Sustainable Production and Consumption 43 (2023) 308–318

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Animal lives embodied in food loss and waste

Juliane Klaura [a], Gerard Breeman [b], Laura Scherer [a,*]

[a] Leiden University, Institute of Environmental Sciences (CML), Leiden, the Netherlands
[b] Leiden University, Institute of Public Administration, P.O. Box 13228, 2501 EE Den Haag, the Netherlands

ARTICLE INFO

Editor: Dr Tomas Balezentis

Keywords:
Animal welfare
Food supply chain
Meat
Policy trade-offs
Reduction scenarios
SDG 12.3

ABSTRACT

While the importance of reducing meat loss and waste is acknowledged due to its substantial environmental impacts, the aspect of animal welfare largely remains unaddressed. The suffering and death that is inflicted on animals to produce food that is never eaten remains invisible. This study aims to bridge the gap between food loss and waste (FLW) accounting literature and animal welfare considerations. It achieves this by estimating the number of animal lives embodied in meat loss and waste of six major meat-producing species along the food supply chain and by modelling three potential reduction scenarios. It shows that approximately 18 billion animal lives were embodied in losses and waste of global meat production and consumption in 2019. The scenarios reveal that wasted and lost animal lives could be reduced by 7.9 billion if best regional efficiencies were mainstreamed, and by 4.2 or 8.8 billion if Sustainable Development Goal 12.3 was implemented, achieving a 50 % loss and waste reduction in the downstream or whole supply chain, respectively. Considering species-specific conscience and sentience, and previous recommendations, the analysis finds leverage points for change at the consumption stage in developed, high-income countries, in Industrialized Asia, judging by absolute, and in North America and Oceania, judging by per-capita numbers, as well as in top countries of FLW and animal life loss. It further identifies trade-offs for animal welfare between reducing FLW of different meat types, especially chicken and beef, and reducing production-based losses while keeping emissions and resource use low and supporting food security.

1. Introduction

1.1. Food loss and waste: a global challenge

In times of accelerating climate change (WMO, 2019), population growth (United Nations Department of Economic and Social Affairs, Population Division, 2022), and growing hunger (WHO, 2022), global food systems are facing unprecedented challenges to match the required food supply while at the same time becoming more environmentally and socially sustainable (Godfray et al., 2010). A research and policy field that cuts across these challenge areas is food loss and waste (FLW). FLW can be defined as “wholesome edible material intended for human consumption, arising at any point in the Food Supply Chain (FSC) that is instead discarded, lost, degraded or consumed by pests” (FAO, 1981; as cited in Parfitt et al., 2010). Approximately a third of the food produced globally is lost or wasted. This FLW amounts to 1.3 billion metric tonnes per year (Gustavsson et al., 2011; Kummu et al., 2012), worth approximately 940 billion USD (FAO, 2015; Lipinski, 2020).

1.2. Food loss and waste reduction on the research and policy agenda

Given the benefits of reducing global FLW, the topic has been gaining attention in recent years (Guo et al., 2020). Both scholars and governments have worked towards estimating where, how, and which amount of food is lost throughout the supply chain (e.g. Caldeira et al., 2019; German Federal Ministry of Food and Agriculture, 2022; Stenmarck et al., 2016). Moreover, researchers have accounted for the environmental impacts tied to the losses (e.g. Beretta et al., 2017; Kummu et al., 2012; Porter et al., 2016) and worked on finding FLW hotspots and leverage points for change (e.g. Guo et al., 2020; Kuiper and Cui, 2021; Read et al., 2020). Already in 2012, the European Parliament adopted a resolution that called for measures to reduce food waste in the European Union by 50 % by 2025 (European Parliament, 2012). In 2016, a similar target was established by the United Nations: Sustainable Development Goal 12.3 (SDG 12.3) aims to halve global food waste per capita at consumer and retail levels by 2030, and reduce food losses in production, post-harvest, and along supply chains (FAO, 2023c). In short,

* Corresponding author.
E-mail address: l.a.scherer@cml.leidenuniv.nl (L. Scherer).

https://doi.org/10.1016/j.spc.2023.11.004
Received 10 September 2023; Received in revised form 3 November 2023; Accepted 7 November 2023
Available online 18 November 2023

accounting FLW and developing reduction strategies have proven to be highly relevant from an economic, environmental, and social standpoint and are on the agenda of researchers and policymakers.

Within achieving FLW reductions, reducing meat loss and waste (MLW) is particularly pressing. Animal-based foods are especially unfavourable to the environment, and although they account for only 12 % of FLW (Lipinski, 2020), they represent relatively more environmental impacts than plant-based foods (Karwowska et al., 2021; Porter et al., 2016). Of all animal-based foods, meat has the highest levels of greenhouse gas emissions per kilogram (Lipinski, 2020), is related to high consumer expenditures (Mena et al., 2014), and (in the case of beef) is one of the top four products in terms of negative biodiversity impact (Beretta et al., 2017). On top of that, global meat production has been rising (Karwowska et al., 2021) and can be expected to rise further in the coming years. Besides the overall rise in food demand driven by population growth, this trend is provoked by rising incomes across the globe, which promote diets that contain higher levels of fats, sugars, and animal products (Drewnowski, 2000; Pradhan et al., 2013).

Overall, the benefits of preventing animal-based products from getting lost or wasted are larger than for other food groups. And although there is a recent strand of academic literature that focuses on animal-based FLW (Bršćić, 2020; Lipinski, 2020) or MLW specifically (Amicarelli et al., 2021; Karwowska et al., 2021; Magalhães et al., 2020; Pinto et al., 2022; Ranaei et al., 2021), certain aspects of the issue remain disregarded.

1.3. Research gap: food & meat loss and waste and animal welfare

Research on sustainable food systems that considers animal welfare is still in its early stages (Scherer et al., 2019). Covering a traditional 'people-planet-profit' notion of sustainability, the existing research leaves the role that animals play in food production and its loss and waste mostly unaddressed. Scholars have thus been calling for studies integrating animal welfare as an additional dimension (Scherer et al., 2018; Talle et al., 2019). This would strengthen research that considers interconnections between diverse criteria of sustainability, which can ultimately carve out interventions that are beneficial across dimensions.

For example, FLW accounting studies commonly assess a small variety of meat and fish alongside other types of food, like fruits and vegetables, without distinguishing them as former living beings (e.g. Gustavsson et al., 2011; Mena et al., 2014; Porter et al., 2016). A multitude of studies also discuss FLW and MLW reduction benefits in terms of the environment, economy, or people, but leave impacts on animal welfare out of the picture (e.g. Beretta et al., 2017; Kuiper and Cui, 2021; Read et al., 2020). This leads to a gap in the scholarly debate, where the animal lives that are lost and wasted "in vain" (Gustavsson et al., 2011, p. v), along with the resources and emissions mentioned, remain invisible. Consequently, the superfluous death and suffering inflicted on animals to produce food that is never eaten remains disregarded as well.

In the academic discourse, the only instance in which the individuals behind FLW become tangible is when the measuring unit 'animal heads slaughtered' is used for calculations of meat losses, as is the case in Amicarelli et al. (2021), and in some of the formulae used by Gustavsson et al. (2013). The limitation of such more explicit accounts is that it remains unclear how many of these animals would strictly be needed to produce the amount of food that is eventually eaten. The only context in which the "invisible dead" (Luckmann, 2021, p. 23) are explicitly accounted for is in the societal discourse. The environmental NGOs *Friends of the Earth*, *BUND*, and *Heinrich Böll Stiftung* make estimations of animal lives embodied in meat waste for their *Meat Atlas* and introduce the practices and structures that currently lead to MLW (Luckmann, 2021). For 2016, they estimate a loss of 11.9 % of global meat production between slaughter and retail, amounting to 39 million tonnes, which they estimate to be equivalent to 115 million cattle or 413 million pigs (Luckmann, 2021). They, however, neither specify their methods nor cover the whole FSC and only provide three sources for their calculations. As reported by The Guardian, journalists Philip Lymbery and Isabel Oakeshott also attempt an estimate in their book "Farmageddon – The True Cost of Cheap Meat", namely that 12 billion animal lives are lost due to household food wastage per year (Hird, 2014).

1.4. Beyond the research gap: food product or dead body?

There is a tendency to disconnect meat from animals, particularly in industrialized food systems (Joy, 2020). As a result, meat-eating is dissociated from the reality of requiring killing (Rothgerber, 2020). Especially when killings happen unnecessarily because the resulting meat is lost or wasted, re-establishing the connection to the living beings that are impacted could bring more weight to the case of reducing FLW. After all, regardless of whether one objects to raising animals as a source of human nutrition, killing an animal that serves no purpose is unnecessary and wasteful (Kasperbauer and Sandøe, 2015).

The need to address lost and wasted animal lives is further emphasized by mounting evidence which suggests that consumers are conflicted about eating animals (Rothgerber, 2020; Rothgerber and Rosenfeld, 2021). Their attitude and behaviour towards animals are often inconsistent, exemplified by building loving relationships with pets and considering themselves animal-friendly while simultaneously maintaining the consumption of meat and dairy as a societal norm (Rothgerber, 2020). Besides health and environmentalism, animal rights are also known to be among the top motivations for (western) individuals to become vegetarians (Fox and Ward, 2008; Hopwood et al., 2020). All in all, it seems that creating tangible information which makes the animal lives embodied in FLW more explicit is a powerful opportunity. Potentially, this updated perspective could convince more decision-makers and consumers to step up reduction efforts.

1.5. Re-establishing a connection: animal lives embodied in food loss and waste

Altogether, there is a rich academic discourse around FLW accounting, environmental impacts of FLW, and FLW reduction, including recent additions focusing on animal products or meat. However, the discussion on the impacts of the food system on animal welfare is still limited, as are estimates of how many animal lives are lost or wasted in global food production.

To close the identified research gap, this study bridges FLW accounting research with animal welfare considerations. More precisely, it combines and augments existing FLW accounting methods to allow for estimations of MLW not only in mass wasted but also in the number of animals affected. To that end, it employs a conception of animal welfare that includes killing as a welfare issue, as the transport to slaughter and slaughter itself is likely to involve suffering (Carrasco-García et al., 2020; Nethra et al., 2023; Shields and Orme-Evans, 2015), it is becoming increasingly evident that animals are sentient and able to suffer (Scherer et al., 2019), and premature death prevents animals from reaching natural life expectancy (Scherer et al., 2018) and living positive experiences (Kasperbauer and Sandøe, 2015; Yeates, 2010). Ultimately, the analysis aims to make animal lives lost more explicit and visible and to carve out how many animal lives could be saved by reducing global FLW and where in the world and supply chain change would be most effective.

To uncover in which countries and parts of the supply chain MLW reductions could best prevent deaths in vain, the analysis covers all FSC stages and accounts for meat losses and waste globally. Additionally, species' sentience and conscience levels are considered using a moral discount factor (Scherer et al., 2018, 2019) to estimate where interventions are most needed to avoid as much suffering as possible. The concept uses humans as a reference value for cognitive ability proxied by animals' number of neurons or brain mass (Scherer et al., 2018). Moreover, this research explores how many animal lives would be saved if SDG 12.3 was reached. Inspired by Kummu et al. (2012), it shows how big savings would be if the currently observed minimal levels across regions were reached globally. Taking into consideration previous recommendations for leverage points from the academic discourse, it then discusses whether efforts to spare animal lives, minimize environmental impacts, and strengthen food security share leverage points. This helps to point policymakers towards the parts of the supply chain and locations in which interventions are likely to have the largest positive impact from a holistic point of view.

2. Materials and methods

2.1. Overall approach

Two approaches, which utilize FAOSTAT data and loss factors in a model that traces global FLW along the FSC, were used to calculate MLW (Gustavsson et al., 2013; Porter et al., 2016). The calculations were done for 2019, which is the latest year for which a complete set of food balance sheet and livestock production data is available from the Food and Agriculture Organization (FAO) that was not impacted heavily by the Covid-19 pandemic (FAO, 2023a, 2023b).

2.2. Definition: outlining food loss and waste

Mainly using equations from Gustavsson et al. (2013), MLW was estimated for pig, cattle, sheep, goat, chicken, and turkey meat in 158 countries, 7 region groups, and 5 supply chain steps. To avoid inconsistencies in the analysis, their definition of FLW was employed. It is based on Parfitt et al. (2010) and defines FLW as the decrease in edible food throughout the part of the supply chain that is directed towards human consumption. Consequently, all products that leave the FSC at any stage before being eaten are considered loss or waste (Section S1). This also applies if a product is (potentially) used elsewhere later, e.g. recovered as energy, biofuel, or feed. While food losses happen during production, post-harvest, and processing of food, later losses are called waste and relate to consumer and retailer behaviour (Parfitt et al., 2010, 2021).

Although the definition clearly outlines what Gustavsson et al. (2011, 2013) consider FLW, some more detailed distinctions are implicit in their work. They calculate MLW in carcass weight, meaning the weight of the dressed body of an animal. With slight differences depending on the species, this excludes blood, feathers, offal, heads, and hoofs but includes bones (Eurostat, 2019) (Table S1). Thus, MLW results must be transferred into bone-free meat to grasp how much meat was lost that could have been eaten (Table S2).

2.3. Food loss and waste calculations

Other than the specific definition of FLW used by Gustavsson et al. (2011, 2013), the use of so-called loss factors is characteristic of their work. Thus, this analysis employed their loss factors and derived FLW estimates by combining them with 2019 FAOSTAT production and food balance sheet data (FAO, 2023b, 2023a). The idea is that it can be expected that a certain percentage of the food that runs through each FSC stage is lost or wasted (Table S3). The authors assembled loss factors for a broad range of commodities per FSC stage in seven region groups based on insights from the scientific literature and their expert assumptions (Gustavsson et al., 2013). While the FSC stages constituted the main structure for the calculations, the region groups accounted for the practices as well as climatic and infrastructural circumstances in different world regions, which influence how much FLW occurs.

For this analysis, the five supply-chain stages and seven region groups were adopted from Gustavsson et al. (2011, 2013) and Porter et al. (2016). The five stages include: FSC1 – Production – this stage involves the breeding and raising of animals; FSC2 – Storage and Handling – in this stage, animals are transported and checked for suitability as food products; FSC3 – Processing and Packaging – here, animals are slaughtered, dressed, and partly prepared as packaged and processed food products; FSC4 – Distribution – in this stage, meat and meat products enter the market and are retailed; FSC5 – Consumption – finally, meat is prepared and consumed in households or gastronomy.

However, the precision of the original work by Gustavsson et al. (2011, 2013) is geographically limited, as they calculate FLW per region group. Inspired by Porter et al. (2016), this analysis went more into depth and used the base provided by Gustavsson et al. (2011, 2013) on the more granular country level. Although the loss percentages remained uniform within the region groups, this allowed to untangle contributions to the losses per country based on production, trade, and consumption volumes. Said region groups include North America & Oceania (N. Am. & Ocean.), Europe, Industrialized Asia (Ind. Asia), North Africa, Western & Central Asia (N. Afr., W. & C. Asia), Latin America (Lat. Am.), Sub-Saharan Africa (Sub-sah. Afr.), and South & Southeast Asia (S&SE Asia). The selection of countries is based on Gustavsson et al. (2013); only a few adjustments were made (Section S5).

Once the list of countries and their corresponding region groups was established, they were matched with FAOSTAT production and food balance sheet data. Although Porter et al.'s (2016) loss factors are more recent, Gustavsson et al.'s (2013) loss factors and formulae were used to calculate the weight of meat lost or wasted, as they go more into depth in calculating meat losses during FSC2. The calculations were done separately for the major species of meat-producing animals. In the case of 'mutton and goat' and 'poultry' data, the data was partly only available as a shared data point. This meant that the species' share of the overall commodity had to be estimated (Section S6).

For calculating life losses in the upstream part of the supply chain ($ALE_{FSC\ 1-2}$ *in Heads*), meat production (*Production in Heads*) was multiplied with loss factors that represent losses during breeding and rearing (LF_1), deaths during transport ($LF_{2.1}$), and animals that are rejected from the slaughterhouse during quality control ($LF_{2.2}$). Given that the FAO collects production data in the moment of slaughter, not accounting for the whole number of animals that need to be raised to provide said supply at slaughter, the previous number of animals raised, transported, and rejected (*ARS in Heads*) at the slaughterhouse needed to be reconstructed step by step. This way, the animals that are lost before the moment of slaughter could be accounted for despite not being captured statistically and were added to the calculation backwards. Therefore, rejection losses were calculated first, followed by transport losses (FSC2, Eqs. (1) and (2)) and eventually breeding losses (FSC1, Eq. (3)), as follows:

$$ALE_{FSC\ 2.2jk} = \frac{LF_{2.2jk}}{1 - LF_{2.2jk}} \times Production_{jk} \tag{1}$$

$$ALE_{FSC\ 2.1jk} = \frac{LF_{2.1jk}}{1 - LF_{2.1jk}} \times \left(Production_{jk} + ARS_k\right) \tag{2}$$

$$ALE_{FSC\ 1jk} = \frac{LF_{1jk}}{1 - LF_{1jk}} \times \left(Production_{jk} + ALE_{FSC\ 2jk}\right) \tag{3}$$

As visible when looking at the steps outlined above, the calculations include animal heads as a unit of measurement during production (*FSC1*) and storage and handling (*FSC2*). This means that numbers on animal life loss are already available during these steps, and no further transformation is needed. To illustrate how much meat loss ($MLW_{FSC\ 1;2}$ *in Tonnes*) this entails, results must be multiplied by the country- (k) and species-specific (j) average carcass weight (*CWperAnimal in* $\frac{kg}{Head}$):

$$MLW_{FSC\ 1;2jk} = ALE_{FSC1;2jk} \times \text{CWperAnimal}_{jk} \div 1000 \tag{4}$$

To calculate waste amounts in the downstream FSC, starting from processing & packaging (*FSC3*), production data were replaced with consumption data, namely the account of how much raw (*Food in Tonnes*) and processed (*Processing in Tonnes*) meat was available for human consumption per country in 2019. As part of the food available in a country is often sourced from abroad, this change in variable ensures that the wasting of traded meat is not simply assigned to the producing country. From this step on, no previous volumes needed to be reconstructed, which means that the reported volumes were simply multiplied with their corresponding loss factors (LF_{njk}) and subtracted by losses or waste from the previous FSC stage $(MLW_{FSC\ n-1jk}\ in\ Tonnes)$:

$$MLW\ \text{Food}_{\text{FSCnjk}} = LF_{njk} \times \left(\text{Food}_{jk} - MLW\ \text{Food}_{FSC\ \text{n}-1jk}\right) \tag{5}$$

$$MLW\ \text{Processing}_{\text{FSCnjk}} = LF_{njk} \times \left(\text{Processing}_{jk} - MLW\ \text{Processing}_{FSC\ \text{n}-1jk}\right) \tag{6}$$

In contrast to the original formula from Gustavsson et al. (2013), MLW from *Food* and *Processing* were calculated separately for the results to be added up later, as *Processing* meats are unlikely to contain bones, which needs to be accounted for to allow the transformation to animal lives:

$$MLW_{FSCnjk} = MLW\ Food_{FSCnjk} + \frac{MLW\ Processing_{FSCnjk}}{BFMperCW_j} \tag{7}$$

To allow adding the results up, MLW from processing had to be adjusted to the unit carcass weight. Thus, it was divided by the average meat yield in bone-free meat per animal body of each species (*BFMperCW*).

As different data and formulae were used in this second half of the FSC, numbers on the animal heads slaughtered that could be directly connected to the results were no longer available. Consequently, additional formulae were set up to account for the animal lives lost per FSC stage, country, and region group. They simply divide the MLW volume in carcass weight with the average carcass weight of an animal body. This is partially done using a global export-weighted average (*GlobalMeanCWperAnimal in* $\frac{kg}{Head}$) to account for the foreign portion of meats, and partially using the country-specific average carcass weight (*CWperAnimal in* $\frac{kg}{Head}$) to represent meat from domestic production:

$$ALE_{FSC\ 3-5jk} = \frac{MLW_{FSC\ njk} \times 1000 \times ShareDomestic_{jk}}{CWperAnimal_{jk}} + \frac{MLW_{FSC\ njk} \times 1000 \times ShareImported_{jk}}{GlobalMeanCWperAnimal_j} \tag{8}$$

Details on how the share of meat from domestic production (*ShareDomestic*) versus the share of imported meat (*ShareImported*) was estimated can be found in Section S7.

The results of the calculations outlined above created the base of the analysis and revealed where in the FSC and in which locations most animal lives are lost and wasted. Since previous research has established factors (*BFMperCW*) that transform MLW from carcass weight to edible meat yield (Table S2), they also permitted calculations to determine how much meat this represents in terms of bone-free meat yield:

$$BFML_{FSC\ njk} = MLW_{FSC\ njk} \times BFMperCW_j \tag{9}$$

Once results are established, Scherer et al.'s (2018, 2019) moral adjustment factors can be used to compare total loss results between species in the light of the different species' ability to suffer and perceive their situation (MVF_j). Starting from the moral adjustment factor 1, which is assigned to humans, animals are assigned proportional moral adjustment factors, e.g. 0.027 for pigs, depending on their number of neurons or brain mass (Table S5). The results were thus multiplied by the adjustment factors to account for the moral value of the animal lives in question:

$$Morally\ Adjusted\ ALE_{Total\ per\ Species} = ALE_{Total\ per\ Species} \times MVF_j \tag{10}$$

This resulted in a morally adjusted estimate of the animal lives embodied in the total losses per species $(Morally\ Adjusted\ ALE_{Total\ per\ Species}\ in\ Heads)$, which adds a new dimension to the discussion on where interventions are most needed [Eq. (10)].

2.4. Reduction scenarios

In a separate calculation, selected loss factors were employed to represent a minimal-level reduction scenario. Out of the loss factors among all region groups, the smallest factors per FSC stage and species were chosen and assembled into a new loss factor table (Table S6). The results represent a hypothetical scenario in which MLW would be reduced to the smallest levels currently observed across the globe. Or, put differently, the scenario does not assume the implementation of a political goal but explores which efficiencies seem possible by looking at existing regional supply chains. For example, this would mean that goat and sheep losses during breeding would go down to 10 %, as is currently the case in five region groups. Compared to the e.g. 33 % lost in Sub-Saharan Africa, this would entail a significant decrease in premature deaths for certain countries.

Similarly, a reduction in line with SDG 12.3 was explored. As SDG 12.3 is in part worded vaguely, the details of reduction ambitions in the first three stages of the supply chain remain unclear. However, achieving its minimum ambition would at least require waste reductions of 50 % in Distribution and Consumption. Thus, the scenario was modelled by reducing worldwide FSC4 and FSC5 loss factors by 50 % for a pessimistic implementation scenario and halving loss factors for all FSC stages for an optimistic implementation scenario (Tables S7 and S8).

3. Results

3.1. Animal life losses embodied in 2019 meat loss & waste

In 2019, 77.4 million tonnes of meat from the six major meat-producing species of animals were lost and wasted along the food supply chain. This is equivalent to approximately 52.4 million tonnes of bone-free, edible meat (Fig. S1). In this MLW, the lives of close to 18 billion animals were embodied, which were raised and killed without serving a purpose for human nutrition. Of the estimated deaths, 74.1 million individuals or 0.4 % were cattle, 188 million or 1.1 % goats, 195.7 million or 1.1 % sheep, 298.8 million or 1.7 % pigs, 402.3 million or 2.2 % turkeys, and 16.8 billion or 93.6 % chickens. Thus, for an average citizen, there were 2.4 lost or wasted animal lives embodied in meat production and consumption.

Of all the life losses estimated, 24.9 % occurred in FSC1, 7.8 % in FSC2, 20.0 % in FSC3, 20.6 % in FSC4, and 26.7 % in FSC5. Hence, in the supply chain, most life loss occurs during agricultural production (FSC1) and consumption (FSC5), whereas life losses during storage and handling (FSC2) were found to be especially low. Patterns per region group, however, differ (Fig. 1). Consumption-based losses dominate in North America & Oceania, Europe, and Industrialized Asia. Production-based losses are highest in Latin America, North Africa, Western & Central Asia and especially Sub-Saharan Africa. Losses in South and Southeast Asia are entirely different, being dominated by Distribution (FSC4) and Processing & Packaging Losses (FSC3). In summary, losses during the upstream stages of the FSC lead to slightly more needless animal deaths (52.7 %) than waste in the downstream stages of the FSC (47.3 %).

3.2. Morally adjusted results

80.8 million morally adjusted deaths occurred across species, of which 63.9 million or 79.11 % were chicken, 8.1 million or 10.0 % were pig, 2.6 million or 3.2 % were cattle, 2.4 million or 3.0 % sheep, 2.3 million or 2.8 % were goat, and 1.5 million or 1.9 % turkey deaths

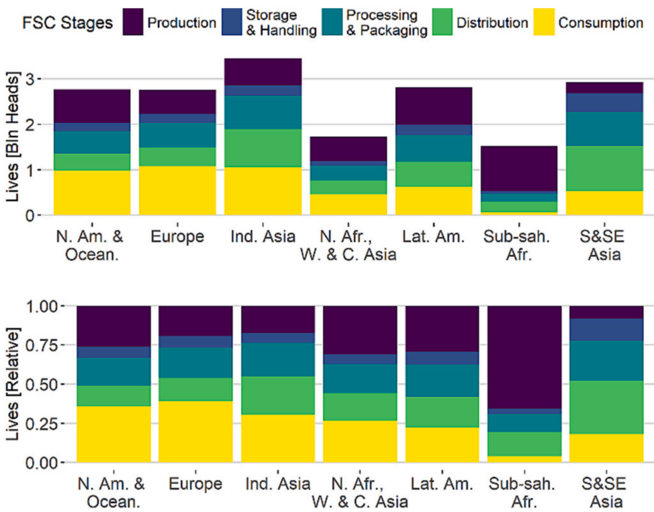

Fig. 1. Animal life loss throughout the FSC. See the corresponding data in Table S9.

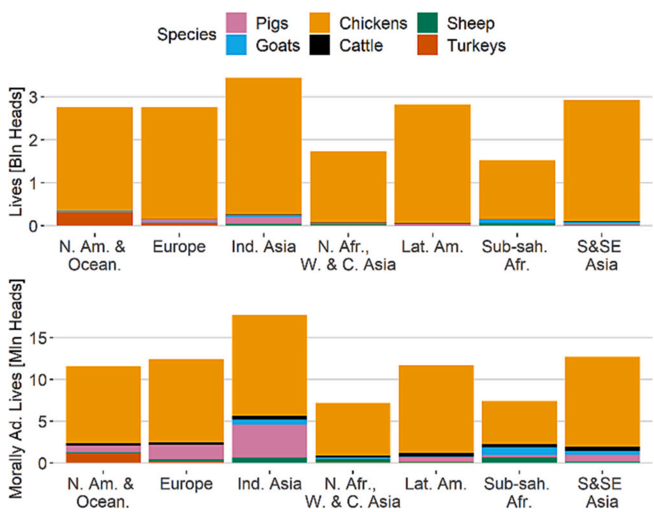

Fig. 2. Animal life loss per species and region group in absolute and morally adjusted terms. See the relative version in Fig. S2 and the corresponding data in Table S10.

(Fig. 2). Applying the moral adjustment factors (Scherer et al., 2018, 2019) thus shows that although chickens are assigned a relatively low moral value, they still represent the species that accounts for most life loss and suffering. Although turkeys are the second most impacted species in terms of absolute deaths, pigs are more impacted after results are morally adjusted and account for the suffering animals go through based on their cognitive abilities. Cattle, sheep, and goats embody both relatively low absolute and morally adjusted deaths. However, based on their higher moral adjustment factor, cattle gain relevance compared to sheep and goats after moral adjustment.

3.3. Geographical animal life & welfare loss hotspots

Location-wise, the top life-loss countries were identified to cause the bulk of animal life loss. 57 % of the life losses occurred in the top 10 countries of animal life loss (Table 1). Out of these top ten, two countries – the US and South Africa – are also part of the top ten list of life loss per capita and morally adjusted life loss. Although South Africa's MLW in tonnes per capita is much lower than that of the US, it stands out for its high losses of chicken lives per capita (Fig. 3). In addition, Brazil is a top ten country in terms of absolute life loss and morally adjusted life loss, and a top twenty country in terms of life loss per capita. Thus, the US, South Africa, and Brazil can be considered geographical hotspots of animal life loss and welfare loss embodied in MLW.

Looking at the regional distribution, Industrialized Asia was the region group with the most, namely 19.2 % of animal life losses, and Sub-Saharan Africa was the region group with the least animal lives lost, namely 8.5 % (Table 2). However, the 19.2 % share of global animal life loss in Industrialized Asia is spread out over 21.8 % of the population accounted for in this analysis. In comparison to that, the region group with the highest per-capita life loss, North America and Oceania, has a considerably higher average loss and waste with 6.98 animal lives embodied per capita in 24.5 kg of edible meat loss and waste compared to only 2.07 animal lives embodied in 7.71 kg of edible meat loss and waste in Industrialized Asia. For their share in population, the food systems of North America and Oceania thus cause disproportionately much of the global animal life loss. Latin America, North Africa, Western & Central Asia, and Europe were also identified as regions whose shares in animal life loss are disproportionally high compared to their global population share. This pattern roughly follows the GDP per capita, which tends to be higher in regions with a higher life loss per capita (Table 2).

3.4. Reduction scenarios

If reductions were achieved that would cut MLW to minimum observed loss and waste levels across the whole supply chain in all region groups, 7.9 billion animal lives could be spared while producing the same amount of meat for human consumption (Fig. 4). This would entail a reduction of 7.3 billion chicken, 301.7 million turkey, 111.2 million pig, 79.2 million goat, 80.9 million sheep, and 42.9 million cattle deaths. Implementing a reduction to minimal observed levels would equal a

Table 1
Top ten hotspot countries of animal life loss embodied in MLW. Darker colours indicate higher losses.

Country	Total Losses	Global Share	Morally Adjusted Losses	Morally Adjusted Global Share	Life Loss per Capita
China, mainland	2,810,070,845	16%	14,928,721	18%	1.96
United States	2,337,903,259	13%	9,692,344	12%	7.10
Brazil	1,136,881,478	6%	4,712,935	6%	5.39
Indonesia	961,273,037	5%	3,730,315	5%	3.55
Russian Federation	644,817,235	4%	2,758,813	3%	4.42
India	555,472,722	3%	2,600,796	3%	0.40
Mexico	543,040,982	3%	2,254,495	3%	4.26
South Africa	515,079,810	3%	2,028,796	3%	8.80
Egypt	348,114,268	2%	1,344,589	2%	3.47
United Kingdom	323,057,438	2%	1,371,090	2%	4.79

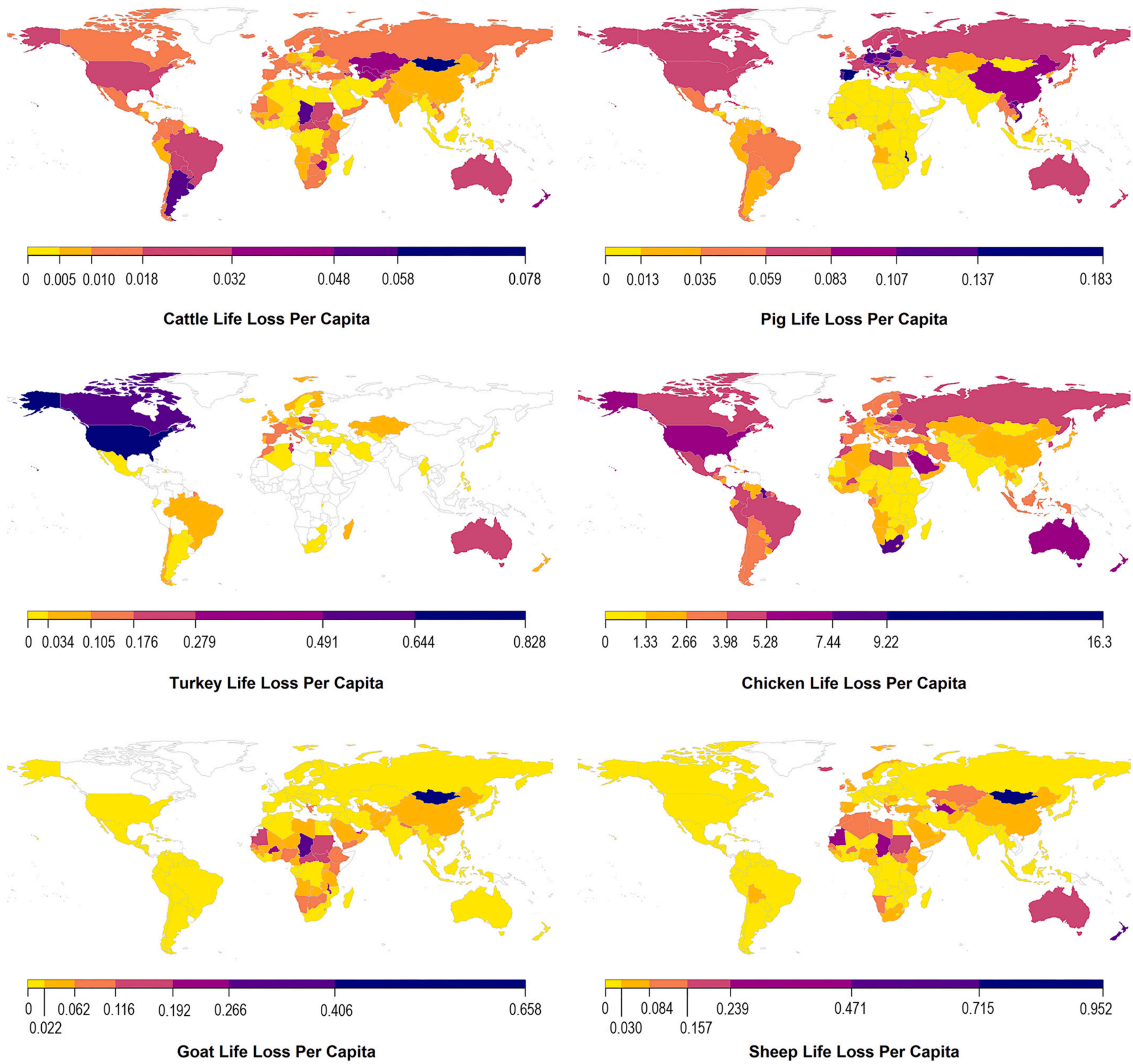

Fig. 3. Global per-capita animal life loss embodied in MLW in 2019. Countries in white lacked data or were not covered in the analysis.

Table 2
Animal life loss share per region group compared to global population share. Darker colours indicate higher values.

Region Group	No. of Countries	Total Life Loss	Life Loss Share	Population Share	GDP per Capita (USD)	Life Loss per Capita
Industrialized Asia	7	3,449,213,601	19.2%	21.8%	12,967	2.07
South & Southeast Asia	17	2,926,672,931	16.3%	33.7%	2,790	1.14
Latin America	24	2,813,967,720	15.7%	8.4%	8,347	4.39
North America & Oceania	4	2,767,792,671	15.4%	5.2%	61,448	6.98
Europe	43	2,762,316,567	15.4%	10.0%	28,653	3.61
North Africa, Western & Central Asia	22	1,728,955,657	9.6%	6.8%	7,587	3.34
Sub-Saharan Africa	41	1,522,692,752	8.5%	14.2%	1,584	1.40

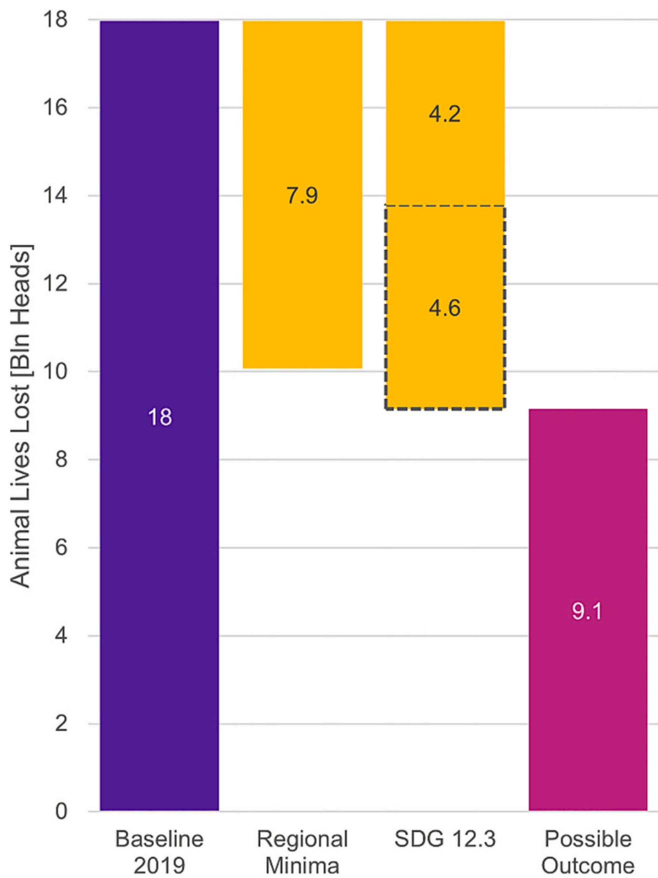

Fig. 4. Reduction scenarios. The upper SDG bar represents a minimal SDG implementation; the lower bar represents an additional reduction in case of a full, optimistic implementation.

reduction of MLW and life losses of 43.9 % across the supply chain compared to current loss and waste levels.

If reductions in line with SDG 12.3 were implemented, 4.2 billion animal lives could be spared if minimal goals were achieved, meaning that FSC4 and FSC5 MLW would be reduced by 50 %. If losses and waste were reduced by 50 % across the entire supply chain, 8.8 billion lives could be spared (Fig. 4).

4. Discussion

The results presented above show that vast animal life and welfare loss occurs embodied in global MLW and that considerable death and suffering could be avoided if SDG 12.3 or minimal loss levels were achieved in the coming years. Estimating animal lives embodied in MLW along the supply chain and across the globe has also revealed several hotspots of life loss, where change could prevent most animal deaths in vain and reduce MLW best. However, the complexity of global food systems and FLW accounting calls for careful interpretation of these results. Scholars agree that a multitude of dimensions plays into selecting target points for FLW reduction policies and that trade-offs between them can arise (Cattaneo et al., 2021a; Guo et al., 2020; Kuiper and Cui, 2021). Finding appropriate target points for interventions thus requires comparing the above results to findings of research with other focal points, e.g. climate change mitigation, biodiversity, or food security.

4.1. Trade-offs between meat-producing species

Among the main meat-producing species, chickens are by far the most impacted group in terms of animal welfare and life loss, followed by turkeys in terms of life loss and pigs in terms of welfare loss. This reveals a first trade-off between sustainability goals in MLW reduction. Consistent with what Scherer et al. (2018) found, beef loss and waste are associated with the smallest number of deaths and a comparably low morally adjusted life loss. This is in stark contrast with the environmental impacts associated with either meat type. Bovine meat has been identified as the main contributor to greenhouse gas emissions within global FLW (Guo et al., 2020). This is because ruminants like cattle, goats, and sheep have several guts and produce methane through enteric fermentation during their digestive process (Clune et al., 2017). Meat from non-ruminants like chickens, turkeys, and pigs is less problematic in this regard (Clune et al., 2017). Furthermore, Beretta et al. (2017) have identified beef waste as the commodity with the second highest pressure on biodiversity in terms of land and water use. Poultry meat is, however, known to have the lowest environmental impacts of meats (Scherer et al., 2018). Simply going by the number of animal life losses per species to determine target points for interventions is thus undesirable, whereas focusing solely on environmental impacts may lead to increasing animal welfare and life loss.

4.2. Focal points along the supply chain & rebound effects

Based on the results of this analysis, it would be advisable to focus MWL reduction efforts on the first and last stages of the supply chain. This perspective aligns with the examination of overall FLW and crop loss and waste accounts (Guo et al., 2020; Kummu et al., 2012), as well as with recommendations from studies on the environmental impacts of FLW, which emphasize the need to concentrate on reducing consumption waste in industrialized countries (Beretta et al., 2017; Read et al., 2020). However, several constraints apply. Firstly, this analysis found that FSC2 is the stage with the lowest losses. This is not the case for crop losses, which are third highest in FSC2 and lower in FSC3 and FSC4 compared to meat and animal life losses (Guo et al., 2020; Kummu et al., 2012). Thus, prioritizing among the middle FSC stages aimed at general FLW reduction presents a challenge. Furthermore, although deaths during transport and handling before slaughter are relatively low, animal welfare during FSC2 influences the quality of the yielded meat, e.g. because of possible bruising and the release of stress hormones when animals are treated badly. This can, in turn, influence the shelf life and quality of the resulting meat products and how likely they are wasted in FSC4 or FSC5 (Carrasco-García et al., 2020; Flanagan et al., 2019; Nethra et al., 2023). This illustrates that separating FSC stages to prioritize intervention points has limitations, as they remain interconnected and dependent on each other. It also emphasizes that policies differentiating animal products from crop products are more likely to achieve substantial reductions.

Secondly, older FLW accounting research assumes that FLW reductions generally save resources and reduce emissions (e.g. Kummu et al., 2012; Read et al., 2020). However, more recent research has criticized this main "thrust" of the literature and encouraged a debate on rebound effects (Cattaneo et al., 2021ap; Kuiper and Cui, 2021). These scholars argue that due to price transmission effects and emission shifts to downstream stages of the supply chain (Cattaneo et al., 2021a), greenhouse gas emissions can, in fact, rise because of FLW reductions, especially at the production stage. For example, sinking prices may lead to growing purchases by consumers, economic expansion in other sectors, or loss reductions may result in larger food volumes moving through the supply chain, throughout which additional emissions are caused, e.g., through cooling (Cattaneo et al., 2021a; Kuiper and Cui, 2021). Therefore, FLW reduction at the production stage needs to be targeted carefully and should best be accompanied by other measures like emission- or resource-pricing instruments (Cattaneo et al., 2021a; Kuiper and Cui, 2021).

4.3. Geographical leverage points for change

More clarity emerges when looking at geographical leverage points for change. As Guo et al. (2020) show, 60 % of FLW originates from the top ten countries. With 57 % of animal lives embodied in MLW of the top ten animal life-loss countries, similar results have surfaced in this analysis. Seven of these countries match Guo et al.'s (2020) top ten, namely China, India, the US, Indonesia, Brazil, Russia, and Mexico. If general FLW of all commodities was reduced especially in these high-impact countries, a considerable number of animal lives could be spared as well. China, the US, and Brazil alone account for 35 % of global animal life losses. Furthermore, Guo et al. (2020) and Porter et al. (2016) identify the same region group causing the highest FLW mass – Industrialized Asia. This is consistent with the results of this analysis and another potential target point for intervention where synergies between reducing general FLW and MLW versus animal lives embodied in MLW seem possible.

Two of the top ten countries identified by Guo et al. (2020), the US and Brazil, match the three hotspot countries of animal welfare and life loss identified in this analysis. Moreover, studies which discuss the details of local FLW patterns, causes, and ideas for interventions are available for the US (Cuéllar and Webber, 2010; Read et al., 2020), South Africa (Oelofse et al., 2021; Oelofse and Nahman, 2013), and Brazil (Dal'Magro and Talamini, 2019; Magalhães et al., 2020). This is not the case for many other countries and is an opportunity for scholars and policymakers to work on finding country-specific paths to waste reduction that consider different sustainability dimensions, including that presented here.

Guo et al. (2020) mention North America & Oceania as a hotspot of greenhouse gas emissions, which largely arise from consumer beef waste. This is consistent with Read et al.'s (2020) recommendation, who, besides recommending improving processing efficiency, advise to focus on meat waste reduction in food service and households in the US. Furthermore, Porter et al.'s (2016) findings indicate that North America & Oceania is the region group with the highest per-capita greenhouse gas emissions. This also aligns with the finding from this analysis that developed countries should prioritize the consumption stage to reduce animal life losses, which hit the highest per-capita values in North America and Oceania. Thus, focusing on FSC5 reductions in developed countries, and especially in North America & Oceania, seems to be a good option to achieve win-win outcomes for the environment and animal welfare.

Lastly, countries causing animal life loss through production are not solely responsible for such losses. Instead, producers and consumers demanding their products should share the responsibility. Such a shared responsibility could also reflect that some countries, such as those with a higher GDP per capita, have a higher capability to implement change (Sun et al., 2022; Vasconcellos Oliveira, 2020).

4.4. Achieving reductions in low-income countries & food security

Besides possible trade-offs between leverage points for change, the overall aim of MLW reductions can vary. The underlying assumption of this work has been that if reduction measures are successfully implemented, meat supply can remain at a steady level (or even reduce) while using fewer animals and resources, thus becoming more sustainable. This aim would already be achievable in the scenario of a minimally successful SDG 12.3 implementation, which would focus on reducing MLW in FSC4 and FSC5, where most MLW occurs in developed countries and where rebound effects are less likely to occur. It is, however, questionable how desirable this path is for low-income countries.

As has been shown in previous studies and is reflected in the results of this analysis, with the exception of South & Southeast Asia, most of the food waste in developed regions occurs towards the end of the supply chain (Hodges et al., 2011; Karwowska et al., 2021), whereas the upstream stages are especially inefficient in developing, low-income countries (Flanagan et al., 2019; Hodges et al., 2011). Especially in Sub-Saharan Africa, FSC1 MLW is extraordinarily high (Gustavsson et al., 2011). As low-income countries are also likely to be more food insecure, targeting production losses could not only save more animal lives but additionally improve food security levels by making more meat available (e.g. Aragie, 2022; Cattaneo et al., 2021a; Kuiper and Cui, 2021). This is specifically relevant for reducing meat losses, as meat is the most concentrated source of vitamins and minerals in developing countries and ruminants can use grassland that is unsuitable for crop agriculture (Godfray et al., 2010). Reductions would, however, entail a different path, on which efficiency gains would not be used to scale down livestock agriculture but to produce more meat at current levels of inputs. Thus, MLW reductions could potentially imply that the same number of animals are killed for nutrition, but fewer animals remain uneaten and are killed in vain.

This thought also sheds light on the limited practicability of SDG 12.3. Especially if the focus is placed on FSC4 and FSC5 reductions, substantial outcomes of reduction efforts are mostly limited to developed countries. Meanwhile, developing countries may be under pressure to reduce waste levels that are already extremely low by half, e.g. from 2 % to 1 % in FSC5 of Sub-Saharan Africa, without yielding significant results. Potentially, aiming for achieving the current minimal loss and waste level scenario could allow for a more just and effective transition, knowing that, at least from an animal life loss perspective, it yields almost as much reduction as a full, optimistic implementation of SDG 12.3.

4.5. System boundaries

Given that the FLW accounting literature does not use a shared definition for FLW (Amicarelli et al., 2021; Corrado et al., 2019), definitions depend on the goals and system boundaries of studies (Corrado et al., 2019; Hartikainen et al., 2018). Therefore, other scientific accounts of FLW are bound to differ from the results of this analysis, for example, if they include inedible parts of products in their accounts or exclude recovered shares of FLW from the balance (e.g. Stenmarck et al., 2016). As Hartikainen et al. (2018) address, scholars also do not always account for the losses before slaughter or harvest.

Furthermore, Gustavsson et al.'s (2013) loss factors for the consumption stage FSC5 exclusively consider avoidable food waste – as opposed to possibly avoidable and unavoidable waste (Beretta et al., 2013). The distinction implies that some FLW occurs because food is no longer wanted or has expired (avoidable), because it depends on the individual whether a certain item is perceived as edible or a food item is sorted out due to specific criteria like shape or colour (possibly avoidable), or because losses are inevitable due to technological restrictions or unsuitability for consumption (unavoidable) (Beretta et al., 2013). Estimations of animal lives lost at the consumption stage would be higher if possibly avoidable waste was considered, like the fatty rim that people cut off ham, and the other loss factors might change as well if the distinction was applied to them. Thus, future analyses that focus on global MLW and animal lives could find differing shares of contributions from the FSC stages, depending on the methodological choices they make.

4.6. Research outlook

There are several opportunities for further research. Firstly, the analysis only investigated meat production in terms of meat carcass weight. This excludes analyzing loss and waste of fats and edible offal, which are accounted for by the FAO separately (FAO, 2023b). Furthermore, it excludes dairy and egg production, as well as fisheries, in which substantial further animal lives are embodied. Especially shedding light on the welfare loss of fish is desirable in future research, as fish are often perceived as a less sentient, uniform group (Joy, 2020) falling victim to speciesism (Caviola et al., 2019). Accounting for the culling of male chicks in egg production (Reithmayer and Mußhoff, 2019) may also reaffirm how badly chickens are affected by superfluous killing as a species.

Conversion factors from academic literature were used to determine how much bone-free meat was available from the carcass weight of each species and thus edible. In combination with setting aside fats and offal and treating each part of carcass-weight-based meat as equal, blind spots regarding (culturally dependent) meat-eating preferences arise. For example, some cultures may deem animal parts edible that are seen as inedible in other cultures, or there may be biases in which parts are more likely to be discarded than others. Overall, it is likely that this analysis features loss and conversion rates that are Western-biased, as the bulk of FLW research is still rooted in the Global North (Aragie, 2022; Guo et al., 2020). This connects to another limitation: the loss factors. Scholars from the Global South criticize that a lack of studies and context-specific local expertise was used to compile loss factors for the Global South (Oelofse et al., 2021). This is especially relevant for South Africa, which has been identified as a hotspot of animal life loss. Taking into consideration more local knowledge, Oelofse et al. (2021) make alternative suggestions for loss factors to calculate South African losses, which could lead to different results.

Besides the differing quality of loss factors, the remaining data quality and availability also varied. For some species like pigs and cattle, data coverage from FAOSTAT was good and complementary studies, e.g. providing up-to-date conversion rates, were also available. This was not the case for separate data for poultry, as well as goats and sheep, which are partly treated as a uniform group. Data availability on geese, ducks, and pigeons was so poor that they could not be considered in this analysis. Similarly, regionally important species like Camels (Alshabanat et al., 2021) could not be accounted for. Lastly, authors have reported that in the case of developing countries, FAOSTAT data is not particularly accurate (Guo et al., 2020) and that reliable commodity-specific information on FLW extent is not yet available, which makes loss factors less reliable, especially for Sub-Saharan Africa (Aragie, 2022; Aragie et al., 2018).

Furthermore, the European fitness check on animal welfare policy revealed that the quantitative evidence base measuring animal welfare and policy outcomes in the field is limited and that more reliable information to measure policy success is needed (European Commission, 2022). Calculating animal life loss and waste can provide exactly that – a new evidence base to gain insight into the current and changing state of the food system, revealing quantifiable leverage points for policies. Improving the database for such calculations would enhance the precision of results and elevate its usefulness for policymakers further. Moreover, research has revealed cases where consumers were more willing to accept policies like meat taxation for animal welfare protection than for climate change mitigation reasons (Perino and Schwickert, 2023). This ties back to the finding that vegetarians are often motivated by animal rights (Fox and Ward, 2008; Hopwood et al., 2020) and consumers feel conflicted about eating animals (Rothgerber, 2020; Rothgerber and Rosenfeld, 2021). Overall, making unnecessary suffering and death visible seems to be a relevant lever for policy and behavioural change. These are just some examples that illustrate that more detailed data and research are needed, e.g. in the shape of a database for country-specific loss factors to elevate the quality of estimates, deeper knowledge on FLW in the Global South, and accounting for farmed animals across all sectors of the food system, including 'niche' species. Ideally, future studies could also integrate data on the mass flow of commodities to avoid possible inconsistencies between datasets (Caldeira et al., 2019).

5. Conclusions

This analysis has contributed to closing two research gaps highlighted by Cattaneo et al. (2021b), (1) Trade-offs among various objectives related to FLW reduction as well as (2) additional critical loss points were identified, particularly by incorporating an animal welfare dimension into FLW accounting research. The study has shown that nearly 18 billion animal lives are embodied in losses and waste of a year of global meat production and consumption. These deaths in vain could be reduced by 7.9 billion if the different world regions would achieve the best currently observed efficiencies across the global FSC, and by 4.2 or 8.8 billion if SDG 12.3 was implemented to a minimal or full extent, meaning if MLW was reduced by 50 % in the last two or all stages of the FSC.

The analysis has also revealed leverage points for change. They especially lie at the consumption stage of the FSC in developed, high-income countries, in Industrialized Asia, judging by absolute, and in North America and Oceania, judging by per-capita numbers, as well as in top countries of FLW and animal life loss. However, tackling life loss at the production stage and prioritizing species for reduction efforts comes with trade-offs, and reduction policies need to be adjusted to the local context, for example, if food insecurity is a prevalent issue. This makes reducing animal life loss a challenging task in low-income countries, which is further aggravated by the vague wording of SDG 12.3, currently mainly focusing on downstream stages of the supply chain.

While trade-offs between intervention points exist and FLW reduction policies should best be embedded in a supportive network of environmental policies, reducing FLW and especially MLW bears many benefits for animals, people, nature, and the economy. As Lipinski (2020) argues: the reduction journey begins with measurement. Targeted interventions become possible only when the extent and causes of FLW are known (Lipinski, 2020). The same is true for lost and wasted animal lives: This study gives the first comprehensive understanding of the extent of the problem by reconnecting meat as a product with the living beings that it comes from. Potentially, creating awareness among policymakers and consumers that FLW comes with such vast consequences for living beings can serve as a new motivation to step up reduction efforts. This work has thus provided a missing puzzle piece to the picture and shown that more data is needed to support future similar studies as well as other projects that aim to consider a multitude of sustainability dimensions, equipping policymakers and consumers with a more complete view of global food systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.11.004.

References

Alshabanat, Z., Alkhorayef, A., Ben Haddad, H., Mezghani, I., Gouider, A., Tlili, A., Allouche, M.A., Gannouni, K.A., 2021. Quantifying food loss and waste in Saudi Arabia. Sustainability 13 (16), 9444. https://doi.org/10.3390/su13169444.

Amicarelli, V., Rana, R., Lombardi, M., Bux, C., 2021. Material flow analysis and sustainability of the Italian meat industry. J. Clean. Prod. 299, 126902 https://doi.org/10.1016/j.jclepro.2021.126902.

Aragie, E., 2022. Efficiency and resource implications of food losses and waste in sub-Saharan Africa. J. Asian Afr. Stud. 57 (3), 446–461. https://doi.org/10.1177/00219096211020490.

Aragie, E., Balié, J., Morales-Opazo, C., 2018. Does reducing food losses and wastes in sub-Saharan Africa make economic sense? Waste Manag. Res. J. Sustain. Circ. Econ. 36 (6), 483–494. https://doi.org/10.1177/0734242X18770247.

Beretta, C., Stoessel, F., Baier, U., Hellweg, S., 2013. Quantifying food losses and the potential for reduction in Switzerland. Waste Manag. 33 (3), 764–773. https://doi.org/10.1016/j.wasman.2012.11.007.

Beretta, C., Stucki, M., Hellweg, S., 2017. Environmental impacts and hotspots of food losses: value chain analysis of Swiss food consumption. Environ. Sci. Technol. 51 (19), 11165–11173. https://doi.org/10.1021/acs.est.6b06179.

Bršćić, M., 2020. Refining consumer attitudes to milk and dairy product purchase and use to reduce food waste and improve animal welfare on-farm. J. Dairy Res. 87 (S1), 9–12. https://doi.org/10.1017/S0022029920000631.
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.
Carrasco-García, A.A., Pardío-Sedas, V.T., León-Banda, G.G., Ahuja-Aguirre, C., Paredes-Ramos, P., Hernández-Cruz, B.C., Murillo, V.V., 2020. Effect of stress during slaughter on carcass characteristics and meat quality in tropical beef cattle. Asian Australas. J. Anim. Sci. 33 (10), 1656–1665. https://doi.org/10.5713/ajas.19.0804.
Cattaneo, A., Federighi, G., Vaz, S., 2021a. The environmental impact of reducing food loss and waste: a critical assessment. Food Policy 98, 101890. https://doi.org/10.1016/j.foodpol.2020.101890.
Cattaneo, A., Sánchez, M.V., Torero, M., Vos, R., 2021b. Reducing food loss and waste: five challenges for policy and research. Food Policy 98, 101974. https://doi.org/10.1016/j.foodpol.2020.101974.
Caviola, L., Everett, J.A.C., Faber, N.S., 2019. The moral standing of animals: towards a psychology of speciesism. J. Pers. Soc. Psychol. 116, 1011–1029. https://doi.org/10.1037/pspp0000182.
Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783. https://doi.org/10.1016/j.jclepro.2016.04.082.
Corrado, S., Caldeira, C., Eriksson, M., Hanssen, O.J., Hauser, H.-E., van Holsteijn, F., Liu, G., Östergren, K., Parry, A., Secondi, L., Stenmarck, Å., Sala, S., 2019. Food waste accounting methodologies: challenges, opportunities, and further advancements. Glob. Food Sec. 20, 93–100. https://doi.org/10.1016/j.gfs.2019.01.002.
Cuéllar, A.D., Webber, M.E., 2010. Wasted food, wasted energy: the embedded energy in food waste in the United States. Environ. Sci. Technol. 44 (16), 6464–6469. https://doi.org/10.1021/es100310d.
Dal'Magro, G.P., Talamini, E., 2019. Estimating the magnitude of the food loss and waste generated in Brazil. Waste Manag. Res. 37 (7), 706–716. https://doi.org/10.1177/0734242X19836710.
Drewnowski, A., 2000. Nutrition transition and global dietary trends. Nutrition 16 (7), 486–487. https://doi.org/10.1016/S0899-9007(00)00295-1.
European Commission, 2022. Commission Staff Working Document Fitness Check of the EU Animal Welfare Legislation. https://food.ec.europa.eu/system/files/2022-10/aw_eval_revision_swd_2022-328_en.pdf.
European Parliament, 2012. Parliament Calls for Urgent Measures to Halve Food Wastage in the EU. News | European Parliament, 19. January. https://www.europarl.europa.eu/news/en/press-room/20120118IPR35648/parliament-calls-for-urgent-measures-to-halve-food-wastage-in-the-eu.
Eurostat, 2019. Glossary: Carcass Weight. Statistics Explained, 13. February. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carcass_weight.
FAO, 1981. Food loss Prevention in Perishable Crops (No. 43; FAO Agricultural Services Bulletin). FAO Statistics Division. https://www.fao.org/3/S8620E/S8620E00.htm.
FAO, 2015. Food Wastage Footprint & Climate Change. FAO. https://www.fao.org/3/bb144e/bb144e.pdf.
FAO, 2023a. FAOSTAT. Crops and Livestock Products. https://www.fao.org/faostat/en/#data/QCL.
FAO, 2023b. FAOSTAT. Food Balances (2010-). https://www.fao.org/faostat/en/#data/FBS.
FAO, 2023c. Indicator 12.3.1 - Global Food Loss and Waste. Food and Agriculture Organization of the United Nations. https://www.fao.org/sustainable-development-goals/indicators/1231/en/.
Flanagan, K., Robertson, K., Hanson, C., 2019. Reducing Food Loss and Waste: Setting a Global Action Agenda. World Resources Institute. https://doi.org/10.46830/wrirpt.18.00130.
Fox, N., Ward, K., 2008. Health, ethics and environment: a qualitative study of vegetarian motivations. Appetite 50 (2), 422–429. https://doi.org/10.1016/j.appet.2007.09.007.
German Federal Ministry of Food and Agriculture, 2022. Lebensmittelabfälle in Deutschland: Aktuelle Zahlen zur Höhe der Lebensmittelabfälle nach Sektoren. Bundesministerium für Ernährung und Landwirtschaft, 23. September. https://www.bmel.de/DE/themen/ernaehrung/lebensmittelverschwendung/studie-lebensmittelabfaelle-deutschland.html.
Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818. https://doi.org/10.1126/science.1185383.
Guo, X., Broeze, J., Groot, J.J., Axmann, H., Vollebregt, M., 2020. A worldwide hotspot analysis on food loss and waste, associated greenhouse gas emissions, and protein losses. Sustainability 12 (18), 7488. https://doi.org/10.3390/su12187488.
Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste – Extent, Causes and Prevention. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i2697e/i2697e.pdf.
Gustavsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. The Methodology of the FAO study: "Global Food Losses and Food Waste Extent, Causes and Prevention" - FAO, 2011 (SIK Report No. 857). The Swedish Institute for Food and Biotechnology. https://www.diva-portal.org/smash/get/diva2:944159/FULLTEXT01.pdf.
Hartikainen, H., Mogensen, L., Svanes, E., Franke, U., 2018. Food waste quantification in primary production – the Nordic countries as a case study. Waste Manag. 71, 502–511. https://doi.org/10.1016/j.wasman.2017.10.026.
Hird, V., 2014. The Meat We Eat … Or Don't Eat. The Guardian, 19. March. https://www.theguardian.com/lifeandstyle/2014/mar/19/meat-dairy-waste.
Hodges, R.J., Buzby, J.C., Bennett, B., 2011. Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. J. Agric. Sci. 149 (S1), 37–45. https://doi.org/10.1017/S0021859610000936.
Hopwood, C.J., Bleidorn, W., Schwaba, T., Chen, S., 2020. Health, environmental, and animal rights motives for vegetarian eating. PloS One 15 (4), e0230609. https://doi.org/10.1371/journal.pone.0230609.
Joy, M., 2020. Why We Love Dogs, Eat Pigs, and Wear Cows: An Introduction to Carnism, 10th Anniversary edition. Red Wheel.
Karwowska, M., Łaba, S., Szczepański, K., 2021. Food loss and waste in meat sector—why the consumption stage generates the most losses? Sustainability 13 (11), 6227. https://doi.org/10.3390/su13116227.
Kasperbauer, T.J., Sandøe, P., 2015. Killing as a welfare issue. In: Višak, T., Garner, R. (Eds.), The Ethics of Killing Animals. Oxford University Press, pp. 17–31. https://doi.org/10.1093/acprof:oso/9780199396078.003.0002.
Kuiper, M., Cui, H.D., 2021. Using food loss reduction to reach food security and environmental objectives – a search for promising leverage points. Food Policy 98, 101915. https://doi.org/10.1016/j.foodpol.2020.101915.
Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci. Total Environ. 438, 477–489. https://doi.org/10.1016/j.scitotenv.2012.08.092.
Lipinski, B., 2020. Why does animal-based food loss and waste matter? Anim. Front. 10 (4), 48–52. https://doi.org/10.1093/af/vfaa039.
Luckmann, J., 2021. A lot less than the whole hog. In: Mundy, P., Chemnitz, C., Becheva, S. (Eds.), Meat Atlas - Facts and Figures About the Animals We Eat. Heinrich Böll Stiftung & Friends of the Earth Europe, pp. 22–23. www.friendsoftheearth.eu/meatatlas-2021.
Magalhães, V.S.M., Ferreira, L.M.D.F., César, A. da s., Bonfim, R.M., Silva, C., 2020. Food loss and waste in the Brazilian beef supply chain: an empirical analysis. Int. J. Logist. Manag. 32 (1), 214–236. https://doi.org/10.1108/IJLM-01-2020-0038.
Mena, C., Terry, L.A., Williams, A., Ellram, L., 2014. Causes of waste across multi-tier supply networks: cases in the UK food sector. Int. J. Prod. Econ. 152, 144–158. https://doi.org/10.1016/j.ijpe.2014.03.012.
Nethra, P.V., Sunooj, K.V., Aaliya, B., Navaf, M., Akhila, P.P., Sudheesh, C., Mir, S.A., Shijin, A., George, J., 2023. Critical factors affecting the shelf life of packaged fresh red meat – a review. Measur. Food 10, 100086. https://doi.org/10.1016/j.meafoo.2023.100086.
Oelofse, S.H., Nahman, A., 2013. Estimating the magnitude of food waste generated in South Africa. Waste Manag. Res. J. Sustain. Circ. Econ. 31 (1), 80–86. https://doi.org/10.1177/0734242X12457117.
Oelofse, S.H., Polasi, T., Haywood, L., Musvoto, C., 2021. Increasing Reliable, Scientific Data and Information on Food Losses and Waste in South Africa [Waste Research Development and Innovation Roadmap Research Report].. Department of Science and Technology Directorate Environmental Services and Technologies & Council for Scientific and Industrial Research. www.wasteroadmap.co.za/wp-content/uploads/2021/06/17-CSIR-Final_Technical-report_Food-waste.pdf.
Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc., B 365 (1554), 3065–3081. https://doi.org/10.1098/rstb.2010.0126.
Parfitt, J., Croker, T., Brockhaus, A., 2021. Global food loss and waste in primary production: a reassessment of its scale and significance. Sustainability 13 (21), 12087. https://doi.org/10.3390/su132112087.
Perino, G., Schwickert, H., 2023. Animal welfare is a stronger determinant of public support for meat taxation than climate change mitigation in Germany. Nat. Food 4 (2), 160–169. https://doi.org/10.1038/s43016-023-00696-y.
Pinto, J., Boavida-Dias, R., Matos, H.A., Azevedo, J., 2022. Analysis of the food loss and waste valorisation of animal by-products from the retail sector. Sustainability 14 (5), 2830. https://doi.org/10.3390/su14052830.
Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Total Environ. 571, 721–729. https://doi.org/10.1016/j.scitotenv.2016.07.041.
Pradhan, P., Reusser, D.E., Kropp, J.P., 2013. Embodied greenhouse gas emissions in diets. PloS One 8 (5), e62228. https://doi.org/10.1371/journal.pone.0062228.
Ranaei, V., Pilevar, Z., Esfandiari, C., Khaneghah, A.M., Dhakal, R., Vargas-Bello-Pérez, E., Hosseini, H., 2021. Meat value chain losses in Iran. Food Sci. Anim. Resour. 41 (1), 16–33. https://doi.org/10.5851/kosfa.2020.e52.
Read, Q.D., Brown, S., Cuéllar, A.D., Finn, S.M., Gephart, J.A., Marston, L.T., Meyer, E., Weitz, K.A., Muth, M.K., 2020. Assessing the environmental impacts of halving food loss and waste along the food supply chain. Sci. Total Environ. 712, 136255 https://doi.org/10.1016/j.scitotenv.2019.136255.
Reithmayer, C., Mußhoff, O., 2019. Consumer preferences for alternatives to chick culling in Germany. Poult. Sci. 98 (10), 4539–4548. https://doi.org/10.3382/ps/pez272.
Rothgerber, H., 2020. Meat-related cognitive dissonance: a conceptual framework for understanding how meat eaters reduce negative arousal from eating animals. Appetite 146, 104511. https://doi.org/10.1016/j.appet.2019.104511.
Rothgerber, H., Rosenfeld, D.L., 2021. Meat-related cognitive dissonance: the social psychology of eating animals. Soc. Personal. Psychol. Compass 15 (5), e12592. https://doi.org/10.1111/spc3.12592.
Scherer, L., Tomasik, B., Rueda, O., Pfister, S., 2018. Framework for integrating animal welfare into life cycle sustainability assessment. Int. J. Life Cycle Assess. 23 (7), 1476–1490. https://doi.org/10.1007/s11367-017-1420-x.
Scherer, L., Behrens, P., Tukker, A., 2019. Opportunity for a dietary win-win-win in nutrition, environment, and animal welfare. One Earth 1 (3), 349–360. https://doi.org/10.1016/j.oneear.2019.10.020.

Shields, S., Orme-Evans, G., 2015. The impacts of climate change mitigation strategies on animal welfare. Animals 5 (2), 361–394. https://doi.org/10.3390/ani5020361.

Stenmarck, Å., Jensen, C., Quested, T., Moates, G., 2016. Report on Estimates of European Food Waste Levels. IVL Swedish Environmental Research Institute & EU FUSIONS. https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf.

Sun, Z., Behrens, P., Tukker, A., Bruckner, M., Scherer, L., 2022. Shared and environmentally just responsibility for global biodiversity loss. Ecol. Econ. 194, 107339 https://doi.org/10.1016/j.ecolecon.2022.107339.

Talle, M., Wirehn, L., Ellstrom, D., Hjerpe, M., Huge-Brodin, M., Jensen, P., Lindstrom, T., Neset, T.-S., Wennergren, U., Metson, G., 2019. Synergies and trade-offs for sustainable food production in Sweden: an integrated approach. Sustainability 11 (3), 601. https://doi.org/10.3390/su11030601.

United Nations Department of Economic and Social Affairs, Population Division, 2022. World Population Prospects 2022: Summary of Results (UN DESA/POP/2022/TR/NO. 3). https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf.

Vasconcellos Oliveira, R., 2020. A methodological framework for developing more just footprints: the contribution of footprints to environmental policies and justice. Sci. Eng. Ethics 26 (1), 405–429. https://doi.org/10.1007/s11948-019-00100-8.

WHO, 2022. UN Report: Global Hunger Numbers Rose to As Many As 828 Million in 2021. World Health Organization, 6. July. https://www.who.int/news/item/06-07-2022-un-report–global-hunger-numbers-rose-to-as-many-as-828-million-in-2021.

WMO, 2019. 2019 Concludes a Decade of Exceptional Global Heat and High-Impact Weather. World Meteorological Organization, 3. December. https://public.wmo.int/en/media/press-release/2019-concludes-decade-of-exceptional-global-heat-and-high-impact-weather.

Yeates, J.W., 2010. Death is a welfare issue. J. Agric. Environ. Ethics 23 (3), 229–241. https://doi.org/10.1007/s10806-009-9199-9.