Mounting Nutritional and Environmental Pressures of the Global Food Loss and Waste Call for Urgent Policy Action

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Abstract

Food losses and waste (FLW) are at the core of secure and sustainable food systems. A consistent quantification of the FLW across food supply chains at the global level, however, remains a major challenge. In this study, we compile a comprehensive 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 using a multi-region input-output framework. Our findings reveal a substantial increase in FLW across global regions between 2004 and 2014, with plant-based FLW being primarily concentrated in regions with poor recycling facilities. Nutritional losses have principally increased in low-income countries, with the global south accounting for over 70% of global land use, 82% of water use, and 76% of greenhouse-gas emissions embedded in FLW. Policies should focus on reducing domestic waste at the final consumption stage in high-income regions and on decreasing large farm-level losses in middle- and low-income countries. Here, while promoting the profitable reuse of unavoidable FLW, policies should increase agricultural production efficiency to enhance water and nutritional security.

Main

Global food losses and waste (FLW) lie 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 (FAO, 2011) FLW database 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). The FAO-FLW database (FAO, 2019) focuses on low-income countries and plant-based commodities covering mainly primary stages of the FSC (i.e. Agricultural Production and Post-Harvest Handling & Storage). The OECD (2021) Food Waste database covers the final stages of the FSC (i.e. Distribution & Retailing and Consumption) but has very limited geographical coverage, focusing on OECD members and China.

Other global databases (Xue et al., 2017; FAO, 2011; Parfitt et al., 2010; Kummu et al., 2012; Kaza et al., 2018) use different FLW definitions and supply chain coverage approaches, making estimates largely incomparable (Delgado et al., 2020). This substantially complicates the cross-verification possibilities across available studies (Xue et al., 2017). Estimates often vary in the inclusion/exclusion of inedible food parts in FLW flows (Delgado et al., 2020), and in the (non-)consideration of food flows diverted to other (non-food) uses (Corrado et al., 2019).

A second barrier is associated with the presence of conflicting approaches to quantifying FLW. Methodologies used to derive FLW estimates are often lacking a proper accounting of the agents' behavior and/or do not consistently represent the physical biomass flows along all stages of the global FSC. Technical studies (FAO, 2011; Caldeira et al., 2019; 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, neglecting stakeholders' interactions and value-chain dynamics (Chaboud & Daviron, 2017). Flows of traded biomass are often misrepresented in the accounting framework but remain crucial for tracing food from farm to fork and accurately defining FLW along global FSC. Quantifying FLW embedded in the production and consumption of primary and processed foods, and food services (i.e. food from restaurants, hotels, educational institutions, etc.) while accounting for international trade developments requires a proper representation of economic interactions along global FSC. In this regard, economic studies on FLW (de Gorter et al., 2020; Lopez-Barrera & Hertel, 2020; Britz et al., 2019) consistently address agents' behaviour and trade along FSC but are often defined in monetary values only, lacking information on physical food flows key to quantifying FLW.

Finally, a third barrier lies in the absence of a multidisciplinary framework able to address wide-ranging challenges around FLW. As available studies lack a consistent cross-check analysis between FLW and net/gross food intakes, no effective guidelines for nutritional security are provided. Several studies link FLW estimates with nutritional losses (Chen et al., 2020; Alexander et al., 2017; Wesana et al., 2019) but report no information on how food and nutritional intakes are affected by FLW along the FSC. Expanding the nutritional analysis on FLW requires tracing flows of nutrients along global supply chains in order to quantify where interventions can most efficiently contribute to improving global food security. Additionally, as FLW and nutritional security directly link to the environment (West et al., 2014), a framework capable of merging nutritional analyses and embedded environmental footprints allows for developing policies from a broader multidisciplinary perspective. Several earlier studies have focused on the assessment of environmental impacts embedded in FLW (Lipinski et al., 2013; Porter et al., 2016; Alexander et al., 2017), while a first attempt to merge nutritional and environmental analyses of FLW is provided by (Chen et al., 2020). However, as (Chen et al., 2020) merely focus on food waste and rely on inconsistent FLW estimates from (FAO, 2011), a major data and methodological gap still needs to be addressed in order to comprehensively contextualize FLW in the multidisciplinary framework of the Sustainable Development Goals.

In this paper, we attempt to address the main barriers and limitations of available FLW studies, compiling a global FLW database using a food supply-chain perspective. 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".* Adopting a multidisciplinary approach, we merge technical and economic modelling of FLW to capture physical flows of lost or discarded food biomass along each stage of global FSC. Building on a recent development that incorporates physical and nutritional flows in a global economic framework (Chepeliev, 2022), we define country-level gross food and nutritional supply across stages of global FSC, matching estimates provided in the FAO Food-Balance-Sheets (FBS). We collect from the literature the best available estimates on shares of lost and discarded foods along FSC remaining consistent with our definition of FLW. We merge the FLW estimates with gross food and nutrient supply to quantify net food and nutritional intakes. With this, we explore county-level FLW developments across a ten-year time frame (2004-2014), relying on the global multi-region input-output (MRIO) Global Trade Analysis Project (GTAP) version 10 Data Base (Aguiar et al., 2019).[1] We quantify the magnitude, composition, geographical location, and nutritional contents of FLW, consistently accounting for the role of international trade in the global food system. Finally, we integrate additional 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 future policies on FLW reduction and circularity. The remainder of this study is structured as follows. First, we present the contents of our global FLW database (reported in the Supplementary Information) providing an overview of the resulting data with respect to FLW magnitude, nutrition flows, and environmental footprints. Successively, we discuss our results comparing our estimates with available estimates from the literature and devise potential policy guidelines based on the contents of our database. Finally, we briefly discuss the methodology adopted to construct the database, providing a more detailed description in the Supplementary Information.

[1] This is the most up-to-date publicly available version of the GTAP Data Base at the time of the paper's writing.

Results

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

A larger and richer global population raises global food demand, resulting in a sharp increase in FLW reaching 1.92 billion Mtons in 2014 (a +24.0% or 372 million Mtons 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 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 Mtons of FLW or around 49.6% of the global share. Over ten years, food waste in Distribution & Retail has increased by 22.4% (or 49.5 million Mtons), while Consumption waste increased by 21.3% (or 86.1 million Mtons), reporting the lowest relative increase in the observed time frame. 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. Horticulture FLW have risen by 25.5% (or 185 million Mtons), primarily in Manufacturing (38.8%) and Distribution & Retail (27.3%), while sugar beet/cane FLW increased by 27.4% (or 70.6 million Mtons), mostly at farm-level stages (48.4%). A relatively lower increase is observed in losses and waste from cereals (26.3% or 66.0 million Mtons) and oilseeds (8.9% or 6.2 million Mtons), reporting peaks at Post-Harvest Handling & Storage and at the Consumption stage. Animal-sourced foods are on average less perishable than plant-based products and report a significantly lower amount of FLW. Meat (including ruminant and nonruminant) FLW (+20.7% or 17.5 million Mtons), increased largely at Agricultural Production and Post-Harvest Handling & Storage (33.1%), while Dairy FLW (+13.2% or 14.8 million Mtons) have mainly concentrated at Consumption stage (+12.9%). The largest relative increase is observed for fish FLW (+27.1% or 12 million Mtons) which particularly grew at Manufacturing (17.3%) and Consumption (32.6%) stages.

In terms of geographical distribution, the largest absolute amounts of FLW are generated in North America (mainly the United States), China, and India (Panels A and C - Figure 2), constituting around 42.6% of global FLW in 2014. However, observing per-capita estimates (Panel C - Figure 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 and India have population 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 3). When compared across countries, we find that per-capita GDP and average gross food demand are found to be direct drivers of FLW generation. 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 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-seven times lower than in many high-income countries. Consumers in many developing countries, including Laos, Bangladesh, Kenya, Myanmar, and Nigeria, spend over 50% of their income on food, which is more than five times higher than in such high-income countries, like the United States (6.7%), the United Kingdom (8.7%), Australia (10%) or Canada (10%) (USDA, 2022). As a result, households in low-income countries have substantially higher economic incentives for reducing (not increasing) FLW, as the marginal benefit of such action is much more significant than for the consumers in high-income countries.

With respect to 2004, Panel B of figure 2 and Panel C of figure 3 illustrate changing trends of total FLW. Differently, Panel D of figure 2 reports changes in per-capita FLW across global regions. While in Panels B and D of figure 2, changes are computed directly on FLW amounts, in Panel C in figure 3 changes in FLW are based on changes in population, per-capita GDP, gross food consumption per unit of GDP, and FLW generation over gross food consumption, following the approach of (Kaya & Yokoburi, 1997). From Panel B of figure 2 and Panel C of figure 3, it is possible to observe that between 2004 and 2014 FLW has mainly increased in India (47.4%), Sub-Saharan Africa (average 43.2%), Southeast Asia (average 37.2%) and China (35.0%). The largest relative increases in FLW occur 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%). In these countries, the sharp increase in per-capita GDP (and incomes) represents a main driver of FLW generation. An additional 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 levels of FLW for 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*" drives 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%).

Food loss and waste embedded in global food trade represent around 27.2% of total global FLW generation in 2014. The highest shares of trade-related FLW (Panel E - Figure 2) are associated with large food-trading regions such as the Middle East (an average of 80.5% of total FLW is related to food trade), Southern Africa (an average of 75.6% of total FLW is related to food trade), Oceania (an average of 65.4% of total FLW is related to food trade) and Europe (an average of 45.3% of total FLW is related to food trade). Differently, shares of FLW embedded in food trade are averagely lower in regions where high levels of total domestic food consumption results in large flows of domestic FLW generation. This is more evident in largely populated countries such as China (an average of 8.4% of total FLW is related to food trade), India (an average of 9.6% of total FLW is related to food trade) and in some central African regions (i.e. Nigeria, Malawi, Tanzania, and Cameroon where an average 7.4% of total FLW is related to food trade). Across the analysed time frame, changing trends of trade-related FLW are linked to changes in the food-sourcing patterns of countries. Increasing trends of trade-related FLW are observed in Middle East (average +9.8%), Western Asia (average +7.6%), and Eastern Europe (average +4.3%) due to an increase in food imports. Differently, a demographic growth coupled with an increase in domestic food demand resulted in decreasing trends of trade-related FLW in North Africa (an average of -7.6%) and South-central Africa (an average of -3.4%).

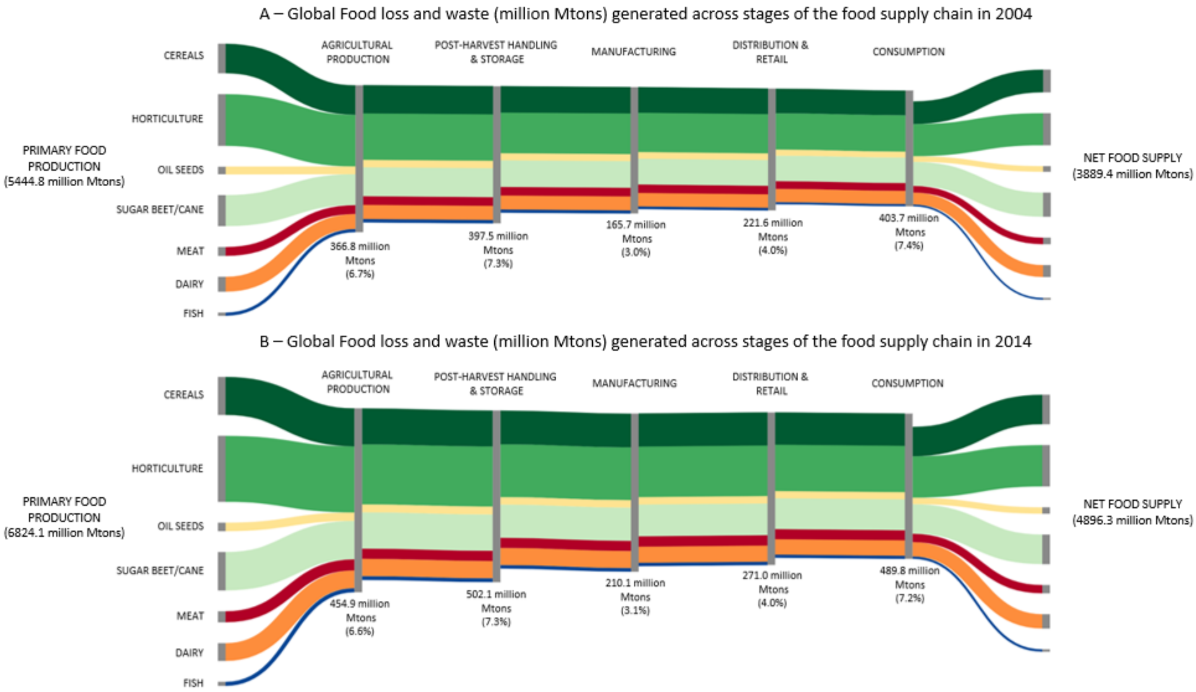

Figure 1. Flows of FLW (Million metric tons) by primary food product generated along different stages of global food supply chains (by reference year). Estimates report million metric tons of generated FLW from primary production to final consumption. Panel A reports global FLW generation by FSC stage in 2004. Panel B reports global FLW generation by FSC stage in 2014. The largest hotspots of global FLW are farm-level stages of FSC i.e. Agricultural Production and Post-Harvest Handling & Storage. The majority of global FLW is composed of plant-based food products such as horticulture, cereals, and sugar beet/cane.

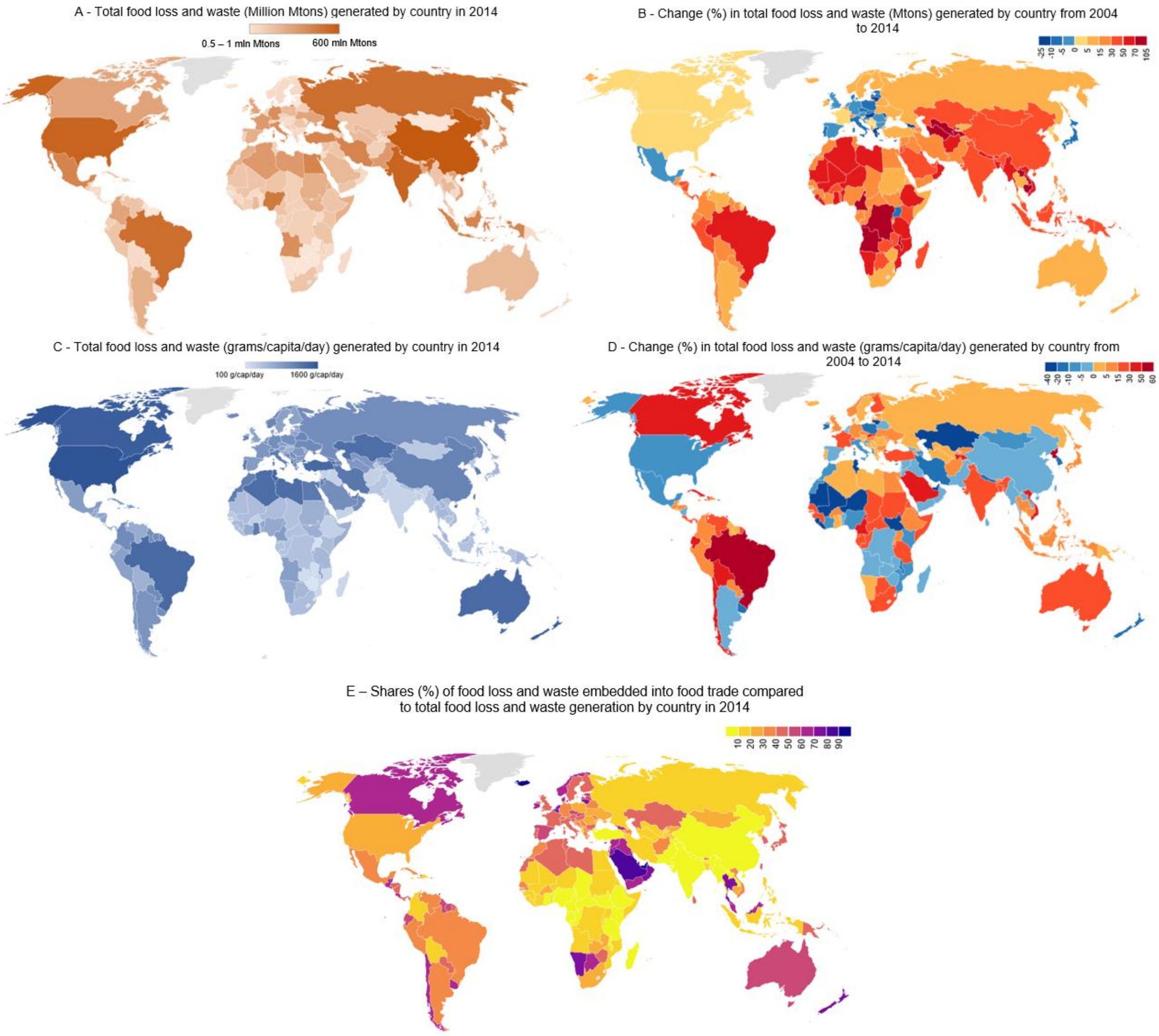

Figure 2. Total food loss and waste generation (Mtons), per-capita food loss, and waste generation (grams/capita/day) and trade-embedded food loss and waste by country. Estimates reported in the figure refer to FLW generation and are specified in different metrics according to the panel. Panel A illustrates the total FLW generation (Mtons) 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. Total FLW generation mainly increases in low- and middle-income countries while tending to decrease (or increase relatively less) in higher-income countries. Changes in per-capita estimates are more scattered across the income spectrum of countries, although the largest global hotspots for FLW generation are associated with higher-income countries in 2014. Panel E reports shares (%) of food loss and waste embedded into the food trade compared to total food loss and waste generated by country in 2014. Such estimates refer to amounts of food loss and waste associated with food imports/exports at any stage of the FSC.

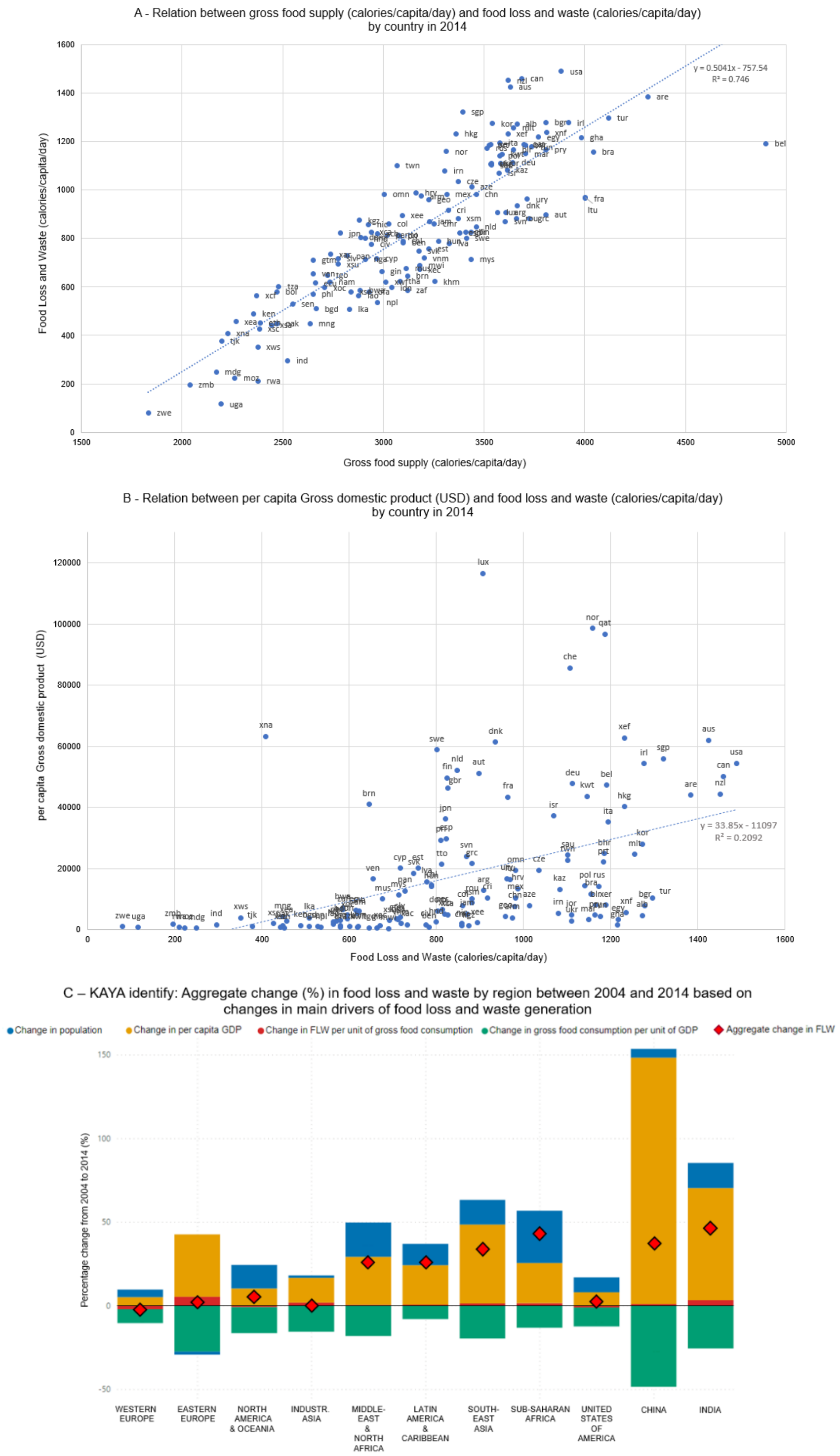

Figure 3. Relation between food loss and waste, gross food supply and gross domestic product by country in 2014 and changes in food loss and waste based on KAYA identity from 2004 to 2014. Panel A illustrates the relation between food loss and waste generation (calories/capita/day) and gross food supply (calories/capita/day) by country in 2014. Panel B reports the relation between food loss and waste generation (calories/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.

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

The increasing magnitude of FLW in countries around the world 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 is concentrated in high-income regions and specifically 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) enlarge the calorie content of FLW (Panel A - Figure 3). 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 exacerbate 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). With respect to 2004, calorie losses have increased mainly in North Africa (an average of 14.6%) and South-central Africa (an average of 16.7%), following an increase in average food consumption and/or rising volumes of food exports (Panel B - Figure 3). Similarly, calorie losses have increased in Brazil (an average of 23.2%) and Southeast Asia (including China and India) (an average of 30.1%), while showing a decreasing trend in North America (an average of 2.4%) and Europe (an average of 1.8%) mainly due to a high decrease of 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 3). 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 countries. 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 trend in North America (an average of -3.2%) and Europe (an average of -2.1%) (Panel D - Figure 3) due to an increase in shares of protein-poor plant-based FLW within total FLW.

Losses of fats (Panel E - figure 3) 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.

Finally, while losses of carbohydrates have similar geographical distribution compared to other macronutrients (Panel G - Figure 3), the evolving concentration of carbohydrates losses (Panel H – figure 3) presents a different trend, decreasing across regions. 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 (on average with lower carbohydrate content) has lowered 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 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) presented instead the lowest amounts of carbohydrates losses given a lower food consumption rate compared to other global regions.

Table 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 Mtons of CO_2 eq.)	GHG emissions embedded in FLW (Million Mtons of CO_2 equiv.)
European Union – 27	3652	1018 (27.9%)	137,620	15,262 (11.1%)	64.2	9.3 (14.5%)	52,437	1,688 (3.2%)
North America & Oceania	3815	1457 (38.2%)	777,724	133,492 (17.2%)	243.8	35.5 (14.6%)	87,173	3,580 (4.1%)
High-Income Asia	3029	985 (32.5%)	5,302	1,788 (33.7%)	69.7	24.9 (35.7%)	29,108	489 (1.7%)
Rest of Europe & Central Asia	3387	1025 (30.3%)	501,883	86,035 (17.1%)	185.6	28.3 (15.3%)	44,773	2,091 (4.7%)
Middle East & North Africa	3475	1035 (29.8%)	386,637	3.71 (93.0%)	375.2	95.4 (25.4%)	50,933	1,553 (3.1%)
Latin America & Caribbean	3418	954 (27.9%)	695,387	0.79 (12.7%)	280.1	38.5 (13.7%)	97,826	5,707 (5.8%)
Southeast Asia**	2953	621 (21.0%)	1,111,151	1.83 (20.9%)	2038.6	287.0 (14.1%)	432,193	13,973 (3.2%)
Sub-Saharan Africa	2749	591 (21.5%)	1,025,693	2.64 (26.0%)	100.9	12.9 (12.8%)	104,170	3,851 (3.7%)
Global	**3116**	**775 (24.9%)**	**4,641,401**	**734,790 (15.8%)**	**3,358.3**	**531.9 (15.8%)**	**898,615**	**32,934 (3.7%)**

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

** Including China and India.

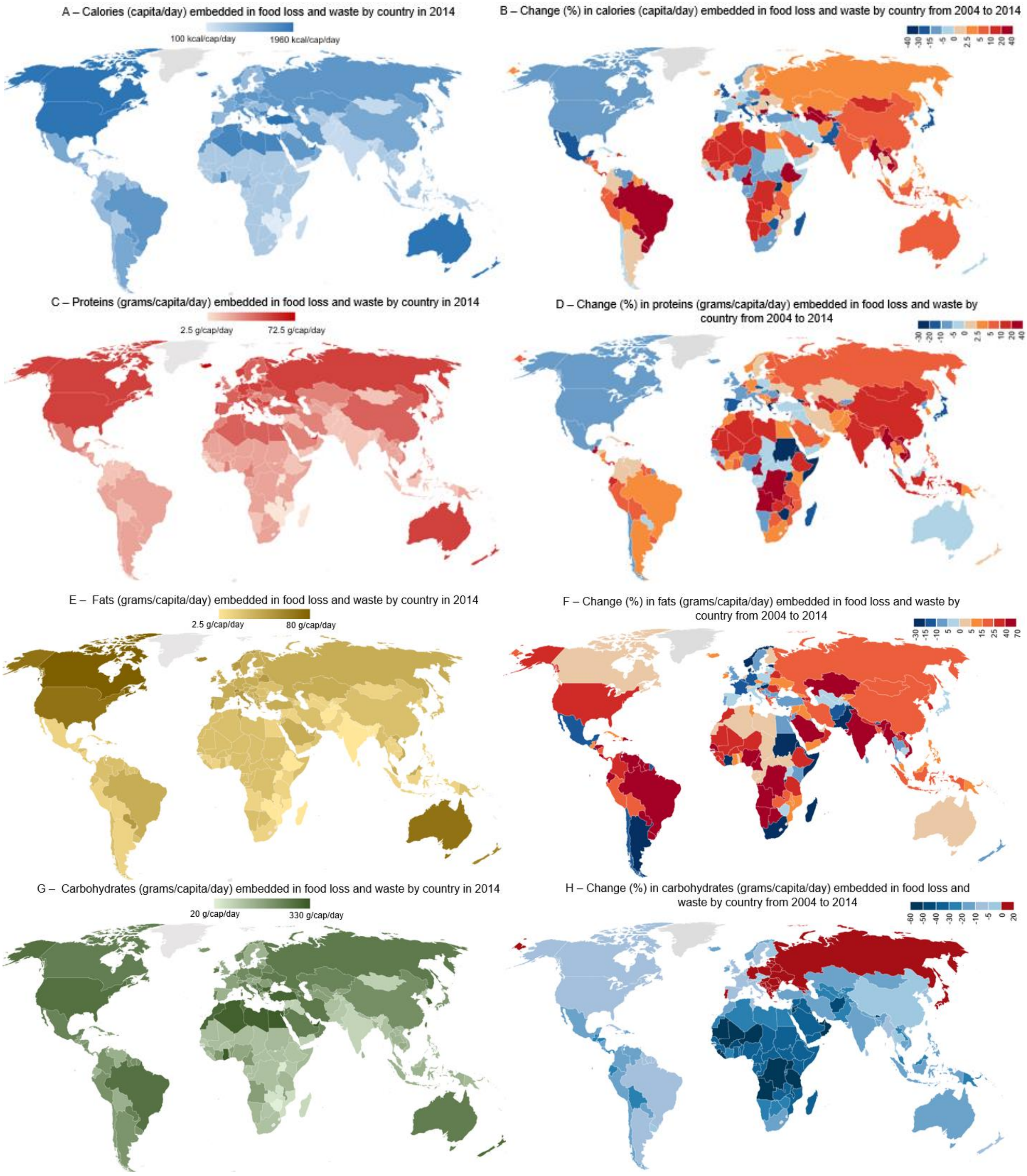

Figure 4. Nutritional composition of FLW (grams/capita/day) generated along global FSC.
Estimates reported in the figure refer to the amount of macronutrients (capita/day - calories and grams of macronutrients) embedded in lost or discarded food (grams/capita/day). Panel A illustrates the total amount of calories (capita/day) embedded in FLW generated by country 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.

Environmental impact embedded in food loss and waste along global food supply chains.

In 2014, around 15.8% of global agricultural land was used to produce food that was lost or wasted along the FSC (Table 1). As we compute land use and water use embedded in FLW using the consumption-based perspective, in some cases corresponding environmental impacts might be larger than the actual amount of agricultural land or water used for domestic food production. This is particularly evident in the Middle Eastern countries, where food imports substantially contribute to FLW at the Distribution & Retail and Consumption stages but are associated with the use of land and water in other countries. Land use embedded in FLW is higher in large agrifood-producing countries such as Brazil (32.1 million hectares) and Kazakhstan (36.2 million hectares). The largest amounts of land use embedded in FLW are observed in China (88.7 million hectares), the United States (78.4 million hectares), and Australia (46.1 million hectares) (Panel A - Figure 4). In Europe, the level of land use embedded in FLW is relatively low due to high efficiency of the agricultural production process in the region. Between 2004 and 2014, global land use embedded in FLW generation increased by 2.9% (Panel B - Figure 4). The largest increases are observed in Latin America (an average of 25.2%), Central Asia (an average of 12.5%), and Southeast Asia (an average of 14.4%). Growing food demand parallelly increased FLW-embedded land use in China (50.6%) and East Africa (an average of 32.7%), while a decreasing trend is observed in Southern and Eastern Europe (an average of 22.1%).

Around 15.8% of the water globally used for food crops is embedded in lost or discarded food along the supply chains (Table 1). The largest amounts of water use embedded in FLW (Panel C – Figure 4) are observed for large agricultural producers such as China (97.2 billion cubic meters), India (76.9 billion cubic meters), and the United States (34.1 billion cubic meters), and for largely populated countries such as Pakistan (20.7 billion cubic meters) and Indonesia (27.6 billion cubic meters). Differently, the lowest amounts of water use embedded in FLW generation in 2014 are observed in Europe (an average of 0.05 billion cubic meters) where a relatively higher agricultural production efficiency but also different crop mix and geographical conditions, results in lower water use per ton of food produced, and in Africa (an average of 0.1 billion cubic meters), where lower amounts of FLW and limited water availability result in average lower amounts of water use embedded in FLW. However, global water use increased by 35.3% across the analysed time frame. Increasing trends of water use embedded in FLW generation are observed mainly in Central and Southern African countries (average 87.5%) and in Central Asia (average +103.5%), (Panel D – Figure 4) and potentially exacerbate the burden of water scarcity in sensitive low-income regions. Similar to land use trends, average FLW-embedded water use has decreased in Europe, mainly in eastern (-39.8%) and southern (-25.5%) countries given a more efficient use of water in food production across the analysed time frame.

Global greenhouse gas (GHG) emissions generated in the production of food that is lost or discarded along the FSC amount to 32.9 billion metric tons of CO_2 equivalent accounting for around 3.7% of global GHG emissions in 2014 (Table 1). Around 14.9% of total emissions correspond to the production and consumption of fresh fruits and vegetables. On the other hand, the majority of emissions (56.6%) are generated by the production and consumption of processed foods, with 25.6% of those emissions coming from animal-based products. Along global food supply chains, the majority of emissions occur at the farm level (46.0% of total FLW-related GHG emissions) and at the final consumption stage (26.9% of total FLW-related GHG emissions). In 2014, the largest amounts of FLW-embedded GHG emissions were generated in China (5.8 billion metric tons of CO_2 eq.), Brazil (3.5 billion metric tons of CO_2 eq.), United States (2.8 billion metric tons of CO_2 eq.), and India (2.3 billion metric tons of CO_2 eq.) (Panel E – Figure 4). These four countries, together with Indonesia (1.7 billion metric tons of CO_2 eq.) and Russia (1.0 billion metric tons of CO_2 eq.), cumulatively account for 49.5% of global FLW-embedded GHG emissions.

However, compared to total GHG emissions generated across countries (from food and non-food sectors), the highest shares of FLW-related emissions occurred in Bangladesh (13.7% of total country-level consumption-based GHG emissions), Lao PDR (12.4%), Albania (11.1%), and Belarus (10.9%). Such shares are significantly lower for China (2.5%), the United States (4.1%), and India (2.3%) where large amounts of GHG emissions are associated with non-food sectors but remain relatively high for Brazil (8.2%) due to the country's large livestock sector. The lowest shares of FLW-embedded GHG emissions are primarily observed in high-income countries in the middle east such as Bahrain, Kuwait, Oman, and Qatar (an average of 0.3%). Compared to 2004, GHG emissions from FLW have primarily increased in low-income regions such as Sub-Saharan Africa, Southeast Asia, and Latin America & Caribbean (Panel F – Figure 4). The highest increases are observed in the former Soviet Union block (Tajikistan, Turkmenistan & Uzbekistan – an average of 109%), and south American countries (Uruguay, Paraguay, Brazil, and Argentina – an average of 99.6%), where consumption of animal-based foods increased. Differently, decreasing trends of GHG emissions embedded in FLW are mainly observed in the European Union (average -29.1%), North America & Oceania (-17.9%), and East Asia (including China) (average -25.3%). These patterns are associated with alterations in the composition of FLW, wherein the proportion of plant-based foods has demonstrated a comparatively greater increase than animal-based products, leading to a reduction in emissions embedded within discarded or lost food.

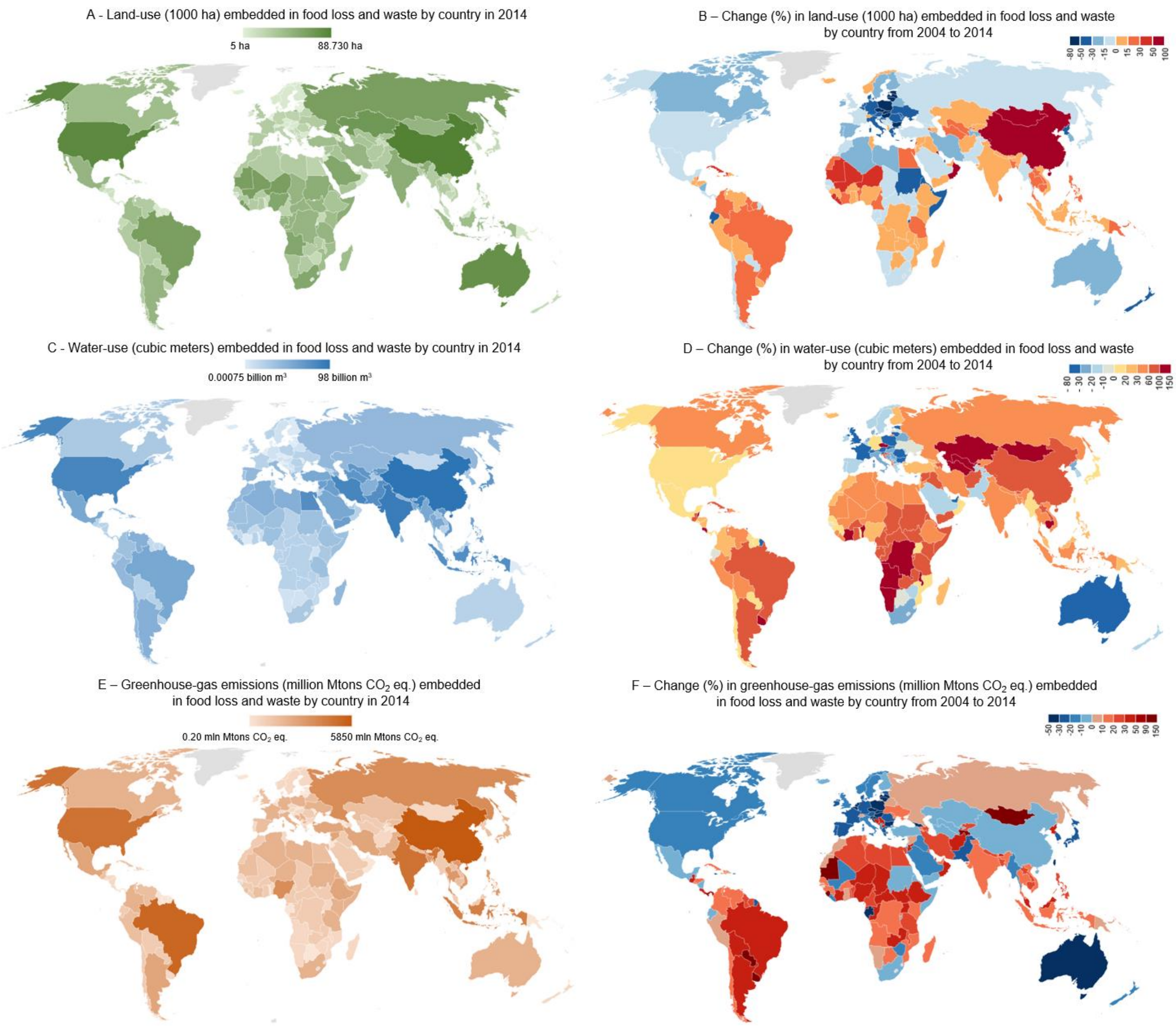

Figure 5. Land use, Water use, and greenhouse-gas emissions embedded in food loss and waste generated along global food supply chains. Estimates reported in the figure refer to the amount of land use, water use and greenhouse-gas emissions embedded in tons of lost or discarded food along all the stages of global food supply chains. Panel A illustrates the amount of land use (square kilometres) embedded in Mtons of FLW generated by country in 2014. Panel B illustrates the change in total land use (square kilometers) embedded in FLW generated by country from 2004 to 2014. Panel C reports the amount of water-use (cubic meters) embedded in Mtons 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 Mtons of CO_2 equivalent) embedded in Mtons of FLW generated by country in 2014. Finally, Panel F illustrates the percentage change in total greenhouse-gas emissions (million Mtons of CO_2 equivalents) embedded in FLW generated by country from 2004 to 2014.

Discussion

In this study, we aimed to comprehensively analyse food loss and waste (FLW) along global supply chains by quantifying its magnitude, composition, and location, as well as investigating the nutritional and environmental impacts embedded in lost and discarded food. To achieve this, we adopted a multidisciplinary approach, merging technical and economic modelling of FLW to trace the physical and nutritional flows of biomass along supply chains. To overcome the limitations and inconsistencies of currently used global databases, we built upon the economywide framework developed by Chepeliev (2022) and compiled a new harmonized global FLW database relying on the comprehensive literature review. Our updated estimates are computed in line with the FLW definition of UN-SDG 12.3. Using the developed framework, we quantified the nutritional losses and environmental footprint embedded in global FLW for 141 countries and regions around the world. This development contributes to the further contextualization of the FLW in the wide-ranging multidisciplinary framework of the U.N. Sustainable Development Goals (SDG). Our findings provide valuable insights for policymakers and stakeholders allowing for the development of better-targeted interventions to address the issue of FLW, achieve SDG 12.3, and contribute to sustainable food systems.

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

Our study reveals that the FLW have been increasing particularly rapidly for horticulture, cereals, and sugar beet/cane at the early stages of the food supply chain (FSC), resulting in increasing shares of non-processed plant-based biomass within total FLW. Notably, plant-based FLW offer a broader range of reuse possibilities (Parfitt, 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 and van Ittersum, 2018). However, the expansion of domestic and international markets has led to an increase in the share of food losses associated with food trade (leakage effect). While farm-level losses are mainly located in low- and middle-income regions, large shares of these losses remain 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 infrastructures and technologies hampers FLW reuse (Kaza et al., 2018). At the same time, this decreases reuse possibilities in high-income regions with a better infrastructure for reuse: due to increasing imports larger share of losses associated with food consumption in developed countries occurs abroad (in developing regions). While FLW reuse still represents a valid option for high-income regions 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 study provides novel insights into the issue of nutritional losses in the food system, specifically focusing on the often-overlooked stages of Agricultural Production to Manufacturing. To our knowledge, no previous studies have examined nutritional losses occurring during these stages of the food supply chain at the global level, making our findings particularly valuable for the development of comprehensive and effective policies to reduce FLW and improve the nutritional quality and sustainability of the food system. Our estimates suggest that nutritional losses have increased across global regions, with the exception of carbohydrates, which losses have decreased due to a shift in global dietary patterns away from cereals and starchy vegetables rich in carbohydrates and toward animal-source foods (ASF). However, calories and protein losses have principally increased in low-income regions such as Southeast Asia, North Africa, and Sub-Saharan Africa, posing a major challenge to food security. Interestingly, 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 food supply chain (FSC). Agricultural Production is found to be the largest hotspot for losses of calories across regions (318 calories/capita/day). This advocates for interventions to improve agricultural production efficiency, especially in low-income countries where the application of more advanced production techniques can significantly improve food security.

As several earlier studies have focused on nutritional losses related to food waste, our estimates can be directly compared to these previous findings. We estimate an average loss of 277 calories/capita/day embedded in food waste, 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 calculated 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 by (Brennan & Browne, 2021; Khalid et al., 2019 and Spiker et al., 2017).

In our study, we found that approximately 15.8% of the global agricultural land and water used for growing food crops is dedicated to producing food that is ultimately lost or discarded. Our results indicate that there is a growing inefficiency in land used for agricultural production, particularly in low-income regions such as sub-Saharan Africa, where land use embedded in FLW is increasing. While food exports can contribute to economic growth in these regions, they also 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 in these regions.

Similarly, our findings demonstrate a concerning trend of increasing water use embedded in FLW generation, particularly in Central and Southern African countries and Central Asia. These regions are already facing water scarcity, and the rising water demand for food production could exacerbate the issue, further threatening food security, especially when combined with the expected climate change impacts. To address this issue, policy interventions are necessary to reduce the water footprint of food loss and waste. This could be achieved by implementing measures to improve the efficiency of water use in agriculture, reduce food waste at the producer level, and incentivize the recovery and reuse of food waste as animal feed or energy sources. Additionally, policies that support sustainable agricultural practices (and water management), such as agroforestry and conservation agriculture, could help to reduce water demand and promote resilience to climate change impacts, serving as an efficient adaptation strategy.

Finally, our study shows that the generation of food loss and waste (FLW) contributes approximately 4% of global greenhouse gas (GHG) emissions. This is lower than the 6% previously reported by Poore and Nemecek (2018), who calculated total GHG emissions in 2010, when global emission levels (especially in non-food sectors) were lower than in 2014, the reference year of our study. Furthermore, our lower levels of GHG emissions are attributable to our exclusion of land use and land use change emissions in the calculation of total emissions embedded in FLW.

Our findings highlight the significant contribution of animal-based processed foods to FLW generation and GHG emissions, further emphasizing the need for policy interventions, particularly at the farm-level production stages in low- and mid-income countries.

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 growth rates 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 food consumption 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 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 (Willet et al., 2019; Springmann et al., 2018) while simultaneously lowering farm-level losses in exporting middle- and low-income regions. By decreasing export demand, land use can be shifted towards domestic food production, helping low-income regions achieve adequate nutrition levels. 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 animal-source food (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 mid-income regions to decrease farm-level losses, while also supporting the profitable reuse of unavoidable FLW as a production input.

As usual, these findings are subject to a number of caveats and limitations. The main methodological limitations lie in the application of fixed food loss and waste shares across reference years. While earlier studies (Fabi and English, 2018) advocate that shares of FLW are relatively stable across years, we do not investigate how FLW rates may respond to changes in economic structure or income within the considered time frame. As we derive FLW shares from current literature, the lack of representative high-quality FLW data (Delgado, 2020) is particularly apparent for low- and middle-income regions, especially at the final stages of the FSC. Such 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 share had to be adjusted downward. While the corresponding issue has been identified only in a small subset of countries, it points out the broader need for conducting detailed and comprehensive surveys at the country level aimed at the consistent quantification of the FLW at different stages of the supply chain.

Despite the identified limitations, we believe that our 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.

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). 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, 2020), providing a consistent alternative to the heavily criticized (Xue et al., 2017, Sheahan and Barrett, 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 (Mtons) 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 and 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; Xue et al., 2017; OECD, 2021). 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). Further details and the adopted shares of lost and discarded foods along global supply chains and are provided in the Supplementary Information.

From the GTAP-FBS database, we derive gross food biomass supply in physical quantities (Mtons) 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 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 (Mtons), consistently accounting for global food and non-food trade, and the economic behavior 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.

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. 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.

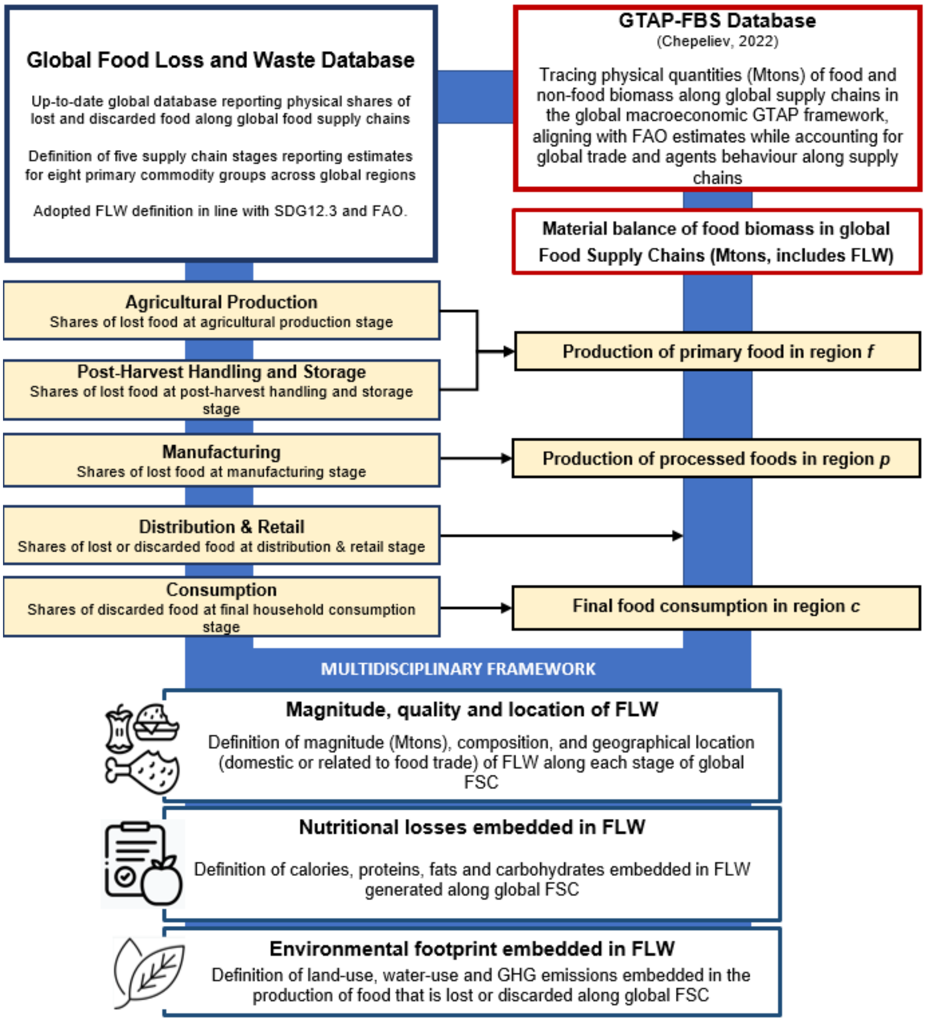

Figure 6. Methodological framework adopted to trace food loss and waste along global food supply chains.

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Supplementary Information for

Mounting Nutritional and Environmental Pressures of the Global Food Loss and Waste Call for Urgent Policy Action

Contents

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

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

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,[2] *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 (Mtons) 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

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

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 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 coefficient (2), tracing FLW along global food supply chains as following

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

(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 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 to avoid the double counting of losses/waste when a processed

[2] 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.

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 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, both 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).

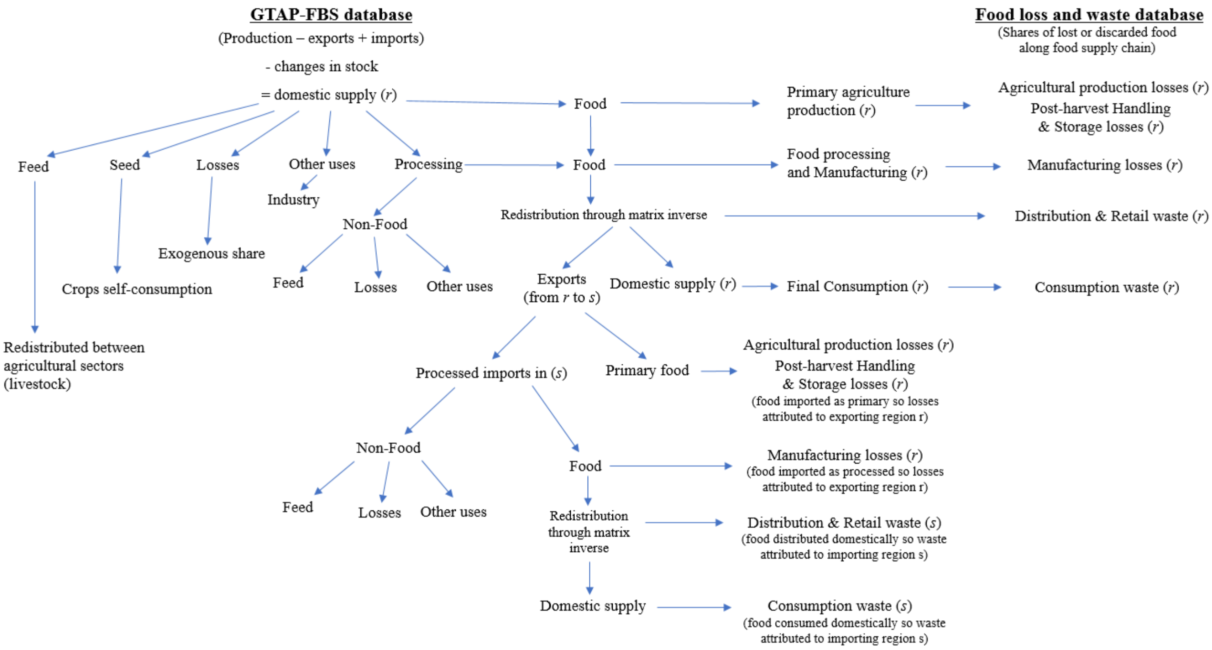

Figure S1. Methodological framework for tracing food loss and waste along global food supply chains.

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 and English, 2018).

Database and integration of data into the GTAP framework

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[3]. 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.

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 in consistency 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 complement 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 and 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.

[3] 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 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]	0.5[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]

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)

[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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[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

[3] Hartikainen, H., Mogensen, L., Svanes, E., Franke, U., 2018. Food waste quantification in primary production – The Nordic countries as a case study. Waste Management. 71, 502–511. https://doi.org/10.1016/j.wasman.2017.10.026 (calculated using the FUSIONS (2014) definition of Food Loss and Waste)

[4] 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

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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]

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[6] Canadian Statistical Bureau. 2010. https://www.statcan.gc.ca/eng/start

[7] 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] OCED Food Waste Database. https://www.oecd-ilibrary.org/agriculture-and-food/data/waste/food-waste_ba9da2b7-en (Accessed 03 2023)

[10] Kulkarni, S. (Undated). Importance of minimizing field losses during soybean harvest, Division of agriculture, University of Arkansas.

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

Table S4 – Industrialised 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[6]	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]	0.1[6]	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]

[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.

[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)

[3] Aerni V., Brinkhof, M.W.G., Wechsler, B., Oester, H., Fröhlich, E. 2005. Productivity and mortality of laying hens in aviaries: A

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]

systematic review. World's Poultry Science Journal 2005; 61(01):13

[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 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)	15.0[3]	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] 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)

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] 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.

[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[4]	0.5[4]	7.4[4]
Dairy (rmk)	6.0[4]	8.2[2]	1.5[4]	13.8[3]	5.5[4]
Other animal prod. (oap)	1.8[1]	1.0[5]	2.0[4]	7.5[7]	2.0[4]
Fish (fsh)	5.7[4]	14.3 - 27.3[2]	9.0[6]	12.3[7]	4.8[4]

[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
[3] Wesana, J., Gellynck, X., Dora, M.K., Pearce, D., De Steur, H., 2019. Measuring food and nutritional losses through value stream mapping along the dairy value chain in Uganda. Resour. Conserv. Recycl. 150, 104416. https://doi.org/10.1016/j.resconrec.2019.104416
[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.
[5] Assumption based on values for West Europe.
[6] Assumption base on values for Industrialised Asia.
[7] Assumption made by taking the higher boundry of the interval reported for West Europe.

[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.

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]

[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.

[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.

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]

[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 S13. 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	Industrialised Asia
jpn	Japan	Industrialised Asia
kor	Korea	Industrialised Asia
mng	Mongolia	Southeast Asia
twn	Taiwan	Industrialised 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

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

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
Industrialised 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 15. 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	
Industrialized 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 Industrialized 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 Figures

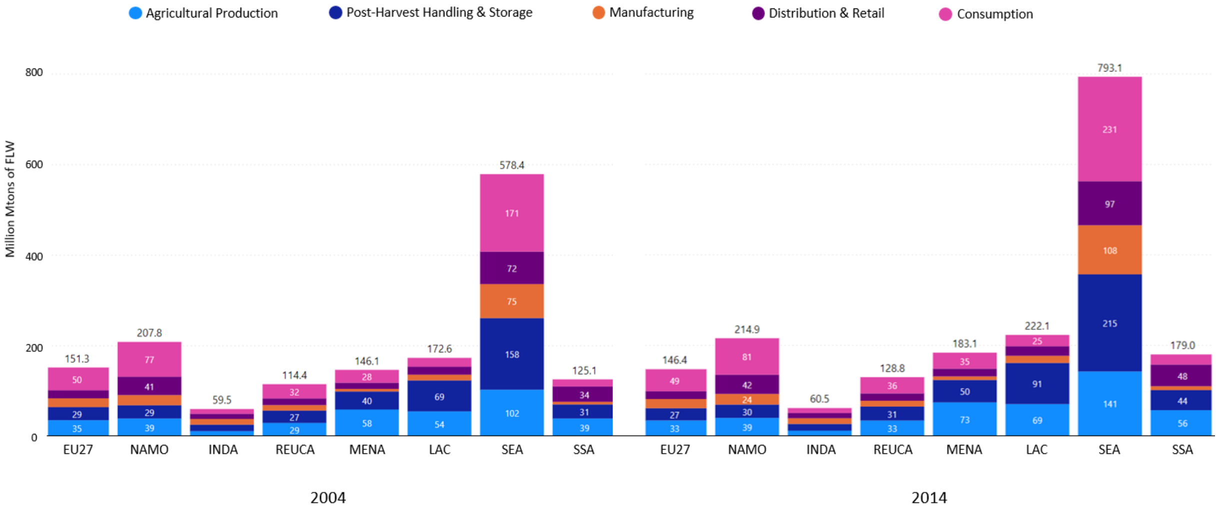
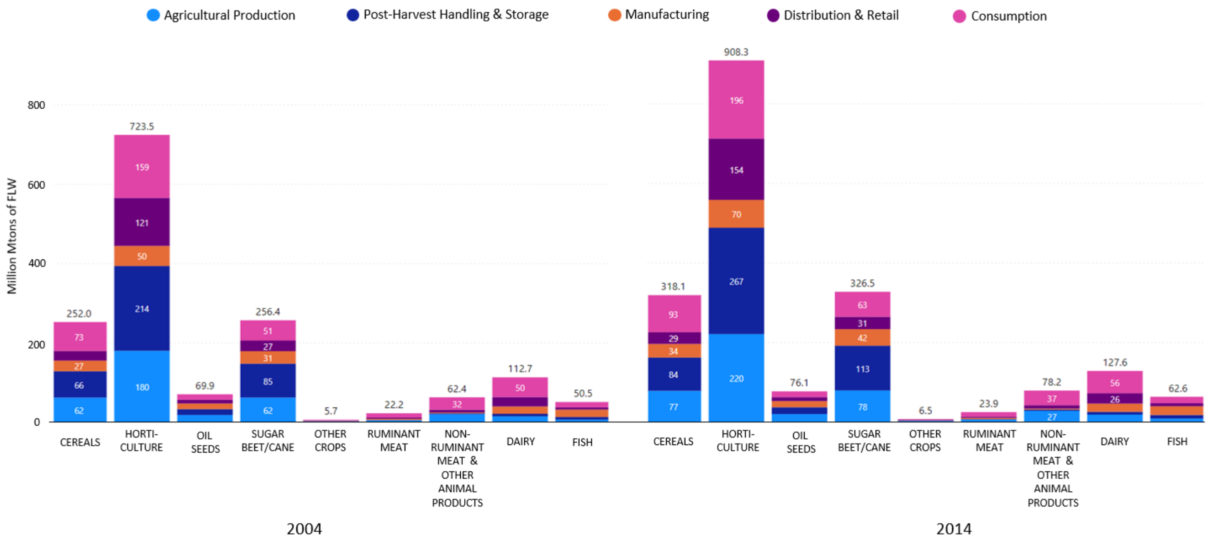


Figure 1. Food Loss and Waste (million Mtons) generated along stages of the food supply chain, by region and reference year.

Figure 2. Food Loss and Waste (million Mtons) generated along stages of the food supply chain, by commodity and reference



year.

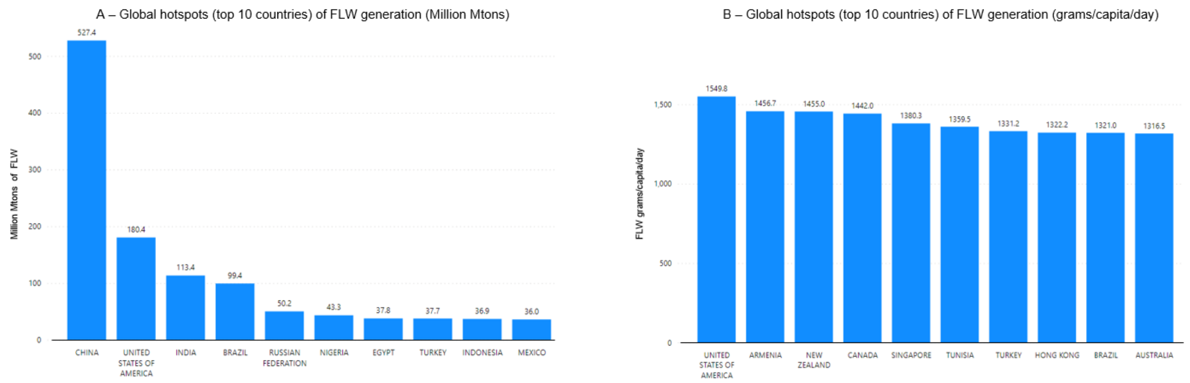


Figure 3. Global hotspots (top 10 countries) of FLW generation (million Mtons and grams/capita/day) along global supply chains in 2014.

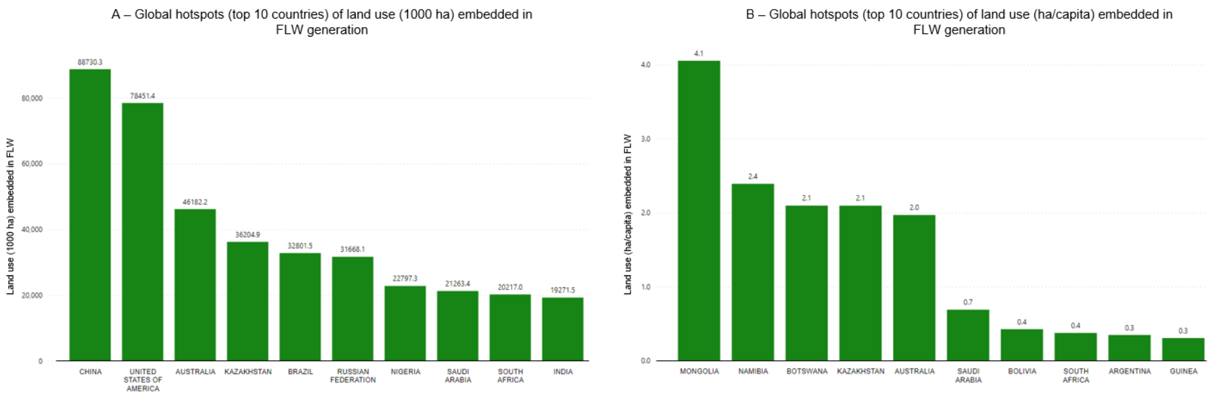


Figure 4. Global hotspots (top 10 countries) of land use (1000 hectares and hectares per capita/year) embedded in FLW generation along global supply chains in 2014.

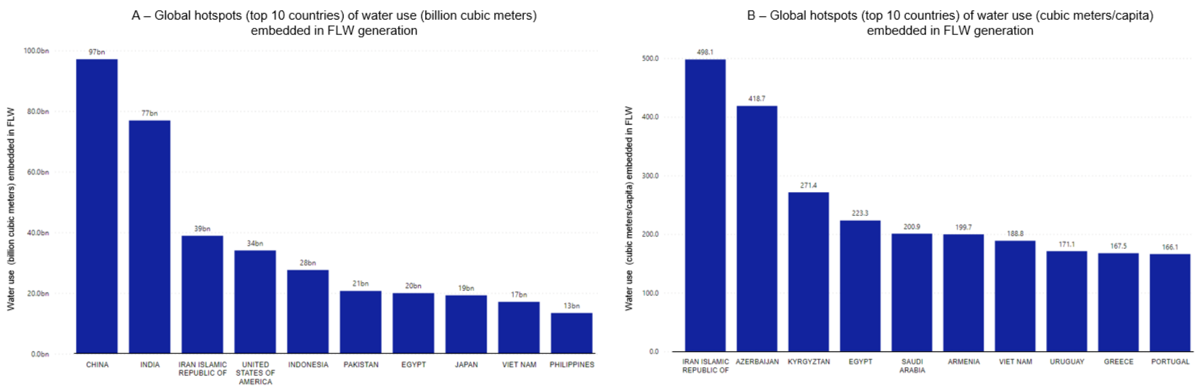


Figure 5. Global hotspots (top 10 countries) of water use (billion cubic meters and cubic meters per capita/year) embedded in FLW generation along global supply chains in 2014.

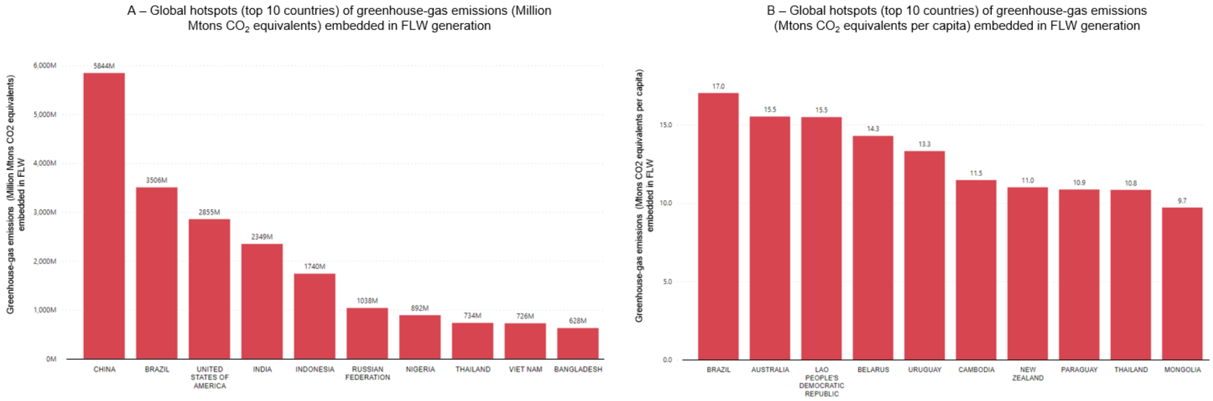


Figure 6. Global hotspots (top 10 countries) of greenhouse-gas emissions (Million Mtons CO_2 equivalents and Mtons CO_2 equivalents per capita/year) embedded in FLW generation along global supply chains in 2014.

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