriate policy measures, the shift towards a circular bioeconomy could trigger a rebound effect, potentially resulting in additional adverse environmental consequences which risk compromising the inherent goals of FLW reduction policies and healthier dietary transitions.</td></tr>
</table>

The following paragraphs provide a detailed overview of synergies and trade-offs investigated through the four research questions explored in this thesis.

Research question 1: What is the magnitude, composition, location, and environmental footprint of food loss and waste generated along global supply chains?

To support this thesis with up-to-date data, Chapter 2 provided a quantification of flows of FLW along global supply chains. Lost or discarded foods along global supply chains reached 1.92 billion Tonnes in 2014, a 24% increase since 2004. Around one-third of produced food is lost or discarded along global supply chains, consistently with previous FLW quantifications (FAO, 2011; 2019; Kaza et al., 2018). Global hotspots of FLW are Agricultural Production and Post-harvest Handling & Storage which cumulatively generated 956 million Tonnes of FLW, around 49.6% of the global share. Around 84.9% of global FLW (1.63 billion Tonnes) derives from plant-based foods, with the majority of losses generated by horticulture and sugar beet/cane production. In high-income regions losses are primarily concentrated at the last stages of the FSC such as Distribution & Retail and Consumption while in low-income regions, losses are larger at the farm level. This diverse location of FLW hotspots reflects the findings of previous investigations (Parfitt et al., 2021; UNEP, 2021; Verma et al., 2020; WRI, 2019) and supports the need for policy interventions at the farm level in low- and middle-income countries and at the consumer level in high-income countries (FAO, 2011, 2019; Kaza et al., 2018). International trade plays a key role in the location of FLW. While around 15.7% of global FLW is associated with traded food, high-income countries remain largely responsible for the generation of FLW in exporting mid- and lower-income regions, exacerbating socioenvironmental pressures. In this, approximately 19.7% of the world's agricultural land and water resources are dedicated to producing food that ends up being lost or wasted along the food supply chain. This process is also responsible for approximately 4.4% of global GHG emissions, equivalent to 1.8 billion Tonnes of carbon dioxide (CO_2) emissions.

FLW remains a critical issue for society, economy, and the environment, and stands at the core of a global transition towards more sustainable food and biomass systems (Gatto & Chepeliev, 2023; Gatto et al., 2023). For this, the remaining chapters analyzed potential interventions to reduce (research questions 2 and 3), or reuse (research question 4) lost and discarded foods along global FSC.

Research question 2: What are potential co-benefits of a global food loss and waste reduction on air pollution and pollution-related mortality risks?

While estimating a positive impact of a global FLW reduction on decreasing air pollution levels (from -15% of SO_2 emissions to -10.2% of NH_3 emissions) and mortality reductions (over 67,000 lives worldwide), Chapter 3 highlighted that rebound effects, wherein a reallocation of consumption from food to non-food commodities, decrease health and environmental benefits by over three quarters compared to the case with no such rebound. The decrease in food consumption associated to the cut in FLW is manually reallocated toward non-food items, assuming different trends of non-food demand (hence magnitudes of rebound effects) across scenarios. In the absence of a rebound effect, a 50% decrease in FLW reduces global air pollution by an average 3%. Positive effects are found on premature mortality risks which decrease, especially in China and India where pollution-related mortality rates are highest (WHO, 2021). However, the presence of potential rebound effects associated with FLW policies has been widely discussed (Druckman et al., 2011; Martinez-Sanchez et al., 2016; Read et al., 2020; Salemdeeb et al., 2017; Reynolds et al., 2019) and changes in demand must be considered once policies targeting FLW are introduced. Rebound effects decrease health and environmental benefits linked to FLW reduction policies. Regions such as China, Nigeria, high-income Asia, and Sub-Saharan Africa experience increased pollution levels due to the shift in consumer demand towards non-food products such as transportation, construction, and manufacturing, which have higher pollution rates compared to food products. This leads to an increase in pollution-related mortality risk and health-related costs, primarily elevating the risk of lower respiratory infection diseases. Differently, in large food trading regions such as Indonesia or Brazil, a decrease in food demand and production results in a lower level of total pollution and related mortality as primary food production sectors are among the main drivers of air pollution.

The findings of Chapter 3 illustrate that understanding how changes in demand respond to system changes is crucial for analysing potential synergies and trade-offs resulting from interventions. The subsequent chapter delves deeper into the exploration of the impact on demand associated with a system transformation. It adds an extra layer of complexity, endogenizing demand changes while considering dynamic price effects—fixed in Chapter 3—which are fundamental drivers of behavioural changes in response to system interventions.

Research question 3: What are the economic, social, and environmental impacts of a global transition towards a healthier and more sustainable diet?

Transitioning towards a healthier and more sustainable diet identified in the EAT-Lancet diet, improves the sustainability of global food systems, decreasing global food demand and thus global biomass production mostly by reducing calorie intakes in all but the poorest countries. While food system benefits of more sustainable diet from previous studies (Tillman & Clark, 2014; Springmann et al., 2018; Willett et al., 2019) are confirmed, Chapter 4 identified several spillover effects related to a global dietary change. The EAT-Lancet diet generates economic spillovers to non-food demand, increasing non-food production and thereby reducing initial land use and GHG emissions gains from the shift in food consumption. As reduced demand for food reduces biomass prices, it increases its competitiveness relative to non-biomass substitutes in non-food use. This mitigates the initial decrease in biomass production, thus further tempering the initial reduction in land use and land prices. The increase in biomass production for non-food use erases almost half of the reduction in emissions achieved by the reduction in biomass demand for food with the diet. The increase in GHG emissions linked to all non-food production (biobased and non-biobased) outweighs the decreased GHG emissions from the food system observed in previous research (Willet et al., 2019; Springmann et al., 2016; Springmann et al., 2018; Laine et al., 2021). Parallelly, social spillovers enlarge the income gap between agricultural and non-agricultural low-skilled workers, while decreasing food affordability for workers employed in agricultural sectors. Less demand for agricultural products leads to lower wages in agriculture relative to the rest of the economy, reducing the average affordability of a healthy foods and staple foods in mid- and low-income regions. In Sub-Saharan Africa the increase in food demand and production necessary to meet the EAT-Lancet diet pushes both average food prices and agricultural wages up. As food prices increase relatively more than wages, food affordability decreases for both agricultural and non-agricultural low skilled workers. Finally, while transitioning towards the EAT-Lancet diet decreases global FLW (-18.9%), food consumption in high-income countries continues to generate large primary losses in mid- and lower-income regions. This continues local environmental pressures, hampering FLW reuse due to lack of proper infrastructure and technologies especially in low-income regions. Impacts of the EAT-Lancet diet on FLW are thus mixed. On the one hand, lower levels of FLW mean less calorie and nutrient losses, while increasing shares of fresh plant-based FLW increase options for reuse. On the other hand, in the absence of proper policies or technologies in locations where FLW is generated, the increasing shares of plant-based FLW risk to lead to higher pollution rates.

In Chapter 4, the shift towards a healthier and more sustainable diet is investigated using a consumer preference-shift which allows changes in food consumption without targeted monetary interventions facilitating such shifts. In terms of policy instruments this could be interpreted as a costless increase in education or awareness on healthier and more sustainable consumption choices radically shifting demand. Moreover, impacts on FLW are computed ex-post and not during the GE model simulations. Building on these choices, the following chapter further integrates two additional layers of complexity. First, monetary policies promoting a more a sustainable production are integrated, and the associated endogenous mechanisms are analyzed. Second, policy-impacts on food losses are endogenized into the dynamics of the GE model, allowing to target these flows with monetary policies that facilitate their upcycling as production inputs.

Research question 4: What are the economic and environmental impacts of policies promoting the upcycling of food loss and waste and other secondary biomass as animal feed?

Feeding animals with LCF such as agricultural residues and by-products, and better use of local feed resources are discussed as strategies for transitioning towards more circular food systems. By incorporating technical characteristics of livestock production into a global economic model Chapter 5 investigated the economic and environmental effects of such a circular food system transition in the European Union (EU27) in relation to the policy instruments used to reach them. A comparison between the impact of LCF stimulating subsidies, budget-neutral price interventions, and import tariffs stimulating domestic sourcing was provided. Findings highlight that providing only subsidies increases circularity and agricultural wages (0.1 to 0.3%), but also animal production (0.1 to 1.5%) with negative indirect effects on land use (0.3 to 1.1%) and emissions (1.3 to 8.0%). Promoting the use of LCF through budget-neutral interventions where subsidies are financed by taxes, and domestic feed sourcing promoted through import tariffs, decreases animal production (-0.1 to -1.6%) and GHG emissions in agriculture (-0.4 to -6.0%). Synergy effects are found from subsidizing DDGS, a biofuel by-product used as feed, which indirectly increases biofuel production, positively contributing to lower GHG emissions (-0.3 to -0.6%) in 2030. However, budget-neutrality drives land use up (0.1 to 0.5%) while decreasing agricultural wages (-0.1 to -0.3%) as highlighted by previous inquiries (Sumner et al., 2017; European Commission, 2018).

6.2 Contributions to the literature: data advancements and enhanced multidisciplinary modelling

This thesis makes two major contributions to the currently existing tools for research on a global transition to more sustainable food and biomass systems (Figure 6.1). The first consists of data advancements on quantifying global FLW and its associated impacts on trade, nutrition, and environmental footprints. The second consists of improving the multidisciplinary modelling of global economic feedback mechanisms induced by shifts in production or demand which unveil trade-offs and synergies in economic, social, and environmental dimensions. Below we summarize the contributions of the different chapters in these two areas and outline possible directions of future research building on this thesis.

In Chapter 2, a global database of lost and discarded foods along global supply chains was provided. This FLW database merges available data to overcome the coverage limitations inherent in individual databases and further enriches research from several points of view. First, currently existing data for specific countries, stages of the supply chain, and commodities were merged in a consistent way to address current debates on FLW definitions, specifications, and computations (Xue et al., 2017; FAO, 2019). Second, the timeframe of existing global FLW databases was improved, providing a collection of up-to-date observations that may more closely resemble today's real-world dynamics. Third, the multidisciplinary useability of the FLW database was expanded by adding dimensions not yet available in existing databases. New estimations of FLW embedded into global trade were provided, filling knowledge gaps around main drivers of lost and discarded foods along global supply chains. Following, new global estimates on macronutrients (calories, proteins, fats, and carbohydrates) and environmental footprints (land use, water use, and greenhouse gas emissions) embedded into FLW were provided. On top of this, an additional first estimation of nine air pollutants embedded in FLW was added in Chapter 3, allowing to connect FLW analyses with research on impacts of air pollution, like pollution-related mortality risks.

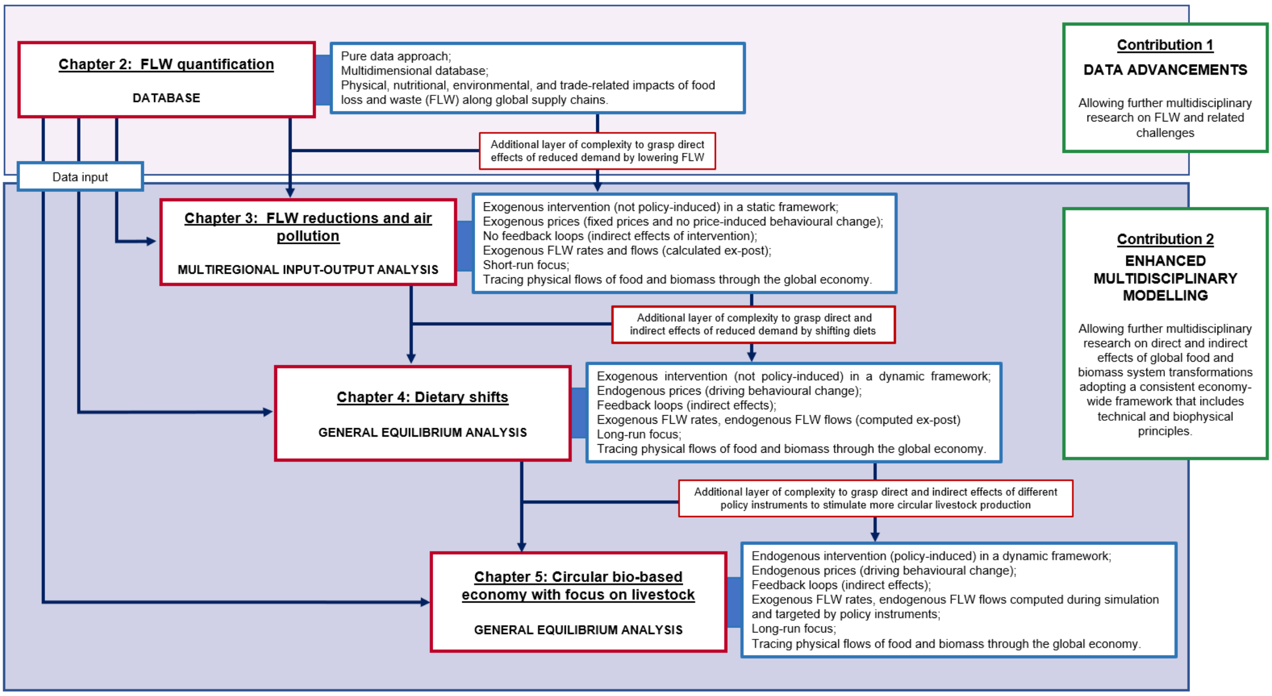


Figure 6.1. Overview of the methodological approach adopted in each chapter of this thesis and core contributions to the literature.

The multidimensional FLW data constructed in this thesis may pave the way for multidisciplinary research on the contribution of food and biomass system transitions to attaining the Sustainable Development Goals (SDGs) (U.N., 2019). With these data FLW (SDG 12.3) can more easily be connected to nutrition (SDG 2) and health (SDG 3), as well as environmental goals (SDG 13, SDG 14, SDG 15), providing an opportunity for exploring ways to reach the SDGs in an integrated manner. More general, the FLW data allow analyses of policies targeting food production and consumption, trade, nutrition, environmental impacts, or health-related challenges to quantify impacts on FLW, supporting policy coherence. This thesis showed two different approaches to using the multidimensional FLW database. The MRIO analysis in Chapter 3 started from a global FLW reduction, exploring multidimensional implications and potential synergies between FLW reductions, air pollution trends, and associated mortality risks. Chapter 4 and 5 using a GE model illustrated the use of the new database to quantify changes in FLW resulting from changes in demand (dietary shifts) or livestock production systems, alongside a wider set of economic, social, and environmental indicators.

The second contribution of this thesis consists of improving the multidisciplinary modelling of global economic feedback mechanisms, in particular the sustainability of food and biomass systems. Research on sustainable dietary transition and the circular biobased economy has to date primarily been conducted through the use of biophysical models (van Selm et al., 2022; van Zanten et al., 2023) or static partial equilibrium models (Springmann et al., 2021). These partial analyses omit potential social and economic-wide drawbacks of transitions, overlooking impacts on labor markets, food/biomass affordability, non-food sectors, and regional patterns in FLW. Chapter 4 investigated the impact of a global transition towards healthier and more sustainable diets, providing an innovative analysis from a broad socioeconomic perspective while also consistently capturing changes in physical material flows and FLW. Currently, while the benefits of dietary changes are widely recognized (Willett et al., 2019), available economic investigations on global dietary changes (Hirvonen et al, 2020; Springmann et al., 2021) misrepresent income and price effects, omitting potential trade-offs in income distribution and food accessibility. Chapter 4 confirms the previous findings linked to dietary transitions in several environmental domains, while adding two additional layers of analysis. By capturing income and price effects, the change in the affordability of healthy foods for different groups of workers was quantified, crucial for the social acceptance of dietary shifts. In addition, consistent tracing of physical material flows in combination with the new FLW database provided new insights on the amount, composition, and geographical location of global FLW. Calculations on FLW were performed ex-post and not during model simulations.

Chapter 5 expanded the economic modeling of a transition towards a circular biobased economy with a focus on livestock production. To date, the majority of investigations around livestock-focused circular food systems are performed through biophysical optimization models (Muscat et al., 2021; Frehner et al., 2022; van Zanten et al., 2023; Van Selm et al., 2023). Although this approach enables exploring the effects of adopting circularity on several ecosystems, these technical inquiries (van Hal et al., 2019; van Selm et al., 2022; Van Zanten et al., 2019) ignore opportunity costs, price changes, and other market responses crucial for anticipating the effect that policy interventions could have in the current economic system. Chapter 5 partially addressed such limitations exploring the transition towards a livestock-focused circular biobased economy from an economic perspective. Incorporating biophysical constraints, crucial for establishing a circular biobased economy, into an economy-wide framework enabled the recognition of social and economic trade-offs often overlooked in purely technical analyses while better capturing technical limitations on livestock production often missing in economic studies. Moreover, the endogenization of farm-level food losses into the used GE framework allowed to target such flows during model simulations, testing the impact of several policies on the reuse of food losses as animal feed. This provided a more integral picture of the synergies and drawbacks of policies promoting circularity in livestock production, complementing earlier findings of technical studies while improving the representation of livestock production in global economic modelling.

The improved multidisciplinary approach to modelling system changes for sustainability transitions offers a foundation for integrating diverse research perspectives. While a singular disciplinary perspective can yield in-depth analyses, it may overlook challenges that may arise in different research fields. This thesis contributes to establishing a shared foundation for merging economic and technical analyses on sustainability. Economic analyses have the potential to extend beyond conventional monetary impacts, incorporating examinations of physical material flows and associated constraints in the design of economic policies. Simultaneously, technical investigations can more easily connect with an economic modelling framework as the inclusion of as physical material flows represents a fundamental common ground on which different disciplines can connect. In this, technical investigations can parallelly broaden their analytical framework, encompassing potential monetary-based effects beyond the scope of technical models.

6.3 Synthesis & Policy recommendations

This thesis provides an unveiling of synergies and trade-offs of interventions across economic, social, and environmental domains that may support designing coherent changes to global food and biomass systems for addressing a major societal challenge of the 21st century – *how to feed a growing world population in a sustainable and inclusive manner which strengthens resilience to climate change and incorporates concerns for planetary security*[18]. To this end, shifts at different stages of global supply chains were explored through a multidisciplinary perspective with the aim of highlighting potential trade-offs and synergies of future policy interventions not yet addressed in the literature. The presented findings show the need for interventions to account for both the sustainability of production and consumption systems, capturing synergies and trade-offs along various stages of global supply chains and across domains. A dietary shift coupled with a transition towards a circular biobased economy may have parallel benefits on FLW reductions, while the latter can reciprocally facilitate achieving the targets of more sustainable diets and circularity. These joint interventions prove to contribute to global nutritional security, resource efficiency, and an overall higher environmental sustainability. However, as spillover effects arise in non-food, non-biomass sectors, parallel policies in resource- and pollution-intensive sectors may be required to preserve the outlined benefits of more sustainable global food and biomass systems.

Recommendation 1: Reducing overconsumption of animal-sourced products in high-income countries may decrease environmental impacts and food loss generation in mid- and low-income regions.

Given the significant role of final food demand in driving food-related environmental impacts and FLW (Chapters 3 and 4), policies must encourage sustainable dietary patterns. Chapter 4 shows that processed foods, particularly those derived from animal sources, contribute substantially to health and environmental problems and are the main culprits behind nutritional losses and environmental impacts related to FLW. Additionally, Chapter 3 illustrates that high-income food consumption continues to generate large primary losses in mid- to lower-income regions even when a healthier and more sustainable diet is adopted globally. This not only continues local environmental pressures. It also hampers FLW reuse due to lack of proper infrastructure and technologies in mid- to low-income regions. To mitigate such effects and reduce overconsumption in high-income regions, measures are necessary.
Latka et al. (2021) conclude that promoting public-awareness campaigns to raise consciousness on the health and environmental consequences of specific food products is not enough and price-based measures such as taxation are required. Recent surveys suggest that the majority (around 70%) of consumers in Germany, France and the Netherlands support a meat tax that reflects environmental costs provided that the tax revenues are recycled via reduction of the value-added taxes (VAT) on vegetables and fruits (TAPPC, 2020; IPES, 2022). These measures may steer consumers toward plant-based products which, as illustrated in Chapter 4, have the potential to alleviate health and environmental burdens. Moreover, as levying taxes simultaneously reduces available income for wealthier consumers, the spillover effects in non-food consumption observed in chapters 3 and 4 might be parallelly reduced. The tax income can be used to compensate low-income consumers to safeguard their affordability of nutritious food.

Recommendation 2: Increase availability of animal-sourced products in low-income countries following circular food system principles while provide income support to afford healthier foods.

[18] Based on IFPRI (2016), United Nations (2019), and Van Meijl et al. (2019).

In low-income regions, animal-sourced products are key for fighting malnutrition, and reaching a healthier diet entails increasing intakes of such products (Chapter 4). Based on this, policies should enhance their production in a sustainable manner. First, Chapter 3 remarks that policies should promote and facilitate the use of innovative technologies at the farm level to increase agricultural efficiency while reducing FLW, key to increase nutrients availability and food security. Second, as a certain level of FLW is inevitable for global food security (FAO, 2019), Chapter 5 stresses that policy interventions should promote the reuse of FLW as animal feed, expanding ASF production through a larger use of LCF (e.g. agricultural residues, by-products, FLW), without relying on additional land, biomass, and natural resources. This could be particularly beneficial in low-income regions where the largest levels of food losses, mainly consisting of farm-level crops and horticulture losses (Chapter 2), are highly suitable for being upcycled as animal feed. Nonetheless, Chapter 4 remarked that adopting a healthier diet results in a decrease in food affordability for both agricultural and non-agricultural workers in Sub-Saharan Africa, as food prices increase more than wages. For this, targeted complementary policies providing income support are required to avoid negative social spillovers and allow consumers to afford healthier and more nutritious foods.

Recommendation 3: Subsidies for sustainability transitions need to be accompanied by regulation of production practices to avoid environmental spillovers potentially undoing benefits.

Chapter 5 illustrated that offering non-budget neutral subsidies to facilitate the shift towards a more circular production system in livestock sectors can lead to an increase in livestock production, driving land use, and greenhouse gas emissions up. As this contradicts the initial aim of the subsidy for sustainability, it calls for a policy package in which such subsidies should be accompanied by stricter regulations of production practices in resource- and pollution-intensive sectors. To achieve an input substitution transition, taxes should be levied on environmental-intensive inputs (e.g. compound feed or crop-based feed) while subsidies should be given for promoting the use of more sustainable alternatives (e.g. discarded biomasses suitable as feed). Taxations schemes should follow a “polluter pays” principle, targeting unsustainable production inputs to rise their average price and discourage their use. Following, the collected revenues from the levied taxes should be used to finance through subsidies the use of more sustainable input alternatives. While this policy package could be desirable from a fiscal point of view, requiring no monetary commitment from government budgets, it could also have the potential to effectively address and mitigate indirect negative environmental externalities (Chapter 5) if appropriately targeted. In cases taxation schemes are insufficient, additional environmentally-driven bans or quotas must be applied to tackle potential environmental and social externalities. Finally, on top of these monetary interventions, a relaxation in the stringent regulation that currently limits the reuse of discarded biomass can increase the reliance of production systems on discarded biomass, residues, and FLW, decoupling productions production from additional resource use.

Recommendation 4: Mitigating economywide GHG emissions requires taxing GHG emissions from both food and non-food sectors.

Chapters 3 and 4 show that dietary transitions and policies aimed at reducing FLW may induce a shift in consumption patterns towards non-food products that commonly associate to higher levels of pollution and greenhouse gas emissions. This shift could result in an increase in pollution-related mortality risks and associated health costs (Chapter 3), illustrating the need for parallel interventions to tackle spillover effects into non-food sectors. First, as remarked in Chapter 3, it is crucial to encourage the use of cleaner technologies in key polluting and emitting sectors. Second, policies should have an economy-wide vision and promote interventions across multiple sectors of the economy to avoid spillover effects. As highlighted in this thesis, preserving the benefits of dietary shifts for reducing GHG emissions requires parallelly addressing non-food GHG emissions. This emphasizes the need for a comprehensive approach, calling for simultaneous GHG emission taxation in both food and non-food sectors, as the current policy focus primarily revolves on non-food sectors. Introducing a taxation to targeted food commodities in high income regions (e.g. red meat), has the potential to curve GHG emission from the food sector, while simultaneously fostering the transition towards a more sustainable and healthy diet. This however would require an additional effort to monitor and potentially tackle negative impacts on food/non-food affordability which may arise due to an increase in products' prices linked to higher taxation. For this, tax revenues should be used for targeted support schemes, aiding vulnerable consumers that might be more exposed to food affordability problems. Finally, emission taxation measures could additionally decrease pollution-related mortality risks, providing health-related economic benefits across years. As economic benefits are enduring, investments to improve pollution and air quality can yield returns not only during the policy implementation period but also in the long-run, helping to support the often unpopular short-run monetary interventions.

Recommendation 5: Supporting measures for workers in agriculture need to complement policies for food and biomass systems sustainability that aim at decreasing production.

While sustainable diets may have a positive environmental impact, Chapter 4 illustrates that the decrease in food and biomass production results in a decline of agricultural wages especially in large agriculture-based exporting countries. Moreover, Chapter 5 shows that taxes to contain livestock production may have a detrimental effect on wages in agriculture. To prevent an increase in rural poverty when shifting to a healthier diet, low paid agricultural workers could be temporary compensated by income support. Among available options, income subsidies such as the current direct payment system within the European Union, could safeguard the welfare of workers in the food system when policies for sustainability are implemented. However, wage support should not be unconditional, temporary, and must be adapted to different contexts. When social support programs or job opportunities in other sectors are available, policies should ensure equal access to these programs while simultaneously reducing barriers to access alternative employment. Education or retraining programs could offer workers better opportunities to explore other employment options, especially in cases where agricultural wages decrease. This implies that if certain sectors are fading due to fair economic competition, policies should focus on facilitating job transitions outside that sector rather than offering unconditional support to wages.

6.4 Limitations of this thesis

While focus allows a more thorough investigation of the chosen topic, by design it also limits the analyses to specific challenges. Improving data on FLW and its impacts, and integrating additional biophysical details into economy-wide modeling frameworks enhances future research possibilities. But it only addresses a fraction of the extensive spectrum of sustainability solutions outlined in Chapter 1. Prioritizing data and better capturing biophysical realities in global economywide modeling primarily serves research purposes. An alternative focus on policy formulation or technological development could potentially establish more robust connections to policymaking, investment decisions, and pressing societal challenges, than the modeling approach taken in this thesis. As global economic models are regularly used for policy assessments and the improvement in modeling of biophysical realities enable links to other disciplines the work in this thesis may still provide a steppingstone to more multidisciplinary policy-focused future studies, indirectly contributing to decision-making. Chapter 5 already provides a first glimpse of how such modeling can support policy design, showing that the choice of policy instruments affects the outcomes.

The methodological framework adopted in this thesis gradually grows in complexity and consisted of a mix of MRIO and GE modelling (Figure 6.1). This choice is based on the specific features each modelling framework offers in regard to the investigated research questions and increasing levels of complexity. The MRIO framework was found to be suited for addressing research question 1 and 2 where the level of disaggregation required to provide country-specific databases was not supported by an often more aggregated GE framework. Moreover, a MRIO framework shares characteristics, such as fixed production technology, akin to the input-optimization models frequently employed in biophysical analyses. The MRIO results may thus be more understandable from a different disciplinary perspective, enhancing the possibilities for combining this approach with non-economic models. For research questions 3 and 4, a GE framework was used to extend the analyses with price effects. These topics allowed a higher level of aggregation, while greatly benefitting from capturing price driven economy-wide second-order feedback effects, only depictable through a GE framework. While in research question 3 the GE framework was used to investigate an exogenous intervention (dietary shift not policy-induced) in a dynamic framework, in research question 4 an additional layer of complexity was added by analyzing different endogenous interventions (policy-induced) to stimulate more circular livestock production. Additionally, while in research question 3 the impacts on FLW were calculated ex-post after model simulations, in research question 4 the impacts on FLW flows were computed during model simulations as FLW was targeted by policy instruments. Although these models are well-suited for analyzing the transition toward more sustainable food and biomass systems, enabling the evaluation of economy-wide effects of global policies impacting various food and non-food sectors, they are subject to several limitations.

In Chapter 2, main methodological limitations lie in the lack of representative high-quality FLW data (Delgado et al, 2021), with gaps particularly apparent for low- and mid-income regions, especially at the final stages of the FSC. As FLW shares are derived from current literature, the quality of FLW data remains rather low and the application of a consistent gap-filling procedure based on FLW shares in comparable regions urges a careful utilization and interpretation of the database as data assumptions and aggregations may impact the magnitude of estimates. Moreover, as FLW data is aggregated through physical mass, the applied methodology does not allow a direct assessment of SDG12.3, for which an indicator based on economic weights (Fabi & English, 2018) is adopted as a quantification approach.

With regards to Chapter 2 and 3, while the strengths and advantages of relying on an MRIO analyses have been broadly outlined in Chapter 1, it has several limitations in terms of the quantification of synergy and trade-off effects. First, a MRIO approach relies on numerous simplifying assumptions, such as fixed production coefficients (Leontief, 1955), static trade patterns, perfectly elastic factor supplies, and exogenously determined final demands (no link between income creation and spending), which may not fully capture the dynamics of real-world economic systems. Moreover, this static framework may struggle to account for changes in production technology (as it relies on a fixed production technology), evolving consumer preferences (e.g. dietary shifts), and changing global trade dynamics, which are increasingly relevant in today's fast-paced world. Finally, as a MRIO framework allows to only depict first-order feedback effects from policy interventions, the omittance of price-driven feedback loops from policy interventions limits the assessment of the broader sustainability implications of evolving economic activities. Although these limitations may not apply to the investigation of research question 1, where no interventions in the current system were explored and the collection and construction of the FLW data was the key focus of the analyses, the analysis conducted to address research question 2 could have been enhanced by utilizing a GE framework. Utilizing a MRIO enables the initial understanding of how a reduction in demand can propagate throughout the global economy with detailed insights into country-specific impacts but overlooks price-driven feedback mechanisms. Research question 3 demonstrates that the use of a GE framework allows to address similar demand-side shocks while additionally incorporating feedback effects across the economy. This would have permitted to devise potential endogenous rebound effects of FLW reductions, and additionally investigate how economy-wide price changes in response to interventions drive consumer purchasing behaviour across food and non-food sectors.

In Chapters 4 and 5 the use of GE models was crucial for depicting direct and indirect effects of policies. A main difference between these two chapters is that in Chapter 4 FLW is calculated ex-post and in Chapter 5 it is modelled endogenously. The latter enables the inclusion of policies to stimulate the use of FLW inside circular activities.

In this thesis, the need to assess indirect trade-offs and synergies required the use of a GE model as several price-related income and substitution effects were not depictable by only using a MRIO framework (Dixon et al., 2012). However, GE models often rely on simplifying assumptions, such as perfect competition and rational economic behavior, which may not fully capture the complexities and nuances of real-world markets and decision-making processes. As agents are assumed to behave perfectly rational, only prices (and quantities) are identified as explicit drivers moderated through elasticities capturing a wide but implicit array of preferences and restrictions. However, such elasticities are often debated, and model results are highly sensitive to the choice of such parameters and assumptions, with small changes leading to significantly different outcomes (Hertel et al., 2007). Additional limitations concern the high level of aggregation, which prohibits capturing heterogeneity in sectors, commodities or households,. With regards to the illustrated modelling scenarios, a consumer preference-shift was assumed for simulating a dietary transition. While this may be far from a real-world situation in which consumers do not change dietary preferences “overnight”, this choice finds its foundations in the absence of clearer understanding of how interventions may steer such a fundamental change in dietary choices across countries. Additionally, it provides a way to connect to existing literature, as available studies (see for example Springmann et al., 2018 or Willet et al., 2019) investigate such dietary transitions adopting similar scenario assumptions.

The presented simulations are thus best interpreted as thought experiments about what the world would be like if the shift in consumption or production had been operative in the assumed circumstances, focusing on identifying spillovers effects affecting the desired impact of the shifts. While GE models are quantitative, they are not empirical in the sense of econometric modeling: they are basically theoretical, with limited possibilities for rigorous testing against experience (Dixon et al., 2012). One could do sensitivity analysis on the parameter values assumed for economic behavior, although less so on the data, because altering one element of the base data requires compensating changes elsewhere in order to keep the national accounts and social accounting matrix in balance (Burfisher, 2011). Of course, many of these criticisms apply to other types of economic modeling, and therefore, while imperfect, GE models remain a cornerstone for ex-ante analyses of global policy issues being able to quantify trade-off and synergy effects across various sectors and objectives (Hertel., 2007, Pyka et al. 2021).

Additional limitations lie in the current state of global databases. While a primary focus was given to filling data gaps around global FLW, the dearth of data concerning agricultural residues, by-products, and other secondary/discarded biomass suitable to be upcycled as production input, limited the sectoral scope of this research with respect to circular food systems modelling. Moreover, while the GTAP database, has served as a valuable resource for all the global economic analyses presented in this dissertation, it is essential to acknowledge its inherent limitations. GTAP, like any database, is a simplified representation of the real world and relies on assumptions and data sources that may not capture all the intricacies of economic systems accurately. The database is based on various sources and estimations, introducing potential inaccuracies and uncertainties into the analysis. The version of the database used for this thesis (GTAP version 10 – Aguiar et al., 2019), provided a rather limited sectoral classification, requiring additional external data (i.e. animal feed, agricultural residues, by-products) and adjustments to the Social Accounting Matrix (SAM) to address our key research questions. Moreover, as the base year of the database is 2014, simulations to update baselines to a more recent year (2020) where performed to answer research questions 3 and 4. Despite so, the reliance on a rather outdated database potentially limits the precision of model outcomes and discrepancies may occur with respect to current economic conditions. These limitations highlight the importance of complementing the GTAP database with additional data sources to provide a more comprehensive understanding of the economic scenarios under investigation.

Finally, on top of our methodological limitations, designing and implementing policies achieving the simulated shifts in production and consumption face several obstacles. The journey towards sustainability in various sectors, including food systems, confronts formidable barriers within the current policy status, governments, and institutions. One of the most prominent challenges lies in the short-term nature of political decision-making, which often prioritizes immediate economic and electoral gains over long-term sustainability goals. This short-sightedness can deter the implementation of ambitious sustainability policies that require substantial investments and may not yield immediate benefits. Additionally, bureaucratic inefficiencies and a lack of coordination among different governmental departments can hinder the coherent execution of sustainable initiatives. Furthermore, the influence of powerful interest groups and industries (e.g. fossil-fuel industries) with vested interests in maintaining the status quo can thwart progressive policies and perpetuate unsustainable practices. Finally, a lack of public awareness and education on sustainability issues coupled with short run personal interests or loss aversion can lead to resistance or indifference, making it difficult for governments and institutions to garner the necessary public support for a transformative change. Overcoming these barriers is essential to expedite the much-needed transition towards a more sustainable future. It is then important to acknowledge that not all type of policy instruments listed above can be included into an economic modelling framework. Due to lack of data the impact of measures such as improvements in education, public awareness or information provision on behavior cannot currently be quantified, and therefore not well represented (if at all) in economic models.

6.5 Recommendations for future research

The limitations of this thesis can be taken as a starting point for future research. First, given the lack of a consistent global FLW database, future research should make use of the newly compiled databases, further investigating policies that favor FLW reduction and reuse. Making the databases developed in this thesis compatible with the GTAP database structure is intended to support this uptake, as the GTAP data are the basis of most global economywide analyses. Future research should further explore the core drivers of FLW generation across income levels, countries, and products.

Within GE models, it is crucial to endogenize FLW rates (i.e. shares of lost or discarded foods) and related dynamics. Introducing waste management sectors or FLW as a separate commodity would permit to formulate monetary policies targeting producers or consumers and identifying resources needed to collect, transform and distribute FLW. Additionally, GE analyses on FLW may greatly benefit from a link with microeconomic household models to assess food affordability and poverty issues. Characteristics such as time, family size, age, gender, and income can affect the generation of food waste and could help translate broader GE-derived policies towards more specific interventions acknowledging this heterogeneity.

Second, future research should enhance the link of technical models and economy-wide frameworks to provide multidisciplinary frameworks apt to investigate the complex dynamics of sustainability transitions. The MRIO extensions with environmental accounts or the integration of biophysical technical details into a value-based GE framework developed in this thesis may serve as a starting point for providing more comprehensive enquiries on sustainability. In this regards, future research may further explore the combination of a MRIO and a GE model. The GE model could offer insights into economy-wide direct and indirect price-induced effects of interventions, and these findings could then be incorporated into a MRIO to achieve a more disaggregated and detailed level of analysis that can be more easily connected to technical studies.

With regards to the analyzed dietary transitions, it is crucial to expand on the investigation provided in this thesis, exploring which interventions are most effective in steering consumer choices towards more sustainable food products at national level, and at what cost. Future studies on dietary shifts should also account for the distributional or social dimensions, as the majority of current studies focus on environmental footprints. Changes in food affordability should be further researched, possibly complementing large scale economy-wide models with more detailed microeconomic models at different scales (e.g. household) apt to provide analyses of additional factors promoting or impeding the adoption of more sustainable diets. In this regard, additional research could further explore different combinations of policy bundles that may mitigate the undesired effects of costless preference shifters observed in this thesis.

Parallelly, for fostering a circular biobased economy transition effective policy mixes that can contain potential drawbacks of circularity transitions as identified in this thesis need to be investigated. On top of this, large scale economic models will require a better representation of circular bioeconomy principles, integrating biophysical constrains and engineering principles to obtain a closer representation of circular production processes. Finally, a significant improvement in MRIO or GE models could consist of including current institutional constrains in the global economy, offering a closer representation of the ongoing political economic debate on sustainability across countries.

While science is finally putting social and environmental sustainability on top of the agenda, relying solely on single disciplinary research is insufficient and may even pose a risk of leading us astray. The need to broaden the multidisciplinary approach for addressing challenges is therefore more pressing than ever. A joint global effort for cooperating across disciplinary boundaries to reshape our global economy in a more sustainable and inclusive manner is a major duty of the scientist of our century.

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Summary

Achieving the U.N. Sustainable Development Goals (SDGs) while addressing the challenge of feeding a growing global population in a sustainable and inclusive manner requires a comprehensive transformation of our food system and the broader bioeconomy. Across the multitude of available solutions, this thesis provides an in-depth exploration of economic, social, and environmental synergy effects and trade-offs of a portion of the potential solutions within the broader context of sustainable food biomass systems: food loss and waste (FLW) reductions, dietary shifts, and transitioning to a circular bio-based economy. In this, this thesis tackles two specific research challenges that, if addressed, would simultaneously help research on sustainable food and biomass systems: (i) filling data gaps related to FLW along global supply chains, and (ii) enhancing the multidisciplinary modelling of global biomass systems to improve analyses on sustainability transitions. Through the different chapters, this investigation takes a step-by-step approach, expanding the complexity of analyses and methods.

Chapter 1 sets the stage and introduces the research topics central to this thesis – FLW quantification, FLW reductions, dietary shifts, and transitioning to a circular bio-based economy – presenting the research questions guiding the individual chapters.

Chapter 2 quantifies FLW along global supply chains, presenting a detailed database for 121 countries and 20 regions. It provides data on FLW magnitude, location, nutritional content, and environmental footprint by supply chain stage and food commodity. From 2004 to 2014, FLW increased by 24%, with significant spikes in sub-Saharan Africa (43.1%) and southeast Asia (37.1%) where growing nutritional losses (average 550 calories/capita/day) impact food security. Key hotspots for FLW are Agricultural Production and Post-harvest Handling & Storage, contributing 49.6% globally. Plant-based foods account for 84.9% of FLW (1.63 billion tonnes), mainly from horticulture and sugar beet/cane production. The multidimensional FLW data constructed in this chapter may assist multidisciplinary research on the contribution of food and biomass system transitions to attaining the Sustainable Development Goals (SDGs). With these data FLW strategies (SDG 12.3) can more easily be connected to nutrition (SDG 2) and health (SDG 3), as well as environmental goals (SDG 13, SDG 14, SDG 15), providing an opportunity for exploring ways to reach the SDGs in an integrated manner.

Chapter 3 explores the potential effects of reducing global FLW, examining its connections to air pollution and related mortality risks. Using an environmentally-extended input-output model, this chapter extends the database developed in the previous chapter with data on air pollution embedded in FLW and evaluates how reducing FLW can decrease air pollution and related premature mortality risks globally. Three alternative scenarios of changing final demand patterns are considered, aligned with the UN-SDG12.3 target. By linking changes in air pollution to a global atmospheric source-receptor model, the impact of FLW reductions and demand changes on premature mortality risks and health-related co-benefits is investigated at a global level. Reducing FLW decreases air pollution levels (up to -10.2% in NH_3 emissions) and leads to over 67,000 fewer premature deaths worldwide. However, rebound effects, wherein a reallocation of a shift in consumption from food to non-food items reduces health and environmental benefits by over three quarters compared to a scenario with no rebound. Mitigating these rebound effects requires policies encouraging a shift in consumption towards less pollution-intensive products.

Chapter 4 simulates the global transition towards a healthier and more sustainable diet. Dietary shifts are key for enhancing the sustainability of current food systems, but need to account for potential economic, social, and environmental indirect effects as well. By tracing physical quantities of biomass along supply chains in a global general equilibrium model, this chapter investigates the benefits of adopting the EAT-Lancet diet as well as other

social, economic, and environmental spillovers to the wider economy. The chapter highlights that decreased global food demand reduces global biomass production, food prices, trade, land use and FLW, but also reduces food affordability for low-income agricultural households. In Sub-Saharan Africa, increased food demand and higher prices decrease food affordability also for non-agricultural households. Economic spillovers into non-food sectors limit agricultural land and GHG reductions as cheaper biomass is demanded more for non-food use. From an environmental perspective, economy-wide greenhouse gas emissions increase as lower global food demand at lower prices frees income subsequently spent on non-food items.

Chapter 5 investigates the transition towards a circular biobased economy, exploring the economic and environmental effects of policy instruments promoting a livestock-focused circular food system. Feeding animals with low-opportunity-cost feed (LCF) such as agricultural residues and by-products, and better use of local feed resources are discussed as circular food systems strategies. A comparison between the impact of low-opportunity-cost feed (LCF) stimulating subsidies, budget-neutral price interventions, and import tariffs stimulating domestic sourcing is provided. This chapters finds that providing only subsidies increases circularity and agricultural wages (0.1 to 0.3%), but also animal production (0.1 to 1.5%) with negative indirect effects on land use (0.3 to 1.1%) and emissions (1.3 to 8.0%). As counterfactual, promoting the use of LCF through budget-neutral interventions where subsidies are financed by taxes, and domestic feed sourcing promoted through import tariffs, decreases animal production (-0.1 to -1.6%) and GHG emissions in agriculture (-0.4 to -6.0%). Synergy effects are found from subsidizing DDGS, a biofuel by-product used as feed, which indirectly increases biofuel production, positively contributing to lower GHG emissions (-0.3 to -0.6%) in 2030. However, budget-neutrality drives land use up (0.1 to 0.5%) while decreasing agricultural wages (-0.1 to -0.3%). This calls for complementary policies to mitigate drawbacks and enhance benefits of a more circular food system.

Finally, Chapter 6 provides a general discussion of the results, drawing additional conclusions by looking at all chapters together and relating them to societal and scientific debates. Furthermore, the chapter summarises the results from the previous chapters, providing policy recommendations linked to the main findings. The last section discusses limitations and suggestions for further research. Additional research is particularly needed to investigate sustainability transitions through a multidisciplinary perspective, as relying solely on single disciplinary research is insufficient and may even pose a risk of leading us astray. For this, a joint global effort for cooperating across disciplinary boundaries to reshape our global economy in a more sustainable and inclusive manner is a major duty of the scientist of our century.

Authorship statement

Chapter 1 *Introduction*. The general research question and its general scientific and social perspective were proposed by my promotor. I delineated the research question, described how it fits in the current scientific literature and described its potential social impact. I revised the text after comments of my co-promotor.

Chapter 2 *New Estimates of Food Losses and Waste Along Global Supply Chains Show Increasing Nutritional and Environmental Pressures.* Conceptualization of the chapter was done by my co-author Dr. Maksym Chepeliev and myself. Methodology was done by my co-author Dr. Maksym Chepeliev and myself. Data construction and formal analysis of the chapter was done by my co-author Dr. Maksym Chepeliev and myself. I wrote the original draft of the chapter and revised the text several times, after comments of my co-author.

Chapter 3 *Reducing global food loss and waste could improve air quality and lower the risk of premature mortality*. Conceptualization of the chapter was done by my co-author Dr. Maksym Chepeliev and myself. Methodology was done by my co-author Dr. Maksym Chepeliev and myself. Data construction and formal analysis of the chapter was done by my co-author Dr. Maksym Chepeliev and myself. I wrote the original draft of the chapter and revised the text several times, after comments of my co-author.

Chapter 4 *Economic, social, and environmental spillovers decrease the benefits of a global dietary shift*. Conceptualization of the chapter was done by my promotor, co-promotor, and myself. Methodology was done by my co-promotor and myself. Data construction and formal analysis of the chapter was done by my promotor, co-promotor, and myself. I wrote the original draft of the chapter and revised the text several times, after comments of my promotor and co-promotor.

Chapter 5 *Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system.* Conceptualization of the chapter was done by my promotor, co-promotor, co-author Dr. Corina van Middelaar, and myself. Methodology was done by my co-promotor, co-author Dr. Corina van Middelaar, and myself. Data construction and formal analysis of the chapter was done by my promotor, co-promotor, co-author Dr. Corina van Middelaar, and myself. I wrote the original draft of the chapter and revised the text several times, after comments of my promotor, co-promotor, and co-author.

Chapter 6 *Discussion and Conclusion.* I wrote the first draft of the text. I revised the text after comments of my promotor and co-promotor.

About the author

Alessandro Gatto was born in Rome on November 21, 1995. He spent his formative years in the city center of Rome, also attending school abroad in Australia and the United States. In 2017, he completed his Bachelor's degree in Economics and Management in Rome before moving to Wageningen, Netherlands.

In Wageningen, Alessandro pursued a Master's degree in International Development with a focus on Development Economics and a specialization in Environmental Economics. After earning his Master's degree in 2019, he embarked on a PhD journey with the Department of Agricultural Economics and Rural Policy and the International Policy group of Wageningen Economic Research.

Currently, Alessandro's primary research interests lie in general equilibrium modeling applied to the bioeconomy, circular economy, and sustainability transitions, particularly focusing on food and energy systems.

Beyond academia, Alessandro has diverse interests. He has been playing water polo at a national level in Italy and enjoys playing and watching football, specifically supporting A.S. Roma. He also loves mountain sports such as hiking, trekking, and skiing, often combining them with camping trips. With family ties to the southern coast of Italy, he enjoys fishing with relatives. Additionally, Alessandro has been playing guitar since the age of ten and has developed a passion for beer brewing with close friends, resulting in successful productions of tasty beers.