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A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain

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Abstract

Research on loss & waste of food meant for human consumption (FLW) and its environmental impact typically focuses on a single or small number of commodities in a specific location and point in time. However, it is unclear how trends in global FLW and potential for climate impact have evolved. Here, by utilising the Food and Agriculture Organization's food balance sheet data, we expand upon existing literature. Firstly, we provide a differentiated (by commodity, country and supply chain stage) bottom-up approach; secondly, we conduct a 50-year longitudinal analysis of global FLW and its production-phase greenhouse gas (GHG) emissions; and thirdly, we trace food wastage and its associated emissions through the entire food supply chain. Between 1961 and 2011 the annual amount of FLW by mass grew a factor of three – from 540 Mt to 1.6 Gt; associated production-phase (GHG) emissions more than tripled (from 680 Mt to 2.2 Gt CO₂e). A 44% increase in global average per capita FLW emissions was also identified – from 225 kg CO₂e in 1961 to 323 kg CO₂e in 2011. The regional weighting within this global average changing markedly over time; in 1961 developed countries accounted for 48% of FLW and less than a quarter (24%) in 2011. The largest increases in FLW-associated GHG emissions were from developing economies, specifically China and Latin America – primarily from increasing losses in fruit and vegetables. Over the period examined, cumulatively such emissions added almost 68 Gt CO₂e to the atmospheric GHG stock; an amount the rough equivalent of two years of emissions from all anthropogenic sources at present rates. Building up from the most granular data available, this study highlights the growth in the climate burden of FLW emissions, and thus the need to improve efficiency in food supply chains to mitigate future emissions.

keywords

food waste; GHG emissions; climate change; emission factor; loss factor; supply chain

1 Introduction

Since at least the 1970s, reducing post-harvest losses of food was identified as an element integral to supporting a growing population, particularly in developing countries (Hall 1970; Bourne 1977; GAO 1977). However, the issue of food wastage – food produced for human

consumption that is ultimately not eaten – has of late become a topical issue, especially for governments who have appreciated the financial and climate change implications. For example, in the UK, the Department for Environment, Food & Rural Affairs review of waste policies applicable in England included specific mention of the priority of dealing with food waste, in addition to those related to commercial refuse and industrial waste (Defra (2011)). They estimated food waste accounted for half of landfill GHG emissions – roughly 40% of such waste was directed to landfills at the time. However, this perspective only related to the consumer stage of the food supply chain (FSC). In contrast, the European Union’s (EU) 2015 proposed directive on waste (European Commission 2015) directly recognised FLW may occur at any stage of the FSC. As drafted, this directive will require Member States to implement and monitor preventive measures to reduce waste generation, though it is not yet in force.

The subject of this paper identifying – using a whole-system approach – where FLW occurs and its associated production-phase only GHG emissions (in CO₂ equivalents – CO₂e). We aim to estimate the magnitude of GHG emissions arising from FLW across and within the whole of the global FSC from a bottom-up perspective. To do so, we focus on what we term the production-phase emissions – those emissions embedded in food due only to domestic agricultural practices. We acknowledge that additional emissions will arise through the FSC as food is stored, transported and processed, and how any final resulting waste is managed. However, as we explain in Methods, these additional FLW-related emissions occurring ‘beyond the farm-gate’ have been omitted from our analysis.

The UN’s most recent medium-variant estimate of the global human population in 2050 is 9.6bn (versus 7.2bn currently). This is an increase of 33% from 2013 estimated levels, almost all of which is projected to come from developing countries (UNDESA 2015). Concurrent economic development should be expected, with the fastest growth rates from developing countries. Despite recent variations, World Bank Group (2016) forecasts of GDP growth to 2018 for high income countries will be less than half that of developing countries (1.6 – 2.1% versus 4.3 – 5.3% per annum, with rather higher rates projected for India and China, in the region of 7 – 8% pa).

As wealth increases, there is a tendency for diets to shift away from cereals to a diet more similar to that in developed nations, often containing higher levels of fats, sugars and animal products

(Drewnowski 2000); [Pradhan 2013]. Whilst cereals provide about half of the global calorie supply, there can be large differences between developing and developed nations. For example, cereals provide up to 70% of calories in some African countries versus approximately 30% in the UK. Meat consumption in developing countries as a whole has quadrupled since 1963, and by almost a full order of magnitude in China (Kearney 2010). Such a shift may be a cause of concern from a climate change perspective. The higher level of embedded GHG emissions per tonne of meat, versus other sources of nutrition (e.g. 19.4 – 39.1 t CO₂e t⁻¹ beef versus 1.4 – 5.2 t CO₂e t⁻¹ rice; Table 1) magnify the climate change impact of food waste.

As a sector, agriculture contributes 10 – 12% of global annual GHG emissions. This is the equivalent of 5 – 5.8 Gt CO₂e y⁻¹, roughly 70% of which arise from how soils are managed and the raising of dairy and meat cattle (Smith et al 2014). The combination of feeding an additional 2.4bn people by 2050, together with a shift to more emissions-intensive diets, is likely to put further strain on the global climate via increased production-phase GHG emissions (Pradhan et al 2013; Hallström et al 2015). Given its magnitude, current estimates of FLW indicate this lost food is equivalent to that required to meet global demand in 2050 (FAO 2013a). FLW therefore represents a prime target for addressing the challenges both of climate change and of food security.

The food supply chain (FSC; see Figure 1) is a system that cuts across several sectors (i.e. agriculture, transport, industrial processes, retail, waste, land use) involving various stakeholders. The FSC is also transnational – to illustrate, the UK imports more than 50% of the food consumed domestically from many different countries (de Ruiter et al 2016). These horizontal characteristics of the food industry complicate its examination and evaluation as a system from a top-down approach – one where emissions from seemingly distinct and separate economic industries are apportioned across a horizontal system. Our approach here is bottom-up; building up the picture of food loss and waste step-by-step from the most granular level available – food commodities by country. The chosen boundary for associated GHG emissions is the farm-gate; (see Methods for further details on the rationale). We are concerned with the embedded production-phase emissions from FLW – those from agricultural production – and attribute them to specific commodities, countries and FSC stages.

<Insert Fig 1 about here>

Studies into food supply chain losses have typically focused on a particular country or local region and a small subset of commodities over very short periods of time. Two of the earliest, Wenlock & Buss (1977) and Wenlock et al (1980), examined losses at the UK household level (FSC5) and estimated wastage to be about 5% of food brought into the home. Some thirty-five years later, Quedsted et al (2013) used a similar method of household surveys with the addition of weighing food waste from refuse, and estimated UK household food wastage to be in the region of 22%. In the U.S. Kantor et al (1997) estimated wastage from the downstream part of the FSC (specifically, retailers, food service and consumers) to be about 27%, similar to the figure of 29% estimated a decade later by Buzby & Hyman (2012). However, as discussed below, only relatively recently have FSC inefficiencies been broadened beyond a commodity-country focus and framed in a climate change perspective.

Monier et al (2010) explored FLW for the EU-27 in 2006 (the 27 member states of the EU at that time) from the farm-gate onwards, including end-of-life. Specifically excluding losses on the farm during production or harvest, they concluded that households and food manufacturing had the largest proportion of total losses (42% and 39%, respectively). Their estimate of total wastage of all food in that year (i.e. including that portion not usually consumed such as fruit and vegetable peelings and animal carcasses) at the EU-27 level was 89 Mt, or 179 kg per capita. Bräutigam et al (2014), however, was unable to replicate these results. Using the approach of Gustavsson et al (2011), they estimated per capita food wastage in the EU-27 to be 60% higher (288 kg).

The first study to quantify food loss and waste at a global scale, Gustavsson et al (2011), did so for the year 2007 based upon data from the Food and Agriculture Organization of the United Nations (FAO) Food Balance Sheets (FBS). They concluded roughly one-third of food produced for human consumption (equivalent to 1.3 Gt y^{-1} globally) is lost or wasted at some point between the farm and the consumer. A follow-up technical paper applied GHG emission factors to these losses to arrive at a ‘cradle-to-grave’ estimate of roughly 3.3 Gt CO₂e – the majority of which, 63%, occurred during the agricultural production stage (FSC 1; (FAO 2013b). In contrast, Hiç et al (2016) used a more top-down approach to estimating GHG emissions associated with what they called surplus food – the difference in calories produced versus consumed. This method yielded emissions estimates 27% lower than that of FAO (2013a) for the year 2005 (410

versus 560 Mt CO₂e y⁻¹). However, they did not take into account the GHG impact of wastage further along the supply chain.

In this paper we explore where in the FSC food wastage (as defined by mass) has occurred, building up from the most granular level, and discussing the extent of this wastage and how it has changed over the past 50 years. By combining data from the literature to create GHG emission and loss factors for specific food commodities, region, and FSC stage (Table 1; and Tables SI 1 and SI 2), we then estimate the magnitude of FLW-associated production-phase GHG emissions. These estimates, and the processes used to calculate them, are another step towards a more complete understanding of the causes of FLW, the potential future scenarios of FLW, related GHG emissions and mitigation potential. In this manner, we extend across time the analysis of Gustavsson et al (2011) and deepen the food commodity detail of Hiç et al (2016). Hereafter ‘loss’ is used when referring specifically to upstream stages (FSCs 1, 2 & 3) and ‘waste’ for downstream stages (FSCs 4 & 5). The general terms of ‘food loss and waste’ (FLW) or ‘wastage’ are used when a distinction is not required.

2 Methods

The FAO’s FBS database (FAOSTAT) was the primary source of global and national food supply chain data used in this study. The detail of countries and commodities included in this paper is provided in Tables SI 3 and SI 4. We used a bottom-up, linear mass-flow model to estimate country-level food produce inputs, losses, and outputs at each FSC stage. The embedded GHG emissions of any food loss and waste were thus estimated at the most granular level possible (i.e. a country-commodity-stage trio). The FAO food data comprised 150 countries, 25 food commodities and five FSC stages, which were then aggregated separately as required. This method was similar to that used by Gustavsson et al (2011), but with three key simplifying differences. The first was a philosophical difference and the latter two driven by data availability.

The first simplification was that conversion factors – factor values that reduce FLW to only the edible proportion – were not included. As the entire food commodity must be produced for the edible parts to be consumed, any wastage of that commodity has embedded production-phase emissions that should be counted. For example, whilst only the flesh and offal of an animal are

consumed, the bones/carcass also have an impact on emissions. The emission factors used in the present analysis incorporate the embedded emissions of the inedible portion of a food commodity, though only for that portion of the consumable food lost or wasted. As such, production-phase emissions for both edible and inedible components of FLW are included, but all emissions associated with food that is ultimately consumed are not.

The second simplification was to apply the farm-gate as the boundary for life-cycle analysis (LCA) GHG emission factor estimates. A literature search for estimates of emissions and loss factors (Section 2.2) highlighted the dearth of full cycle cradle-to-grave LCA analyses. Nearly 70% were cradle-to-farm-gate; only 10% incorporated the complete cycle. Additionally, those few studies that included the downstream stages of the life cycle demonstrated that, regardless of region, the predominant source of total emissions occurred on-farm (i.e. farm-gate production-phase emissions). For example, of full-life GHG emissions Hamerschlag & Venkat (2011) estimated the production stage accounted for roughly 90% from beef and lamb, 70% from pork and 50% for poultry. Similarly, the production phase tended to be the dominant source of GHG emissions for non-meat commodities, with estimates of 60% for milled cereals (Shi et al 2011), 85% for dairy (Sheane et al 2011) and similar percentages for various types of fruit and vegetables (Cellura et al 2012). The third simplification was that all FLW from any FSC stage was absolute; no other use, recovery or management of the wastage was applied. The relevant production-phase emission factor was therefore applied to the entire estimated mass of FLW for a given commodity, region, and FSC stage. The LCA and FLW literature is not yet sufficiently granular to apply separate country-commodity emissions factors or country-commodity-stage loss factors. Thus, for data availability reasons, a further assumption of our study was that spatially large regions (such as sub-Saharan Africa) had homogenous characteristics with regards to loss and GHG emissions factors.

2.1 Mass-flow model

We considered the FSC as a closed, multi-stage, linear system. The system included only food production that was destined for human consumption. It was closed in that net food available for domestic consumption was the starting point; this net amount takes into account imports, exports and changes to government food stocks each year. At no later point did food enter the system. The input to each stage – the activity data – was the output (after losses) of the activity data of

the previous stage. A loss factor (Table SI 2) was applied to the mass of each commodity for a given country-stage pair to estimate the quantity of the commodity (e.g. amount of bone-free meat or milled wheat equivalent) not available as an input to the following stage. The emissions necessary to produce the animal carcass or wheat sheaf that is the precursor to the desired food commodity are thus captured by estimating the loss of the commodity. Against this quantity of stage-level FLW, we then applied an appropriate commodity-country emission factor to estimate the production-phase GHG emissions in CO₂e for that commodity-country-stage trio. This multi-stage process was repeated for each commodity-country-stage-year combination from 1961 to 2011. Due to lack of longitudinal data, the emissions and loss factors applied were held constant over time. This approach may under-estimate past emissions as any efficiency gains the various food systems may have experienced during this period were not captured.

Thus, for each combination:

Equation 1

$$EM_{i,j,k,t} = \sum AD_{i,j,k,t} * LF_{i,j,k} * EF_{j,k}$$

where, *EM* is emissions, in tonnes of CO₂e, *AD* is activity data in tonnes of food, *LF* is the loss factor (as a proportion of *AD*), and *EF* is the production-phase GHG emission factor in tonnes of CO₂e per tonne of food at FSC stage *i* for commodity *j* in country *k* and year *t*.

Not all agricultural produce is destined to be food for human consumption. A proportion is diverted for other uses such as feed for cattle, seed for future crops, use as bioenergy feedstock, or other non-food products such as soap. The allocation factor (*AF*) provides an estimate of this split, which was calculated from the FAO FBS data for each commodity *k* in country *j* for year *t* as follows:

Equation 2

$$AF_{j,k,t} = 1 - \left(\frac{Feed_{j,k,t} + Seed_{j,k,t} + OtherUses_{j,k,t}}{DomesticSupply_{j,k,t}} \right)$$

The corresponding *Production* and *AF* values were multiplied together to estimate the activity data for FSC 1. This is the amount of food produced in a given country in given year meant for human consumption to have a base for calculating losses and associated GHG emissions (Equation 3). For FSC 2, the activity data starting point is net food supply (i.e. after accounting for international trade and changes to government stocks) less the sum of non-human uses. From this point forward, loss-adjusted outputs from the preceding stage are the inputs for the following stage. The impact of such diverted food thereby avoids being double-counted.

Equation 3

$$AD_{1,j,k,t} = \sum Production_{j,k,t} * AF_{j,k,t}$$

where, AD_l is the activity data (mass of food) of FSC1 in tonnes, *Production* is the mass of agricultural produce in tonnes, and *AF* is the allocation factor for commodity *j* in region *k* and year *t*.

2.2 Emission and loss factors

A meta-analysis of peer-reviewed literature published between January 2000 and August 2015 on food wastage and life cycle analysis of food commodities was conducted to estimate loss factors and production-phase emission factors. Emissions factors were region-commodity specific whilst loss factors included a third element – FSC stage. The literature search of emission factors used the following keywords: life cycle assessment; food; carbon footprint. These terms were selected as they captured the central themes of this study. The databases included in both the emissions and loss factor searches were: ScienceDirect, Web of Science, Scopus, APHLIS, and AGRICOLA. From initial results of 2000+ papers for emissions, 121 were focused on one or more particular food commodities and thus selected for the purposes of this paper. Of this number, 83 (69% of total) used a cradle-to-farm gate LCA boundary; 13 (11% of total) were a full cradle-to-grave analysis. The remainder stopped their analysis at various points between the farm-gate and post-consumer waste management. In all instances in the literature where the boundary was beyond the farm-gate, there was sufficient granular detail to determine cradle-to-farm gate emissions factors and thus include them in our database. We recognise this boundary does not capture GHG emissions arising from activities taking place in later stages of

the FSC. As previously discussed, production emissions comprise the majority of FLW-associated emissions and there is very little literature on emissions from FSC 2 – 5 or end-of-life.

Search terms used for loss factors estimates were: food loss, food waste, post-harvest loss, supply chain, and food. This search produced fewer than 750 entries. Of these, 43 were relevant to the present study – i.e. they provided explicit, or calculable, loss estimates for a food commodity at some stage along the supply chain (from producer to consumer). Emission and loss factor estimates were made as granular as the literature permitted, and standardised to be comparable. Not all commodities in all countries had one or more studies undertaken to estimate their emissions factor or losses. Therefore, we grouped countries into seven regions (Europe, North America & Oceania – NAMOce, Industrialised Asia – IndusAsia, North Africa, West & Central Asia – NAWCA, Latin America – LatAm, sub-Saharan Africa – SSA, South & South-East Asia – SSEAsia; full details are provided in Table SI 3) and applied the same factors to all countries within the region. Where more than one study covered the same commodity-region, the means of the studies’ factor values were used. The exception to this was the loss factor for FSC 2 (LF_2), where the process included additional steps to incorporate annual FAO FBS *Waste* figures (Equation 4). This was consistent with the FAO (2001) description of this data item: ‘(food) lost at all stages between the level at which production is recorded and the household, i.e. losses during storage and transportation’. A summary of emission factors compiled and calculated from the literature and used in this study are provided in Table 1 (fully referenced in Table SI 1); similarly, loss factors, and their sources, are provided in Table SI 2.

Equation 4

$$LF_{2,j,k,t} = \frac{Waste_{j,k,t}}{DomesticSupply_{j,k,t}}$$

where, LF_2 is the loss factor for FSC 2, and *Waste* and *DomesticSupply* are in tonnes for commodity j in country k and year t .

< Insert Table 1 about here >

3 Results

The present study seeks to add further dimensions to existing literature on FLW as discussed in the Introduction to enable deeper understanding. In the following, we examine the longitudinal trends of FLW and its associated emissions at global, regional per capita and commodity levels.

3.1 Quantities of food loss & waste

During the 50-year period under review, our data show total global annual FLW grew a cumulative 203%, from 536 Mt in 1961 to 1626 Mt in 2011, equivalent to 2.2% per annum (Figure 2a). All seven regions exhibited increases in FLW, though with marked differences in the rate of change. This ranged from 0.4% pa for Europe and 1.5% pa for NAmOce to 3.6% pa in NAWCA – Table SI 5. Each of the other developing regions (LatAm, SSEAsia, and SSA) exhibited an annual growth rate at or near 3%. By 2011, absolute FLW in Europe had increased 20% from 1961 levels (to 221 Mt), whereas comparable figures for IndusAsia were 341% and 443 Mt. A key driver of the rise in FLW in this latter region was China, where food wastage grew 403%, from 82 Mt to 411 Mt y^{-1} (increasing its regional share of FLW from 82% to 93%). The impact of these differential growth rates was to shift the occurrence of the majority of FLW to developing countries. In 1961, developed countries (those of NAmOce, Europe, and Japan) produced 52% (or 279 Mt) of global FLW; by 2011, developing countries accounted for 75% (or 1218 Mt).

< Insert Fig 2 (a, b, c) about here >

The proportional rise in total FLW observed was greater than population growth. In each decade since 1961 global annual average per capita FLW rose; from 177 kg in 1961 to 240 kg in 2011. Every region contributed to the overall growth in per capita FLW (Figure 2b). All showed increases in their respective per capita values, though again largely split along relative wealth lines (Table SI 6). Developing countries' growth rates were typically faster than that of developed countries. Of particular note was China, which saw a 306% rise in per capita FLW, from 70 kg in 1961 to 284 kg in 2011. In contrast, in Europe it rose 5%, from 285 kg to 298 kg.

The different commodity groups exhibited varying magnitudes and patterns of FLW (Figure 2c). Together, three of seven food groups – *Fruit & Vegetables*, *Cereals*, and *Roots & Tubers* – accounted for around 80% of FLW by mass across the past five decades. This is greater than their proportion of global food production, which has been consistently around 70% (FAOSTAT). The most notable change in wastage of food commodities was in the *Fruits & Vegetables* group. Beginning the period at roughly the same proportion of annual global wastage as *Cereals* (about 30%), this group saw an acceleration beginning in the early 1990s to comprise 42% of all FLW by 2011 (Table SI 7).

3.2 Estimated GHG emissions from food loss & waste

Over the 50-year period of 1961 to 2011, global annual production-phase emissions associated with food wastage rose from 680 Mt CO₂e to 2.2 Gt CO₂e, or 2.4% per annum on average. The more rapid growth in FLW in SSEAsia and IndusAsia (Figure 3a) saw these two regions lead all others in FLW-associated GHG emissions by the mid-1990s. Combined, they produced 45% of global FLW-related emissions in 2011 versus 28% in 1961 (Table SI 8). Mirroring changes in FLW mass discussed in the previous section, the slowest growth in food wastage-related GHG emissions was exhibited by the developed regions of Europe (0.6% pa) and NAmOce (1.3% pa).

Global per capita FLW production-phase emissions rose 44% between 1961 and 2011, from 225 kg CO₂e to 324 kg CO₂e, equivalent to 0.7% per annum. Each of the seven regions in this study exhibited increases in per capita FLW emissions, though to different extents (Figure 3b; Table SI 9). Europe and NAmOce showed the lowest cumulative FLW-related emissions growth over this period, at 17% and 10%, respectively. In contrast, per capita FLW-related emissions in IndusAsia rose 240% during this 50-year period (from 83 kg CO₂e to 283 kg CO₂e y⁻¹). Despite the largest percentage rise, per capita FLW in this region remains second-smallest of the seven regions (surpassing SSEAsia in 1993). China was again the driver in IndusAsia's growth in per capita emissions, rising 306% from 70 kg CO₂e per person in 1961 to 284 kg CO₂e in 2011.

< Insert Fig 3 (a, b, c) about here >

Variation in estimated FLW production-phase GHG emissions of food commodity groups is striking due to very different emissions factors (Table 1). For example, our *EF* estimates, in tonnes of CO₂e per tonne of food produced, for bovine meat vary between 19.4 in NAWCA and 39.1 in SSEAsia, whereas the *EF* for wheat ranges from 0.36 in NAmOce to 0.62 in IndusAsia. Such differences are linked to transformation efficiency of the respective regional systems (Opio et al 2013). As a result, the three groups *Cereals*, *Fruit & Vegetables*, and *Roots & Tubers*, together consistently accounted for approximately 40% of FLW-associated global GHG emissions across the 50 years under review, rather than near 80% if emissions were proportional to FSC losses. In contrast, despite being just 3 – 4% of total FLW by mass, the *Meat* group (which includes poultry, bovine, goat, mutton, and swine) accounted for 34 – 38% of all FLW production-phase GHG emissions. The groups that experienced the largest percentage rise in emissions were *Marine* (411%) and *Oilseeds & Pulses* (385%) – Table SI 10.

3.3 U.S. & China – the two largest FLW countries

What food is lost or wasted, and how much, also varied by FSC stage. Regions consisting of developed countries consistently experienced greater total wastage of food in downstream than upstream stages – i.e. where the end-consumer is involved. With the exception of NAWCA, the reverse held for developing regions – more food was lost upstream than wasted downstream. Aggregating FLW and its associated emissions to the region level can obscure the intra- and inter-regional variability in food wastage at the country level. The proportion of FLW-associated emissions in the developed regions of NAmOce and Europe was stable across time by food type but differed in importance by stage. This stability was absent in IndusAsia due to the changing structure of food availability in China. Within these two regions, the U.S. and China dominated generation of FLW-associated emissions (in excess of 90%) and highlight some of the differences that may exist more broadly between countries classed as developed and developing (Figure 4).

Atypically for developing regions, FLW emissions in China are roughly equally spread across all FSC stages – indeed marginally more are attributed to FSC 5 (consumer) than FSC 1 (agricultural production). The country's profile for food wastage and its associated emissions are converging towards that of the U.S., particularly in the increase in emissions from meat across all FSC stages relative to cereals. Depending on the type, the *EF* of meat in IndusAsia is 5 – 30x

that of rice per unit of mass (as compared to per calorie or other unit of nutrition) – incremental increases in the wastage of the former has a disproportionate impact on FLW emissions.

< Insert Fig 4 (a, b, c) about here >

As a measure of overall emissions intensity of regional FLW, the annual mean production-phase *EF* (i.e. t CO₂e t⁻¹) changed over time. The mean *EF* in IndusAsia exhibited a steady rise and increased by the greatest proportion (53%) of all regions; though at 1.0 t CO₂e t⁻¹, food wastage of this region is the least GHG intensive. Despite having the highest per capita FLW emissions, NAmOce saw an improvement on this measure. Mean *EF* decreased 13% from 1.72 t CO₂e t⁻¹ in 1961 to 1.50 t CO₂e t⁻¹ in 2011. At the food group level, the most notable changes were the weighted average *EF* of *Meat* and *Fruit & Vegetables* which fell by 24% and 19%, respectively, declining from 15.1 to 11.4 t CO₂e t⁻¹ and from 0.94 to 0.51 t CO₂e t⁻¹. All other commodity groups exhibited increases in their mean *EF* values at the global scale.

4 Discussion

4.1 Context

At an estimated 2.2 Gt CO₂e in 2011, FLW-related production-phase GHG emissions show no indication of slowing at the global level. Production of food that is ultimately not consumed is damaging on many levels, not least of which is the potential climate change impact of the embedded emissions of this wastage. Should food production need to rise by 70% to support a population of over 9 billion in 2050 (FAO 2009) then, without efficiency improvements across all stages of the FSC, FLW-associated emissions will also increase. Hiç et al (2016) estimates that due to additional production and a global change of dietary composition towards animal products, such emissions in 2050 will 160 – 260% greater than current levels. Applying that growth rate to our estimates would result in FLW GHG emissions of 5.7 – 7.9 Gt CO₂e in 2050, roughly equivalent to all GHG emissions of the U.S. in 2011 (World Bank Data).

Much of the FLW literature to date has focused on a specific stage of the FSC, geographic region, and year of interest. The results from our study provide additional context of FLW and its associated GHG emissions. Our approach of including the full mass of FLW rather than that of only the edible parts of lost and wasted food, and assuming no waste recover or management, tends to estimate higher levels of wastage than those in the literature. In contrast, estimates of FLW-associated GHG emissions are more mixed; about 3% lower versus those of both Gustavsson et al (2011) and Monier et al (2010), yet 18% higher than Hiç et al (2016); see Table 2. Although necessary in the present study due to a sparse dataset, treating any large region as a single homogenous agglomeration of separate countries hinders the extension of large-scale, global studies to relevant local initiatives. There is a dearth of studies on food loss outside of Europe, and whilst there is a larger body of LCA studies there remains much work to be done in the area of understanding the more localised FLW-associated emissions.

< Insert Table 2 about here >

4.2 FLW not just a developed world issue

Although per capita FLW-related emissions seem to have levelled off in the developed regions of NAmOce and Europe, we have not observed this pattern in developing nations, where it continues to rise and in some cases has accelerated. As such, the relative importance of regions to GHG emissions from food wastage has changed over time. In 1961, Europe and NAmOce produced half of global FLW-related emissions whereas by 2011, these regions accounted for a quarter (Table SI 7). In line with reported national-level GHG emissions (World Bank Data), growth in total global FLW-related emissions since the early 1990s has been largely driven by developing nations. Increases in global population is projected to be predominantly in developing countries and regions, particularly Africa. Median estimates for this region estimate its population will more than double from the current 1.2 billion to 2.5 billion by 2050 and add nearly another billion by 2100, putting it on par with Asia (UNDESA 2015). Without interventions to reduce inefficiencies in the food supply chain, the trend for developing countries

to produce ever-greater proportions of global FLW and its associated GHG emissions looks likely to continue.

To gauge the potential magnitude of FLW-related emissions in 2050 at a global level, it may seem reasonable to assume food waste consequences as at a bench-mark date of 2011 – the latest available – are fixed, and model for population growth. The global average per capita value for FLW-related emissions in 2011 was 324 kg CO₂e. Multiplying this value by the median expected population in 2050 and 2100 would see emissions from FLW grow to in excess of 3.1Gt CO₂e by 2050 (32% increase) and to 3.6 Gt CO₂e by 2100 (53% increase). However, as we have shown, FLW is not a global constant – per capita values are very different between regions. Trends in related GHG emissions also vary between regions, with the developing world tending to show an increasing trend versus a pattern of stabilisation for developed countries. Economic and population growth expectations are also generally higher for developing versus developed nations – the former now account for three quarters of FLW-associated GHG emissions. Developed country populations are expected to stabilise and then decline (UNDESA 2015), further increasing the proportion of global FLW from developing nations. We note that a simple straight-line relationship of emissions based upon population change alone, as presented here, does not reflect more complex socio-economic development paths. However, whilst crude, such estimates are a good starting point. They are similar to that of Hiç et al (2016) for 2050 and reveal some potentially very large implications for global climate change mitigation.

4.3 FLW GHG emissions shifts

Gerbens-Leenes et al (2010) postulates that wealthier nations derive a larger proportion of their macronutrient intake from fats and animal sources (i.e. meat and dairy) than from carbohydrates as compared to poorer countries. Our data indicate that over the past 50 years, emissions from meat production and consumption inefficiencies have consistently been the largest contributor to FLW emissions. This pattern exists in all but two regions, SSA and SSEAsia, which are composed entirely of developing countries. Dietary protein in these two regions is predominantly plant-based (Ranganathan et al 2016), which is less emissions intensive than animal-based protein. However, rapid and significant dietary shifts can occur in a relatively short time-frame. For example, within 10 years (1977 – 1987), the aggregate diet in China shifted twice. The first shift was from a low calorie to moderate diet, and then from moderate to high calorie diet, with a

corresponding impact on energy-input intensity (Pradhan et al 2013). This shift is seen in the mean *EF* for China – rising from 0.2 to 1.0 t CO₂e t⁻¹ food between 1961 and 2011. This uplift in emissions intensity of food consumed in China seems to coincide with its rapid economic development. Increases in per capita wealth have been linked to shifts in diet to more emissions-intensive foods, and that changes to behaviour in more affluent nations can have climate change mitigation benefits (Hallström et al 2015). The finding underlines the challenge of satisfying demand for such products in a climate-friendly, sustainable manner.

As indicated in other studies (e.g. Gustavsson et al 2011; Whitehead et al 2013; Moller et al 2014), there does appear to be a link between income and food losses and emissions at particular stages in supply chain as well as the types of food commodity that suffer wastage. Higher income consumers – developed countries – tend to waste more food than lower income, developing country consumers, perhaps due to the lower cost relative to income of food in the former versus the latter. In contrast, on-farm and handling losses are proportionately greater in developing countries, possibly as a result of inferior technology and/or infrastructure.

All systems contain inefficiencies; where and why they exist will also differ from system to system. A bottom-up approach can help drive systems to greater efficiency; the advantages of such an approach versus traditional top-down directives are many. Improvements are typically driven by individuals or small groups who are directly affected; changes are often low cost, can often be rapidly implemented, and tend to generate greater buy-in (Manos 2007). However, whether bottom-up, top-down or some mixture of the two, in order to improve efficiency, we first need to understand a given FSC. Specifically, where losses have tended to occur over time in terms of country, commodity, and stage. By applying an appropriate emissions factor to these losses, it is possible to visualise and prioritise where to apply mitigation efforts.

Here we have used mass as the metric to estimate wastage of food produced but not ultimately consumed. We then converted this metric to CO₂e, after adjusting for production not intended for human consumption. Such a metric is useful to gain an understanding of the quantity of potentially avoidable additional stock of atmospheric GHGs if the food supply chain were perfectly efficient and food production could then be proportionately reduced. However, whilst measuring waste by mass may be key to understanding the climate component of FLW, the societal impact of calorific and/or nutrient loss from such wastage is equally important to

understand (Hiç et al 2016). Although no process can be 100% efficient, we have provided additional context to improve the food supply system from a climate change mitigation perspective.

5 Conclusion

In this paper, we have drawn upon existing literature to further develop a granular set of factors for food loss & waste and its associated emissions. The resulting dataset provides further clarity on the issue of food wastage and its climate burden. In so doing, it has become evident that to truly understand how efficient a food supply chain is, a more robust, complete, and differentiated approach to data collection is required; the gaps in knowledge of food commodity loss are particularly large. The Food Loss & Waste Protocol (WRI 2016) could be a meaningful step forward in such an endeavour, but will need time to gain acceptance and broad use.

Combining the loss and emissions factor dataset with FAO FBS data leads us to conclude that developing nations are now the majority source of FLW and its associated GHG emissions. These countries are expected to provide all net global population growth between today and 2050; they are already demonstrating rising per capita FLW, related emissions, and rates of economic growth. Although per capita FLW emissions of China are less than half that of the U.S. (the latter of which have been on a downward trend since the 1990s), that nation exhibited a five-fold increase in emissions intensity of its aggregate diet as it shifted towards one higher in calories and animal products. Whilst this development is cause for reflection in and of itself, it is also indicative of the potential scale of GHG emission increases elsewhere, should other lower-income nations be unable to pursue a more environmentally-friendly development pathway as they grow their populations and economies. The impact of projected economic and population growth on the FSC in sub-Saharan Africa is of particular significance in this context.

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