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Production-phase greenhouse gases embedded within food loss and waste: magnitude, drivers, and mitigation potential

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Abstract

There is considerable loss and waste of food (FLW) all along the agri-food supply chain from the producer through to the consumer. Production-phase greenhouse gas (GHG) emissions are embedded within food that is lost or wasted, increasing the overall carbon intensity of food ultimately consumed. There is limited understanding of the level of carbon inefficiency of food production as a function of loss and waste. The purpose of this thesis is to provide additional clarity on the GHG mitigation potential of addressing food loss and waste.

Here, I quantify the embedded production-phase emissions across the food supply chain from multiple perspectives, at varying geographical and temporal scales, and across food commodities. I assess the current and historical context of FLW, how that translates into embedded GHG emissions, and the impact of EU policy and structural barriers within the agri-food chain on FLW.

Whilst there is a general scarcity of robust data on FLW or emissions intensity of food production, I find the embedded emissions from avoidable milk waste are about 200 kt CO_2e yr^{-1} in the UK and about 25,000 kt CO_2e yr^{-1} globally, 5.7% and 2.4% of that from respective milk production. I find the embedded emissions of global food wastage increased more than 3-fold in 50 years through 2011 to 2.2 Gt CO_2e yr^{-1} (about 4% of net annual GHG flux of about 50 Gt CO_2e in this final year). Emissions grew more quickly than the wastage itself, implying a change in production and dietary preferences towards more emissions intensive foods. Further, per capita FLW emissions increased in developing regions whilst were stable-to-decreasing in developed regions. Deliberate withdrawal and destruction of fresh fruit and vegetables (FFV) from the food supply chain through EU Common Agriculture Policy mechanisms amounted to a cumulative 23,600 kt), with embedded emissions of 5100 kt CO_2e for the 26-year period to 2015. This is equivalent to about 2% of EU FFV production and 0.15% of emissions from managed soils in the EU). Despite changes to EU policy resulting in a 95% reduction in such withdrawals, the proportion of withdrawals typically destroyed remained consistent about 60%. This suggests the existence of institutional barriers to the use of non-retail sales channels. Finally, I find up to 4100 kt and 51,500 kt of FLW arise each year from the application of cosmetic standards to FFV within the UK and EEA, respectively. This equates to embedded emissions of up to 970 kt and 22,500 kt CO_2e yr^{-1}, about 7% and 14% of UK and EEA managed soil emissions.

This research demonstrates considerable absolute production-phase GHG emissions mitigation could be achieved by reducing food loss and waste. Such savings are predicated upon less food being produced to compensate for greater quantities available due to less wastage. Alternatively, greater throughput for the same input could be achieved from improved efficiencies within the agri-food system. Per capita FLW, emissions intensity of food, and possibly food insecurity may all be reduced; a ‘triple-win’ for sustainable production.

Lay Summary

Getting nutritious food from farm to fork is a complex undertaking. The activities required involve a great many participants, including individuals and institutions. Such participants include the farmer, packer, lorry driver, retailer, and consumer. The greater the complexity of a system the more likely it is for there to be losses within that system. The same can be said of the supply chain that ultimately provides food for the consumer – not all of the food produced by farmers is ultimately eaten by the consumer. A considerable amount of food is lost or wasted along this supply chain.

In addition to the calories and nutrients lost from wasted food, there is a cost to the climate of producing food that will never be eaten. In contrast to most other economic activity, this climate cost does not come in the form of carbon dioxide (CO_2), but instead the greenhouse gases methane and nitrous oxide. The emissions arise from producing food and are thus effectively contained within it – which I refer to as embedded production-phase emissions. These are stronger climate change gases than CO_2 and reducing them is challenging, particularly with a growing population to feed and nourish. Understanding how much food is lost or wasted along the supply chain, and why it occurs, can help provide insight into how to reduce the losses and the accompanying climate cost.

In this research, I seek to quantify these embedded production-phase emissions that are a result of supply chain inefficiencies. I do so from multiple points of view, at various scales from global to local, and for many types of food (from fruit and veg to meat and dairy). I do this not only as a snapshot in time looking at today, but also provide a historical context of food loss and waste. Additionally, I examine the influence policy and other in-built hurdles have on levels of food waste and its embedded emissions.

Using the modest amounts of good data on food waste, I find the level of embedded emissions to be considerable and concerning. The production-phase emissions needed to produce food that is lost or wasted is a meaningful part of annual global emissions. The historical view demonstrates food waste and embedded emissions show little sign of slowing down, never mind falling. The level of food losses that are avoidable, such as binning drinkable milk or tossing out ‘ugly’ food, are significant as are their embedded emissions.

There is considerable scope to reduce food waste, and thus the climate cost of food supply. There are hurdles to overcome, be they behavioural, technological, or institutional in nature. How we choose to do so is up to us – but we are capable.

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Declaration

I, Stephen Porter, declare:

a) this thesis has been composed by me;
b) this thesis is entirely my own work, except where otherwise acknowledged;
c) this work has not been submitted for any other degree or professional qualification;
d) the publications included as Chapters 2 – 5, are my own work, conceived, conducted, analysed, and written under the guidance of my co-authors as indicated in each chapter.

Signed: ________________________________

Date: 25 Jan 2019

Acknowledgements

I started this process thinking, naïvely, that there would be a grand finale. A singular truth would be uncovered, an answer; there would be a “the end”. Not quite – actually, not even close. Whilst several ‘answers’ have been provided within this thesis, many more questions have arisen as a result. The ripples in the pond of ignorance grow ever wider as we test the limits of current understanding. There remains a great deal to understand – and that’s the joy of it.

This thesis could not have come about without the (infinite) patience and positive encouragement from my three supervisors – Profs Dave Reay, Elizabeth Bomberg, and Pete Higgins. Even at their most constructively critical – which was necessarily often with me as a student! – each has the admirable, yet very rare, knack and skill to inspire in others self-confidence and desire to persevere. To each I am immensely grateful and hold them up as exemplars in whose footsteps I would be humbled to walk. I also thank my Examiners, Profs Mark Rounsevell and Rachel Norman, for providing a collegial environment for the viva voce. Their detailed review and recommendations have improved the final thesis product.

Most importantly, however, I could not have embarked upon this long and arduous journey without the immense and continual support of my wife, Claudia, and my family – to whom I am profoundly grateful to allow me to indulge myself and return to academia without truly knowing what the end result may be. How they have managed to put up with the ogre that I can sometimes be is beyond me – but appreciated beyond measure.

…the journey continues…

Chapter 1
Introduction

Food loss and waste, and its climate impact

1.1 Introduction

In the Paris Agreement of COP21, global governments agreed to limit global warming to “well below 2 °C above pre-industrial levels and pursu(e) efforts to limit the temperature increase to 1.5 °C” (UNFCCC, 2015, art. 2, para 1a). Human activity has added about 2,000 Gt of CO_2 (carbon dioxide) to the atmosphere’s global stock of CO_2 and other greenhouse gases (GHGs) relative to estimated ‘pre-Industrial’ levels, with about half emitted since 1970 (IPCC, 2014a). The extra heat trapped by these GHGs has increased global average temperatures by almost 1 °C from this baseline (NASA, n.d.). To *likely*[1] stay below 2 °C, global emissions need to reduce drastically from the current trajectory (IPCC, 2014a). The ‘emissions gap’ to do so relative to the current ‘business as usual’ (BAU) trajectory is estimated at almost 23 Gt $CO_2e\ yr^{-1}$ (CO_2 equivalents) in 2030 (den Elzen et al., 2017). Even assuming all nationally determined contributions linked to the Paris Agreement are fully achieved, there remains an ‘emissions gap’ of about 13.5 Gt $CO_2e\ yr^{-1}$ in 2030 relative to a 2 °C target (den Elzen et al., 2017). On the current trajectory of global GHG emissions in the region of 50 Gt $CO_2e\ yr^{-1}$ (World Bank, n.d.), the status quo would *likely* see global average temperatures 3 – 5 °C higher by 2100 than the pre-Industrial baseline (Collins et al., 2013).

The effects of such a BAU increase could be catastrophic due to feedback and tipping cascade, perhaps even if the Paris Agreement 2 °C goal is met (Steffen et al., 2018). Food production could experience declines in yields as early as the 2030s, with the impact increasing over time (Challinor et al., 2014). The Global South could be especially hard hit with reductions and increased variability in monsoonal precipitation (Putnam and Broecker, 2017), resulting

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[1] Where italicised in this section, ‘likely’ refers to the IPCC Assessment Report terminology, i.e. >66% chance.

in increases in food insecurity and hunger (Porter et al., 2014). Adaptations such as different crop breeds, changes to production practices, and/or policies to improve agri-food systems will be required to delay or avoid such declines (Beddington et al., 2012; Vermeulen et al., 2012a). Violent conflict may increase in areas that are largely agrarian societies that rely upon predictable precipitation for their livelihoods (Adger et al., 2014). Political and civil instability between nation states may rise should inequality of wealth distribution lead to differing capacities to fund adaptive infrastructure measures (Keohane, 2015).

To reach levels of emissions reductions necessary to avoid this worst-case scenario, GHG emission mitigation needs to occur in all economic sectors and activities, including transformative change within the agri-food system (Campbell et al., 2018). Agriculture – specifically the food supply chain – is especially important. Agriculture's share of global emissions between 1961 and 2016 has consistently been 10-12%, while absolute annual emissions have almost doubled to about 5.2 Gt CO_2e (FAOSTAT, n.d.). The United Nation's Food and Agriculture Organization (FAO) estimates absolute emissions will continue to increase; to 5.8 Gt CO_2e by 2030 and to 6.3 Gt CO_2e per annum by 2050 (FAOSTAT, n.d.). Including indirect emissions from land-use change, food production is responsible for about a quarter of global GHG emissions (Smith et al., 2014).

In the remainder of this chapter I provide a background to the food supply chain, the GHG impact of inefficiencies in that supply chain – specifically related to food loss and waste – and drivers. I conclude by introducing the aims of this thesis and core research questions.

1.2 Food supply chain & its actors

The food supply chain (FSC) is a multi-web of actors strung together in a more or less linear fashion to grow, supply, process, and distribute food meant for human consumption. A supply chain is concerned with interactions between three or more organisations to deliver a flow of goods from suppliers to end user (Mentzer et al., 2001). For convenience and ease of compartmentalisation, the FSC is divided into various stages, typically a five-stage model based upon Gustavsson et al. (2011) for the FAO. Briefly, as illustrated in Figure 1-1, these five stages are:

Figure 1-1. Simplified schematic of the food supply chain.

Production: All activities in this stage occur on-farm. Cereals, vegetables, and fruit are sown and harvested, and livestock reared for slaughter for meat as well as derivative food products such as milk and eggs.

Postharvest storage & handling: The activities that define this stage may be fully on-farm, or partially on- and off-farm. 'Handling' involves the procedures of harvesting as well as how that harvest is physically transported to the pre-packing/processing storage facility.

Processing & packaging: Included in this stage are packing activities that may take place directly on the farm or at a regional, multi-farm packing facility to process the field crop for delivery to supermarket customers. Industrial processing includes transformations of raw ingredients into final food products, such as breads, chesses, canned goods, and the dressing of animal carcasses for their meat.

Distribution: This stage incorporates the actual market environments (wholesale and retail sales channels) and the movement of food from packing facilities to these markets.

Consumption: This final stage focuses on the end consumer's purchase and use of food. It includes individual consumers as well as households, restaurants, and other hospitality and catering services.

1.3 Shifts in global demographics

In 2017, there were an estimated 7.6bn people living on the planet with median projections of 2.2bn more by 2050, and a further 1.4bn by 2100 (UNDESA, 2017). The net growth is expected to be entirely from 'less developed regions' of the Global South; half from sub-Saharan Africa in the near term and nearly all of it longer-term as Europe and Asia experience a plateauing and gradual decline in population beyond 2050 (UNDESA, 2017). Economic growth in the Global South is expected to outpace that for the relatively wealthy countries of the OECD. Seven of the 10 largest economies in 2050 could be countries currently classed as 'developing' or 'emerging'[2], with GDP more than double that of the current members of the G7[3] (PwC, 2017).

To meet the calorific and nutritional needs of this growing population, it has been estimated that about 50% more food must be produced relative to current levels (Hunter et al., 2017). Increased demand for meat and dairy products will require a doubling of crop yields for animal feed (Tilman et al., 2011). Concurrently, as wealth increases there is typically a shift in diets away from low-calorie, primarily plant-based protein to more resource intensive high-calorie diets featuring meat-based protein and greater dairy consumption (FAO, 2017; Pradhan et al., 2013). Per capita supply of meat and dairy supply in Europe is two to three times the global average and four to five times that for relatively less wealthy Africa (FAOSTAT, n.d.; see Table 1-1). These foods are typically more emissions intensive per unit than cereals, fruits, or vegetables (Gustavsson et al., 2011). Shifts in diets that increase meat and dairy intake will thus increase the climate impact of agricultural production needed to cater for these preferences.

Such shifts are related to increases in wealth, and have been observed in China, with per capita pork and beef consumption increasing four- and five-fold, respectively, since the 1970s (He et al., 2018). Resources for food

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[2] PwC has dubbed these economies the 'E7': Brazil, China, India, Indonesia, Mexico, Russia, and Turkey

[3] G7 countries: Canada, France, Germany, Italy, Japan, United Kingdom, and United States

production, such as grains and cropland, are thus serving a much less efficient process – feed conversion ratios for intensively reared meat in the U.S. averages just 7%; ranging from 3% for beef cattle to 13% for poultry (Shepon et al., 2016). Assuming intensification levels for meat production of Western Europe are achieved globally, such dietary shifts will require crop yields for animal feed that are beyond the capacity of available cropland (Röös et al., 2017a). Creating the extra cropland and/or grazing land will likely resulting in land-use change that is carbon-negative relative to current use. However, a reverse shift in the Global North – i.e. recalibrating protein intake to be more similar to that of the Global South – could see the North's GHG emissions drop by up to 90% from the combination of less emissions intensive food production and afforestation of land previously used for livestock (Röös et al., 2017b). Avoided deforestation from the Global South not following the Global North's dietary trends would reduce the upwards pressure on agriculture emissions in the South – a relative 'saving' from business-as-usual pathways.

Table 1-1. Per capita domestic food supply (in kg yr^{-1}) by region of meat, dairy, and protein. Source: FAO food balance sheet data for 2013, the latest available (FAOSTAT, n.d.).

Region	Meat	Milk	Protein from meat	Protein from plants
Europe	77	215	21	16
World	43	90	12	18
Africa	19	44	6	19
Asia	33	60	10	19

1.4 Climate change impact on food production

Global food production is more than sufficient to provide adequate nutrition for the world's current population (Wood et al., 2018). However, due to expected climate change impacts for scenarios up to an average warming of 2 °C, that capability may diminish in the near future. By 2030, 75-80% of estimates of future crop yields show a decrease from current levels; by 2050 nearly half of all projections are for declines of at least 10%, with a fifth projecting yield decreases of 25% or more (IPCC, 2014b). The impact of climate change on food production is likely to differ by region. The Global South may experience negative yield growth whilst the Global North may see some yield expansion, particularly in the more northerly latitudes, due to shifts in arable zones (Porter et al., 2014). Some regions are already demonstrating yield changes that could be linked to climate change, such as in Asia and Africa where wheat and rice yields have stagnated (Ray et al., 2012). These two developing regions may see yields for all crops decline an average of 8% by 2050 (Knox et al., 2012).

There are other potential negative impacts on yields from the effects of climate change on agriculture and food production. Changes to local climate can alter ecosystems, which can introduce new pathogens or pests against which crops may not be resistant (Gregory et al., 2009). Increases in temperature may also increase insect metabolisms and populations resulting in yield declines of up to 25% for some staple cereals through higher field and storage losses to pests (Deutsch et al., 2018). The nutritional value of crops may also be affected from increased levels in atmospheric CO_2 (Dong et al., 2018), increasing risk and prevalence of mineral deficiency, particularly in low-income areas of the world such as Africa and South Asia where food insecurity is already highest (FAO et al., 2017; Smith and Myers, 2018). A growing population needs a system that is capable of reliably providing sufficient calories and nutrients. The impacts of climate change present a real risk to food production.

1.5 Food production impact on climate change

At the same time as climate change may affect food production, there is also a reverse relationship. Food production is a factor in climate change due to the GHG emissions that arise from global agricultural activity. As a sector, agriculture is the third-largest source of global GHG emissions (Smith et al., 2014). As a whole, the agri-food system – i.e. including off-farm activities that are part of the FSC but not necessarily agriculture – is responsible for up to about 30% of global emissions (Vermeulen et al., 2012b).

Agriculture is unique amongst the ‘sectors’ covered by IPCC Assessment Reports. The vast majority (90+%) of GHG emissions from this sector are non-

CO_2 (Smith et al., 2014). Of these emissions, 65% are split equally between methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from soil management; the remainder is predominantly from 'other sources' (such as residue burning), manure, and rice cultivation (U.S. EPA, 2012). CH_4 and N_2O are the second and third-most important with respect to radiative forcing, only behind CO_2 (Myrhe et al., 2013). As the sources of these emissions are biological, they cannot be reduced to zero even under the most ambitious mitigation regime (IPCC, 2014a).

1.5.1 Nitrogen

N_2O is a long-lived greenhouse gas 265 times more potent than CO_2 (Myrhe et al., 2013). Agriculture is the most important source of emissions of this GHG, primarily from fertiliser use and land-use change (Reay et al., 2012). Where there is no penalty to the farmer for N_2O emissions from soils to the atmosphere or water courses, the short term economic incentives work in favour of applying potentially more fertiliser than necessary to ensure maximum possible yield of crops (Zhang et al., 2015). There is a public cost, however, to the use of such fertiliser if a greater amount is applied than can be taken up by crops – N_2O is released into the atmosphere and water courses from soils due to natural processes of nitrification and denitrification (Ciais et al., 2013).

1.5.2 Methane

Agriculture is the most important anthropogenic source of methane, a short-acting GHG 28 times more powerful than CO_2 (Myrhe et al., 2013). Though there is uncertainty surrounding the annual flux of methane emissions, recent estimates include approximately 130 Mt yr^{-1} of CH_4 (3.6 Gt CO_2e) from agriculture production as a whole (Reay et al., 2018) and 119 Mt yr^{-1} of CH_4 (3.3 Gt CO_2e) from livestock only (Wolf et al., 2017). The primary source of this agricultural methane is enteric fermentation from ruminant livestock such as beef and dairy cattle, though rice production is also an important source (Reay et al., 2018).

1.5.3 Emission factors

An emission factor is "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (U.S. EPA, 1995, p1). Different production methods and production impacts can result in a wide range of emission factors even for the same commodity. Grass-fed beef cattle from Brazil has an emission factor that 50% higher than similar UK sourced beef due to slower growth and thus more release of CH_4 from enteric fermentation (Webb et al., 2013). The variation in emissions factors for milk produced in grass-fed versus mixed systems is similarly wide at 2.7 vs 1.8 t CO_2e t^{-1} (Gerber et al., 2010). Fruit and vegetables emission factors will also vary, even within the same region. Tomatoes grown under polytunnels in Spain have a lower emission factor than the same crop grown in the UK under heated glass; 0.3 vs 2.1 t CO_2e t^{-1} (Webb et al., 2013). The efficiency that animal feed can be turned into edible product for humans also impacts that product's emission factor. This 'feed conversion factor' for beef cattle is less than it is for swine or poultry, which raises the former's emissions factor relative to the latter two (Shepon et al., 2016). A further element that influences the emission factor of a particular food product is the edible proportion of that product; *ceteris paribus*, the higher the proportion, the lower the emission factor per kilo of end product. The proportion of the slaughter weight of beef cattle that can be consumed as meat is about 50% versus up to 90% for fruit and vegetables (Gustavsson et al., 2013).

1.6 Production-phase emissions

The production, consumption, and waste management of food has several potential impacts on the environment. These are typically measured in life cycle analyses (LCAs) as global warming potential (GWP), acidification, and eutrophication. GWP is the emissions embedded within a product, in CO_2e, for a given LCA boundary. Each life-cycle stage along the FSC adds to the embedded emissions of the food product. Production-phase emissions arise from methods and materials used up to the farm gate for food production. They do not include emissions from management of food or its waste, interim processing, or transport from the farm gate to end consumer. When it comes to the climate cost of food, cradle-to-cradle life cycle analyses indicate the majority of embedded emissions (up to 90%, depending upon food commodity) are incurred in the pre-farm gate production phase (e.g. Cellura et al., 2012; Hamerschlag and Venkat, 2011; Sheane et al., 2011; Shi et al., 2011).

1.7 Food loss and waste

Food loss and waste (FLW) is a classic (Rittel and Webber, 1973) 'wicked problem' – it has multiple interconnecting dimensions leaving it inconsistently-defined, global in nature, and requires policy and political judgement at multiple levels for resolution. The world's population is expected to grow 25% by 2050 and over 40% by 2100, largely driven by greater life expectancy from better health and education in Africa (UNDESA, 2017). A third to a half of all food grown doesn't end up being eaten (Gustavsson et al., 2011; IMechE, 2013). Food losses at the farm level (production and storage) is greatest in developing countries (Gustavsson et al., 2011), comprising a third of global food wastage (FAO, 2013a). Yet, over 800m people remain chronically hungry, a state affecting one in five Africans, and food insecurity is on the rise (FAO et al., 2017). Food waste by consumers is most important in developed countries, where about two-thirds could be avoided (Quested and Parry, 2017). If food wastage were a country, only China and the U.S. would be larger emitters of greenhouse gases (FAO, 2013b). Food-related emissions could rise 80% by 2050, using up about half of the emissions budget to keep global warming below 2 °C (Springmann et al., 2016). Inefficiencies within the food supply chain – i.e. lost or wasted food – increase the embedded emissions of the food remaining within the chain. Food becomes more emissions intensive as the proportion of loss along the chain increases. The GHG emissions spent to deliver that quantity of food cannot be unspent and is thus accounted for in that food which remains in the system. Eliminating, or even significantly reducing, FLW could be a meaningful piece of the puzzle to tackle climate change mitigation.

At each stage of the food supply chain, additional emissions are embedded within the food product from the activities in that stage. How much is added at each stage depends upon the length of the supply chain and its complexity – there are often many actors and steps between production and consumption. How FLW is defined also matters for how it is measured, and thus how embedded emissions are measured and reported. Similarly, the boundaries that define what gets measured is not fixed and varies between studies. Depending upon the perspective and/or scope, one definition may be more appropriate than another. There are several definitions for food, food loss, and food waste in the extant literature. Here, I briefly present those of the FAO, WRAP, and FUSIONS (EU); they are discussed in more detail in Chapter 2.

The FAO definition of FLW, from Gustavsson et al. (2011), is the edible portion of food meant for human consumption that otherwise leaves the food supply chain (FSC). This includes losses that ultimately end as feed where the initial purpose of the food used as feed was for human consumption. Losses of produce originally intended for 'non-food' use – i.e. not directed to consumption by humans (such as animal feed or other industrial use), and the inedible portion of food (such as bones) is excluded.

In the UK, the WRAP definition (see Quested and Johnson, 2009) differentiates between varying levels of 'avoidability' of FLW. For example: disposal of bones as 'unavoidable' as they are not directly edible; disposal of peels is 'potentially avoidable' as they may be treated as edible by some consumers (e.g. potato peels); disposal of milk is 'avoidable' as all of the product is potentially consumable.

In a wider European context, the FUSIONS project uses the same terminology and distinctions of avoidability as WRAP (Monier et al., 2010). The key difference of FUSIONS compared to the FAO's or WRAP's approaches is the use of the European Commission (2008) definition of food, which specifically excludes non-harvested produce. Further, the destination of FLW determines whether it is treated as waste; amounts going to feed are not considered waste as it is being used for product that is intended for human consumption. By contrast, in the FAO definition, where original intent is primary and if diverted from that intent it is considered as FLW. A specific definition was subsequently proposed by the FUSIONS project that is all-encompassing: “Food waste is any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed…” (EU FUSIONS, 2014a, p. 6). This broader definition, which includes ‘pre-harvest’ activities such as ploughing-in, eliminates the ‘avoidability’ divisions and treats all food lost to or diverted from the food supply chain for human consumption as food wastage.

1.8 Drivers of FLW

The drivers of food loss and waste are many and varied. In a comprehensive review, EU FUSIONS, (2014b) identified over 100 distinct drivers of current and future food waste, grouped by context as technological, institutional, or social. Each of these categories of inefficiencies can impact multiple stages of the food supply chain. Examples of key drivers include market standards, consumer preferences, and logistics (Priefer et al., 2016). It is difficult to attribute particular amounts of FLW to specific drivers due to lack of data, particularly at the farm production stage where loss estimates between studies can vary by a factor of five (Teuber and Jensen, 2016). Quantification of FLW and its associated production phase emissions linked to these drivers (i.e. legislation and regulation, information, and behaviour) will assist in climate change mitigation efforts.

1.8.1 Institutional (Regulations, legislation, markets, standards)

Institutional drivers have multiple influences on FLW, and come in many different forms, including legislation, regulations, policies, markets, and standards (EU FUSIONS, 2014b). There are currently only two countries that have enacted legislation with an aim to reduce FLW – France and Italy (French Senate, 2015; Italian Government, 2016). However, some governments have specific and detailed classification standards for food quality (as distinct from food safety), for example the U.S. and European Union (European Commission, 2011, Annex I, pt. B; USDA AMS, 2018). Yet, where government regulation isn’t explicit, private bodies may introduce proprietary standards that suppliers must adhere to if they wish to participate in the trade (Richards et al., 2013). Such 'voluntary' standards are prevalent within the supermarket industries of developed countries, becoming *de facto* 'mandatory' (Davey and Richards, 2013). Non-compliance prevents participation within this sales channel, despite the perverse impact such standards have on creating FLW. And even if all regulations and standards are met, there may be losses of 'seasonal' produce where there isn't sufficient infrastructure or access to sales channels to manage unexpected excess production (ADEME, 2016).

1.8.2 Information / data quality

How regulatory authorities define food presents further dissonance and may have direct impacts on data and information collected and recorded by such bodies. Within the EU, the definition of what 'food' *is not* is provided in the articles that created the European Food Safety Authority (European Parliament and Council, 2002, Art. 2b, 2c). Neither plants prior to harvest nor animals prior to slaughter are considered as 'food'. Therefore, cereals grown for use in animal feed, cattle that die prior to being dispatched for slaughter, vegetables left in the field to be ploughed under, and fruit left on the tree to rot do not need to be considered as food loss for accounting or recording purposes.

The choice of definition of FLW also leads to classifying whether such actions by European/North American farmers are food losses or not. There is not a global consensus on how FLW should be accounted for (Corrado and Sala, 2018). Whilst there is not an EU 'Food Waste Directive', there is a more general 'Waste Directive' that influences FLW by legally defining waste as "any substance or object which the holder discards or intends or is required to discard" (European Parliament and Council, 2008, sec. 3). Food waste is covered as 'bio-waste' within this Directive when such waste originates in the processing, retail, and household consumer stages of the food supply chain. The implication of this bio-waste definition is that food lost before the farm-gate (i.e. pre-harvest and post-harvest storage) is excluded and not required to be reported. Additionally, produce that is not harvested (e.g. ploughed back into fields or left on trees to rot) is not considered food within the EU

(European Parliament and Council, 2002, Art. 2) and thus data is not systematically collected.

1.8.3 Behaviour and attitudes

Drivers of food waste may be interlinked, relevant to multiple sets of actors or particular FSC stages, and their interactions exacerbate FLW (Devin and Richards, 2016). Market and private ‘food quality’ standards may lead to decisions by a farmer to over-produce; they grow more than necessary to meet supply obligations of products of a particular classification (Raak et al., 2017). Also, when provided a choice, consumers will rarely (<10%) select fruit that have visual cues that may suggest internal damage (Jaeger et al., 2018). Altering this preference, for instance by using price and labelling as a distinguisher, can improve the tendency to choose sub-optimal fruit and thereby reduce FLW (de Hooge et al., 2017; Helmert et al., 2017). Consumption and production of meat also rises as a function of rising wealth, increasing the emissions-intensity of our collective diet (Tilman and Clark, 2014). Meat, especially beef from open-grazing ruminants, is an emissions-intensive food commodity (FAO, 2013a). Shifting culturally-embedded attitudes and behaviours is challenging yet can be a powerful lever to bring about a downward shift in emissions (Stoll-Kleemann and Schmidt, 2017). Addressing such interlinked drivers can have positive impacts along the entire FSC network.

1.9 Purpose of the research and research questions

The issue of food loss and waste has become a topical one within the popular media as well as the academic literature. Schanes et al. (2018) highlights a rapid rise in the number of peer-reviewed studies since 2010 that examine why food waste occurs in households. It is a complex problem, incorporating many actors with differing levels of agency. The particular emphasis on production-phase GHG emissions of this thesis adds to that literature. Throughout this thesis, the unit of interest from a climate mitigation perspective is referred to as embedded production-phase GHG emissions. Emission factors used to convert food wastage to CO_2 equivalents are to the farm gate only. Despite the

LCA literature typically including the initial ‘upstream’ stages of farm production and its precursors (i.e. fertilizer manufacture and use; land-use change), there is relatively less research on food losses at this pre-farm gate stage. Focusing on production-phase emissions – those embedded in the food commodity from production activities in the earliest stages of the FSC – therefore differentiates the work presented within this thesis to add original contributions to existing knowledge.

The purpose of this research is to shed additional light on the scale and scope of food losses and their embedded emissions in the earlier stages of the food supply chain. I do so by posing four separate but interlinked questions. These questions are focused on obtaining a better understanding of: the quantity of food loss and waste-related embedded production-phase emissions; some of the drivers of this climate cost; and, potential pathways to achieve a more sustainable future with respect to the food system. What my research – at the intersection of food and climate change – will demonstrate, is the following:

- Aim of Chapter 2: to provide context of the challenges when assessing levels of food loss and waste and provide a single product quantitative estimate of embedded emissions.
    - Primary research question: what food supply chain inefficiencies exist, and what level of emissions are attributable to milk wastage at the global, U.S. and UK levels?
- Aim of Chapter 3: to estimate the historical trends of FLW at global and regional levels, and its associated production-phase emissions over time.
    - Primary research question: how has food loss and waste, and its embedded emissions, evolved over the past 50 years at global and regional scales?
- Aim of Chapter 4: to understand and quantify the impact policy may have on loss and waste of edible food, and its embedded climate cost.

    - Primary research questions: how much edible food has been destroyed, and what is the associated embedded production-phase emissions of that destruction; how much of that is a result of the implementation of the withdrawal mechanism of the EU Common Agriculture Policy?
- Aim of Chapter 5: to assess how structural elements of the food supply chain may combine to result in FLW and quantify the embedded emissions of that wastage.
    - Primary research question: how much food is wasted in the UK and Europe due to cosmetic food quality standards, and what are the associated production-phase emissions?

Within the research I use varying boundaries as appropriate to estimate FLW[4]. Specifically: for the case study on milk wastage in Chapter 2, I presume all waste in this commodity is avoidable. Chapter 3, which presents 50-year trends of food wastage and its embedded emissions, includes all food commodities globally but only that portion originally intended for human production. Food diverted to non-food use once it leaves the farm is deemed a loss. Chapter 4 takes a stricter view of fruit and vegetable losses in the EU to estimate embedded emissions by excluding from 'food loss' that amount which is not destroyed but instead diverted to another non-food use (e.g. such as animal feed or industrial alcohol production). Finally, Chapter 5 examines cosmetic prejudices of food, focusing on farm-level avoidable losses of fruit and vegetables in the UK and EEA, defined as food diverted from its original purpose.

Chapters 2 – 5 separately address these distinct, yet linked primary research questions. Each of these four chapters has been published in a peer-reviewed journal.[5] They begin with the global perspective, then move to the EU, and finish with UK and regional Scottish viewpoints. The methods used in these various chapters are a mix of quantitative and qualitative approaches;

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[4] Scope, boundaries, and definitions are detailed in each of Chapters 2 – 5 separately.

[5] Article details are included in the footnotes on the first page of Chapters 2 – 5.

the former to estimate the production-phase emissions embedded in food wastage, and the latter to explore why this wastage occurs when and where it does. These 'Results' chapters are presented in the order they were written and first published. Though they may be read in any order, the paper that comprises a chapter may refer to one or more of the others that precede it. I end with a final discussion in Chapter 6 to synthesise and place this thesis in current and future contexts.

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Chapter 2
Food Supply Chain Inefficiencies

Addressing Food Supply Chain and Consumption Inefficiencies: Potential for Climate Change Mitigation[†]

Stephen D Porter[*1], David S Reay[1]

ABSTRACT

Globally, more than 30% of all food that is produced is ultimately lost and/or wasted through inefficiencies in the food supply chain. In the developed world this wastage is centred on the last stage in the supply chain, the end-consumer throwing away food that is purchased but not eaten. In contrast, in the developing world the bulk of lost food occurs in the early stages of the supply chain (production, harvesting and distribution). Excess food consumption is a similarly inefficient use of global agricultural production; with almost 1 billion people now classed as obese, 842 million people are suffering from chronic hunger. Given the magnitude of greenhouse gas emissions from the agricultural sector, strategies that reduce food loss and wastage, or address excess caloric consumption, have great potential as effective tools in global climate change mitigation. Here we examine the challenges of robust quantification of food wastage and consumption inefficiencies, and their associated greenhouse gas emissions, along the supply chain. We find that the quality and quantity of data is highly variable within and between geographical regions, with the greatest range tending to be associated with developing nations. Estimation of production-phase GHG emissions for food wastage and excess consumption is found to be similarly challenging on a global scale, with use of IPCC default (Tier 1) emission factors for food production being required in many regions. Where robust food waste data and production-phase emission factors do exist – such as for the UK - we find that avoiding consumer-phase food waste can deliver significant up-stream reductions in GHG emissions from the agricultural sector. Eliminating consumer milk waste in the UK alone could mitigate up to 200 kt CO_2e yr^{-1}; scaled up globally, we estimate mitigation potential of over 25,000 kt CO_2e yr^{-1}.

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2.1 Introduction

Agriculture in its various guises occupies 40-50% of the planet's land mass and accounts for 10-12% of total anthropogenic greenhouse gas (GHG) emissions – 50% of global methane (CH_4) and 60% of global nitrous oxide (N_2O) emissions – with absolute per annum growth of 0.9% between 1990 and 2010. The net CO_2 flux for agriculture (excluding the impacts of forestry or other land use) is very nearly balanced (Smith et al., 2014). Thus, virtually all of emissions attributed to agriculture are the result of food production to feed an ever-growing world population; a population estimated to increase by over 50% to 10.8 billion by 2100, almost all of which will occur within developing countries (UNDESA, 2013). A third to one half of all food produced does not flow through the entire food supply chain (FSC; Grolleaud, 2002). The consumption of excess quantities of food – the proportion beyond the dietary needs of a populace – is also an inefficient use of resources (Cuéllar and Webber, 2010; Hall et al., 2009). The more food that is ultimately lost, wasted or consumed in excess of physical needs increases the overall carbon footprint of the FSC beyond the level necessary to sustain our continued (and growing) collective existence. The IPCC Working Group II identified climate change impacts on production as a key risk to global food security (IPCC, 2014). The embedded emissions from food wastage contribute directly to climate forcing. It follows, therefore, that the status quo of inefficient use of resources for food production and supply is incompatible with successfully addressing global climate change. In this paper we identify and explore the key challenges to assessing the climate change mitigation potential of addressing food wastage across the FSC, and provide a case study on a specific commodity – milk – to illustrate that potential.

2.2 Challenges to quantification of food wastage implications

2.2.1 Differentiating 'food loss' and 'food waste'

There are no universally accepted definitions of the popular terms 'food loss' and 'food waste', although ultimately the end result is the same – non-utilisation of food produced for human consumption. Various participants in the discussion have presented their respective nomenclature and definitions.

The Food and Agriculture Organisation of the United Nations (FAO) distinguishes between loss and waste based upon where along the FSC the quantity of food available suffers a decrease (Gustavsson et al., 2011). ‘Loss’ occurs in the ‘upstream’ production-dominant stages of the FSC; ‘waste’ occurs in the consumer-dominant ‘downstream’ stages. The FAO definitions thereby implicitly link the former (food loss) to operational efficiency and the latter (food waste) to consumer behaviour.

Bourne (1977) and Prusky (2011) use ‘post-harvest losses’ when referring to what is similar conceptually to the FAO’s ‘food loss’ term – i.e. losses at any stage along the FSC prior to the final retail and consumption stages. However, the inclusion of pre-harvest losses at the primary producer stage in the latter’s definition causes a practical disconnect with the terminology. In contrast, Parfitt et al. (2010) does not make any distinctions at all, terming losses at any stage along the FSC as ‘food waste’, and Smil (2000) opts for ‘food loss and waste’ when discussing the FSC as a whole (Figure 2-1). Due to this variability, we present in ‘Waste disambiguation’ our specific nomenclature for loss and waste along the FSC.

Finally, a third category of food supply inefficiency is specifically presented here – that of ‘excess caloric intake’, or more simply, overeating. This is conceptually different to the terms food loss and food waste as described previously – food is consumed rather than lost to spoilage and/or other production inefficiencies along the FSC or thrown away by the end consumer. However, excess caloric intake could still be considered as a waste of globally available food calories (Hall et al., 2009; Lundqvist et al., 2008). Quantities of food are produced that are unnecessary – wasting the embodied energy of that food and creating additional embedded emissions that have avoidable GHG penalties (Michaelowa and Dransfeld, 2008).

2.2.2 ‘Waste’ disambiguation

‘Waste’ is not only an environmental issue, but also an economic and legal issue. What is unwanted production that is rejected by one party may be viewed as an economically valuable resource by another. ‘Waste’ has specific legal definitions and is subject to regulations in many jurisdictions. The use of the term ‘food waste’ as a catch-all for inefficiencies at any stage of the FSC that lead to less food being available for human consumption, in addition to food that is thrown away by the consumer, may not be entirely compatible with such a use.

Due the variation in the literature, for clarity in this paper, the following lexicon is used for the purposes of this paper. The FAO concepts of ‘food loss’ and ‘food waste’ are used, though rephrased as ‘lost food’ or ‘wasted food’ to avoid confusion with the legal concept of ‘waste’. The term ‘post-harvest loss(es)’ is used when referring to inefficiencies between the farm-gate and the retail stages. ‘Food wastage’ is used where a general term irrespective of FSC stage is required and also to refer to inefficiencies along the entire FSC (ie. an amalgamation of ‘lost food’ and ‘wasted food’). ‘Excess caloric intake’ will refer to the GHG impact of excessive food consumption (ie. overeating), which we also consider as inefficient use of resources.

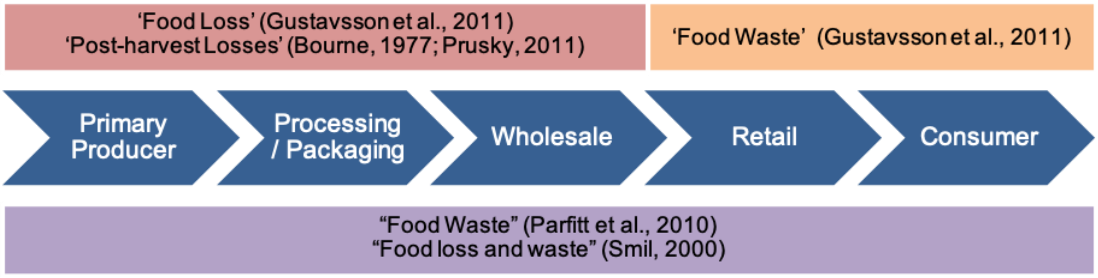

Figure 2-1. A representation of the typical stages in the food supply chain (FSC), minus the raw materials inputs used by primary producers, delineating the terminology used by different authors in the literature.

2.2.3 How food is lost along the supply chain

There is not one global supply chain – rather it is a spider’s web of networks, actors and technologies that are specific to each location, yet evermore interlinked through globalisation. As illustrated in Figure 2-1, the supply chain can be characterised with globally relevant stages, although the importance of each stage and the length of the chain itself is location dependent. From producer to consumer, there are a multitude of opportunities for inefficiencies – ie. for food to be lost and/or wasted – along the FSC. The stage where these inefficiencies occur varies depending upon commodity and region, although overall most is lost or wasted at the extremes of the supply chain (FAO, 2013).

Bourne (1977) set the stage for investigating the causes of food wastage, grouping them into two categories, primary and secondary. Primary causes include losses through pest infestations, mechanical damage to harvested crops, and spoilage, amongst others. The link between primary causes is that they are transient – some partially controllable in the near-term (such as mechanical damage) whilst others are less so (such as losses from weather events). Secondary causes are those that form the conditions for primary causes to occur. They generally stem from structural inadequacies of context surrounding the supply chain that would require greater investments of time and resources to address. These causes include legislation, proper storage/transport, lack of a 'cold chain'. Bourne (1977) considered the FSC only as far as the end-consumer, but did not include that final stage. As we shall see, wastage in the consumer phase can be important source of food wastage and thus greenhouse gas emissions.

2.2.4 Variability in emissions factors of food loss and waste

Comparability across studies in the literature is not always straightforward. The implied average values for the U.S. calculated from Hall et al. (2009) and Cuéllar and Webber (2010) are 1.6 and 5.4 t CO_2e t^{-1} wasted food, respectively. Explicit factor values in Europe range from 1.9 for the EU 27 (Monier et al., 2010) to 3.9 in the UK specifically (Quested and Parry, 2011). At a global scale, the FAO has estimated a factor of 2.5 t CO_2e t^{-1} avoidable food waste (Gustavsson et al., 2011). Differences in scope and methodologies result in emissions factors varying widely, even for the same geographic region.

As the literature in this area is still emerging, correcting for these differences to arrive at more directly comparable values is challenging. The emissions factor from Hall et al. (2009) does not include processing or transport, which Cuéllar and Webber (2010) estimates to account for 35% of all energy used in production of food that is domestically consumed. Whilst the latter includes energy used for the inputs of primary production inputs, the non-CO_2 emissions from agriculture, such as that from excessive fertiliser use, and end-of-cycle waste management are not. Quested and Parry (2011) does not consider waste arising from non-households, such as catering and restaurants. In contrast, Katajajuuri et al. (2014) estimates that 20% of food waste in Finland arises from the food-service sector.

2.2.5 Lost and wasted food data issues

Bottom-up research into food wastage has largely been limited to a single or small number of commodities in a specified region at a particular stage in the FSC (e.g. Clarke (1989) – barley harvest losses in Western Canada; Liang (1993) – post-harvest grain losses in China: Babu et al. (2013) – storage losses of spice in one Indian state). Some are in excess of 20 years old and continue to influence more recent studies that have a broader scope (national, continental or global).

The first global estimate of food wastage and the embedded GHG emissions (Gustavsson et al., 2011) relied upon single-commodity, location specific life-cycle analysis (LCA) studies. Depending upon the commodity, there could be very few studies used (e.g. two for both starchy roots and milk) whilst others, such as meat, were almost exclusively from high income, OECD nations. The large variability in practice and technologies available across locations and commodities result in a GHG emission estimate range that spans over 200%; a central estimate of 3.3 Gt CO_2e, +/- 1.7 Gt CO_2e (FAO, 2013).

There are similar challenges at a national level. Buzby and Hyman (2012) estimates the economic cost of wasted food in the U.S. is based upon the United States Department of Agriculture (USDA) Loss-Adjusted Food Availability (LAFA) data series. The LAFA series contains detail on some 200 different food commodities starting from 1970, with estimates for losses at various stages of the FSC for each commodity. A review of the loss estimates since inception of the series resulted in little aggregate change for total lost food at the supermarket level (Buzby et al., 2009). Overall loss factors have thus been backward adjusted to inception based upon these reviews and therefore appear static through time. There is not a consensus on the implication of

USDA's practice - it could put a lower bound on post-harvest loss estimates (Cuéllar and Webber, 2010) or inflate them (Koester, 2013).

Potential data issues are not constrained to the age of some estimates – the use of FAO food balance sheet data to derive post-harvest loss estimates has also been criticised. Questions arise on viability of estimates for crops sown, harvested and sold in areas of the world subject to unrest where physical access to these areas can be severely restricted, if there is any access at all (Parfitt et al., 2010; Smil, 2000). Elsewhere, differences in production methods across farms, countries and regions could have a material impact on embedded emissions of a given commodity, thereby diminishing the value of using a particular emissions factor estimate across time or region. In their carbon foot-printing methodology, Chapagain and James (2011) have recognised this limitation in their use of single, global life-cycle analysis (LCA) emissions factors for individual commodities.

2.3 Food supply chain inefficiencies

2.3.1 Embedded emissions of inefficiency

In the U.S., greater availability of cheaper food is a factor in the increasing average weight of the American populace, as well as a rise in wasted food (Hall et al., 2009). Over the 30-year period 1974-2003, it was estimated that per capita wasted food steadily increased from about 30% available food to nearly 40%, compared to the USDA's roughly constant annual assumption of about 27%. The GHG emissions associated with producing an estimated 150 trillion kcal of wasted food energy is 129 Mt CO_2, implying a CO_2e emission factor of 1.6 t CO_2e t^{-1} wasted food.

On a global scale, the FAO estimates embedded GHG emissions of 3.3 Gt CO_2e by applying a factor of 2.5 t CO_2e t^{-1} to estimated post-harvest and consumer losses of 1.3 Gt (Gustavsson et al., 2011). The range of CO_2e emission factor estimates from the limited amount of literature currently available suggests annual GHG emissions from food wastage could range from 2.1 Gt CO_2e to 5.9 Gt CO_2e globally (see Table 2-1). GHG emissions arising from the provision of excess caloric intake in OECD countries would raise these levels a further 230 – 652 Mt CO_2e each year (see section 2.3.2). Adding these embedded emissions to the upper value of food wastage results in potentially 6.6 Gt CO_2e yr^{-1}; this value is close to that of U.S. 2011 nation-wide GHG emissions (excluding land-use, land-use change and forestry) of 6.7 Gt CO_2e (UNFCCC, n.d.). Population growth forecasts and dietary change in the developing world could ultimately lead to wasted food levels and associated GHG emissions that dwarf these current estimates.

Table 2-1. GHG emissions factors per tonne of food wastage. The current literature in this area is sparse, tending to be focused on single nations or regions. Factors may not be directly comparable due to differences in scope of study and robustness of inputs used (the former are generally acknowledged limitations). The "EU 27" does not include the current Member State of Croatia – it had not yet acceded to the European Union at time of source publication.

Region	Factor ($t\ CO_2e\ t^{-1}$)	Unit (t^{-1})	Source
EU 27	1.9	Food waste	Monier et al. (2010)
EU 27	2.0	Avoidable food waste	Monier et al. (2010)
UK	3.9	Avoidable food waste	Quested and Parry (2011)
USA	1.6	Food waste (excl processing and transport	Hall et al. (2009)
USA	5.4	Food waste	Cuéllar and Webber (2010)
Finland	2.5	Avoidable food waste (all sectors)	Katajajuuri et al. (2014)
Global	2.5	Avoidable food waste	Gustavsson et al. (2011)

2.3.2 Impact of excess caloric intake

The mean adult body mass of the U.S. population increased by 16.7% between 1962 and 2010, from 70.3 kg to 82.1 kg – roughly 0.2 kg per decade. The corresponding mean Body Mass Index (BMI) rose from 25.4 to 28.7 whilst the proportion of the population classed as overweight (BMI > 25) rose from 47% to 65%; obesity levels (BMI > 30) more than doubled from 14% to 31% (NHANES, 2014). There is a positive relationship between greater levels of food energy supply and mean body mass; for each 7.1% of increased body mass a net extra energy input of 10% is needed (Swinburn et al., 2009b). A consistent and continual gap of 30 kJ (7.2 kcal) per day between energy intake and expenditure is all that is required to produce this observed level of weight gain (Hall et al., 2011). Thus, to raise the mean per capita adult mass by an additional 11.8 kg (a 16.7% increase) between 1962 and 2010 (NHANES,

2014) would require a cumulative increase of 23.5% in net food energy intake, or about 0.5% per annum, over the 1962 base value.

Greater body mass requires increased energy intake to balance higher baseline energy expenditure. The GHG penalty of the food production to provide this excess caloric intake is permanent unless a negative perturbation is imposed. To return to the mean body mass of the mid-1970s (just on the border of a "healthy" body mass index level) from those of the early 2000s would require a sustained daily reduction in consumption of 500 kcal, the difference in adult energy intake between 1970s and 2000s (2398 kcal d^{-1} vs 2895 kcal d^{-1}), a sustained increase of nearly two hours in daily physical activity, or some mixture of the two (Swinburn et al., 2009a). There is a basic assumption that this calorie reduction could occur within an otherwise balanced diet; a diet that meets the body's physiological needs of vitamins and minerals. By 2010 this daily difference is estimated to have increased to 600 kcal (USDA, 2010), equivalent to 20% of the implied mean energy intake of about 3000 kcal d^{-1}.

This 600 kcal of excess caloric intake in the U.S. is equivalent to 69 Mt of food that need not be produced; 20% of 347 Mt utilised domestically in 2010 by U.S. consumers (FAOSTAT, n.d.). Applying the FAO's wasted food CO_2e emission factor of 2.5 t CO_2e t^{-1} of wasted food (Gustavsson et al., 2011), we estimate annual embedded emissions from U.S. over-eating are 173 Mt CO_2e. Assuming the U.S. level of excess caloric intake is consistent across the OECD countries, this 600 kcal step-change in food intake is equivalent to avoidance of 227 Mt of excess food produced and consumed per annum (FAOSTAT, n.d.); 20% of 1137 Mt. Applying the same FAO wasted food CO_2e emission factor as for the U.S. the annual GHG emissions savings from this reduced food demand would amount to 568 Mt CO_2e. Added to the 30-50% of food the FAO estimates is lost or wasted along the FSC, then the actual embedded emissions of all inefficiencies could be the equivalent to as much as 70% of global food production.

These estimates assume that this “extra” food need not be produced and thereby save the embedded GHG emissions. One could also argue that rising mean weight is a manifestation of an inefficient use of scarce resources; that the “extra” food consumed by developed countries could be made available where it is needed most - those parts of the world where hunger remains. While if this reallocation were undertaken a large reduction in production-phase GHG emissions food production might not be achieved, large reductions in the numbers of people suffering chronic hunger could be still be had.

2.3.3 Population growth and food supply

Increased per hectare agricultural yields since the 1960’s have offset much of what would have been required in terms of land being utilised by the sector (up to three-quarters per Smith et al. (2013)) while at the same time reducing cumulative emissions relative to business-as-usual (BAU) by some 590 Gt CO_2e (Burney et al., 2010). However, current projections of population through to 2050 are in the region of 9.6 billion (and 10.8 billion by 2100; UNDESA, 2013) - requiring 70% to 100% more food production (Godfray et al., 2010).

Most of this population growth is expected to come from the Less Developed Regions (as defined by the UN), as populations in China and the “West” plateau. While 60% of the global population currently resides in Asia, this proportion is expected to fall to about 43% by 2100. The population of Africa is expected to increase by over 300% in the same time period (and by over 130% by 2050), driven by rapid growth in Western Africa in particular (UNDESA, 2013). China and India alone account for about 37% of today’s global population and have economies that have been amongst the fastest growing in the past two decades to 2012 - they currently rank as 2nd and 10th-largest, respectively (World Bank, 2014). Average diets in developing world nations, as they become wealthier, can be expected to incorporate greater proportions of GHG emission-intensive meat and dairy products (Poleman and Thomas, 1995). This is particularly notable with respect to Africa, where the proportion of energy intake from animal protein is only a quarter of that of the OECD (Gerbens-Leenes et al., 2010).

In China, by 2004, about one-quarter of the adult population was overweight, up from 9.7% in 1982 and 14.9% in 1992 (Guo et al., 2000) – growing at a slightly faster rate than the U.S. or UK (Popkin, 2008). On this trajectory, about 40% of the population of China could be classed as overweight by 2050, roughly where the U.S. was in 1960 (NHANES, 2014). Chinese population and food production is similar to that of the OECD as a whole. The rise in excess caloric intake required for overweight and obesity rates comparable in magnitude to that of the OECD could thus induce additional food-based GHG emissions in the region of 500 Mt CO_2e.

The U.S. 'obesity epidemic' has developed over 50 years to a significant health problem, one that also has climate implications. In the next 85 years to 2100, World Bank (2014) estimates 8.8 billion people will reside in what today are 'developing' nations of Asia and Africa. This would be 82% of the global population, with 1 billion of them in China (300 million fewer than current). It is conceivable that, as their wealth grows, these 'developing' nations follow a dietary pathway similar to that of the OECD – a trajectory China appears to be on. Should that occur, embedded emissions of the excess caloric intake of these nations could be some six-times greater than previously presented estimates for the OECD, over 3 Gt CO_2e yr^{-1} (some 6% of latest available World Bank (n.d.) global total GHG emissions for 2012).

2.3.4 Developed countries vs emerging countries

The absolute and per capita amount of food wastage, on a mass-flow basis, across the whole of the FSC differs across global regions. The embedded emissions of that wastage also vary considerably between regions; a function of different crops, production methods, infrastructure and culture. The sheer magnitude of population in Asia – 4.2 billion persons at 2010 estimates (UNDESA, 2013) is a key factor in their accounting for 50% of all global food wastage with 55% of embedded emissions from that global wastage. However, Asia itself is not homogenous; non-industrialised South & Southeast Asia exhibit the lowest per capita levels of food wastage across the entire FSC at roughly 160 kg yr^{-1}. On a per capita basis North America & Oceania and Europe were the most wasteful regions, with per capita food wastage of roughly 340 kg yr^{-1} (FAO, 2013).

The particular stages or phases where along the FSC food wastage occurs can also vary between regions. On a per capita annual basis, lost food in the 'upstream' portion of the FSC (agricultural production, post-harvest handling & storage and distribution) is roughly similar across regions – about 150 kg yr^{-1}; South & South East Asia, at about 100 kg yr^{-1}, is an exception (FAO, 2013). Why there should be such 'upstream' similarities in per capita wastage across regions that have different characteristics is unexpected and an area for future research. In contrast, consistent with Quested et al. (2013) and Monier et al. (2010), which identify greater levels of wasted food at consumer-focused phases, there is larger variation in wasted food in the 'downstream' stages of the chain (distribution and consumption), a pattern that tends to follow relative national income levels. The most profligate region on per capita basis is high-income North America & Oceania at about 200 kg yr^{-1}; the least wasteful, at approximately 60 kg yr^{-1}, is low-income South & South East Asia (FAO, 2013).

However, even within a high-income region such as the European Union, different countries exhibit very different levels of per capita wasted food by households (see Table 2-2). Combining national-level wasted food estimates identified by Monier et al. (2010) with 2006 population estimates (UNDESA, 2013) generates an average level of food wasted in the home by EU consumers of 87 kg yr^{-1}; from a high of 137 kg yr^{-1} in the UK to a low of 17 kg yr^{-1} in Finland. Grossed up to all of Europe, consumers are wasting about 65 Mt of food (38% of all post-farm wastage), with embedded emissions of 123 – 356 Mt CO_2e.

Losses in the primary production phase in Europe – and possibly by extension to other high-income regions – are important. Monier et al. (2010) estimates post-harvest and consumer per capita wastage in the then EU 27 of 179 kg yr^{-1}, 43% (76 kg yr^{-1}) of which is wasted food by households. This estimate explicitly excludes farm-level wastage; thereby suggesting nearly half of all wastage occurs before the farm-gate when compared to the full-supply chain per capita estimate of 340 kg yr^{-1} (FAO, 2013). However, as is shown in our case study on milk (section 2.5), the financial cost of such per capita profligacy by developed nations can be low on a commodity-by-commodity basis – as such households may not be motivated by seemingly small financial savings they could make by reducing wasted food.

Table 2-2. Per capita wasted food estimates for EU countries for which nation-level studies of household waste exist (Monier et al., 2010). Population estimates for all countries are for 2006 from the UN Population Division (UNDESA, 2013).

EU Member State	Wasted food by households (t)	Population (000s)	Per capita wasted food (kg yr^{-1})
Austria	784,570	8277	95
Demark	494,914	5441	91
Estonia	82,236	1319	62
Finland	90,000	5268	17
France	6,322,944	61,845	102
Ireland	292,326	4226	69
Netherlands	1,837,599	16,376	112
Sweden	905,000	9090	100
UK	8,300,000	60,621	137
Average			87
95% Confidence interval (upper)			110
95% Confidence interval (lower)			64

2.3.5 Food commodities and wastage pattern shifts

Not all food commodities suffer the same loss/waste levels (e.g. Canadian grains, as low as 2%, (Clarke, 1989); Southeast Asia vegetables, an average of 17% (Weinberger et al., 2008); fish in developing world, 10-60% depending on season and species (Wall et al., 2001)). Globally, cereals, starchy roots, fruits and vegetables account for nearly 85% of all post-harvest losses of food destined to human consumption (FAO, 2013). Relative proportions by commodity-region are variable: nearly 40% of post-harvest loss in Industrialised Asia arises from vegetables and about 27% from cereals; in Sub-Saharan Africa over 60% is from starchy roots; in North America & Oceania milk accounts for some 15% of post-harvest losses, but almost none in Industrialised Asia (FAO, 2013). Local and regional dietary preference may be playing a significant role is these differences. However, as discussed previously, diets in the developing world are expected to shift to a more 'Western' composition.

This shift could see a concomitant change in food wastage patterns and heightened risks in other areas. As Khoury et al. (2014) points out, the post-World War II increase in food production and crop yields has occurred simultaneously with a decrease in varieties cropped. Attendant risks to food supply are raised as risk of large-scale pre-harvest crop loss from disease/pest vulnerability increases as genetic variety decreases (Zhu et al., 2000). Risk to overall health also increases with a move to a 'Western' diet, for example via an increase in obesity rates as seen in China as the population has become wealthier (Wang et al., 2007).

Such a change in diet would put further stresses on global climate forcing as not all FSC inefficiency is equal in terms of its net GHG impact. The emissions intensities of various commodities varies by 17-times from the lowest to the highest. Starchy roots account for 19% of global food wastage, yet account for just 5% of emissions (a relative emissions intensity factor of 0.3). In contrast, little meat is lost or wasted – just 4% globally. However, the high emissions intensity of the product results in meat accounting for 21% of emissions from food wastage; a relative factor of 5.2 (FAO, 2013). Identifying the food-region pairs and food-region-stage trios with the greatest levels of inefficiencies may help better target mitigation action. Cost-benefit analyses would be useful tools to develop achievable mitigation strategies.

2.4 Potential Interventions and Barriers

2.4.1 Cold chain

The 'cold chain' – the refrigeration of highly perishable food commodities (such as fruit, vegetables, meat and fish) – is an important component in an efficient FSC as an ever greater proportion of food is exported (Magnussen et al., 2008). Not only is it a key determinant of quantity of food lost pre- and post-consumer, but the 'cold chain' also functions to improve the safety of food by reducing the prevalence of food-borne disease. Gaps in the chain introduces potential for lost and wasted food through spoilage as well as health issues (Coulomb, 2008). There are also preventable embedded emissions in this lost and wasted food.

A complete and functioning cold chain would result in fewer losses therefore less production would be required to meet end-user needs; emissions could be reduced as less food volume would be processed through the chain. Building, maintaining and using such infrastructure is energy and capital intensive; absence of an extensive and reliable 'cold chain' is an emerging country issue. While growth in 'cold capacity' has increased in some developing countries (such as Brazil, India and China), there has been little growth elsewhere (Yahia, 2010). Lack of reliable energy needed to power the cold chain or financial resources to access the technology are possible factors hindering more rapid deployment.

2.4.2 Carbon accounting

Differences between the IPCC-NI (national inventory) and life-cycle analysis carbon accounting methodologies can lead to different results and potential actions by agents along the FSC. The former method tends to attribute less mitigation to local agriculture than the latter. Some emission reductions from improved farm-level production efficiency are allocated to the energy sector (e.g. production of bioenergy/biomass crops) and/or industrial sector (e.g. fewer chemicals/detergents) rather than the agricultural sector. Farmers may thus not be incentivised to take mitigation actions if they do not fully benefit from emissions reductions achieved as a result of their actions (O'Brien et al., 2014).

The IPCC methods permit global/continental default emissions factors and equations (Tier 1) to more discrete country specific factors and equations (Tier 3); Tier 2 recommends country specific factors for the largest emitters alongside Tier 1 defaults for others (Dong et al., 2006). Implementing Tier 3 is resource intensive and so many developing nations use Tier 1 defaults for all inputs – including the most important GHG emission sources – which can lead to inaccurate national inventories being calculated. Without a robust starting point, mitigation efforts can therefore be hampered from the beginning. This is a particular issue within agriculture, where the under-reporting of methane and nitrous oxide emissions can be significant (Ogle et al., 2014).

2.4.3 Economic viability of potential mitigation

Marginal abatement cost curve (MACC) estimates that arise from evaluating emissions mitigation options are temporally limited to the present. They do not explicitly take into account technological or policy changes, although scenario analysis could be used to develop a series of hypothetical MACCs. However, they remain useful as a tool to identify potential mitigation technologies that could be implemented at a particular price of carbon. The importance of technological change, both incremental as well as sudden, is highlighted in Burney et al. (2010). They estimated that each dollar invested in increasing global agricultural yields over the period 1961 to 2005 resulted in a 249 kg CO_2e emission reduction relative to 1961 technology – equivalent to 13.1 Gt CO_2e per annum at a cost of US$ 4 t^{-1} CO_2e. Of those studies examining the economics of mitigation, most have been focused on the developed world at the broad agricultural sector level (e.g. Moran et al., 2011; O'Brien et al., 2014; Schulte and Donnellan, 2012; Smith et al., 2008; Whittle et al., 2013).

MACCs can be created using different approaches, which may not necessarily arrive at the same result. A biophysical MACC analysis that examines all available technologies and processes that could be employed to mitigate emissions is likely to overestimate what is economically viable. Smith et al. (2008) estimates global, pre-harvest mitigation potential from agriculture that is technically possible of 5500 – 6000 Mt CO_2e yr^{-1} by 2030, yet a lower range of 1500 – 4300 Mt CO_2e yr^{-1} that is economically viable. Without an off-setting incentive, farmers are not expected to adopt and implement mitigation technologies or practices that do not at least cover the costs of doing so (Whittle et al., 2013). Economic viability is a key factor to achieving mitigation levels that are technically feasible.

In the short-term, such viability depends on the carbon price. A higher price for carbon increases the range of technologies that can be judged as economically viable. Whilst carbon is a standard commodity, it is not traded as a standard commodity. Although carbon markets are emerging across the globe (eg. California, EU ETS, Chinese pilots), they are closed markets, restricting who can participate and what instruments can be traded. Further, the instruments are not 'fungible' – i.e. the same instrument cannot be purchased on one market and sold in another. Tax regimes for carbon are also highly variable depending upon location (World Bank, 2014). With few exceptions, carbon pricing continues to be a 'developed world' phenomenon. As population and potential economic growth primarily expected from 'developing nations', their lack of a carbon price could removes a key incentive to mitigate future emissions. A global MACC such as that of Smith et al. (2008) is a useful reference. However, country or region-specific MACCs that take into account the specific local economic, developmental, and/or technological context need be constructed to provide sufficient, adequate and appropriate detail to guide mitigation policy and implementation. There is currently a dearth of such analysis for 'developing' nations, and few for 'developed'.

2.5 Case Study – Milk

2.5.1 Consumer-phase wasted milk and estimation of avoidable GHG emissions

This case study examines production-phase non-CO_2 GHG emissions driven by lost/wasted milk and highlights the impact of inefficiencies in the FSC. At least 90% of milk products' life cycle GHG emissions occur during primary production of raw milk (Foster et al., 2006). Though other foodstuffs may have greater loss levels and emissions intensities, milk is used as an example here as, at least in developed countries, virtually all waste in the consumer phase is deemed 'avoidable' (Quested et al., 2013).

In addition to the potential for reducing agricultural GHG emissions during the production phase, reductions in food loss and waste – especially for emissions-intensive foodstuffs such as meat and dairy foodstuffs – may provide globally significant climate change mitigation benefits via demand side measures. For instance, a simplistic comparison of global average food loss and wastage rates (~30%, Gustavsson et al., 2011) with agricultural N_2O emissions suggests potential N_2O emissions reductions through complete avoidance of food loss and wastage in excess of 1 Mt N_2O-N yr^{-1} (Reay et al., 2012). Robust quantification of such mitigation potential is challenging given uncertainties in wastage rates, life-cycle emissions for each food, and the degree to which any wastage is truly avoidable. Without such reliable estimation, development of effective supply-chain interventions aimed at achieving large and sustained reductions in overall agricultural GHG emissions becomes impossible. In this case study we examine the potential for non-CO_2 greenhouse gas (CH_4 and N_2O) emissions reductions through avoidance of UK milk wastage during the consumer phase. As well as estimating avoided emissions we examine the utility of and limits to this approach in determining such mitigation potential for other food types, supply chain phases, and geographical areas.

2.5.2 UK Milk Wastage & Production Emissions

Approximately 290,000 tonnes of milk was wasted by UK consumers in 2012, with all of this wastage being classed as 'avoidable'. The Waste Resource Action Programme (WRAP) report that almost half of this milk wastage was a result of it not being used in time and about 25% being a result of too much being served (Quested et al., 2013).

Production-phase greenhouse gas emissions for the consumer-phase milk wastage were estimated using an emission factor of 14.5 g CH_4 per kg milk produced (EU EEA, 2013, pp. 496, 506) and 7.1 kg N_2O-N per 10,000 litres of milk produced (Quested et al., 2013; Williams et al., 2006). N_2O-N was converted to N_2O using the standard mass conversion factor of 44/28. Greenhouse gas emissions occurring in the post-farm supply chain phases were not included in this analysis. Non-UK milk volume data (UK wasted milk data was already in mass units) was converted into mass using the assumption that milk has a density of 1.03kg per litre (Anton Paar, 2009). The reported mass of consumer-phase milk wastage was then combined with these emission factors to derive estimated 'avoidable' production-phase CH_4 and N_2O emissions (Figure 2-2). 'Avoidable' non-CO_2 emissions were then converted to CO_2 equivalents using a Global Warming Potential (GWP) for CH_4 and N_2O of 25 and 298 respectively (Forster et al., 2007).

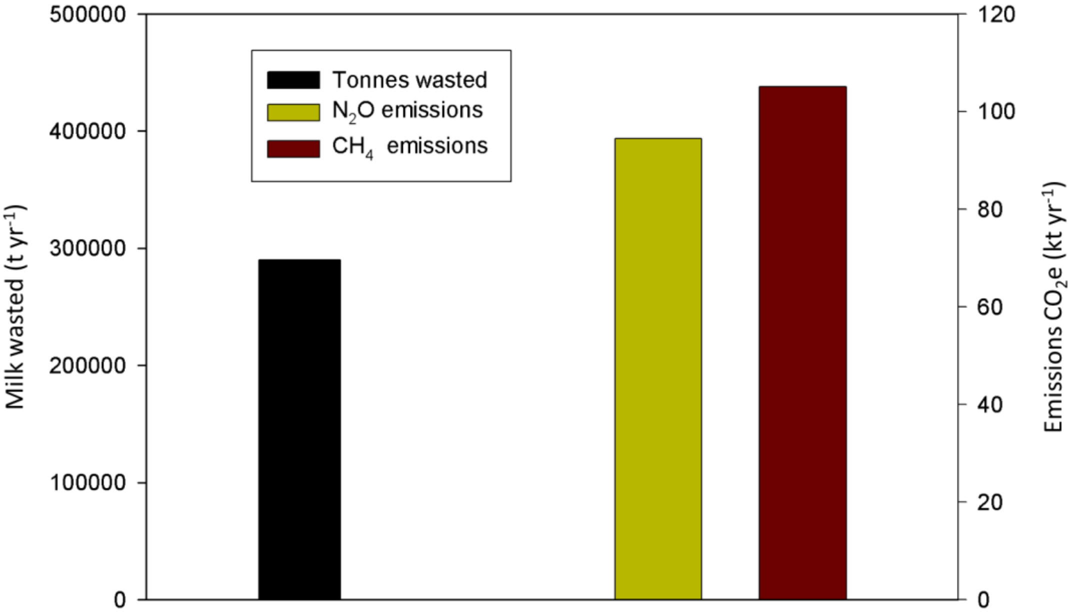

Figure 2-2. Estimated mass of consumer-phase 'avoidable' milk waste (left-hand axis), and 'avoidable' production-phase CH_4 and N_2O emissions (right-hand axis) in the UK in 2012.

Our analysis indicates very substantial cuts in production-phase CH_4 and N_2O emissions for UK milk are possible through avoidance of consumer-phase waste. Potential reductions in methane emissions (4.2 kt CH_4 yr^{-1}) were much larger than those for nitrous oxide (0.3 kt N_2O yr^{-1}) but, on a net climate-forcing basis, avoiding milk waste results in similar climate change mitigation for these two GHGs – 105 kt and 94 kt CO_2e yr^{-1} respectively – with a total reduction in CO_2e of almost 200 kt yr^{-1}. In this instance, the UK milk wastage rate, production-phase CH_4 and N_2O emissions, and proportion of waste that is deemed 'avoidable' in the consumer-phase are all reasonably well constrained. Such large-scale consumer food waste surveys (Quested et al., 2013), combined with Tier 2 or 3 emission factors for the production phase, is certainly not something that is available for every country and every food type around the world. To produce comparably robust estimates for many other nations, food types, and supply-chain phases will therefore require careful use of IPCC default (Tier 1) emission factors in combination with well-justified extrapolation of data on food wastage from comparable times, locations and circumstances.

2.5.3 Milk loss in the U.S.

There are considerable uncertainties surrounding the scale of losses reported by different sources. WRAP in the UK estimates 3% of overall UK milk production is wasted by the consumer (Quested et al., 2011). The USDA's estimate for this stage in the FSC is over seven times higher at 22% (USDA, n.d.), while the FAO's food balance sheets apply zero waste to milk production in both countries through all stages (FAOSTAT, n.d.). The embedded non-CO_2 emissions from the U.S. production of this wasted milk thereby range from a low of zero (using FAO data) – which is implausible – to a high of 21,200 kt CO_2e (from USDA data) through the entire milk supply and consumption chain (methane and nitrous oxide combined). Using this latter figure, the embedded emissions of wasted milk in the U.S. would be over 56 times higher than that of the UK in absolute terms and some 13-times greater on a per capita basis. While FAO loss and waste estimates globally of 2.4% appear on the low side (developing regions have a loss rate of about 4%), the 31.5% applied by the USDA seems high.

In absolute terms some 7.3 billion litres of milk is lost or wasted annually in the U.S. The value of this milk wastage is equal to about US$ 6 billion a year at an average price litre^{-1} in 2009 of USD 0.82 (US BLS 2014). With a population just exceeding 300 million and 2.6 people per household (U.S. Census Bureau, 2012), the per capita cost of this wasted milk is only about US$ 20 per annum, or about 30 U.S. cents per household per day. At just 30% of the US$ 1.07 cost of all lost/wasted food per day per family (Buzby and Hyman, 2012), it seems unlikely the average U.S. household would notice this level of financial cost.

2.5.4 Developing world milk losses

A lack of cooling technology availability and/or appropriate use in developing regions, such as many African states, where the small-holder, rather than industrial producer, is a key player in the supply chain are factors influencing milk losses (Gachango et al., 2014). FAO milk loss estimates vary across developing world regions – for example, 1.9% in South-eastern Asia and 6.6% in Eastern Africa. Applying these post-harvest loss rates to regional production results in embedded emissions estimates of 60 kt CO_2e as N_2O and 80 kt CO_2e as CH_4 for South-eastern Asia and 283 kt and 378 kt CO_2e respectively for Eastern Africa.

2.5.5 Global scaled-up milk losses

Current global milk production is estimated to be 692 billion litres yr^{-1}, with losses averaging 2.4% (FAOSTAT, n.d.). A weighted-average CH_4 emission factor of 47.6 g kg^{-1} of milk was calculated for global production using the IPCC's Tier 1 default regional CH_4 emissions factors (Dong et al., 2006). Using an N_2O emission factor of 7.1 kg N_2O-N per 10,000 l of milk as a global constant (Williams et al., 2006), the embedded emissions from global production of milk ultimately not consumed are 5400 kt CO_2e as N_2O and 19,700 kt CO_2e as CH_4 per annum. The combined total of 25,100 kt CO_2e from inefficiencies along the milk supply chain alone is approximately 0.2-0.3% of the 7,300-12,700 Mt CO_2e attributed to agriculture globally. As the developing world moves towards a more 'Western' diet – one that is more meat and dairy intensive – such waste-related emissions, without concomitant improvements in production efficiency, look set to rise.

In addition to the GHG emission penalties incurred from producing food that is either not consumed or excessively consumed, there are also substantial economic costs. The economic value of such inefficient resource use ranges from 0.8% of GDP in the UK (Quested and Parry, 2011) to 1.3% of GDP in Canada (Gooch et al., 2010). If a 1% of GDP impact were consistent at the global scale, this annual loss would be equivalent to US$720 billion in 2012 (World Bank, 2014) – about the average annual value of investment in low carbon technologies estimated to be required through to 2035 to not exceed 450ppm of atmospheric CO_2 (IEA, 2011). However, inefficiencies in the FSC are not consistent either within a commodity across regions or within a region across commodities (FAO, 2013) – GHG and economic loss mitigation potential and methods to achieve that potential may, therefore, require bespoke solutions for the different food-region pairs.

2.6 Conclusion

Substantial quantities of food produced are lost or wasted along the FSC – up to 50%. However, when excess caloric intake (over-eating) is included, as much as 65% of all global food production is not allocated efficiently. The embedded emissions, particularly from CH_4 and N_2O, in these post-harvest losses create avoidable GHG penalties roughly equivalent to the annual emissions of the U.S. The emissions from the losses from a single commodity, such as milk, can be substantial. However, supply chain inefficiencies are different between food commodities and global regions. The stage along the supply chain where inefficiencies occur is also variable between the developed and developing countries. Achievable mitigation potential – technologically practicable and economically viable – is likely also to require specific analysis and solutions for a given region-commodity. Additional research into abatement costs, the barriers to and opportunities for mitigation (such as differential practices, technologies, policies and education) at discrete stages along the FSC for specific region-commodity pairs is needed. This will help to more systematically address the growing issue of food-related emissions.

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Chapter 3
Trends in FLW & embedded emissions

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

Stephen D Porter[*1], David S Reay[1], Peter Higgins[2], Elizabeth Bomberg[3]

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 CO_2e). A 44% increase in global average per capita FLW emissions was also identified – from 225 kg CO_2e in 1961 to 323 kg CO_2e 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 CO_2e 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.

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3.1 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 (Bourne, 1977; GAO, 1977; Hall, 1970). 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 (Defra) 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.[4]

The subject of this paper is identifying – using a whole-system approach – where FLW occurs and its associated production-phase only GHG emissions (in CO_2 equivalents – CO_2e). 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 section 3.2, these

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[4] A new Directive (EU) 2018/851 based upon this proposal was adopted on 30 May 2018, subsequent to the publication of this chapter.

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 et al., 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 CO_2e t^{-1} beef versus 1.4 – 5.2 t CO_2e t^{-1} rice; Table 3-1) 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 CO_2e yr^{-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 (Hallström et al., 2015; Pradhan et al., 2013). 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 3-1) 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 section 3.2 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.

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 and Buss (1977) and Wenlock et al. (1980), examined losses at the UK household level (FSC 5) and estimated wastage to be about 5% of food brought into the home. Some thirty-five years later, Quested 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 and 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.

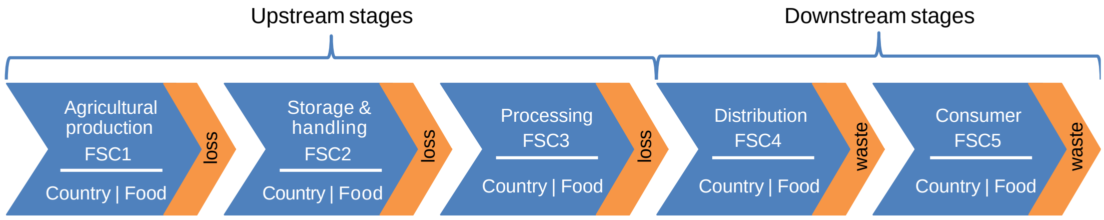

Figure 3-1. Food produced for human consumption passes through various stages to get from the farm to the consumer. The first three stages are considered 'upstream', where the term 'loss' is used; the latter two stages are considered 'downstream' with 'waste' being used. The structure of the FSC stages is conceptually the same for each country and food commodity. Food wastage can occur at any point along the supply chain. Agricultural losses are those arising from harvest activities such as from damage and/or quality; post-harvest handling and storage is waste between the farm and process/distribution facilities, including losses during transport; processing loss refers to unrecoverable losses from industrial spillage and/or degradation; distribution wastage arises during the market system (wholesale and retail); and consumption waste may occur in or out of the home by consumers (Gustavsson et al., 2011).

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 yr^{-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 CO_2e – 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 CO_2e yr^{-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 3-1; and Table A-1and Table A-2 in Appendix A), 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.

3.2 Methods

The FAO's FBS database (FAOSTAT, n.d.) 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 Table A-3 and Table A-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 3.2.2) 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 and Venkat (2011) estimated the production stage accounted for roughly 90% for beef and lamb, 70% for 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.

3.2.1 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 A-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 CO_2e 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 3-1

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

where, *EM* is emissions, in tonnes of CO_2e, *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 CO_2e 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 3-2

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

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 3-3). 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 3-3

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

where, AD_1 is the activity data (mass of food) of FSC 1 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*.

3.2.2 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.[5] 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 and applied the same factors to all countries within the region (Europe, North America & Oceania – NAmOce, Industrialised

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[5] Additional detail on the approach to the literature search for these meta-analyses is provided in Appendix A.1

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 A-3). 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 3-4). This was consistent with the FAO (2001, p. 13) 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 3-1 (fully referenced in Table A-1); similarly, loss factors, and their sources, are provided in Table A-2.

Table 3-1. Summary table of mean emission factor (*EF*) values (t CO$_2$e t^{-1} food) used to calculate FLW-associated GHG emissions. The corresponding *EF* was applied to all wastage at any FSC stage for a particular region-commodity pair; sources are provided in Table A-1.

Group	Europe	NAmOce	IndusAsia	SSA	SSEAsia	LatAm	NAWCA
Cereals							
Barley	1.57	0.40	0.63	0.80	0.75	0.84	0.49
Maize	0.45	0.38	0.44	1.56	1.73	0.81	0.56
Millet	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Oats	0.61	0.93	0.93	0.93	0.93	0.93	0.93
Rice	2.88	1.77	1.43	5.23	1.91	2.58	2.36
Rye	0.46	0.50	1.02	0.38	0.70	0.76	0.69
Sorghum	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Wheat	0.61	0.36	0.62	0.46	0.46	0.60	0.61
Other Cereals	0.43	0.93	0.93	0.93	0.93	0.93	0.93
Fruit & Veg							
Apples	0.25	0.15	0.17	0.12	0.34	0.15	0.71
Bananas	0.35	0.28	0.56	0.54	0.45	0.30	0.51
Citrus	0.36	0.09	0.17	0.27	0.23	0.19	0.16
Grapes	0.42	0.67	0.62	0.40	0.62	0.67	0.55
Other Fruit	2.30	1.00	0.35	0.19	0.84	0.41	0.34
Vegetables	0.84	0.58	0.30	1.53	0.81	0.31	0.27
Marine							
Fish & Seafood	4.09	4.42	2.77	9.19	5.29	3.01	6.86
Meat							
Bovine	22.86	22.08	33.26	33.96	39.08	35.01	19.44
Mutton & Goat	23.89	15.35	15.45	16.89	15.71	20.89	20.29
Pig	5.06	4.29	5.85	4.27	6.92	4.65	5.67
Poultry	3.58	4.39	12.06	4.89	4.68	3.38	4.55
Milk & Eggs							
Eggs	3.49	3.66	4.39	6.18	3.06	5.20	5.54
Milk	1.33	1.13	1.26	4.16	2.31	2.52	2.77
Oilseeds & Pulses							
Oilcrops	1.13	0.56	1.10	3.94	1.96	0.91	1.59
Pulses	0.93	0.44	0.37	0.12	0.34	0.15	0.71
Roots & Tubers							
Starchy Roots	0.25	0.17	0.19	0.52	0.16	0.18	0.15

Equation 3-4

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

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.

3.3 Results

The present study seeks to add further dimensions to existing literature on FLW as discussed in section 3.1 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.

3.3.1 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 3-2a). 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 A-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 yr^{-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).

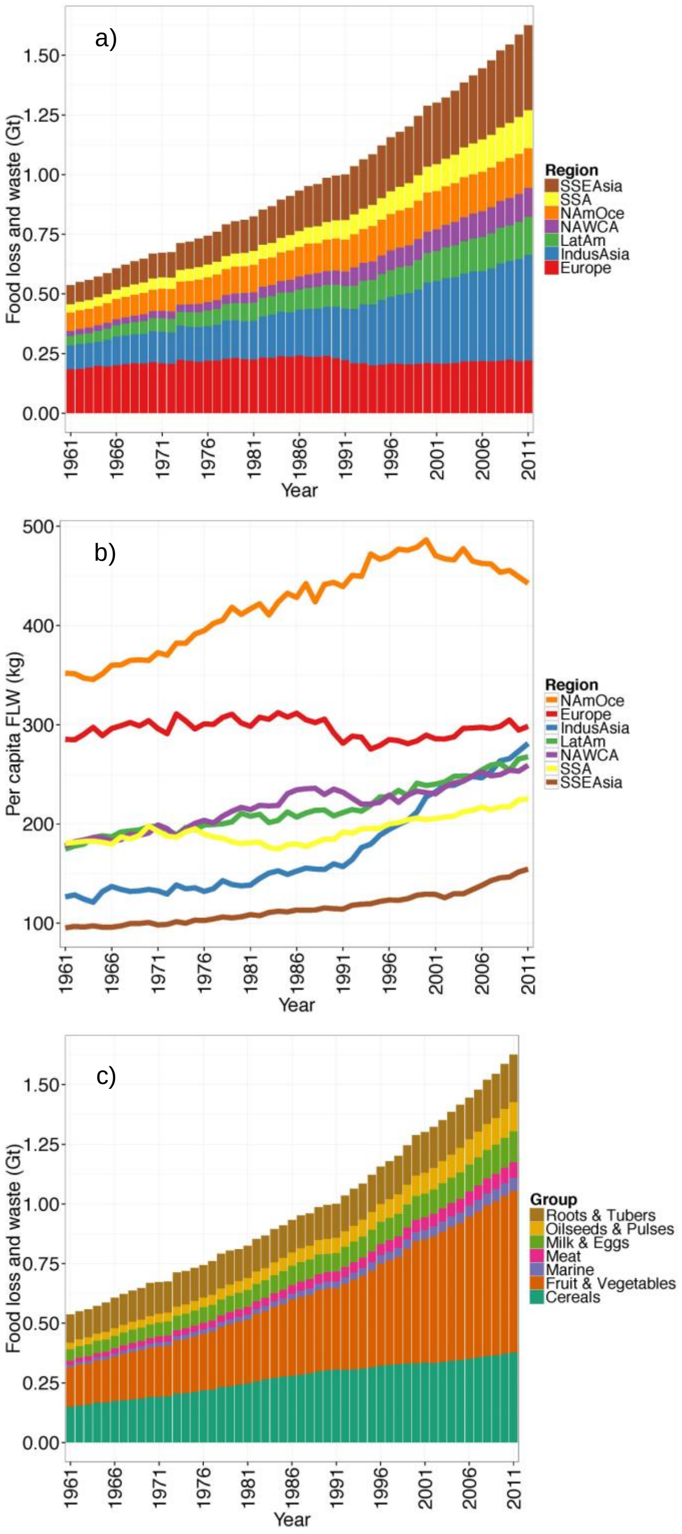

Figure 3-2. Annual mass of food loss & waste. **(a)** is the total FLW each year by region, in Gt; **(b)** is per capita FLW by region (in kg); **(c)** depicts cumulative annual regional FLW (in Gt) by food Group. The time period is the available history of the FAO FBS database.

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 3-2b). All showed increases in their respective per capita values, though again largely split along relative wealth lines (Table A-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 3-2c). 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, n.d.). 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 A-7).

3.3.2 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 CO_2e to 2.2 Gt CO_2e, or 2.4% per annum on average. The more rapid growth in FLW in SSEAsia and IndusAsia (Figure 3-3a) 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 A-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 CO_2e to 324 kg CO_2e, 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 3-3b; Table A-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 CO_2e to 283 kg CO_2e yr^{-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 CO_2e per person in 1961 to 284 kg CO_2e in 2011.

Variation in estimated FLW production-phase GHG emissions of food commodity groups is striking due to very different emissions factors (Table 3-1. For example, our *EF* estimates, in tonnes of CO_2e 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%) (see Table A-10).

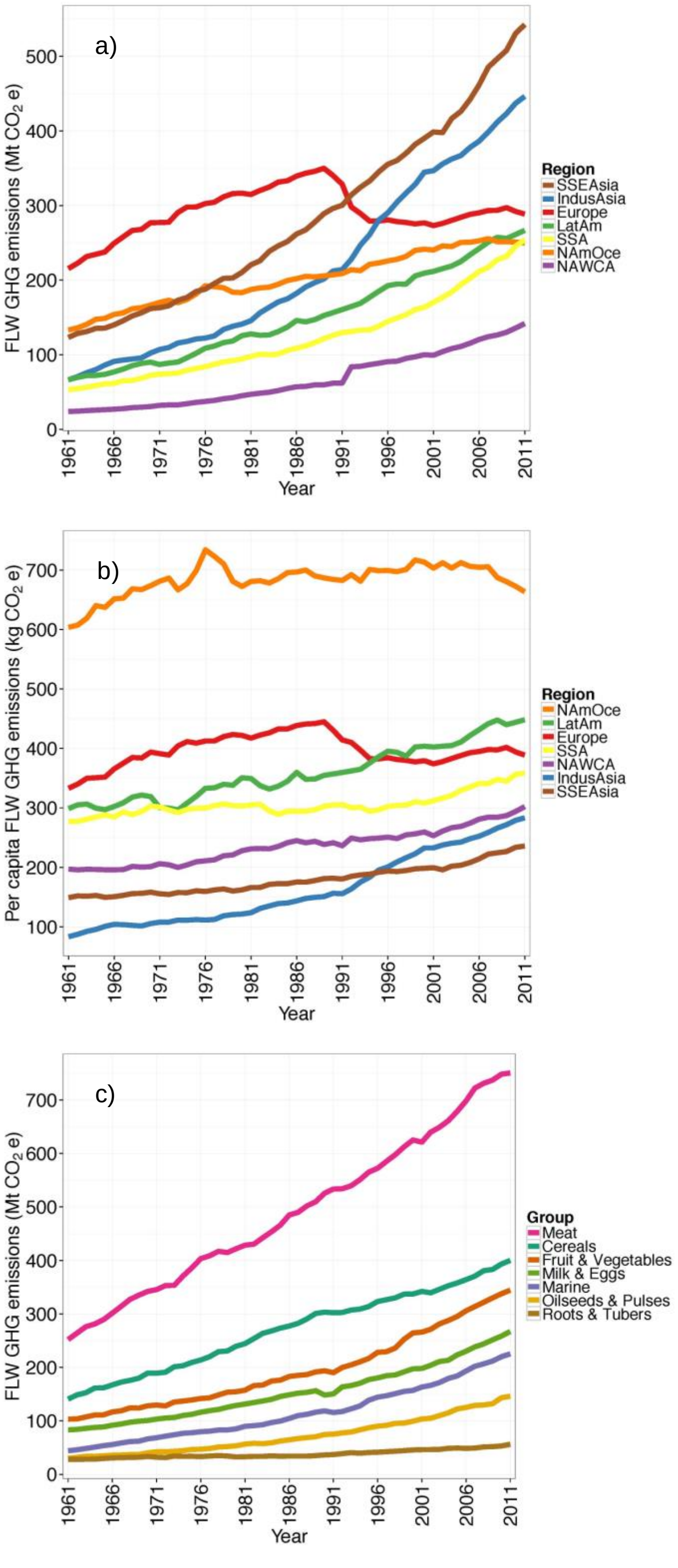

Figure 3-3. Annual production-phase FLW-associated GHG emissions by region and food group. **(a)** is total emissions per annum by region, in Mt CO_2e; **(b)** is regional per capita emissions per annum (in kg CO_2e per person); **(c)** shows the trend in total annual emissions by food group (in Mt CO_2e). The time period is the available history of the FAO FBS database.

3.3.3 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 3-4).

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.

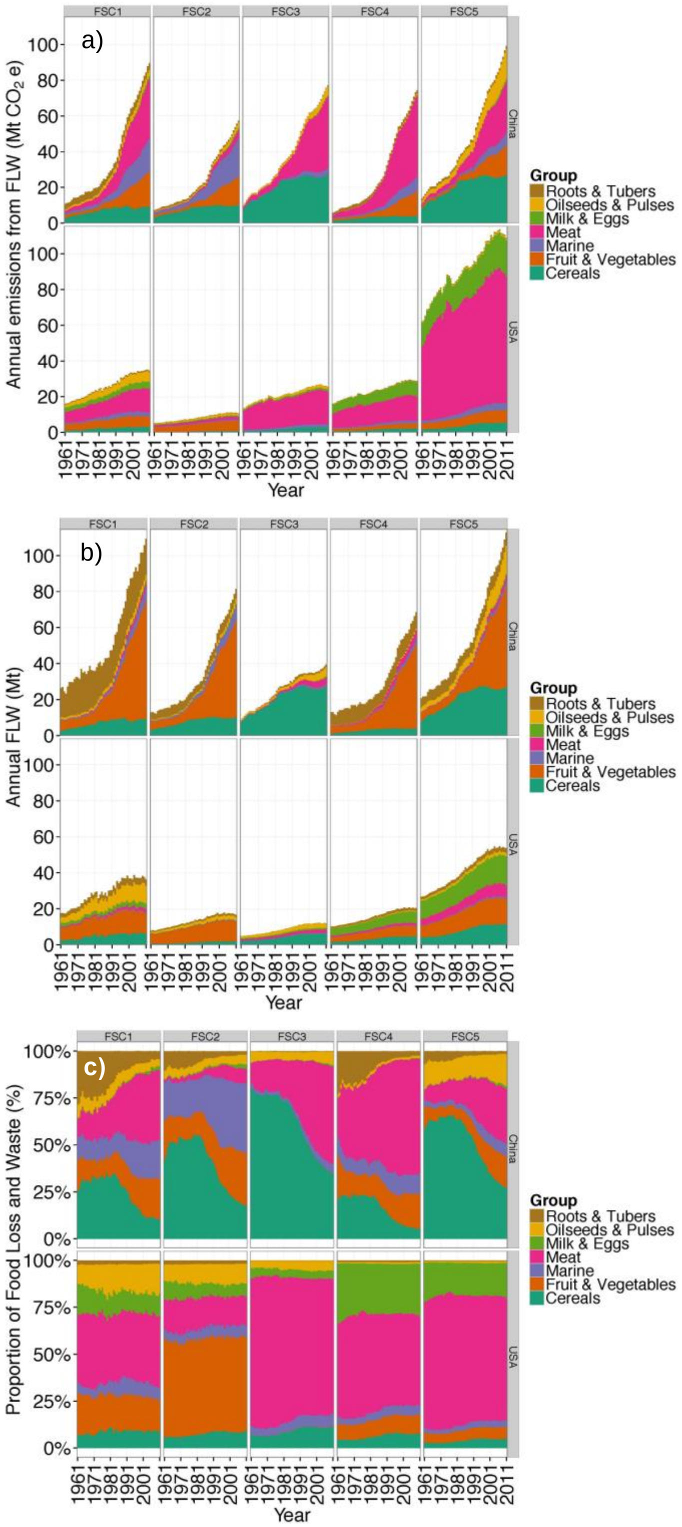

Figure 3-4. Amount and proportion and amount of food wastage differ across the FSC in time by food group and country. **(a)** compares annual FLW-associated emissions in China and the U.S. whilst **(b)** provides the underlying wastage; panel **(c)** shows the proportion of FLW emissions by food group. The time period is the available history of the FAO FBS database.

As a measure of overall emissions intensity of regional FLW, the annual mean production-phase *EF* (i.e. t CO_2e 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 CO_2e 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 CO_2e t^{-1} in 1961 to 1.50 t CO_2e 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 CO_2e t^{-1} and from 0.94 to 0.51 t CO_2e t^{-1}. All other commodity groups exhibited increases in their mean *EF* values at the global scale.

3.4 Discussion

3.4.1 Context

At an estimated 2.2 Gt CO_2e 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 CO_2e in 2050, roughly equivalent to all GHG emissions of the U.S. in 2011 (World Bank, n.d.).

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 recovery 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 3-2. 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.

Table 3-2. Comparison of food wastage and associated production-phase GHG emissions with existing FLW literature.

Region	FSC stage	FLW (Mt)	Production-phase GHG emissions (Mt CO_2e)	Year of Data	Source
Global	All (1-5)	1300	2081	2007	Gustavsson et al. (2011)
Global	All (1-5)	1445	2025	2007	present study
Global	FSC 5		410	2007	Hiç et al. (2016)
Global	FSC 5		483	2007	present study
EU-27	FSC 2 – 5	89	170	2006	Monier et al. (2010)
EU-27	FSC 2 – 5	110		2006	Bräutigam et al. (2014)
EU-27	FSC 2 – 5	111	164	2006	present study
USA	FSC 4 & 5	60		2010	Buzby et al. (2014)
USA	FSC 4 & 5	74		2010	present study

3.4.2 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 A-7). In line with reported national-level GHG emissions (World Bank, n.d.), 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 CO_2e. Multiplying this value by the median expected population in 2050 and 2100 would see emissions from FLW grow to in excess of 3.1Gt CO_2e by 2050 (32% increase) and to 3.6 Gt CO_2e 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.

3.4.3 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 a moderate calorie diet, and then from a moderate calorie to a 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 CO_2e 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; Møller et al., 2014; Whitehead et al., 2013), 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 CO_2e, 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.

3.5 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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Chapter 4
Policy, food waste, and embedded emissions

Production-phase greenhouse gas emissions arising from deliberate withdrawal and destruction of fresh fruit and vegetables under the EU's Common Agricultural Policy[†]

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ABSTRACT

Since 1962 the Common Agriculture Policy (CAP) of the European Union (EU) has enabled payment of subsidy to some food producers for withdrawal of specific commodities – including fresh fruit and vegetables (FFV) – where market prices have fallen below a pre-set level. These deliberate withdrawals have led to large amounts of usable food (~60% of withdrawals) being destroyed on farms across the EU. Such wasted food incurs a significant climate change cost through its production-phase greenhouse gas (GHG) emissions. Here, we assess the magnitude of this FFV withdrawal and destruction, its spatial and temporal trends, and its associated GHG emissions between 1989 and 2015. We find the total mass of avoidable FFV losses occurring as a result of these EU CAP market interventions for this 26-year period to be 23.6 Mt. The production-phase GHG emissions associated with the withdrawn FFV that was subsequently destroyed amount to 5.1 Mt CO_2e over this period. We also find that, with each successive Common Market Organisation (CMO) reform there has been a marked reduction (~95% between 1989 and 2015) in the quantity of such deliberate withdrawals. Surprisingly, however, whilst the absolute quantity of FFV withdrawn and destroyed has fallen, the proportion of withdrawals that is destroyed remained roughly static at an average of about 60%. Finally, to inform debate on action needed to address FFV specifically, and food loss and waste more generally, we highlight potential scenarios and mechanisms to reduce withdrawals, avoid FFV destruction, and improve alternative use of withdrawn food in the future.

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4.1 Introduction

4.1.1 Avoidable food loss & waste

The avoidable loss or waste of food is an inefficient use of resources (Porter and Reay, 2016), not discounting other potential environmental impacts of agriculture such as land use change, soil degradation, and pollution run-off (IPCC, 2000, sec. 1.4). These resources include, amongst others, labour, fertilisers, pesticides, and finance. The growing of food for human consumption generates significant greenhouse gas (GHG) emissions, with global agriculture responsible for 10-12% of total anthropogenic emissions (Smith et al., 2014). These are GHG emissions that arise from food production activities. Everything we eat represents a particular share of those emissions. What we don't eat or otherwise destroy – food loss and waste (FLW) – is representative of GHG emissions that may have been avoided by producing less or using it more efficiently.

Much of the literature on FLW to date has focused on estimating the quantity of food that leaves the food supply chain. The first large-scale study of food waste, Monier et al. (2010), examines the phenomenon within the European Union (EU). They estimate 89 Mt of food is lost or wasted from the farm-gate to the consumer (i.e. excluding wastage occurring on the farm itself), equivalent to 170 Mt CO_2e in embedded GHG emissions. At the global level, (Gustavsson et al., 2011) estimates food wastage across the food supply chain (FSC), including on-farm losses, to be approximately one-third of all production (by mass). One of their main conclusions is that most wastage occurs at the final, consumer, stage of the FSC in relatively wealthy countries, whilst poorer countries see relatively more losses in the early stages (i.e. production and storage). Hiç et al. (2016) points to oversupply of food, particularly in OECD countries, as a key contributor to food waste. Porter et al. (2016) demonstrates that fruit and vegetables are the most wasted food commodities globally across the entire FSC; its wastage accounts for over 40% by mass and is the third-highest in terms of embedded emissions (behind meat and cereals) of all FLW.

4.1.2 EU CAP, CMOs, and market withdrawals

Implemented in 1962, the Common Agricultural Policy (CAP) was intended to provide support for agricultural operations and thereby ensure adequate food supply and support farm income of the six Western European States that crafted the Treaty of Rome (Roederer-Rynning, 2015, p. 197). Specific regulations, referred to as Common Market Organisations (CMOs), were set up for products most important to these countries; those for fruit and vegetables in 1972 (European Council, 1972). With the aim of achieving domestic food security and supporting farm income, a key policy lever of the CAP was to provide guaranteed minimum prices to farmers (Daugbjerg, 2003). The more farmers produced the more they earned, subsidised by the consumer through higher EU prices than world market forces would otherwise indicate (Ackrill and Kay, 2006; Daugbjerg, 2014). Amongst other levers to protect prices (and thereby indirectly supporting farmer income) was the potential to withdraw production surpluses from the market (DG-AGRI, 2011).

Some commodities, such as cereals and dairy, are subject to market intervention of ‘buying-in’, and are typically stored for selling back into the market when prices stabilise at acceptable levels (European Parliament and Council, 2013). Fresh fruit and vegetables (FFV) that are withdrawn from market, in contrast, may not be returned to the food supply chain via a sales channel; CMO regulations specify particular destinations, including destruction (European Council, 1972, 1996, 2007). Prior to 1988, when a maximum limit on CAP spending was introduced (European Council, 1988), there were no controls on the level of monetary support allocated via this policy. With less need to heed market signals, EU production increased beyond marketable levels (Ackrill and Kay, 2006). The result: before the first major CAP reform in 1992 (to address its ‘trade distorting impact’ (Daugbjerg, 2014) and to increase its ‘market orientation’ (DG-AGRI, 2013)), spending on support for markets and export subsidies to address excess agricultural production was over 90% of all CAP expenditure (DG-AGRI, 2011). Further CAP reforms were enacted in 2003 and 2013, to ‘decouple’ production from income under the single payment scheme, and introduce sustainable agriculture and 'green' direct payments, respectively (DG-AGRI, n.d. a). Amendments to the FFV CMO regimes followed in 1996 and 2007 to achieve particular objectives. Table 4-1 summarises the aspects of each regime relevant to FFV withdrawals.

Table 4-1. Key aspects of CMO regulations with respect to FFV withdrawals from the market for each regime. Sources: European Council (1972, 1996, 2007) for CMO Regimes 1-3, respectively.

Regime	CMO regulation	Objective	Market Inventions	Key change(s)
1st (1989-1996)	Regulation (EEC) No 1035/72	Maintain stable prices, using market interventions when necessary, avoiding destruction when possible	Fixing of a basic and buy-in price at start of each year.	Permitted destination of withdrawals are specified, including 'non-food uses'.
2nd (1997-2007)	Council Regulation (EC) No 2200/96	Change perception of withdrawals as an acceptable alternative outlet to the market.	Specific flat rates for withdrawals of each commodity set for next six years. Typically decline 25% over time period.	Upper limit of compensation of withdrawals set at 35% of marketed value in year 1, declining to 10% by year 6. 'Free distribution' for withdrawals is emphasised. Destruction by 'composting/biodegradation' an acceptable destination.
3rd (2008-2015)	Council Regulation (EC) No 1182/2007	Improve competition and market orientation, and achieve sustainable production.	100% of 'free distribution' will be compensated (up to 5% volume limit)	Maximum compensation falls to 4.1% for withdrawals that are not 'free distribution'. All destinations of withdrawals compensated at 50% of value, including 'destruction'. Introduces 'green' and 'no-harvest' crisis management tools, that have same effect as withdrawals.

With the exception of 'free distribution' (i.e. donation), withdrawn FFV is no longer considered food and must be disposed of, becoming 'avoidable' food loss. Channels for such food loss include alcohol distillation, animal feed, green harvesting/non-harvesting of crops, and biodegradation (European Council, 2007). For withdrawn FFV, destruction (e.g. via composting and ploughing into soils) is a likely disposal route. Here, for the first time, we examine the climate change cost of such food withdrawal and destruction within the EU, specifically estimating the embedded production-phase emissions of such loss. Our focus is on fresh fruit and vegetables within the EU for the period 1989-2015, to provide policy-relevant insights that inform the debate on avoidable FLW.

4.2 Methods

We estimate annual embodied production-phase GHG emissions for destroyed FFV within the EU from the exercising of the CAP food withdrawal mechanism for the period 1989-2015. We do so using three quantifiable elements; amounts of FFV withdrawn, proportion destroyed, and production-phase GHG emissions factors of the destroyed food. The relationship is shown using the model in Equation 4-1, whose factors are detailed in the paragraphs and table that follow. We also compare the elements and output of the model across the three CMO regimes identified in Table 4-1.

Our analysis of the embedded emissions focuses on avoidable permanent food losses – food that is safe to eat yet is withdrawn from the supply chain and destroyed. Food that is repurposed (such as to animal feed) or redirected (e.g. to charities for ‘free distribution’) is therefore not included in our estimates. As the CAP only directly applies to Member States, changes to EU constituents over time are accounted for in each year. That is, only data for actual EU Member States in a given year are included in the estimates, and not all 28 (at time of writing).

Equation 4-1

$$EM_{j,t} = \sum Withdrawals_{j,t} * Destroyed_{j,t} * EF_{j,k}$$

where: *EM* is production-phase embedded GHG emissions, in tonnes of CO_2e; *Withdrawals* is the mass of food subjected to market intervention, in tonnes, and *Destroyed* is the fraction of *Withdrawals* that undergoes complete destruction, for commodity *j*, in year *t*. *EF* is the production-phase GHG emission factor, in tonnes of CO_2e per tonne of food, for commodity *j* in country *k* (or Europe-level if country data are not available).

Annual data for *Withdrawals* quantity and *Destruction* factors are sourced from Agrosynergie (2007), the Directorate General – Agriculture and Rural Development (DG-AGRI, n.d. b), and personal communication from the DG-AGRI of 27 Oct 2017. Of the full period 1989-2015, there are no available *Withdrawals* data for 2008 or 2009, or *Destruction* data for 1994-1996 and 2005-2009. Different degrees of data granularity exist for different years during the period under review. The spectrum ranges from the commodity-by-country level (most granular available), to country or commodity only (least granular).

Destruction factors for the missing time periods were estimated as the average of prior years' values within the same CMO Regime for which data were available. Therefore, 1994-96 was given a *Destruction* factor of 50.3% (the average of 1989-1993) and 2005-2007 was given a factor value of 69.9% (the average of *Destruction* data for 1997-2004). For individual years of the period 2010-2015, we assumed that the values for 'Other Destination' provided by DG-AGRI were equivalent to *Destruction*. Where commodity-level data were not available (i.e. 1997-2004), the same *Destruction* factor was applied to all *Withdrawals* in a country.

Table 4-2. Production phase Emission factors (*EF*s) for fruits and vegetables in Europe. EU country short forms: IT=Italy, UK=United Kingdom, SE=Sweden, DK=Denmark, NL=Netherlands, ES=Spain. Source: Porter et al. (2016, Supplementary Information).

Fruit / vegetable	Emission factor (Europe-level) (t CO_2e t^{-1})	Emission factor (country-level) (t CO_2e t^{-1})
Apples	0.29	0.22 (UK); 0.19 (IT)
Pears	0.43	0.32 (UK)
Apricots	0.43	
Peaches (incl. Nectarines)	0.31	
Oranges (incl. Clementines)	0.31	0.70 (IT)
Mandarins (incl. Satsumas)	0.51	
Lemons	0.51	0.42 (IT)
Melons	1.89	1.25 (IT)
Watermelons	1.33	
Grapes	0.42	
Cauliflower & Broccoli	0.48	1.00 (SE); 0.26 (UK)
Eggplant	1.30	
Tomatoes	0.72	3.62 (DK); 0.60 (IT); 2.83 (NL); 0.30 (ES); 3.00 (SE); 5.10 (UK)

Production-phase *Emission factors (EFs)* for the FFV commodities destroyed were derived from Porter et al. (2016). Country-level *EF*s are available for FFV commodities for the period 1997-2004, where destruction data were most granular in the DG-AGRI product reports (DG-AGRI, n.d. b). For the remaining years within the time period under review, Europe-level *EF*s were applied (Table 4-2).

4.2.1 Data limitations & key assumptions

FFV withdrawn from the market cannot use a sales channel to re-enter the food supply chain, though it may do so via other channels. 'Free distribution' to the most needy within the bloc is one of the EU's preferred channel for food withdrawals (DG-AGRI, n.d. c). Such withdrawn food remains within the food supply chain for human consumption. Other destinations/channels for withdrawn food include animal feed, direct distillation, and complete destruction. For the purposes of this paper, withdrawals destined for animal feed and distillation are excluded as they retain an element of use in the food supply chain. For the period 1989-2004, only the data which Agrosynergie (2007) categorises as 'Destroyed' are used to calculate embedded emissions. For 2005-7, where specific data on amounts or proportion 'Destroyed' are not available, the average of the previous years in the 2nd CMO Regime (i.e. 1997-2004) is assumed. For the years 2010-15, data received from the EU's DG-AGRI (pers. comm., 27 Oct 2017) are only categorised as 'free distribution' or 'other destination'. For these years, we assumed the latter is fully 'destroyed'.

The data for the Regime 2 period of 1997-2007 are the most granular; the DG-AGRI produced reports that disaggregated amounts withdrawn and destroyed for most FFV commodities at the country level. Thus, country-level *EF*s were used where available to estimate production-phase GHG emissions; and EU-level *EF*s where they were not. Annual commodity-level destruction data is only available for 2010-2015 (DG-AGRI, pers. comm., 27 Oct 2017). For the period 1989-1993 and 1997-2004, we applied annual overall destruction rates from Agrosynergie (2007) to all commodities in a given year. For 1994-1997 and 2005-2007, destruction data were not available. To account for this, we applied the average destruction rate of the other years within the respective CMO regime.

4.3 Results

4.3.1 Withdrawals of fruit and vegetables

Total quantity of FFV withdrawals by EU Member States between 1989 and 2015 was 23.7 Mt. Annual average quantities fell in each successive CMO regime from 2018 kt yr^{-1} in Regime 1, to 80 kt yr^{-1} in Regime 3 (the latter excluded 2008 and 2009 where data are unavailable; Table 4-3). However, an intra-Regime downward trend only occurs within the 2nd Regime of 1997-2007; the 1st and 3rd regimes do not demonstrate a strong trend in any direction. The total quantity of withdrawals at the end of the 1st and 3rd Regimes was 6% and 10% higher than at their respective beginnings (1.78 Mt vs 1.68 Mt and 67.6 kt vs 61.5 kt, respectively). In contrast, there was a 97% fall during the course of the 2nd Regime.

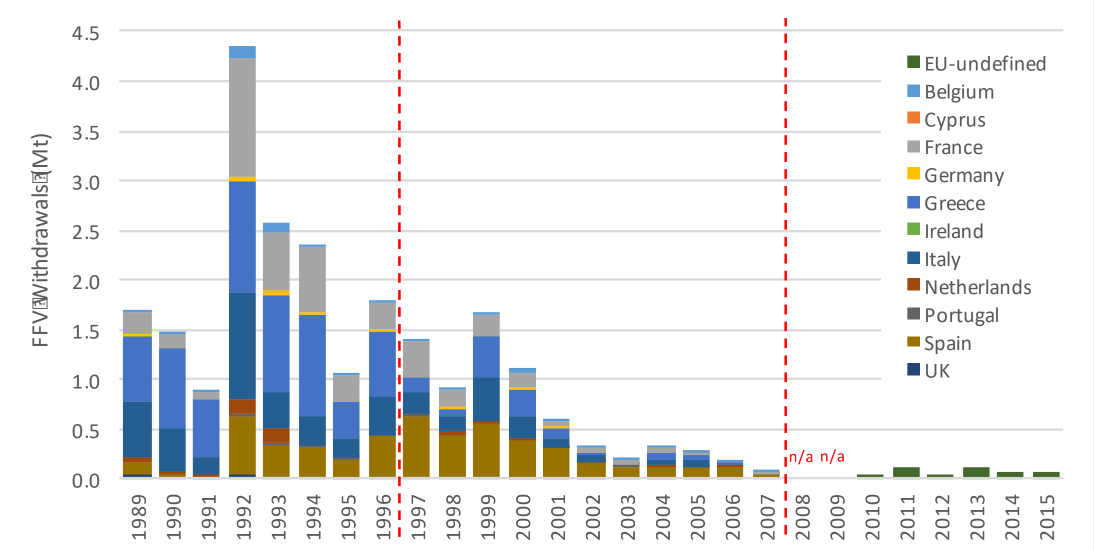

Figure 4-1. Annual withdrawals of food by country (in Mt). Sources: 1989-2004, Agrosynergie (2007); 2005-2006, DG-AGRI (n.d. b) product pages; 2010-15, DG-AGRI (pers. comm., 27 Oct 2017). Data was unavailable for 2008-9 and only EU-level aggregate data available for the period 2010-15. The dashed vertical lines separate the CMO regimes; 1st Regime (1989-1996), 2nd Regime (1997-2007), 3rd Regime (2008-2015).

Reviewing FFV withdrawals by country highlights the dominance of just four EU Member States. In each year of the 1st and 2nd Regimes (i.e. between 1989 and 2007) bar one, France, Greece, Italy, and Spain together accounted for at least 90% of all FFV withdrawals. The exception was 1993, where FFV withdrawals in these four Member States represented 87% of the EU total. Total withdrawals by these Member States during the full 1989-2015 period (21.6 Mt) were 93% of the EU total. In the 1st Regime, Greece withdrew the greatest quantity of food each year except 1992, accounting for 38% (or 6.17 Mt) of FFV withdrawals in that period. The 2nd Regime similarly saw one country, Spain, dominating the use of the mechanism each year and withdrawing almost 42% (or 2.93 Mt) of all FFV between 1997 and 2007 (Figure 4-1; country-level data were not available for Regime 3 and appear as 'EU-undefined' in this period for completeness).

4.3.2 Destruction vs 'free distribution' across CMO Regimes

The CAP has undergone significant reforms three times during the period under review, in 1992, 2003 and 2013. As a result, the original 1972 CMO regulations for FFV that specify how the CAP is to be implemented were similarly updated in 1996 and 2007 (Table 4-1; European Council, 1972, 1996, 2007). The effect of these policy changes has been to reduce the quantity of withdrawals and permitted destruction of FFV produce suitable for human consumption.

Destruction has been the destination for the majority of withdrawals in nearly all years under review (Figure 4-2); the only exceptions being the first two years of the 1st Regime (1989 and 1990). The average annual tonnage of FFV withdrawn from EU markets dropped 96% between the 1st and 3rd CMO Regimes, from an average of 2000 kt yr^{-1} to 80 kt yr^{-1}. Of these amounts, an annual average of 1100 kt yr^{-1} and 53 kt yr^{-1} were destroyed, respectively. 'Free distribution' saw a 6-fold increase in its share of withdrawals between the 2nd and 3rd Regimes (from 6% to 38%). However, there was little change in the average annual quantity freely distributed between these two Regimes (30 kt yr^{-1} vs 28 kt yr^{-1}), which is a third less than the average of 43 kt yr^{-1} during Regime 1. At the same time, the proportion of withdrawals that was destroyed rose from 50% to 62% (Table 4-3).

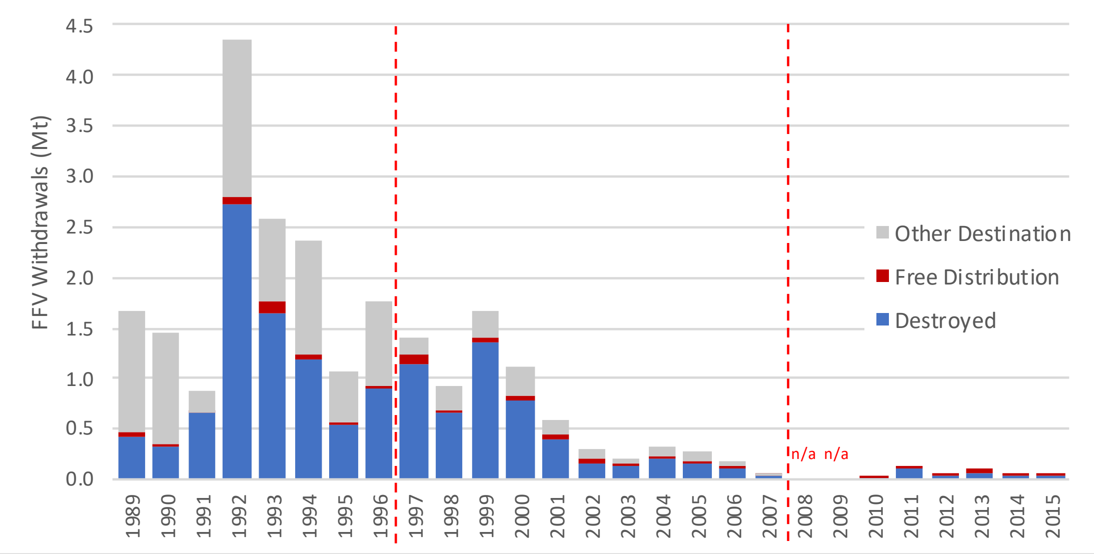

Figure 4-2. Destination of food withdrawals, aggregated to EU level (in Mt). Sources: 1989-2004, Agrosynergie (2007); 2005-2007, DG-AGRI (n.d. b), product pages; 2010-2015, DG-AGRI (pers. comm., 27 Oct 2017). No data available for 2008 or 2009. The dashed vertical lines separate the CMO regimes; 1st Regime (1989-1996), 2nd Regime (1997-2007), 3rd Regime (2008-2015).

4.3.3 Embedded emissions of withdrawn and destroyed FFV

Total production-phase GHG emissions of FFV withdrawn and destroyed via the CAP withdrawal mechanism during the 1989-2015 period are estimated at 5.1 Mt CO_2e. However, there has been a reduction of 91% in average annual embedded emissions of destroyed FFV withdrawals between Regime 1 and 3; from 365 kt CO_2e yr^{-1} to 31 kt CO_2e yr^{-1}. Most of this decline occurred during the 2nd Regime, falling from an intra-Regime peak of 595 kt CO_2e in 1999 to 23 kt CO_2e in 2007. Within this CMO Regime, embedded emissions steadily declined from the peak year (Table 4-3). In terms of the proportion of production withdrawn from markets, this was consistently below 3% during Regime 2, despite the existence of an upper limit of 10% for support. This contrasts with withdrawals of up to 50% of production, depending upon commodity and country, in the 1st and 2nd Regimes (Agrosynergie, 2007, p. 52). Since 2010 and under Regime 3 – where the maximum permitted withdrawal is 5% (for ‘free distribution’), the proportion of production withdrawn from market has not exceeded 0.5% for any FFV commodity (DG-AGRI, pers. comm., 27 Oct 2017).

The granularity of the data available during Regime 2 allows a detailed examination of embedded emissions that can be attributed to Member States. However, there remained some proportion of destroyed FFV that was not captured at the country level in this period. This information is denoted herein as 'EU-undefined' (Figure 4-3). As with the mass of FFV withdrawn, we again find a clear North/South divide in terms of attributing emissions from withdrawn FFV that was subsequently destroyed. During Regime 2, the Southern European countries of Italy, Spain, Greece, Portugal, and Cyprus accounted for 1180 kt CO_2e of country-attributable embedded emissions, 86% of the total 1370 kt CO_2e. Spain alone accounted for 45% (624 kt CO_2e) of this 'climate cost', with Greece and Italy adding a further 23% (313 kt CO_2e) and 17% (232 kt CO_2e), respectively. This division reflects differing agricultural production of Member States of withdrawal-eligible FFV commodities (Eurostat, n.d.).

The proportion of embedded emissions associated with destruction of particular FFV commodities has varied during the period under review (Figure 4-4), as have their absolute quantities (Table 4-4). Although there is generally less variation within a given CMO Regime, some trends emerge when viewed across Regimes. One such trend is the relative reduction in production-phase emissions associated with the destruction of stone fruit (e.g. peaches and nectarines) and of top fruit (apples and pears). Whereas these two commodity groups were responsible for over 60% of all embedded emissions in the 1st Regime, this fell to 15% in the 3rd Regime. In contrast, melons, which are relatively emissions intensive compared to other FFV (Table 4-2), saw a steady proportional increase in importance during Regimes 2 and 3. Vegetables (here comprising tomatoes, broccoli and cauliflower, and aubergines) have consistently accounted for the greatest proportion of production-phase emissions associated with destroyed food in the 2nd and 3rd Regime periods at around 40%. In 'climate cost' terms, each commodity group exhibited lower absolute annual average levels of embedded emissions from destroyed withdrawals in Regime 3 than in previous regimes where withdrawals were permitted (melons entered in Regime 2, for example).

Table 4-3. Variation in annual mean withdrawals and destruction of food (in kt), and embedded emissions (in kt CO_2e) during the three CMO regimes. The values in brackets are standard errors. (*) Data for Regime 3 only covers the six years of 2010-2015 due to lack of availability in 2008 and 2009.

CMO Regime	FFV withdrawn (kt yr^{-1})	FFV to 'free distribution' (kt yr^{-1})	FFV destroyed (kt yr^{-1})	Embedded emissions of destroyed FFV (kt CO_2e yr^{-1})	Average emission intensity of destroyed FFV (kt CO_2e kt^{-1})
1st Regime	2018	43.1	1053	365	0.18
1989-1996	(366)	(11.2)	(264)	(88.3)	(0.021)
2nd Regime	640	31.8	472	212	0.33
1997-2007	(158)	(5.3)	(130)	(55.9)	(0.011)
3rd Regime	80.2	28.2	52.0	31.1	0.39
2008-2015*	(13.3)	(5.2)	(12.2)	(8.06)	(0.038)

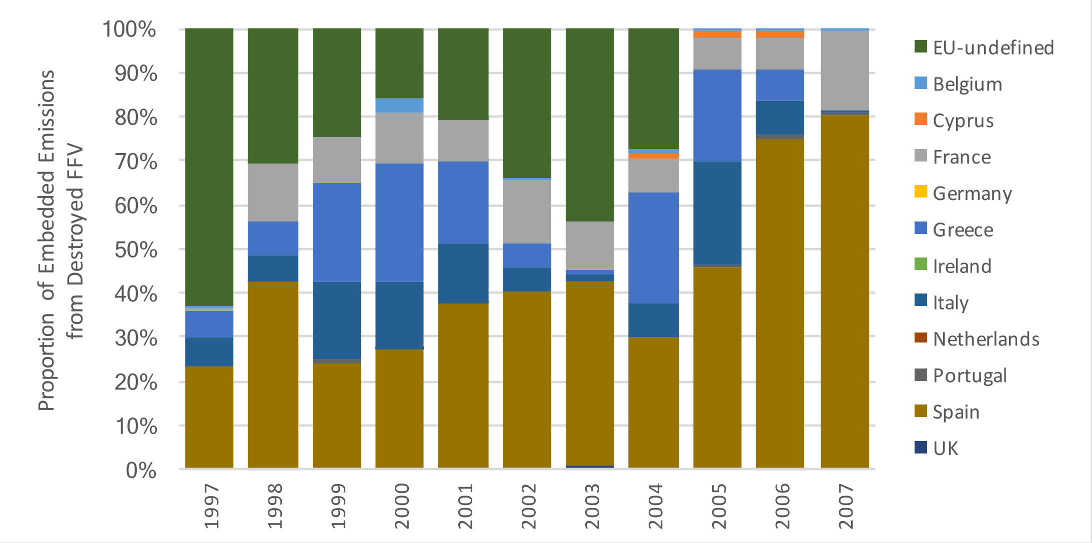

Figure 4-3. Proportion of embedded emissions of destroyed food. Sources: Country-level data was aggregated from DG-AGRI (n.d. b) commodity-level data; 'EU-undefined' data is from Agrosynergie (2007) for those commodities not captured at country-level (cauliflower & broccoli, aubergines/eggplants (EU data uses both terms interchangeably; 'aubergines' is used within this paper to refer to either), melons, and grapes).

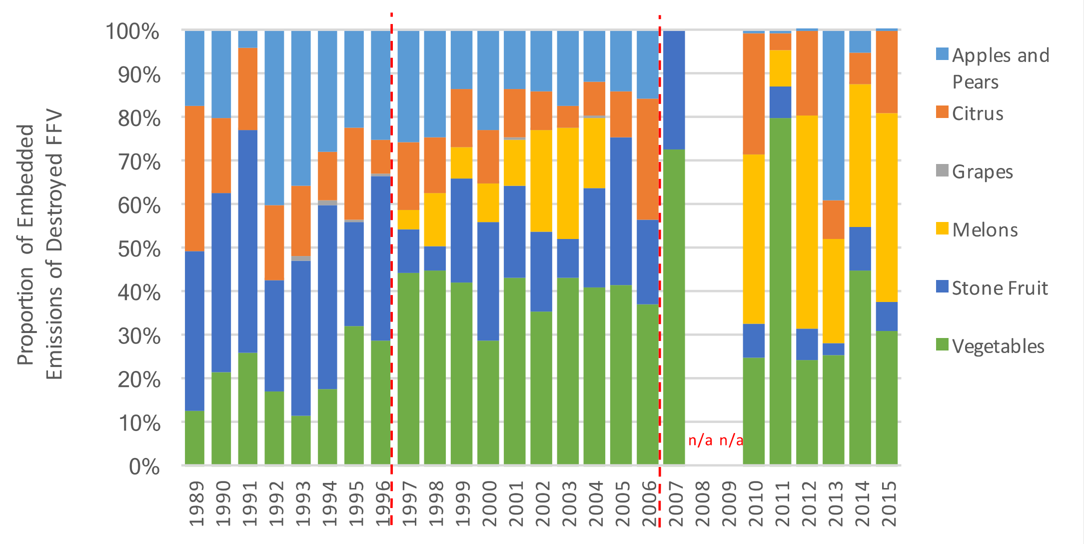

Figure 4-4. Embedded emissions by commodity (in kt CO_2e) of food destroyed annually between 1989 and 2015. Sources: 1989-2004, Agrosynergie (2007); 2005-2007, DG-AGRI (n.d. b), product pages; 2010-15, DG-AGRI (pers. comm., 27 Oct 2017). No data available for 2008-09. The dashed vertical lines separate the CMO regimes; 1st Regime (1989-1996), 2nd Regime (1997-2007), 3rd Regime (2008-2015). Due to the degree of reductions of absolute emissions between Regimes, this figure should be considered alongside Table 4-4 for context.

Table 4-4. Annual means of gross and proportionate emissions attributed to main FFV commodity groups across the full 26-year time period (1989-2015) and for each respective CMO regime. (*) Data for Regime 3 only covers the six years of 2010-2015 due to lack of availability in 2008 and 2009.

Commodity Group	Emissions (kt CO_2e yr^{-1})			
	Overall (1989-2015)	Regime 1 (1989-1996)	Regime 2 (1997-2007)	Regime 3* (2008-2015)
Apples & Pears	53.0 (16%)	108.4 (24%)	40.2 (16%)	2.4 (8%)
Citrus	31.8 (14%)	59.6 (18%)	27.1 (11%)	3.3 (14%)
Grapes	0.5 (0.1%)	1.7 (0.4%)	0.04 (0.0%)	0.01 (0.0%)
Melons	10.3 (12%)	0 (0%)	19.2 (10%)	7.8 (33%)
Stone Fruit	57.9 (22%)	125.7 (37%)	38.6 (20%)	2.1 (7%)
Vegetables	64.3 (35%)	69.6 (21%)	87.0 (43%)	15.5 (38%)

4.4 Discussion

4.4.1 Destruction as institutional inertia during market crises: Russian ban on EU FFV exports

Once harvested, fresh fruit and vegetables deteriorate in quality with a rate that is a function of heat and humidity – a quick transfer to optimal storage is key to maintaining quality (Blackburn and Scudder, 2009). This 'highly perishable' nature of the FFV seems to present particular challenges to minimising avoidable food losses when a market crisis occurs. One such challenge has been to reduce the proportion of withdrawn FFV that is destroyed. Despite a dramatic fall in excess of 95% in the quantities of FFV withdrawn from the market, the average proportion destroyed in CMO Regime 3 is higher than that in Regime 1 (65% vs 52%, Table 4-3). By their nature, crises are unexpected events. The failure to eliminate destruction of withdrawals suggests institutional inertia – once introduced, it is easier to continue to use existing provisions in the CAP than to stop and replace them (Peterson and Bomberg, 1999, pp. 142–143). When a crisis occurs, the provisions within the CAP that compensate for the use of destruction as an acceptable destination could result in an increase, albeit perhaps temporary, in the amount of avoidable food waste in the system. The following presents just such a crisis as an example.

In August 2014, Russia instituted a ban on imports of certain agri-food products from the EU, including FFV. Some have classed the ban as a retaliation for Ukraine-related sanctions imposed by the EU on Russia (Boulanger et al., 2016; Liefert and Liefert, 2015; McEldowney, 2016). Whilst predicated on international relations disagreements, the European Commission deemed it would precipitate a severe crisis for FFV producers within the EU. About 29% of EU FFV exports, valued at almost €2bn, were destined for the Russian market (McEldowney, 2016). Without that sales channel, EU FFV markets were at risk of from excess domestic supply. In a series of Commission Delegated Regulations between 2014 and 2017, the European Commission put into place 'exceptional support measures' to reduce the impact to farmers of this ban (European Commission, 2014a, 2014b, 2016, 2017). Each of these 'temporary' regulations waived the upper limit for FFV withdrawals, though did specify a maximum permitted tonnage that would be compensated. The measures have been fully taken up by producers, equivalent to an extra 1.1 Mt of withdrawals. Assuming 65% of these withdrawals are destroyed (the average for 2010-2015 that did not go to 'free distribution'), this single crisis event would result in the equivalent of an extra 335 kt CO_2e of embedded production-phase emissions.

Put another way, that is almost 2.5-times the estimate for total emissions for 2010-15 of destroyed FFV withdrawals in Table 4-3.

4.4.2 Using food destined for destruction via 'free distribution'

Reallocation of withdrawn FFV may support food programmes in EU Member States. These may be organised at any level; individual charity/NGO, the Member State, or the EU. An example of an EU-level programme is the School Fruit & Vegetables programme. In the 2015-16 school year, the programme provided an average of 53 portions of FFV to 11.7m school children in participating Member States (DG-AGRI, 2016); this is equivalent to 82.5 kt of food. Redirecting the average amount of FFV withdrawn and destroyed annually in CMO Regime 3 (52 kt, from Table 4-3) could increase the amount of fresh fruit and vegetables available to the programme by over 60%. This could benefit an additional 7.5m school children by maintaining current average portion levels, and possibly do so for less cost per portion than currently. The average cost of providing fresh fruit and vegetables to schools was €2.44 kg^{-1} (€0.33 per portion of 135 g; DG-AGRI, 2016). To put this cost into perspective, it is over 11-times the highest price (for oranges) and 41-times the lowest price (for aubergines) the EU would pay producers for these same commodities under the withdrawal mechanism (European Commission, 2007, annex X).

Producers also benefit from redirecting to 'free distribution' destinations those withdrawals that would otherwise be destroyed. The EU fully funds 'free distribution' withdrawals, which is up to twice the level of compensation as for other destinations (DG-AGRI, n.d. c). Withdrawals sent to organisations such as food banks, and local and third-country free food distribution schemes managed by NGOs would be eligible (European Council, 2007, art. 10, para. 4). Up to 15% more meals could be distributed to help alleviate hunger of an additional 900,000 people within the EU if the full amount of annually destroyed food were donated to, and accepted by, food banks. This estimate is based upon the 535 kt of food distributed to 6.1 million people in 2016 by members of the European Federation of Food Banks (FEBA, n.d.).

Transport costs of ‘free distribution’ are eligible for fixed rate reimbursement to the organisation incurring the costs (European Commission, 2007, art. 82). In practice, this provision may mean that the receiving organisation is required to first pay for the logistics costs of the donations. Alternatively, the producer could be liable for first paying such costs. It may be difficult for a receiving charitable organisation or the sending producer to fund the extra working capital necessary for delivery or receipt of additional food donations. Other costs that may be incurred to operationally manage the distribution of fast-perishable food such as FFV– such as cold storage and quick delivery – are not eligible for compensation. Should the fixed tariffs for transport not be sufficient to cover costs, further funding issues may arise for parties wishing to avoid unnecessarily destroying safe, edible food.

In addition to the monetary costs of transport and cold storage, energy (usually predominantly fossil fuel-based) is required to provide such services. Distributing food that is ‘extra’ to a planned system may therefore result in some increase in supply chain emissions. Presently, food available for consumption within the EU exceeds nutritional needs by 30-40% (Hiç et al., 2016), much of which ends up as waste (Gustavsson et al., 2011) or excess intake (Swinburn et al., 2009). Increasing food availability, by not withdrawing and destroying production in excess of market capacity to absorb, could increase the amount wasted in later stages of the supply chain. As a result, the embedded emissions of that waste may be higher than if destroyed pre-farm-gate. On the other hand, the bulk of FFV lifecycle emission occur in the production phase. They can be as high as 50% of the total for poultry and as low as 10% for beef, with FFV at about 15%, on a full cradle-to-grave LCA analysis (Porter et al., 2016). If redistributed FFV displaces other produce, and so lowers production demand, it is still likely to reduce GHG emissions relative to destruction.

4.4.3 Sustainable Development Goals (SDGs), diets, and climate targets

In the lead up to COP 21 in Paris, the UN General Assembly adopted the *2030 Agenda for Sustainable Development*, which included the 17 Sustainable

Development Goals (United Nations, 2015). Whilst there are synergistic interactions between many of SDG pairs, SDG 12 as a whole ('Responsible Consumption and Production') may be at odds with many others due to competing trade-offs (Pradhan et al., 2017). These include eliminating poverty and hunger (SDGs 1 & 2), and promoting good health and well-being (SDG 3). Achieving the SDGs relies, at least in part, on increasing incomes in non-OECD countries, which is also related to increases in GHG emissions from pursuing economic development (Costa et al., 2011), changes to diets (Pradhan et al., 2013; Tilman and Clark, 2014), and higher levels of food waste by consumers relative to production (EU FUSIONS, 2016; Gustavsson et al., 2011), amongst others. Further complicating potential synergies are official national dietary guidelines to promote healthy eating that are largely incompatible to achieving the 1.5 °C climate-change ambitions of the Paris Agreement as they are skewed to protein from meat and dairy (Ritchie et al., 2018).

Reducing avoidable losses of FFV at the production stage of the agri-food supply chain can have a direct impact in a number of these areas. A higher proportion of FFV entering the supply chain can reduce the amount needed to be grown, thus lowering production emissions. FFV are key elements to a healthy diet, yet consumption within the EU is well below levels recommended by the World Health Organization; the highest reported proportion being one-third, in the UK (Eurostat, 2016). Increased availability of affordable FFV, coupled with coordinated programmes to re-educate the populace on improved consumption could benefit diets as well as climate (the latter through lower food waste and possibly less livestock-based protein). Alternatively, holding production constant and achieving a greater throughput would lower production emissions intensity – a greater 'yield to market' for the same emissions cost. Therefore, progress towards SDG 12.3 – to "halve per capita global food waste at the retail and levels and reduce food losses" earlier in the FSC (United Nations, 2015, p. 22) – can be made by producers. Having those food waste improvements feed through the downstream FSC will require changes to attitudes, behaviours, markets, and policy. The EU's Platform for

Food Losses and Food Wastes is intended as a forum to bring together public and private sector stakeholders that have an interest in reducing FLW to do just this (DG-Health, 2016).

4.4.4 Policy successes & failures

The various reforms of the CAP and resultant CMO regimes have had the consequence of reducing FFV withdrawals. Instituting an upper limit on the proportion of individual FFV commodities that may be withdrawn, beginning with 10% during the 2nd CMO regime and tightening to 5% in the 3rd Regime, has been shown to be successful. Fewer withdrawals from the market have meant a lowering of the production-phase GHG emissions associated with this policy, as smaller quantities of FFV have been destroyed. The FFV commodity with the highest average annual withdrawal rate during Regime 3 was peaches, at 0.52% of production. Further, in this Regime there were only three instances of individual annual withdrawals greater than 1% of production; satsumas (1.25%) and pears (1.22%) in 2015 (Eurostat, n.d.), and nectarines (1.03%) in 2012 (DG-AGRI, pers. comm., 27 Oct 2017). This compares to the 1st CMO Regime when such proportions would at times exceed 20% of production (e.g. peaches in 1992-1994, and nectarines in 1992, 1994, and 1996; Agrosynergie, 2007, p. 36).

Another 'success' that might be attributed to the reforms of the CMO Regimes is the average proportion of withdrawals channelled to the neediest within the EU via 'free distribution'. This average increased with each CMO reform, from 2% in the 1st Regime to 38% in the 3rd. However, whilst the quantity of withdrawn FFV has fallen overall, so the absolute total amount directed to the 'free distribution' channel has also declined; from an average of 43 kt yr^{-1} in the 1st Regime to 28 kt yr^{-1} in the 3rd. Furthermore, the proportion of food destroyed increased from 52% to 65% for the same regimes (though Regime 2 saw the highest average rate of destruction of 74%). This suggests the existence of institutional barriers to redistribution that need to be overcome.

One such barrier could be other EU regulations that may be perceived as having primacy over the concept of 'free distribution'. For example, only food that is deemed safe to consume should be permitted to be sold or otherwise distributed within the EU, or exported. Very explicitly, "food shall not be placed on the market if it is unsafe" (European Parliament and Council, 2002, art. 14, para. 1). However, what is 'unsafe'? Van der Meulen (2012) offers the interpretation on the language used as the EU accepting that the concept is a continuum, with regulation that puts more stock in being safe than avoiding unsafe. Bartl (2015) highlights the lack of clarity of defining terms used in EU food safety regulation. The result is potential uncertainty of interpretation within the 'grey area' between what are clearly 'safe' and 'unsafe' by actors within the EU's food supply chain. The highly perishable nature of fresh FFV could lead potential recipients and donors to avoid the risk of distributing food that is 'unsafe', even though its condition may fall into the 'grey' area. Additionally, consumers may be unwilling to accept and/or feel slighted that they are being offered 'ugly food' that falls below a minimum acceptable visual 'quality' aesthetic (Aschemann-Witzel et al., 2017; de Hooge et al., 2017) – a concept we explore in a forthcoming paper.[4] Destroying withdrawn food could be seen by the potential parties as being lower risk than taking on the responsibility of ensuring such food is 'safe', and therefore more acceptable. Eliminating this uncertainty could unlock the potential of using more withdrawn food that would otherwise be destroyed.

4.4.5 Lack of specific food waste policy and national legislation as an alternative

We have seen that reduction in food waste can be a result (intended or otherwise) of policy reform, as demonstrated by the CAP. Whilst food may be considered as a commons (Vivero-Pol, 2017), managing the sector from a market-facing perspective has resulted in less use of the withdrawal mechanism over the series of CAP reforms. However, the European Court of Auditors (2016) highlights that, whilst as early as 2011 the EU parliament was

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[4] This "forthcoming paper" is presented as Chapter 5 in this thesis.

pushing the Commission for a concrete commitment to reduce food waste by half and provide leadership in action, little has been achieved. There is no specific EU policy on food waste, and policies that do exist are not fully aligned to combating food waste. Specifically including food waste in the next review of the CAP could address this.

It has thus far been up to individual Member States to take the initiative, something France and Italy did in 2016. As the González Vaqué (2017) comparative analysis illustrates, France's legislation focuses on raising awareness of actors at all stages of the food supply chain with a 'clear food waste hierarchy', but also looks to 'combat' food waste by emphasising prevention and imposing a general ban upon the practice. Critically, making food unsafe for the purpose of easy disposal is prohibited. Italy's legislation also focuses on education and using donations as a channel to reduce food waste, but goes further by specifically incorporating the concept of doing so for 'social welfare' purposes. It is too early yet to evaluate the effect of this legislation, though it should be area for inquiry in the medium term as data become available.

4.4.6 Brexit uncertainties & FFV waste

4.4.6.1 UK/EU FFV trade

In the current environment, it is appropriate to at least mention the impending departure of the UK from the EU. This is due to occur on 29 March 2019, two years after the UK triggered Article 50 of the Lisbon Treaty (UK Government, 2017). The data contained herein demonstrate the UK's use of the CAP's withdrawal mechanism has been minimal compared to other countries in the EU. Thus, the direct impact on quantity of withdrawals and destruction of food due to Brexit may also be minimal. However, the UK has a large trade deficit in FFV; the UK exported just £199m worth of FFV in 2015, less than 4% of the value of imports (AHDB, 2016). Whether or not a comprehensive trade deal is agreed between the EU and UK before Brexit-date could have indirect effects on the use of the withdrawal mechanism and its climate cost.

A 'no-deal' situation would result in the trade between the UK and EU reverting to World Trade Organization, Most Favoured Nation (WTO MFN) rules, the most negative scenario for the UK economy (Miller, 2016, pp. 24–25). The quantity of fruit and vegetables imported by the UK from other EU countries in 2016 was 3.1 Mt (AHDB, 2016). The average WTO MFN tariff applied to fruit and vegetable products was 10.5% in 2016 (WTO et al., 2017, p. 82). Leaving the EU Single Market would see these tariffs imposed on FFV EU imports into UK. The estimated impact would be increasing costs to the UK consumer by 7-11%, whilst at the same time reducing net imports (by a non-specified amount) from the EU (Van Berkum et al., 2016, pp. 30 & 33). EU producers may need to find alternative internal or export markets for any reduction in volume that would have gone to the UK should tariffs be re-imposed after Brexit. The Russian ban (Section 4.4.1) highlights how uncertainty can paralyse action. That ban has been in place since 2014, yet 'crisis prevention measures' permitting higher use of the withdrawal mechanism remained in place at the end of 2017. Should Brexit be viewed similarly if trade negotiations drag beyond March 2019 and/or there is a 'no-deal' outcome, it is conceivable that imports into the UK of EU FFV will decline (as costs rises). The EU could declare such events as a 'crisis' and invoke a relaxation of withdrawal limits, as it has done in response to the Russian ban.

4.4.6.2 Farm labour for harvesting in the UK

A second issue facing the UK food production under Brexit is having adequate labour. The UK's agricultural industry is highly reliant upon non-UK labour for harvesting; EU nationals comprise an estimated 98% of the seasonal labour in horticulture (European Union Committee, 2017, para. 253). A potential unintended consequence of the UK Government's Brexit negotiation's 'red line' of elimination of the free movement of people (Miller, 2017) could conceivably be a sudden loss of labour that is willing and able to undertake such activities within the agricultural sector. Without the necessary labour, there is a risk that a meaningful proportion of food produced within the UK will not be harvested at an optimal time (i.e. harvested early or late) or not harvested at all. The former may thus end up failing regulation and/or supermarkets' independent standards – ending up as inferior ‘Classes’ that command lower prices for the farmer. The consumer may also reject food that does not have the physical appearance they have become accustomed to. Such scenarios could lead to a greater levels of avoidable food loss, with a higher proportion of UK-produced food destroyed. The UK mainstream media has reported these scenarios as occurring during the 2017 harvest season, two years before Brexit (Daneshkhu, 2017; Simpson, 2017).

4.5 Conclusion

We have shown that EU policy can, and has, led to significant amounts of avoidable wastage of FFV and that this is associated with substantial production-phase GHG emissions. However, we have also shown that reforms of policy, even of those not specifically focused on food waste, such as the CAP, can have a positive impact on reducing the volumes of such loss and waste. The successive iterations of the CAP have resulted in changes to the underlying CMO regimes. The changes have resulted in reduced amounts of food avoidably lost within the EU. The quantity of FFV withdrawn from markets is over 95% lower, with the embedded emissions of that FFV 90% lower, than 25 years ago. There is some way to go on reducing the proportion of those withdrawals that are destroyed. However, actions by Member States, such as France and Italy, to keep food loss and waste on the public agenda and legislative record show promise.

Whilst these are potentially positive steps towards institutionalising reductions in avoidable FLW, the EU has not abandoned all market interventions for agricultural produce. The current version of the CAP retains eight specific “crisis prevention and management” measures for fruit and vegetables (European Parliament and Council, 2013, art. 33, para. 3). Two of these measures, withdrawals and green/non-harvesting, continue to lead to destruction of edible food. The European Commission has also demonstrated willingness to set aside, at least temporarily, some of the withdrawal and destination policy limits and expectations for crises. Such ‘short-term’ solutions do not challenge the status quo, risking a ‘back-sliding’ of efforts for the EU to meet its own food waste reduction aspirations.

Through the course of conducting this research, a number of areas for further investigation have presented themselves. There appear to be institutional barriers preventing greater use of destinations for market withdrawals other than ‘destruction’ (e.g. ‘free distribution’). Additionally, once there are sufficient data, an evaluation of the national legislation of France and Italy intended to combat and reduce the quantity food waste could prove useful for EU-level or other national-level policy. These are but two avenues of inquiry – the food loss and waste issue remains ripe with possibilities.

4.6 References

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Chapter 5
Climate cost of 'ugly' food

Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK[†]

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ABSTRACT

The use of aesthetics for classifying and accepting fresh food for sale and consumption is built into food quality standards and regulations of the European Union. The food distribution sector in Europe and the UK is oligopolistic in nature; a small number of supermarket chains control a large market share. The influence of these 'multiples' enables them to impose additional proprietary 'quality' criteria. Produce that doesn't meet these standards may be lost from the food supply chain, never seeing a supermarket shelf – it may not get past the supplier, or even leave the farm. Here, for the first time, we estimate the quantity of food loss and waste of fresh fruit and vegetables arising from cosmetic standards in Europe and UK, and its associated greenhouse gas (GHG) emissions. We find few direct measurements of such losses, resulting in large uncertainties for key commodities. In the context of these uncertainties, we estimate avoidable FLW from on-farm cosmetic grade-outs of up to 4,500 kt yr^{-1} in the UK and 51,500 kt yr^{-1} in the European Economic Area (EEA). Our estimates suggest over a third of total farm production is lost for aesthetic reasons, which equates to as much as 970 kt CO_2e (UK) and 22,500 kt CO_2e (EEA) of embedded production-phase GHG emissions annually. Examining the issue from the perspective of markets, suppliers, and consumers we establish there is an over-emphasis on superficial qualities (i.e. cosmetic appearance) of fresh produce, which leads to its unnecessary loss and waste. Using an illustrative case study, we provide potential avenues to mitigate these losses and the associated GHG emissions.

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5.1 Introduction

Food loss and waste (FLW) is one of the great scourges of our time. In excess of 10% of the global population is chronically hungry (FAO et al., 2017, p. 5), yet we lose or waste about a third of all food meant for human consumption at some point in the food supply chain (FSC; Gustavsson et al., 2011). Producing food accounts for 10-12% of global greenhouse gas (GHG) emissions, primarily nitrous oxide (N_2O) from crop production and methane (CH_4) from meat and dairy production (Smith et al., 2014). Food waste alone may account for up to 16% of environmental impact of the agri-food chain (Scherhaufer et al., 2018). In addition to global food security and nutrition challenges, producing food that does not serve its purpose of feeding the populace has potentially avoidable climate-cost emissions embedded within it.

There are many drivers of FLW, from the technological to the social (Canali et al., 2016). Amongst them in the agricultural production phase are 'aesthetic imperfection' and 'overplanting' of produce (Parfitt et al., 2010; Teuber and Jensen, 2016). These two drivers are linked – farmers must meet their contractual obligations to deliver specified tonnage of produce that meets particular standards (Beretta et al., 2013; Halloran et al., 2014). A proportion of yield is expected not to meet cosmetic criteria and thus may not easily be sold, and possibly not even harvested (Garrone et al., 2014). Cosmetic requirements are an important component of 'quality' standards for fresh fruit and vegetables (FFV) produced and sold in the global North – a greater number of prescribed elements apply to the appearance of FFV than to nutritional or food-safety characteristics (Porter et al., 2018). Produce deemed of too low a quality to enter the food supply chain may take several different non-food routes. It is typically ploughed back into fields, composted, landfilled, used as animal feed, or as anaerobic digestion feedstock (Beretta et al., 2013; Jeannequin et al., 2015; Redlingshöfer et al., 2017).

Reporting of on-farm FLW data by producers is not required by EU regulations – prior to harvest it is not considered to be food (European Parliament and Council, 2002, Art. 2). Discourse on food waste at the production stage has typically focused on accidental loss, such as from natural hazards and disease (Gille, 2012). In contrast, there is a dearth of studies quantifying avoidable food loss due to cosmetic standards and its embedded greenhouse gas emissions. Estimates at this life cycle stage are usually based upon a small number of studies carried out on just a few crops and applied to entire regions (Gustavsson et al., 2011), although others are more locally focused (Franke et al., 2016; Hartikainen et al., 2018). Some studies omit losses in the production phase entirely due to uncertainties (Monier et al., 2010). The few reported losses from failure to meet cosmetic criteria are wide and quite uncertain. The limited evidence of on-farm food losses due to aesthetics suggests upwards of 40% of harvested FFV produce can be lost from the food supply chain at this stage alone (Bloom, 2011, p. 96; Davis et al., 2011, p. 19; Stuart, 2009, p. 102). Recently, a more focused investigation in Germany and the Netherlands, utilising farmer self-assessed losses due to cosmetics, confirmed anecdotal evidence that wastage varies greatly by product, with 'typical' levels of about 20% (de Hooge et al., 2018).

Here, we extend the discourse by viewing food loss and its embedded GHG emissions through the lens of aesthetics. Cosmetics-centred 'quality' criteria derived from physical characteristics of attractiveness alone are imposed on many food producers by down-stream actors (such as regulators, retailers, and consumers). These criteria may stem from in-built consumer preferences, with other actors reacting in response (EU FUSIONS, 2014). Produce that is excluded from the food supply chain (FSC) through not meeting such aesthetic 'standards' can be regarded as avoidable waste. Likewise, greenhouse gas emissions associated with the production of this wasted food can be deemed avoidable, with changes in aesthetic classifications having the potential for emissions mitigation.

In the following, we provide what we believe to be the first estimation of production-phase embedded emissions of fresh fruit and vegetables lost from the food supply chain due to application of cosmetic standards. We then argue a complex and interactive system exists that encourages food waste and is perpetuated by all actors in the typical agri-food chain. As we will show, these actors include governments (via regulations of minimum 'quality standards'), supermarket multiples (via the power to impose private voluntary standards), and consumers (via learned expectations). Finally, we supplement this analysis and argument with a case study of an atypical farming operation within the Central Belt of Scotland to illustrate potential pathways to prevent cosmetic standard-driven FLW.

5.2 Estimations of EEA and UK grade-out losses and embedded emissions

5.2.1 Methods

The geographic areas of focus are the European Economic Area (EEA) and the UK. The EEA is comprised of the EU Member States as well as Iceland, Norway, and Switzerland. These three countries are all members of the EU's 'single market', and are thus bound by the same regulations on food produce as EU Member States. Only EEA and UK FFV crops with at least one published on-farm cosmetic grade-out loss factor (*LF*) and corresponding cradle-to-farm-gate emission factor (*EF*) are included in this analysis. The factors are taken from the underlying sources referred to by Porter et al. (2016), plus additional, more recent, sources from peer-reviewed literature and reputable grey-literature sources. The keywords "carbon footprint" and "life cycle analysis" together with "UK" and "Europe" were used to search the Scopus, ScienceDirect and Web of Science databases for peer-reviewed emissions factors published since 2016. Citation tracking was subsequently used to identify potential grey literature using the same filtering criteria. In addition, the official French database of agriculture emissions, ADEME, (2017), was included. The resulting literature was further filtered to include only those with emissions factor data in CO_2 for the production stage, or had sufficient detail included to make this conversion, for fresh fruit and vegetables. Full details of sources and values for both *LF* and *EF* variables are contained within Table B-1 and Table B-2.

The estimates we used for regional EEA on-farm grade-out FFV loss factors (*LF*s) and their production-phase embedded emission factors (*EF*s) are crop-specific from any EEA country. In the UK, all but two crops have a country-specific *LF*; for pears and cabbages, the respective EEA factors are used as proxies. *LF*s may be reported as a range or as a single estimate; *EF*s are typically reported as a single point estimate. The absolute minimum and maximum estimates are identified for each crop's *LF* and *EF* for the EEA and also within the UK sub-set. We also make a central estimate of the *LF* for each crop by averaging the mid-points of ranges and the single estimates. Alternatively, the central estimate of the *EF*s is an average of all reported estimates for each crop within the EEA as a whole and also for the UK specifically. We present these as 'min', 'max', and 'central' in section 5.2.2. Data for FFV production for the year 2016 was sourced from the eurostat (n.d.) database. Non-food use data was obtained from the United Nation's Food and Agriculture Organization's (FAO) Food Balance Sheet database (FAOSTAT, n.d.); see Table 5-1.

We estimate the mass of on-farm cosmetic grade-out losses with the model shown in Equation 5-1. We use the Eurostat database for FFV crop production in the EEA as a whole and the UK specifically. Most FFV crops have a single entry for *Harvested Production*; this value is used. However, tomatoes, apples, and pears, have two entries for *Harvested Production*. For these three crops, we use the quantity indicated as 'for fresh consumption' in the Eurostat database; cosmetic criteria are not applied to that proportion of these crops intended 'for processing' from the outset. FFV graded-out on-farm does not enter the food chain and therefore is not included in *Harvested Production* data (Redlingshöfer et al., 2017). We adjust for this in the denominator term of Equation 5-1.

Equation 5-1

$$Loss_s = \sum \left(\frac{Harvested\ Production_{j,k} * AF_{j,k} * \ LF_{j,k,s}}{1 - LF_{j,k,s}} \right)$$

where, *Loss* is the total food loss in scenario *s* from on-farm cosmetic grade-outs (in kt); *Harvested Production* is the mass (in kt) of food crop *j* in country *k*, (where *k* is either the UK or EEA); *AF* is the allocation factor of crop *j* in region *k* (Equation 5-2); *LF* is the loss factor (in %) for crop *j*, in country *k*, under scenario *s* (minimum, maximum, central).

Some portion of a crop may be intended for seed or other use, but not recorded in Eurostat as such. To adjust for the non-food uses, we create a weighted-average allocation factor (AF) for each FFV crop. We use annual FAO data for the most recent five-year period available (2009-2013), as shown in Equation 5-2 The only FFV crop affected is potatoes – where the AF is calculated as 0.86 for the EEA and 0.88 for the UK. That is, 14% and 12% of the respective recorded harvests for the EEA and UK is not intended for human consumption and thus do not have cosmetic standards applied to them.

Equation 5-2

$$AF_k = 1 - \left(\frac{Seed_k + Other\ Uses_k}{Production_k}\right)$$

where, for crop j in region k (the EEA or UK) for the period 2009-2013: AF is proportion of the FFV crop not intended for consumption by humans; $Production$ is the amount of crop (in kt); $Seed$ is the amount directly used to propagate a future harvest (in kt); and $Other\ Uses$ is the amount intended for any other non-food purposes (in kt).

Finally, we estimate the production-phase embedded emissions (Em) using the 'minimum, 'maximum', and 'central' peer-reviewed crop and region-specific cradle-to-farm-gate emission factors (EFs) detailed previously. These factors are applied to the three grade-out $Loss$ estimates ('minimum, 'maximum', and 'central') from Equation 5-1 for each FFV crop in the EEA and UK (Equation 5-3). The result is a 3x3 scenario matrix of total EEA and UK, and specific FFV crop Em estimates.

Equation 5-3

$$Em_{j,k,s} = \sum Loss_{j,k,s} * EF_{j,k,s}$$

where, Em is the quantity (in kt CO_2e) of GHG emissions of crop j in country k for scenario s; $Loss$ (in kt) is food loss for crop j in region k from Equation 5-1, and; EF is the emission factor (in kt CO_2e kt^{-1}) for crop j in country k for scenario s. Summary data is provided in Table 5-1.

Table 5-1. Summary of data used to estimate range of on-farm cosmetic grade-outs of FFV. *Harvested Production* for potatoes is adjusted for its allocation factor from Equation 5-2. Fully referenced tables for Loss Factors and Emissions Factors are provided in Table B-1 and Table B-2.

		Harvested Production	Loss Factor (%)			Emissions Factor (kt CO_2e kt^{-1})		
Crop	Region	(kt)	Min	Central	Max	Min	Central	Max
Apple	UK	208	5	15	25	0.11	0.21	0.32
	Europe	9,309	1	10	25	0.02	0.17	0.43
Broccoli + Cauliflower	UK	152	3	12	20	0.29	1.12	1.94
	Europe	2,341	3	12	20	0.29	1.26	2.22
Cabbage	UK	231	8	22	40	0.22	0.22	0.22
	Europe	3,821	8	22	40	0.22	0.35	0.48
Carrot	UK	724	24	31	50	0.05	0.20	0.35
	Europe	5,663	10	23	50	0.02	0.17	0.50
Lettuce	UK	107	5	26	50	1.00	1.39	1.78
	Europe	2,285	5	24	50	0.26	1.01	1.78
Onion	UK	390	9	15	20	0.07	0.22	0.37
	Europe	6,623	8	17	33	0.04	0.23	0.48
Pear	UK	24	10	11	12	0.32	0.32	0.32
	Europe	2,231	10	11	12	0.20	0.32	0.43
Potato	UK	4,888	3	19	40	0.17	0.22	0.26
	Europe	48,729	3	14	40	0.09	0.19	0.51
Strawberry	UK	118	1	12	35	0.80	0.94	1.27
	Europe	1,311	1	10	35	0.30	0.78	1.27
Tomato	UK	97	7	7	7	2.07	4.34	9.40
	Europe	6,969	1	3	7	0.11	1.59	9.40

5.2.2 Results

5.2.2.1 Cosmetic losses

The Eurostat-recorded harvest quantity for FFV in the EEA and UK in 2016 is 89,300 kt and 6900 kt, respectively. Estimated on-farm grade-out losses of FFV in the EEA range from 3700 kt to 51,500 kt and from 470 kt to 4500 kt for the UK in 2016 (see Supplementary Information). Thus, the range of losses for cosmetic reasons is 4 – 58% and 7 – 65% of recorded *Harvested Production* in the EEA and UK, with an 'central' estimate of 17% and 25%. As indicated in Section 5.2.1, *Harvested Production* from the Eurostat database does not include grade-out losses. Adding the losses back gives total actual FFV farm production intended for human consumption of 93,000 – 141,000 kt for the EEA, and 7400 – 11,500 kt for the UK. The estimated range of on-farm cosmetic grade-out losses relative to total farm production in the EEA and UK is 4 – 37%

and 6 – 39%, respectively, with a ‘central’ value of 14% for the EEA and 20% for the UK.

In the UK, cosmetic grade-out losses are dominated by potatoes and carrots (Figure 5-1a). This is a function of their importance as an agricultural crop – potatoes were 70% of the UK FFV harvest by mass in 2016, whilst carrots were 10%. They also have higher minimum, maximum, and central cosmetic grade-out *LF*s relative to other crops. Together, these two crops account for 81 – 88% of grade-out losses by mass. This is equivalent to 380 – 4000 kt of losses, with a ‘central’ value of 1500 kt. Onions and cabbage, the third and fourth most important crop group for UK farming (just under 10% combined total), deliver just 6 – 13% of grade-out losses (250 – 880 kt, ‘central’ estimate of 390 kt).

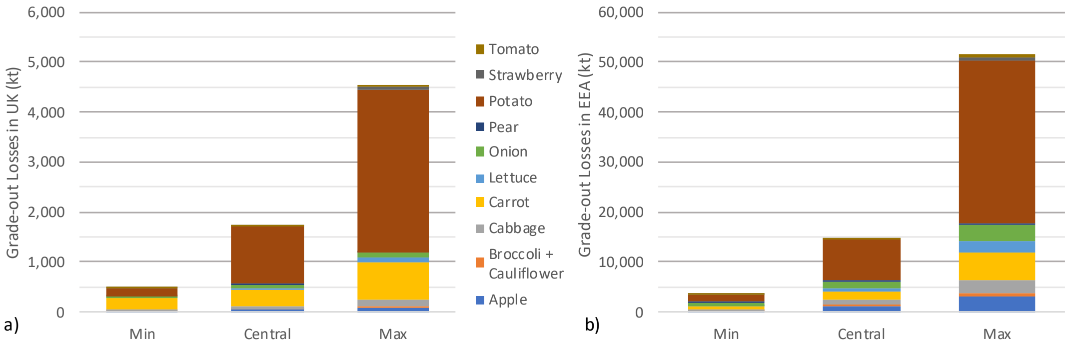

Figure 5-1. Grade-out losses (in kt) in 2016 in **(a)** the UK, and **(b)** the EEA of the different FFV crops, applying the minimum, maximum, and ‘central’ *LF* estimates to recorded *Harvested Production* in Table 5-1 (i.e. the output of Equation 5-1).

Total grade-out losses for FFV within the EEA are estimated to range from 3700 kt to 51,500 kt. Similar to the UK, potatoes dominate cosmetic-related losses in the EEA, accounting for 41 – 63% of all grade-outs by mass (1500 – 32,500 kt, ‘central’ estimate of 7900 kt) from 55% of recorded production volume. Carrots, onions, and brassicas, are key hotspots of grade-out losses in the remaining 45% of the harvest (Figure 5-1b). Together, these latter three crop groups account for FFV losses of 1600 kt – 12,100 kt (‘central’ value of 4400 kt), equivalent to 23 – 44% of EEA on-farm grade-out losses (see Appendix B for details).

5.2.2.2 Embedded emissions of cosmetic losses

Applying three *EF* values (minimum, maximum, and 'central' estimates) for each *Loss* scenario generates nine 'scenarios' of embedded production-phase GHG emissions. The absolute and proportional emissions of three scenarios for FFV in the UK and EEA are shown in Figure 5-2. They are the output of Equation 5-3 using the Min-Min, Central-Central, and Max-Max combinations of *Loss* from Equation 5-1 and *EF* values from Table 5-1. Relative importance of crops and their production-phase emissions is evident when comparing the UK with the EEA at large. Total embedded production-phase GHG emissions of food loss due to cosmetic criteria in the UK range from about 60 kt CO_2e in a 'minimum' scenario to 970 kt CO_2e in a 'maximum' scenario, with a 'central' estimate of 380 kt CO_2e. At the EEA level, total production-phase embedded GHG emissions range from about 340 kt CO_2e to almost 22,500 kt CO_2e, with an 'central' estimate of about 3600 kt CO_2e (details of all scenarios are in Table B-4). To put these latter figures in context, they are up to roughly 5% of the 426,000 kt CO_2e of GHG emissions attributed to the European agriculture sector in 2015 (Eurostat, 2017).

In the UK, the highest levels of embedded emissions from grade-out losses are from potatoes, carrots, and brassicas; together they account for 55 – 77% of the total. Potatoes have a relatively narrow range of UK-specific *EF* estimates (0.17 – 0.26 t $CO_2e\ t^{-1}$), typically at or near the lowest factor value for FFV crops. Even so, because of the high production volume and grade-out losses of potatoes, this crop is apportioned the highest level of embedded emissions. Our estimates of these emissions for the UK potato crop range from 25 to 510 kt CO_2e, with a central estimate of 200 kt CO_2e (or 19 – 67% of the total for the UK). Embedded emissions in grade-out losses of carrots and brassicas range from 14 – 210 kt CO_2e, or 10 – 36% of the UK total. The range of absolute and proportionate emissions of carrots and brassicas reflects the higher level of uncertainty in the *EF* literature of these crops relative to others, particularly potatoes.

Trends at the EEA region level are similar to those for the UK specifically. Potatoes are also the most important in terms of magnitude of embedded GHG emissions in all nine scenarios for the EEA. This one crop accounts for roughly one- to two-thirds of these emissions (or, 130 – 9900 kt CO_2e) with a 'central' scenario estimate of 36% (1300 kt CO_2e). Brassicas and root vegetables (carrots and onions) together account for 19 – 35% of embedded emissions ('central' of 30%), or 120 – 4200 kt CO_2e ('central' estimate of 1100 kt CO_2e; see Appendix B for detailed breakdown by FFV crop).

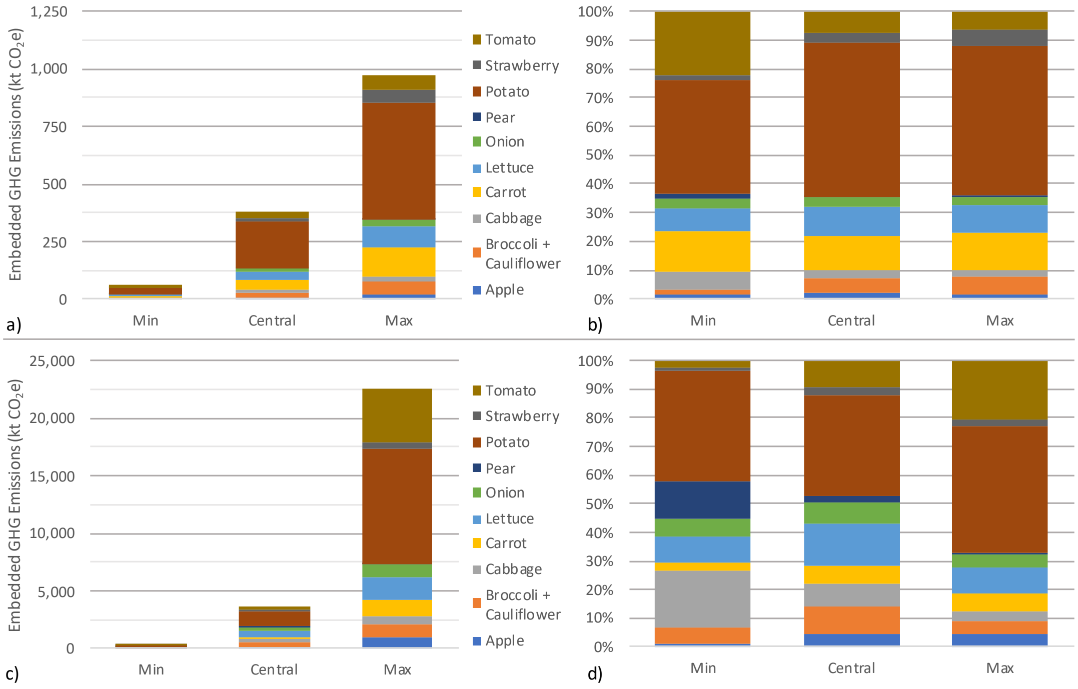

Figure 5-2. Production-phase embedded GHG emissions of grade-out losses by FFV (in kt CO_2e) and as a proportion of total FFV by scenario for the UK **(a, b)** and the EEA **(c, d)**. The three scenarios correspond to application of the Minimum, Central, and Maximum estimates of both the *LF* and *EF* variables from Table 5-2 (i.e. the Min scenario represents Min*LF* and Min*EF*). Details of all nine scenarios examined are contained within Table B-4.

5.2.2.3 Limitations

There is considerable uncertainty in these results, demonstrated by the range of our estimates for absolute FFV losses at farm-level and their respective embedded emissions. We have assumed that studies on these loss factors conducted on a particular crop in one country within the EEA are relevant to the same crop in another country. There is a very limited amount of data currently available on FFV loss factors at farm level. A further significant assumption in our results is that all grade-out food losses have left the agri-food chain for destinations such as composting or ploughing-in and are therefore considered waste whose embedded emissions should be accounted for. There is no discernible consensus on what proportion of cosmetic losses of FFV would have another food-related use (such as animal feed, or used in further food processing). Porter et al. (2018) reports that within the EU under the current Common Agriculture Policy, approximately two-thirds of safe, edible FFV withdrawn from market after harvest is destroyed. De Hooge et al. (2018) states ploughing in, animal feed, and anaerobic digestion were the most common destinations, and that few of their interviewees mentioned selling a lower class product was a viable option. Redlingshöfer et al. (2017) indicates reuse plays a moderate role, but estimates a destruction rate greater than 80% for even the crop most commonly redirected to animal feed (i.e. potatoes). Terry et al. (2013, 2011) indicate the destination of grade-outs depends heavily on the crop, with ploughing-in the common destination for lettuce, tomato, and strawberry, whereas potato typically goes to animal feed or compost. Jeannequin et al. (2015) and Meyer et al. (2017) argue that field-graded produce, whether picked by hand or mechanised, is simply ploughed-in, but post-harvest graded produce is more likely to be redirected to another food use.

Embedded emissions calculations rely on estimates of UK- and Europe-specific emissions factors for fruit and vegetable published between 2000 and 2018. Coverage of food commodities in this literature was variable and sometimes seemingly dated (the oldest source is from 2006). For example, UK cabbage and pear have one *EF* estimate each (from 2009) whereas there are more than a dozen from 1998-2018 for EEA tomatoes (see

Table B-2). A review of the LCA literature by Clune et al., (2017) highlighted the considerable variability in such estimates across food group and showed activity in this area dropping considerably by 2015 relative to the seven years prior. This finding – little data, and with considerable variation – is consistent with the results of our own literature review. It also demonstrates continued, more localised research on greenhouse gas emissions of food across its full life cycle is warranted.

5.3 An over-emphasis on cosmetic appearance of fresh produce

In the following we present arguments for why FFV loss and waste from aesthetic standards – as estimated in the previous section – may occur.

5.3.1 Waste Encouraged by current marketing standards & regulations

Food safety and food quality are treated separately within EU regulations, with safety paramount. Article 14(1) of the General Requirements of Food Law states "food shall not be placed on the market if it is unsafe" (European Parliament and Council, 2002). However, it may be that food safety laws are overly strict, thus creating unnecessary inefficiency in the food supply chain (Aschemann-Witzel, 2016). As a result, only fresh produce that is deemed safe for human consumption is subject to 'quality' standards. Fresh produce has natural variability in terms of size, colour, and shape; cosmetic appearance is not uniform. The EU's Common Market Organisation (CMO) regulations specify particular requirements for different types of fresh produce to grade them (in ascending order) as Class II, Class I, or Extra Class (European Commission, 2011, Annex I, Part B). EU Member States may permit unclassed fresh produce to be sold in retail outlets provided it is clearly labelled as 'for home processing' or similar (Defra, 2017). This regulation implies fresh produce that does not meet arbitrary cosmetic requirements is not fit for consumption in its natural form (see Appendix B.2 for a selection of 'acceptable' aesthetic requirements).

These EU-level marketing standards codify a common set of minimum acceptable criteria across EU Member States which, together with the EU CAP reforms of 2013, are intended to improve the competitiveness of international trade of agricultural produce of those States (DG-AGRI, 2013). For example, it is easier to pack and ship produce of standard, versus varying, proportions. The relative efficiency of the stages between the farm-gate and the consumer would appear to support this preference. Loss rates for fruit and vegetables in Europe at the handling and storage, processing, and distribution stages range from 2-7%, between a tenth and a third of the 20% estimated pre-farm-gate loss rate (Porter et al. 2016, Table SI 1).

5.3.2 Waste Currently endorsed (and 'gold-plated') by retailers

The evidence that sub-optimal ('imperfect'/'ugly') produce won't sell is inconclusive. De Hooge et al. (2017) provides support for the claim. Their choice modelling survey reported a clear preference to 'optimal' foods whether in the home or supermarket. Much variability remains unexplained, but that 'beauty is good' seemed to apply to foodstuffs. At least in an artificial, online environment a price discount was required to equalise optimal and sub-optimal choice preference. In contrast, Aschemann-Witzel et al. (2017) states that 'quality' is linked primarily to characteristics such as taste, nutritional quality, and food safety. As we stated in Section 5.3.1, EU CMO marketing standards only specifically consider the latter. Whilst urban consumers in developing and developed countries (i.e. China and Denmark) may share a preference for 'perfect' produce (Loebnitz et al., 2015; Loebnitz and Grunert, 2015), only 'extremely abnormal' cosmetic appearance affects willingness to purchase in the former (Loebnitz et al., 2015). Within developed countries, a pro-environmental self-identity may also positively influence willingness to purchase 'wonky' veg (Loebnitz et al., 2015). The range of these findings suggests beliefs of what consumers will accept is too narrow, resulting in unnecessary food loss at the production phase by prohibiting 'ugly' produce from entering food supply chain.

The application of retailer's private standards at the farm level influences production and distribution practices. Selective harvesting is an integral component of fresh fruit and vegetable production, with pickers trained to take only the produce that will meet retailer's standards for sale (Gunders, 2012).

Potential edible-quality yield may be greater than that actually harvested, but the extra costs from picking fruit that doesn't meet expected aesthetic standards and will thus be rejected at the next stage in the agri-food chain would drive down economic yield. For the proportion that would not meet standards and thus be left in the field, creative marketing / processing / distribution of such produce could reduce avoidable on-farm loss, potentially increasing farm income and food availability (Stuart, 2009, p. 102). For example, processing 'misshapen' carrots into 'baby' carrots can eliminate virtually all food waste associated with this vegetable (Peterson, 2008). Additionally, some charities and volunteer organisations, such as the St. Andrews Society in the U.S. and Feedback in Europe, engage with the farming community to collect produce for re-distribution that would be rejected by supermarkets (Feedback, 2018; SoSA, 2018). The prices obtained, and thus economic margins, of such out-graded produce may be lower than that of the highest classification (Roels and van Gijseghem, 2017), but provided they at least cover the cost of harvest, then it is worthwhile for the farmer to do so. If not, then the rational economic decision is to 'walk-by' such produce – leave it in the field and plough it under as preparation for the next cycle.

It is not in the farmer's interest to have 'quality' standards based upon appearance that results in produce not being harvested and sold if such produce is safe to eat. Such standards differentiate produce of the same variety, with higher classifications achieving a higher selling price in normal conditions, but can result in substantial levels of on-farm loss pre- and post-harvest (Garnett, 2006, p. 63). Gunders (2012) provides several individual examples of losses for different produce (cucumbers, citrus, tomatoes, stone fruit) regularly reaching or exceeding 50% in a season.

Labelling of fresh produce is another manifestation of private standards and the demonstrates the power of supermarkets in defining a message. The use of devices that permit a 'flexible best-before date' have been successful in reducing loss between processor and distributor (Dobon et al., 2011). However, consumers commonly misinterpret 'quality' labels, such as 'best before' and 'sell-by', as indicative of safety, leading to avoidable waste as food is discarded whilst still safely edible (Lebersorger and Schneider, 2014). Dynamic pricing – reducing the price of produce approaching its 'best before' – can increase purchase activity by the consumer and reduce supermarket waste (Aschemann-Witzel et al., 2016). The potential downside to such a marketing strategy is increased food waste by households if consumption patterns are not adjusted (Brook Lyndhurst and WRAP, 2012). Better 'food knowledge' on behalf of the consumer – knowledge that is built up over time through exposure to food and its uses (which is being lost in developed countries as we are ever more removed from the food chain) – could result in greater acceptability of a greater range of cosmetic appearance.

5.3.3 Waste perpetuated by the structural power of large supermarkets

The food supply chain in many EU countries has undergone such consolidation that it can be considered an oligopoly. For example, at the end of 2017, the five largest chain food retailers ('multiples') had over 75% of the market share in each of the UK, France, and Ireland (KANTAR WorldPanel, 2018). This concentration is a marked change from the early post-WWII years, where multiples in the UK had a market share of 30% (Harvey, 2007). Whilst the number of institutional buyers has fallen through this consolidation, the supply-side of the relationship has not undergone a similar transformation. The relative imbalance in scarcity – there is far more competition for sellers – leads to greater power being held by the retailers as buyers (Cox and Chicksand, 2007).

In addition to horizontal market consolidation of food retailing, some multiples have also consolidated vertically, taking a controlling interest in upstream production (Simons and Skydmore, 2017). Supermarkets exert their buyer power by imposing 'voluntary private standards' of cosmetic specifications for fresh produce (Henson & Humphrey, 2010). The power exerted by the structure of the market – many suppliers for few retailers – acts as extra-governmental regulatory reach by the supermarket multiples. Private rules may be used to enhance or maintain a retailer's reputation as well as managing suppliers (Fulponi, 2006). They are codified within business relationships of the more powerful party and often form part of contractual terms and conditions (Rindt and Mouzas, 2015). This power structure limits producers' ability to influence the imposition of 'quality standards' (Gille, 2012). Such standards lead to avoidable food loss at the farm-level (Devin and Richards, 2016).

The oligopolistic nature of many developed countries' agri-food chains effectively make supplier compliance of 'private' standards mandatory (Davey and Richards, 2013). The more asymmetric the relationship between multiples and their suppliers, the more likely the dominant party will be able to exercise power over the weaker. Within the agri-food chain, this has manifested itself in the proliferation of 'private standards' by the supermarkets (Rindt and Mouzas, 2015). These private rules 'normalise' and auto-reinforce what is otherwise an imbalanced relationship, shifting risk onto the weaker party (i.e. the supplier) via an 'intervention-enforcement-sanctioning' feedback loop (Rindt and Mouzas, 2015). The consolidation of supermarket multiples within the agri-food chain has led to a virtual vertical integration with fewer suppliers and a strengthening of power of those multiples (Hingley, 2005). By coming together as a cohesive group acting in concert (promoted as 'producer organisations' by the EU in recognition of supplier-retailer imbalance as a potential driver of food waste (European Court Auditors, 2016, p. 52), suppliers could shift the power relationship towards a balance with retailers (Maglaras et al., 2015).

5.3.4 Waste perpetuated by the consumer's learned experience

What produce should 'typically' look like guides purchase intentions – consumers are more likely to purchase something that is familiar and recognisable (Gigerenzer and Gaissmaier, 2011). Consumers use simple learned heuristics of visual appearance to make food selection rather than the time-consuming process of comparing large amounts of data (Schulte-Mecklenbeck et al., 2013). Consumers' lack of experience of abnormally shaped food leads them to view such produce as more risky and less natural than produce that conforms to supermarket standards (Loebnitz and Grunert, 2018). Although moderate differentiation/incongruity of produce may increase the attention paid to that product by a consumer (e.g. a new variety of familiar produce), there is a counteracting social risk of being linked with food whose appearance is atypical (Campbell and Goodstein, 2001). Visual perception and setting influences consumers' expectation of taste experience; they are less willing to purchase cosmetically 'sub-optimal' fruit than consume it in the home (Symmank et al., 2018). Consumers appear to apply a 'beauty mystique' – a sociological concept to judgement where goodness is beauty and beauty is goodness (Synnott, 1989) – to fresh produce. Being exposed to broader parameters of 'normal' during the learning phase could lead to an acceptance of 'sub-optimal' food.

Heuristics are well-entrenched, and may interact with each other. Knowledge of origins of food (e.g. organic or not) and acceptance of abnormally-shaped food may be inversely related (Loebnitz and Grunert, 2018). The 'blender effect' of Szocs and Lefebvre (2016) – greater 'processing' is required in the home to achieve acceptable palatability – may reduce likelihood of purchase. Labelling of visually sub-optimal produce that reinforces its taste may have more influence on the purchase decision of 'ugly' food than price discounts relative to optimal produce (Helmert et al., 2017). Loss aversion – e.g. avoiding throwing away 'good money' by binning uneaten produce – is a powerful modifier of behaviour (Moseley and Stoker, 2013). Unintentional or unconscious decisions may result in actions by consumer waste activity not otherwise aligned with their attitudes, referred to as the 'squander sequence' by Block et al. (2016). Wasteful behaviour or attitudes may not be universally held, even within a given culture. Over 65s in the UK exhibit behaviours that typically lead to less food waste relative to younger consumers. For the last generation to have experienced government food rationing 'wastefulness' in general is 'just wrong' (Quested et al., 2013). Consumers are key to sustainable food choices, and those choices can influence upstream efficiency, leading to more or less food loss and waste along the food supply chain.

5.4 Learning opportunities case study

In this section, we use a case study as a small-scale illustration of what may be possible, in a UK context, to address food loss and waste of 'ugly' produce from the endemic drivers discussed in section 5.3 previously. Specifically, we are concerned with avoidable food loss at the farm-level as a function of aesthetics, a key aspect of quality within the food industry and regulatory bodies. Care was taken in choosing a case atypical to the *status quo* UK agri-food supply chain. Conclusions drawn may not be generalisable to other fresh produce or farming operations, particularly for farms and distribution that are much larger in scale and with more complex supply chains. As a single case study, it should be viewed as explorative rather than definitive; a potential precursor to inform larger scale investigations. However, whilst the case's operations may not be fully applicable to industrial food producers, it demonstrates removing the real or perceived need to abide by cosmetic standards unrelated to food safety could lead to significant cuts to food losses. This section is intended to spark discussion and review of policy, custom, and behaviour to improve efficiency across the food system.

5.4.1 Illustrative atypical case study: Description of case and data collection methods

A medium-sized farm (c. 500 acres) in the Central Belt of Scotland was selected as the case study, with strawberry production as the unit of interest. The farm has been run under a perpetual lease by the same family for three generations, with the current generation in place for over 15 years. The farm uses standard production techniques for Scotland, such as raised coir-beds within covered poly-tunnels. This protects the crop, increases the length of the growing season, and eases the effort to harvest.

The case-study farm's changes to its business model allows an examination of each of the four drivers cosmetics-related loss identified in the previous section. Losses from other food supply stages inherent in more complex supply chains – specifically storage, handling, process, and transport to distribution centres – are excluded here for comparability. The farm had previously operated within a typical environment of supplying to supermarket multiples. Dissatisfaction on multiple levels led the owner to completely change to an atypical model. For the past 10 years, the food supply chain of this case study is the shortest possible – direct from farmer to final consumer. There are no other agents in the chain (i.e. no packers, distributors, retail supermarket multiples, or other 'middlemen'). The farm thus has complete control over what it sells to consumers, and when, including the level of grade-outs due solely to aesthetic reasons.

A mix of qualitative and quantitative data collection methods were employed. These included extensive interviews conducted over several months with the farm's owner and general manager, and direct measurements of produce. As part of the case-study, we sought to generate a rough estimate of avoidable aesthetics-related losses in UK-wide strawberry production and their embedded production-phase GHG emissions (Equation 5-4). We use the term 'avoidable loss' as there are no health-based reasons for the fruit to not enter the supply chain; it remains safely edible. Supermarket multiples in the UK are now selling some proportion of non-Class I (i.e. 'sub-optimal') fruit and vegetables as 'ugly', 'imperfect', or 'wonky' – a relatively recent occurrence within the UK. This is taken into account in our estimates of avoidable loss in Table 5-2 as the variable Sub_{Super}. Based upon our interviews, the typical supply chain has no other economic use for out-graded fruit (i.e. that proportion of fruit not meeting Class I criteria); it is composted on-site by the producer, thereby being lost to the FSC.

We estimated the proportion of non-Class I strawberries offered for sale at the case-study farm (i.e. the sub-optimal variable Sub_{Farm} in Equation 5-4). On six days over the course of a 15-day period in the latter half of June 2017 (peak season), we collected a random sample of 10% of punnets for sale in the farm shop. Under the guidance of the farm owner, we applied EU quality standards to categorise each berry in the sampled punnets into Class I and non-

Class I, which we then weighed separately. As a proxy for variable Sub_{Super} (i.e. the proportion of sub-optimal, non-Class I fruit sold by supermarkets), we took direct measurements of shelf linear feet allocated to Class I and Class II strawberries by a national supermarket chain on the same days as we collected the farm samples. $Harvest_{Total}$ is the five-year average of the UK strawberry harvest for 2012-16 (Defra, 2016). Finally, we applied the UK-specific EF for strawberries from Table 5-1 to estimate embedded production-phase GHG emissions of the avoidable loss ($Em_{Avoidable}$).

Equation 5-4

$$Em_{Avoidable} = \left(\left(Sub_{Farm} - Sub_{Super}\right) * Harvest_{Total}\right) * EF$$

5.4.2 Overcoming waste encouraged by market standards/regulations

The case-study farming business uses a more holistic definition of quality than EU marketing standards or retail multiples whilst retaining a quality-control/quality-assurance effort. By selling direct to consumers, the specific EU-level marketing standards on the appearance of the fruit for grading into official Classes needn't be applied. Therefore, the farm shop has greater flexibility to decide what is suitable for sale to its customers. However, interviews with the farm owner and manager indicate that those fruit selected for the farm shop are the best quality available on the plants each day.

> *"Would you be happy paying for and eating that strawberry yourself? We don't mind if there's some misshapen fruit that goes in there or anything like that. Basically, if you're happy to eat it yourself then it's a Class I fruit for us." (Owner)*

Fruit for the farm shop is sold at a price premium relative to supermarkets as 'picked fresh' yet avoidable waste on the case study farm is practically zero. This is due to flexibility in decisions of what fruit is sold and how, by not being beholden to EU classifications. The case study farm has invested in infrastructure such as an industrial kitchen and farm café to be able to use what fresh produce is left unsold at the end of the day in the farm shop. It is processed on-site into other products, such as jams, or otherwise used in the café. Fruit that is unsafe for consumption – the unavoidable losses – is composted on-site. This proportion was estimated by the farm owner at less than 1% of annual harvest yield, though is not systematically recorded.

5.4.3 Avoiding waste encouraged by retailers' cosmetic standards

The case-study farm is both producer and retailer – produce grown on site is sold only on site. They have full control over what and how produce is presented to customers of the farm shop, which differs from EU or the more strict supermarket classification standards. For example, whilst colouration is an aspect of visual appearance taken into consideration during the selection decision of fruit for the farm shop, size and shape are not. This approach is in direct contrast to industry 'quality' standards.

> *"Our spec, it's very loose. It's very rare that I go in and reject any fruit. The basic requirement is that it's picked that day, and that it looks appealing to eat". (Owner)*

The mean proportion of 'ugly', or non-Class I, fruit from farm shop punnet samples was 19%, with a median of 23%, and ranged from 0 to 27%, dependent upon sample. There was one outlier with a measure of zero non-Class I fruit. If this single data-point were excluded – it is more than two standard deviations from the nearest – the minimum proportion of 'uglies' rises to 14%, the mean matches the median at 23%, and standard error contracts to 1.9% from 3.8%. The average proportion of retail space allocated to non-Class I strawberries in the supermarket sample was 12%, just over half the proportion measured from the case study farm (Table 5-2). This suggests actual FLW at farms supplying the large retail multiples may be about 10%, similar to the value in Table 5-2 of 12%.

Annual UK strawberry production in the five years to 2016 averaged 102,000 t (Defra, 2016), of which roughly a quarter (25,300 t) was produced in Scotland (Scottish Government, 2017). Scaling up the difference in non-Class I fruit sold via supermarkets and that produced by our case study farm to the whole of the UK, we estimate approximately 10,000 t of strawberries may be lost from the FSC due to aesthetic standards. This estimated loss has the equivalent of 8000 t CO_2e of embedded emissions. It must be noted that these estimates are very preliminary, and are presented as only potentially indicative of the avoidable loss due to cosmetics. Broader and deeper investigation of the full supply chain for strawberries and other produce in the UK is needed.

Table 5-2. Proportion of 'ugly' fruit sold through different distribution channels. The case-study farm values in this table exclude a single outlier of 0%. Including that data point into the set reduces the mean to 19% and increases the standard error to 3.8%. There were no outliers in the supermarket data.

	Sub-optimal Fruit (%)	
	Case-study Farm	Supermarket
Mean	23	12
Median	23	10
Standard Error	1.9	3.4
Maximum	27	24
Minimum	14	6

5.4.4 Reducing waste encouraged by the structural power of supermarkets

Our case study interviewees clearly communicated the lack of power they had with respect to selling their produce to retail multiples under the previous business model. From their perspective, the supermarkets ‘held all the cards’. At times the participants discarded entire harvests by ploughing under, or even not harvested at all, where the cost of harvesting was more than the price being offered by supermarkets for the produce. Costs to grow the produce would still be incurred, but further losses to harvest and ‘sell’ it would be avoided – a practice they felt was anathema to farming.

Farmers are expected to honour production contracts or risk being dropped. If short of produce, a farmer must source it wherever possible and absorb the cost of doing so. Selling direct to customer puts at least some of that power back into the hands of the farmer – they have full decision-making power over what they offer for sale to the customer. It is not necessary to strictly comply with the EU marketing standards. At the same time, selling direct also exposes the farmer to different risks; they take full responsibility for marketing their produce. Selling produce that lacks value for money could quickly have a negative feedback effect, particularly if it is already selling at a premium to a similar supermarket offering.

> *"I've got 100% control over what we do. If I make a good job of marketing and get customers in to buy the products, then I get a high return. If I make a bad job, then I get a low return. To me that's what gets me up in the morning; it's having control over your own destiny, which you don't have if you're doing it the other ways." (Owner)*

5.5 Conclusion

We have argued there are likely to be several drivers of avoidable loss of 'ugly' food, involving multiple actors within the food supply chain. These include: regulations that incorporate purely cosmetic elements at national and supranational levels; private 'voluntary' grading criteria by retail multiples; power differential between farmer and retailer; and, learned expectations of consumers. Via our atypical case study, we suggest it may be possible for some actors to overcome these drivers, generating multiple benefits. Less discard of safe, edible food for aesthetic reasons could help reduce food insecurity. Less avoidable food loss would also lower the climate cost and increase agriculture's GHG-efficiency, in terms of embedded GHG emissions, by needing to produce less food. An efficient food supply chain, where food loss and waste are minimised within and between the various stages, could increase food availability without the need for producing more.

The use of fresh fruit and vegetable produce that would otherwise be lost or wasted requires alternative routes that are available to farmers, provided a sufficient price to make it economical to do anything other than plough-in or walk-by an out-of-specification harvest. Entrepreneurs have launched new businesses aimed at both consumers and producers, with the aim of using more of the food that is produced (e.g. Olio, Imperfect Produce, FoodCloud, etc.). A law passed unanimously by both French legislative Houses in late 2015 aims to empower all actors within the food supply chain to eliminate avoidable food waste, emphasising efforts to maintain its use as food for human consumption (French Senate, 2015). In contrast to France, a food waste reduction private member's bill, also targeting supermarkets, first tabled in the UK Parliament in late 2015 remains mired at the first stage of the process (McCarthy, 2016). Positively however, all major supermarkets in the UK publicly support the voluntary Courtauld 2025 Commitment of 20% reduction of food waste by 2025 (WRAP n.d.). Further, some supermarkets have seen this as a marketing opportunity, with new branding for fruit and vegetables that would have previously fallen short of their aesthetic/quality criteria (e.g. Asda's 'Wonky Veg' and Tesco's 'Perfectly Imperfect'). This could reduce avoidable food loss at source, generating benefits for the climate through reduced emissions from waste. Other co-benefits, such as less food poverty, and greater stability of farm income, may also be obtained.

A changing political climate within the UK also looms large on the horizon for the agriculture industry. The details and domestic policy implications of the UK's expected exit in 2019 from the European Union (or 'Brexit') remain unknown. Brexit may offer the UK the opportunity to develop and apply policy options for domestically-consumed FFV that current EU regulations may not permit, such as banning the use of cosmetic characteristics as factors in determining 'quality'. However it is far from certain the UK government would adopt such a policy, especially if they choose to keep open the prospects of trade with EU countries. Moreover the UK government has not taken other measures available to it as an EU member (or where membership should not inhibit action), such as: educational initiatives to increase knowledge and familiarity of food produce; and, revisit labelling of foods to provide consumers with clear information they can use in their decision-making process. In short, the potential impact of policy change on food loss warrants further research, building upon that begun by the EU FUSIONS project (EU FUSIONS, 2015).

Much research continues to be focused at the consumer end of the food supply chain in Europe (e.g.: De Laurentiis et al. (2018) on quantification; Gaiani et al. (2018) on attitudes; von Kameke and Fischer (2018) on behaviour change; Aschemann-Witzel et al. (2017a) on success factors). However, there remain considerable levels of uncertainty in many aspects of estimating food loss and waste in early FSC stages and its embedded climate impact. Here, we have attempted to provide some measure of additional clarity on such wastage. Our specific perspective has been one of viewing avoidable loss as a function of arbitrary quality standards. The case study we used focused only upon one crop – strawberries – grown and sold in the UK. The estimates presented with respect to the UK strawberry industry are very rough, based on this small-scale pilot, and are meant to be illustrative of possible climate cost due to application of cosmetic standards to fresh produce. Without generalising from a single specific case, our conclusion is there are very likely to be substantial avoidable losses, yet also a great deal of uncertainty of the quantity. Larger-scale investigations to generate a more robust quantification of food loss at the farm stage, from all drivers, are necessary. We would also welcome further research which recognises the varying dynamics characterising different food crops in different geographic and social contexts.

5.6 References

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Chapter 6
Discussion

Having our cake and eating it too?

6.1 Introduction

The purpose of this thesis has been to quantify the production-phase emissions of food loss and waste (FLW) and develop a greater understanding of its drivers. To do so, I have estimated the quantity of FLW and its associated greenhouse gas (GHG) emissions from various perspectives. In the preceding chapters, I have provided some new insights into several different aspects of inefficiencies in the food supply chain and the multiple lenses through which food loss and waste can be viewed. I have also detailed the embedded production-phase (i.e. pre-farm gate) GHG emissions of FLW over time and identified some UK and European 'hotspots' of particular concern. In this final chapter, I synthesise these various concepts and discuss the potential implications of the findings and relevance to the wider discussion of climate change mitigation. This chapter is structured as follows:

- a summary review of the key findings of Results Chapters 2 – 5;
- a discussion of the broader implications of these findings in terms of interventions and contributions to mitigation policy, using the UN Sustainable Development Goals as a framework;
- acknowledgement of the main general limitations to this work as a whole, and identification of pathways for future research to address these limitations.

6.2 Key Findings

Food loss and waste and its climate cost is a global 'wicked problem'. Chapters 2 – 5 have quantified the embedded production-phase emissions of food that has been lost or wasted from several different perspectives. In the following section, the key findings from each Results chapter are summarised, put into context with the current literature and main limitations highlighted.

6.2.1 The many faces of food loss and waste, and milk waste emissions

- Aim of Chapter 2: To provide context of the challenges with assessing levels of food loss and waste and provide a single product quantitative estimate of embedded emissions.
- Primary research question: what food supply chain inefficiencies exist, and what level of emissions are attributable to milk wastage at the global, U.S. and UK levels?

The main quantitative findings of Chapter 2 relate to production-phase embedded emissions in milk waste at the UK and U.S. national level and the global level, summarised in Table 6-1. Annual wastage along the entire milk supply chain is estimated to be 2.4% of global production, equivalent to almost 27,000 kt CO_2e of GHG emissions or about 0.5% of all global emissions (World Bank, n.d.). At the UK level, production-phase embedded emissions from consumer milk wastage is about 205 kt CO_2e; in the U.S. this figure is up to about 7,300 kt CO_2e. The range of values for the U.S. is a factor of three, depending upon whether USDA (n.d.) or FAO (FAOSTAT, n.d.) wastage estimates are applied. The wastage of milk by the consumer is typically a result of servings being too large or not used before its 'use by' date and is therefore entirely 'avoidable' (Quested et al., 2013). WRAP's restatement of 2007-2015 data UK household food losses left avoidable milk waste (at 290,000 tonnes, or 7% of production) and reasons for wastage unchanged (Gillick and Quested, 2018). Simple interventions, such as reducing average fridge temperature by 1.6 °C (to 5 °C), increasing the 'Use By' date by one day, and freezing milk instead of disposing of it, could reduce milk waste by a third (Fisher and Whittaker, 2018).

I also presented the concept of considering FLW as an 'inefficiency', an alternative approach to viewing it solely as disposal. Within this construct, we can view excess supply and consumption of food as a non-optimal use of food production resources, a perspective also included by Alexander et al. (2017). Here, estimates of excess consumption of food are equivalent to up to 650 Mt CO_2e, or about 20% of estimated global emissions of the 3.3 Gt CO_2e

attributable to FLW. Developing countries – where most of the food insecure population reside – are expected to grow rapidly in population and wealth (PwC, 2017; UNDESA, 2017). Should these countries follow the OECD dietary trends of relatively high per capita consumption of calories and meat protein, I estimated the 'excess consumption' emissions could be the same in 2100 as from all FLW is currently; in the region of 3 Gt CO_2e yr^{-1}. This conclusion is in line with a later study by Ritchie et al., (2018) that found only dietary guidelines from India and the WHO (World Health Organization), which are less emission intensive than 'Western' diets, could be compatible with the carbon budget to keep global warming below 2 °C by 2100.

Table 6-1. Summary of milk wastage by consumers in the UK, USA, and globally, and the respective embedded emissions of that wastage. The range estimate for the USA uses FAO data for the lower boundary and USDA data for the upper bound.

Region	Milk waste ($kt\ yr^{-1}$)	Embedded emissions ($kt\ CO_2e\ yr^{-1}$) [1]	Proportion of 2011 GHG emissions (%)
Global	16,600	27,000	0.05
UK	290	205	0.04
USA	3,400 – 10,100	2,400 – 7,300	0.04 – 0.11

The range in estimates of milk wastage for the U.S. demonstrates a key limitation to this and other desk-based research that relies upon databases or other published literature. The limited amount of data leads to a high level of uncertainty in the 'real' levels of wastage or embedded emissions. Further, the robustness of this data is not of uniformly high quality. For example, the USDA's loss-adjusted food availability database highlights uses constant loss factors across time for each respective food product (USDA, n.d.). Updates of these estimates override the historical values (Buzby et al., 2009), leading to information loss. The other primary database for food products is the FAO's Food Balance Sheets (FAOSTAT, n.d.). The information in this database is sourced primarily from UN Member States themselves, which the FAO acknowledges will be of differing quality; at times, the FAO themselves will

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[1] These values use 100-yr GWPs for CH_4 and N_2O from AR5 (IPCC, 2013). The comparable values in Chapter 2 are different, which are presented as originally published using GWP values from AR4 (IPCC, 2007).

make their own estimates (FAO, 2001). Higher levels of uncertainty may be a barrier to drafting effective policy to address the FLW issue.

6.2.2 Historical climate cost of food loss and waste

- Aim of Chapter 3: to estimate the historical trends of FLW at global and regional levels, and its associated production-phase emissions over time.
- Primary research question: how has food loss and waste, and its embedded emissions, evolved over the past 50 years at global and regional scales?

From Chapter 3, the answer to the ‘problem’ presented in Chapter 1 – the mitigation potential of tackling global food waste – appears to be about 2.2 Gt CO_2e per year of production-phase embedded emissions. At least this was the level in 2011. The global absolute and average per capita embedded emissions of FLW have demonstrated a clear and continual upward 50-year trend of 2.4% and 0.7% per annum, respectively. I also show the quantity of food wastage has grown three-fold over the past 50 years, and the production-phase emissions embedded in this wastage grew even faster. Those emissions were 3.25x greater in 2011 than in 1961. Accounting for future population growth and assuming per capita wastage and current diets remain constant suggests a doubling-to-trebling of embedded emissions within FLW in 2050 versus 2011, to 5.7 – 7.9 Gt CO_2e yr^{-1}.

These projections are roughly in line with a report from the Boston Consulting Group that estimate FLW will grow at 1.9% per annum, reaching 2.1 Gt yr^{-1} by 2030 (Hegnsholt et al., 2018). Without a change to the status quo, such projections may be on the low side. Diets have been shown to become higher calorie and more emissions intensive over time as improving lifestyles are reflected in diets (Pradhan et al., 2013). I showed wealthier, developed regions have typically had higher per capita FLW wastage and thus similarly higher embedded emissions relative to developing regions. However, I also showed the rate of increase in both metrics is rising rapidly for the latter, whilst stable to declining for the former. Increasing absolute FLW is potentially at odds with Sustainable Development Goal 12.3 to halve per capita food waste by consumers and retailers (discussed in some detail in Section 6.4.1).[2] A shift towards a more 'Western' diet – those that are highest in calories and meat-derived protein (Pradhan et al., 2013) – is also incompatible with achieving Paris Agreement global warming targets of 1.5 °C or 2 °C (Ritchie et al., 2018).

The general conclusion from Gustavsson et al. (2011) – that the consumer in the Global North and farming operations in the Global South generate the greatest proportion of FLW – is largely held, though there are some important exceptions. We see in this chapter that absolute levels of embedded emissions from FLW is roughly similar along the FSC in the U.S. With respect to China, we also see that wastage in the consumer stage alone is about equal to all other stages combined. While per capita FLW emissions in China are half that of the U.S., meat wastage accounts for the majority of FLW-associated embedded emissions. Worryingly, average meat consumption in China is double nutritional requirements, and up to four times as much for the most affluent (He et al., 2018).

6.2.3 Policy and related levers

- Aim of Chapter 4: To understand and quantify the impact policy may have on loss and waste of edible food, and its embedded climate cost.
- Primary research question: how much edible food has been destroyed, and what is the associated embedded production-phase emissions, that are a result of the implementation of the withdrawal mechanism of the EU Common Agriculture Policy?

In Chapter 4, I highlighted the impact policy can have on levels of food wastage, specifically that of the market withdrawal mechanism within EU Common Agriculture Policy (CAP). This aspect of the EU CAP is an example of State-sanctioned food destruction for economic and market reasons. Whilst the CAP has undergone significant change over time, the mechanism for destroying

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[2] 'Potentially at odds' is used here as progress towards SDG 12.3 can still be made with increases food waste, provided the population grows faster. SDG 12.3 is a relative, not absolute, metric.

food has remained a constituent part within each version. This mechanism continues to be used, the most recent example being to offset some of the impact from the Russian ban on EU food produce (McEldowney, 2016).

Despite the mass of fresh fruit and vegetable (FFV) destroyed and its embedded emissions falling about 90-95% in absolute terms, there appear to remain institutional barriers to avoiding the ‘easy’ option of destroying withdrawn FFV. The proportion of FFV destroyed has increased from about half of withdrawals in the 1st Regime to two-thirds in the 3rd Regime. Additionally, the emission intensity of FFV destroyed under this mechanism has risen in each of the policy’s three incarnations, more than doubling between 1st and 3rd Regimes (summarised in Table 6-2). The FFV destroyed has been that produce which has had greater than average embedded emissions.

Whilst there has been dramatic improvement in the EU CAP policy that has resulted in lower absolute quantities of edible food withdrawn and destroyed, it is not unique. The U.S., for example, also has a long history of supporting incomes of farmers through similar policies – a recent example being the increases in U.S. government reserves of cheese and butter to prop up dairy prices amidst a multi-year glut (“Got Milk? Too much of it, say U.S. dairy farmers,” 2017). However, a key difference between these two largest producers of dairy (Statista, 2018) is the EU’s policy and physical capability to store excess milk supply as skim milk powder (SMP) which can be reconstituted into liquid milk for re-entry into the market when prices stabilise (AHDB, 2018). The dumping activity in the U.S. of excess milk suggests that U.S. dairy processing and storage capacity is not keeping pace with production growth and is insufficient to provide a buffer for swings in demand and supply (Laine, 2017).

A key limitation to this research was data availability. Piecing together the use of this mechanism, and therefore the embedded emissions of destroyed FFV, was challenging. The public publishing of data to the website of the DG-AGRI (EU Directorate General for Agriculture) for this mechanism ceased in 2010 (DG-AGRI, n.d.). Data for the period of 2011-2015 was obtained only via an EU citizen's request direct to the DG-AGRI (pers. comm. 27 Oct 2017)[3]. Whilst market stabilisation is no longer a 'pillar' of the CAP under the 2007 reform, the market withdrawal mechanism continues to be used. However, it does not appear to be systematically recorded in a manner similar to the period to 2007 (the end of the 2nd Regime). Without an ability to monitor and measure, evaluation of a policy's effectiveness may be too uncertain to be useful.

Table 6-2. Annual mean destruction of FFV (in kt), its embedded emissions and emissions intensity (in kt CO_2e) during the three CMO regimes. (*) Data for Regime 3 only covers the six years of 2010-2015 due to lack of availability in 2008 and 2009 (summary of Table 4-3).

CMO Regime	FFV destroyed (kt yr^{-1})	Embedded emissions of destroyed FFV (kt CO_2e yr^{-1})	Average emission intensity of destroyed FFV (kt CO_2e kt^{-1})
1st Regime (1989-1996)	1053	365	0.18
2nd Regime (1997-2007)	472	212	0.33
3rd Regime (2008-2015)*	52.0	31.1	0.39

6.2.4 Actor agency and power

- Aim of Chapter 5: To assess how structural elements of the food supply chain may combine to result in FLW, and quantify the embedded emissions of that wastage.
- Primary research question: what is the level of production-phased emissions arising in the UK and Europe as a result of food wastage due to cosmetic standards?

The focus of Chapter 5 was the quantification of embedded emissions of fresh fruit and vegetables (FFV) that may never leave the farm due to their being deemed cosmetically sub-optimal (colloquially referred to as 'wonky', 'ugly', or 'imperfect'). These embedded emissions – up to 970 kt CO_2e yr^{-1} and 22,500 kt CO_2e yr^{-1} – are equivalent to about 2% and 5% of GHG emissions attributable to agriculture in the UK and EU as a whole (BEIS, 2018; Eurostat, 2017). The food loss related to these emissions is entirely avoidable as the produce in

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[3] EU citizens have the right to request any data collected by EU institutions, even where such data is not otherwise openly published.

question is safe to eat – it merely doesn't 'fit' within institutional expectations. These expectations are set at the EU and UK regulatory level on 10 FFV product categories (Defra, 2017; European Commission, 2011, Art. 3, para 2), as well as privately by supermarkets across the much wider range of produce they sell.

The wastage that results from these aesthetic standards is a function of the structure of the typical Western agri-food chain. There is a hegemony of large supermarket multiples that tend to exist within supposed market economies (KANTAR WorldPanel, 2018). The oligopolistic nature of these markets has seen agency consolidated by the supermarkets such that they have considerable power over other actors within the food supply chain (Devin and Richards, 2016). However, this power may be also be redirected as a force for positive change. For example, Tesco in the UK is working with its largest providers to halve the level of food lost all along their supply chain and publicly report the results of those efforts (Mark Little, pers. comm., 21 Aug 2018). Tesco's goal is more demanding and encompassing than SDG 12.3, which merely states "reduce food losses along production and supply chains" (United Nations, 2015a, p. 22). Such efforts are to be acknowledged and encouraged, though also remaining critical that other stakeholders are also benefiting.

6.3 Potential interventions to improve efficiency

In this section, I integrate and synthesise the outputs from the Results chapters to discuss several possible pathways/strategies that could improve the efficiency of the food supply chain. Such interventions may or may not result in absolute mitigation emissions from food production. For example, it may be desirable to reduce production as a function of reducing wastage to maintain the same throughput of food within the system. The end result is reduced absolute emissions and lower intensity of production. Alternatively, it may be preferable to maintain production levels and use the improved system efficiency to generate a greater level of throughput; there would be no absolute emissions savings, but emissions intensity of food consumed would still fall for a relative saving. The economics that lay behind evaluating such scenarios, or any mix of the two, was beyond the scope of this thesis but should not be ignored. As we have seen, particularly in Chapters 4 and 5, food production is politically charged – the economics of it being a central pillar.

6.3.1 'Circularisation' of food supply/value chain

The European Union has embraced the concept of creating a circular economy – an economy based upon extracting the maximum value possible from inputs with the least amount of disposed waste (European Commission, 2015). Products and services are then, in effect, offered within a closed system. Minimal new inputs are necessary for subsequent generations of those products/services – mimicking the natural biological world that continually recycles, using 'old' material as feedstock for 'new'. This concept requires a radical rethink of the life cycle of many products to move away from single use – the first priority should be the avoidance of waste, but this needs to be 'designed-in' from the original concept of a product (Ellen MacArthur Foundation and McKinsey Center for Business and Environment, 2018). But, as food is 'natural' – at least in its fresh form[4] – the challenge is how can its provision can be made more circular than it already is.

The degree of food wastage highlighted in this thesis in one form or another begs for other uses to be found for FLW, rather than simply being destroyed. Following the WRAP (2017a) 'food waste hierarchy' in Figure 6-1, destruction should be the final, last-worst option for any product, including food. Value can be extracted anywhere further up the hierarchy. The further up this hierarchy one goes, the greater the retained value, such as creating a new product that utilises edible food that would otherwise be wasted (e.g. the 'baby carrots' produced from out-of-spec carrots highlighted in Chapter 5).

Further down the hierarchy would be using FLW as feedstock for anaerobic digestion (AD) to produce fossil fuel-free energy and heat. Additionally, other innovative products are being created – an example is Vegware, who claim to use unavoidable food waste such as bagasse as

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[4] Use of GMOs, a highly polemical practice, may see this statement being somewhat debatable.

feedstock for their compostable and recyclable cutlery and packaging (Vegware, 2018). Understanding where the ‘hotspots’ are in the FSC can provide information on feedstock (e.g. quantity, type, availability) to create new products and business models that are economically, environmentally, and socially viable. That there remains considerable food loss occurring pre-farm gate even in developed countries (as shown in Chapter 5) suggests existence of barriers to creation, such as a lack of infrastructure and/or incentives. However, research to more fully understand this topic has to date been scarce.

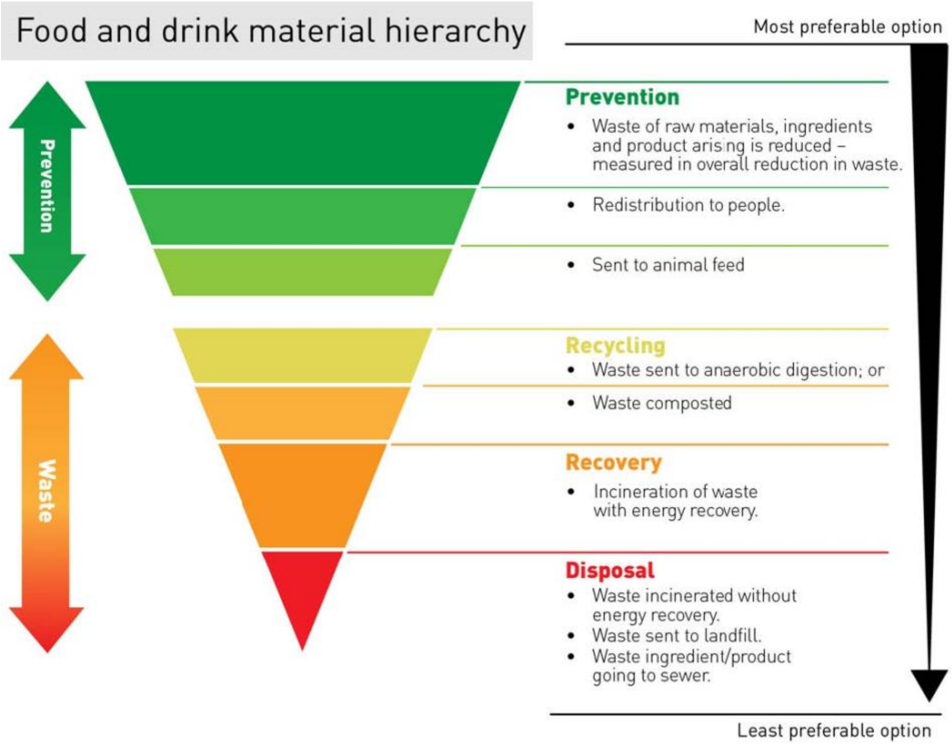

Figure 6-1. Hierarchy of actions to mitigate food waste, and thus its embedded emissions, from most to least preferable (top to bottom). Source: WRAP (2017a)

6.3.2 Confronting the power of supermarket hegemony

The power the current market structure allows supermarkets to wield over other actors within the food supply chain is considerable (Feedback, 2018; Hingley et al., 2006). The supermarket industries of Continental Europe, the UK, and other developed countries such as Australia, Canada, and the U.S. are highly concentrated (KANTAR WorldPanel, 2018). Whilst not true monopolies, where just a single company dominates, national supermarket industries are oligopolistic. Typically, two to four firms have effective control over food distribution to the consumer. As an example, in April 2018 a merger was proposed between Sainsbury's and ASDA, the number 2 and 3 supermarkets by sales (Sainsbury's, 2018). If this were approved and ultimately went ahead, the result would see two largest multiples (Tesco and new Sainsbury's) control over 60% of the industry, instead of 'just' 40% as at present (KANTAR WorldPanel, 2018). We thus seem to be moving backwards with respect to constructive competition when the value chain of food supply as a whole is viewed. It may be time to renew/reinvigorate 'trust-busting' on the agri-food system in general, and supermarkets specifically.

6.3.3 Encouraging seasonal produce

Whist reducing absolute levels of food waste should be a goal, so too should be lowering the emissions intensity of that food. One potential way to reduce embedded emissions may be to consume more seasonal produce. This is more than about reducing so-called 'food miles' – the distance food travels from farm to fork. It is also about considering the embedded emissions of producing and providing that food. Complicating this concept is that depending upon the product and season of consumption, it can be more emissions efficient to import than grow locally. For example, growing tomatoes in the UK for winter consumption, which requires heated glass-houses, is three-times costlier embedded emissions-wise than importing them from Spain (Cranfield University, 2008).

6.3.4 Developing country systems - Storage

Even within what may seem to be a simple system – that of subsistence farming – there are several operational stages where inefficiencies can occur. Prime amongst these in developing countries, where such farming almost exclusively occurs, is food lost as a result of poor storage infrastructure. Pests such as rodents, insects, and birds may devour a meaningful proportion of food during storage. Additionally, moisture may be too high, allowing for contamination and accumulation of toxins. A simple, low-cost intervention to such losses in this early stage of the FSC is improved storage. An example is hermeticallysealed storage bags, which have been shown to virtually eliminate the 20%-plus losses of conventional woven storage bags (Baoua et al., 2014; Mlambo et al., 2017). Metal silos are another potential solution on a larger-scale – these structures also provide hermitically-sealed environments for grain storage (Mlambo et al., 2017). As they can be built to different holding capacities, silos could be used for entire communities, defraying installation and maintenance costs (Tefera et al., 2011). FLW in the earliest FSC stages could represent as much as 20% less revenue for farmers in sub-Saharan Africa (Aragie et al., 2018). Decreasing early-stage storage losses allows for more produce to flow through the supply chain, increasing its efficiency. The additional social benefits of doing so include greater food and income security for subsistence farmers.

6.3.5 Developed countries systems – 'Carbon leakage'

The food supply chain in developed countries can be complex, involving many actors across time and space depending upon the food commodity. For example, the UK imports about 50% of its food supply, 30% from non-EU countries (de Ruiter et al., 2016). Such a food system effectively 'offshores' the GHG emissions of that food production to the exporting countries – a form of 'carbon leakage' that is made possible by a lack of barriers to moving/sourcing this production around the globe. As highlighted in Chapter 3, there is a great deal of food waste occurring at the end of the supply chain in developed countries, with similar amounts lost in the earliest stage. Without the exchange of knowledge and access to finance to update processes and infrastructure, this 'offshoring' of food production to developing world – where upstream wastage rates are typically higher than in developed countries – could be increasing food wastage and thus the climate cost of food production.

6.4 Towards the Sustainable Development Goals

The Sustainable Development Goals (SDGs; formally the *2030 Agenda for Sustainable Development*) were adopted in 2015, ahead of the Paris Agreement. They are a set of 17 high-level goals (see Figure 6-2) intended to drive transformative change for benefit of global society in effort to meet the Paris

Agreement's ultimate goal of keeping global average temperature rise under 2 °C (United Nations, 2015a). Aspects of food loss and waste, and benefits from its reduction, can be found in several of these goals, notably (but not exclusively) SDG 12 (responsible consumption and production) and SDG 2 (zero hunger). In the following, I use the SDGs as a framework to discuss some of the wider implications of the research conducted in this thesis.

Figure 6-2. The official icons of the 17 SDGs. Source: United Nations (n.d.)

6.4.1 SDG 12 – Responsible consumption and production

Reducing upstream and downstream food waste will be positive for SDG 12 in terms of achieving more sustainable production and consumption, respectively. Fewer resources could be used to provide the same level of food as currently reaches the consumer. Alternatively, use of production resources could be maintained at their current level to provide a greater amount of food for consumers. The former would achieve absolute levels of GHG mitigation, whereas the latter would achieve lower emissions intensity and is more directly linked to SDG 12.3. Tackling food loss and waste is an explicit target of

SDG 12.3, which states: “by 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses” (United Nations, 2015a, p. 22).

Achieving this SDG target will require rolling back more than 50 years of increasingly profligate tendencies. The most wasteful regions are North America and Oceania[5]; it has almost three times the level of per capita FLW (and corresponding embedded emissions) as the least wasteful, South & South East Asia (see Tables A-6 and A-9). Importantly, the relative growth rate in per capita FLW is highest in developing regions, where food insecurity is highest, and flat to negative in developed. To achieve SDG 12.3, efforts will ever more increasingly need to be directed to Africa and South-East Asia, where this trend, coupled with the highest expected rates of population and economic growth, is particularly troubling.

The focus on per capita reductions in FLW of SDG 12.3 (and by extension, embedded emissions in that FLW), is key. This metric provides for growth in food production to feed a growing global population. That population growth, however, is expected to be uneven with nearly all of the net additions being in Africa and South East Asia. These two regions have shown to be the least wasteful in the downstream, consumer, stages of the food supply chain. At the same time, the developed regions of Europe and North America, and Oceania have demonstrated declining per capita FLW overall (Figure 3-3b). Whilst there appears to be a positive relationship between wealth (as measured by per capita GDP) and FLW, breaking that link for Africa and South East Asia would improve the probability of SDG 12.3 being met. Countries in these two developing regions have demonstrated some capability to ‘leapfrog’ old technology in the form of largely eschewing land lines and moving direct to mobile telephony for communications with concomitant social benefits (James, 2009; Sinha, 2005). Employing this concept to their FSCs could maintain current low (relative to developed countries) levels of per capita FLW in the

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[5] This is considered a single region in the analysis of Chapter 3.

downstream stages and include improvements in the upstream stages where relatively high amounts of FLW occur.

Trends in FLW, when decomposed by region, suggest whilst reductions are possible, it is likely to be a significant challenge to meet the stated target by 2030. Absolute levels of food waste globally have increased more than three-fold in the past 50 years. At the same time global per capita FLW rose 36% to 240 kg per person. Embedded emissions of this FLW have risen further still; by 3.2x in absolute terms and 44% in per capita terms.

6.4.2 SDG 2 – Zero hunger

The number of chronically hungry fell from 1bn to 800m between 1990 and 2015 (FAO et al., 2015), a halving of the proportion of global population from 23% to 13% (United Nations, 2015b). However, the 2016 estimate saw an uptick to 900m, which brings absolute levels of hunger back to those of the turn of the 21st century (United Nations, 2015b), with various United Nations organisations indicating increase in political instability and conflict, particularly in Africa and the Middle East, being a key cause (FAO et al., 2017). To achieve zero hunger requires food security and sustainable agriculture that can provide sufficient calories and nutrition for a growing population. Reducing absolute food waste could help meet SDG 2.

Goal 2.3 is to "… double the agricultural productivity and incomes of small-scale food producers …" (United Nations, 2015a, p. 15). This thesis has highlighted the high proportion of losses occurring on-farm and during storage in developing countries. Reducing food losses at these earliest stages of the food supply chain could directly benefit small-scale producers. Smallholder farmers (i.e. <2 ha) are most common in sub-Saharan Africa and south and south-east Asia, provide about a third of the global food supply, and are responsible for a similar proportion of global on-farm losses (Herrero et al., 2017; Ricciardi et al., 2018; Samberg et al., 2016). Greater quantities of produce available for sale from the same farming acreage increases yield productivity and potentially the incomes of small-scale producers. Improving yield efficiency in this way may avoid potential negative implications to dietary quality (as opposed to quantity) that the alternative – intensification – may bring about (Ickowitz et al., 2019).

Achieving greater throughput of food through the FSC to the end consumer does not necessarily lower the GHG footprint of agriculture, though less FLW could result in lower emissions from decomposition. Advances in production techniques are still required to reduce GHGs (i.e. N_2O and CH_4) that may arise from soil and manure management practices, particularly given base-line estimates of a doubling of emissions pressure associated with food production by 2050 (Springmann et al., 2018).

6.4.3 SDG 1 – No poverty

The first stated SDG goal (i.e. SDG 1.1), is to "…eradicate extreme poverty everywhere…" (United Nations, 2015a, p. 15). Within the scope of reducing food loss and waste, this goal can be synergistically linked to the previous discussion on SDG 2 (§ 6.4.2). Whilst this thesis has not focused on poverty, lowering food loss at the earliest stages may play a part in its alleviation by increasing available production yield to support a transition from subsistence to commercialised farming (Ogutu and Qaim, 2019). However, fewer than one in five farming households in low-income countries have attempted agricultural intensification (Thornton et al., 2018). Focussing instead on reducing losses and increasing efficiency could deliver improved economic benefits. Once basic needs of smallholder farmers are met, greater amounts of produce may thus be available for sale in markets. As production levels remain unchanged (or even increase) there may not be any savings in absolute embedded emissions of food produced. However, emissions efficiency would improve as a function of less food loss.

6.4.4 SDG 11 – Sustainable cities and communities

Part of Goal 11.6 of reducing environment impact of cities is to "…pay special attention to … municipal and other waste management" (United Nations, 2015a, p. 22). As shown in previous chapters, food waste by the consumer is about 40% of all FLW in developing regions. In the UK, there exists policy to reduce the landfilling of biodegradable municipal waste by 65% by 2020 (relative to the baseline year of 1995 (Defra, 2018a); Scotland's own target within its Zero Waste Plan is a more ambitious maximum of 5% of all waste being sent to landfill by 2025 (Scottish Government, 2010). As part of meeting this policy goal, food waste is collected and treated separately from other municipal waste – it may be used as feedstock for compost or for energy production via anaerobic digestion (Defra, 2018b). Food waste levels from households themselves may not fall, but such policies to redirect food waste away from landfills will reduce the amount of methane release methane into the atmosphere from its decomposition.

6.4.5 SDG 13 – Climate action

Goal 13.2 is to "improve education…on climate change mitigation (and) adaptation…" (United Nations, 2015a, p. 23). Education initiatives could influence behaviours and result in reductions in the considerable FLW that occurs across the supply chain, though there is yet little empirical evidence to definitively support this (Jensen and Teuber, 2018). Regardless, there are multiple examples of grass-roots/NGO initiatives attempting to do so, particularly in Europe. These initiatives include "Love food, Hate waste" by WRAP in the UK[6] , "Stop Spild af Mad/Stop wasting food" in Denmark[7], and "Zu gut für die Tonne/Too good for the bin" in Germany[8]. They focus on educating the consumer about food waste, how it could be avoided, and why it is important to do so from social, economic, and environmental perspectives. As a possible measure of impact of such campaigns, household food waste in the UK is estimated to have fallen by 11% (1.25 Mt of food waste, equivalent to 3 Mt CO_2e[9]) since 2012 (WRAP, 2017a).

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[6] www.lovefoodhatewaste.com

[7] www.stopwastingfoodmovement.org

[8] www.zugutfuerdietonne.de

[9] Based upon a conversion factor of 2.4 t CO_2e t^{-1} of all FLW for the UK from (WRAP, 2011).

6.5 Key limitations of this research

Specific limitations have been discussed in each of the Results chapters and in the previous contextualising sections in this chapter. Here, I briefly present additional general limitations that apply to this project as whole.

The most significant limitation of each of the results chapters presented in this thesis is limited robust data on food loss and waste in general. There are pockets where good data exists, for example: UK household food waste data from WRAP; food withdrawal data in the EU between 1989 and 2008 (after which point it is no longer published). Other data, such as the time series LAFA (loss-adjusted food availability) data in the U.S. and the FBS (food balance sheet) data from the FAO, are made available from reputable organisations, but may itself be subject to static assumptions and/or suffer from less-than-robust data collection methods or efforts. There are also large areas where little to no granular data exists at all – in particular, Africa and Asia. Assuming that such geographically, ethnically, and culturally diverse regions are homogenous was necessary due to sparse data availability but not ideal. The on-the-ground actual situation could be very significantly worse (or better) than presented here.

It is clear that initial and more frequent 'ground-truthing' is needed to more fully understand the levels of FLW that are occurring in different parts of the supply chain in different parts of the world. Yet, to do so requires stable sources of funding – for researchers and/or local institutions (private or public) to regularly conduct measuring, monitoring, and verification (MMV) activities and to make public the data in a usable form. WRAP (Waste & Resources Action Programme) in the UK is an example organisation. Perhaps the highest profile resource efficiency organisation within the UK, it relies upon grants from UK and EU governments for about 90% of its income (WRAP, 2017b). A sudden change in political priorities could quickly end this programme.

A further limitation is the geographic focus of the research presented here – it largely pertains to Europe and the UK. Again, this is for reasons of lack of project funding to incorporate field work in non-local areas, which could begin to address in a small way the data issue. However, FLW is not just a developed world issue. As presented in Chapter 1, whilst the manner in which FLW manifests may be locally determined, it is a global issue.

6.6 Further areas to investigate

As any research should, this project has generated additional questions based upon the greater understanding achieved by making clearer those areas where knowledge remains deficient. Here, I suggest some broader problems that arise after examining this body of work as a whole.

Chief amongst those is to improve our understanding of efficiency of the food system – how much food is lost or wasted within that system, and the emissions embedded within that food. I have provided various estimates of food wastage in each of Chapters 2 through 5 – and in each of those the high level of uncertainty surrounding the values used for losses is evident. Whilst a good deal of research has gone into identifying and understanding the drivers of food wastage, additional works are needed to generate good quality estimates of the quantities of that wastage. Estimates would be sufficiently granular to separate different production systems, geographic locations, and supply chain stages. Longer term, relevant protocols (e.g. based upon the WRI (2016) food waste account standard) would be implemented to permit the systematic collection of such data for continual monitoring. Another example of systematised food wastage data collection was the monitoring of the use of the EU's withdrawal mechanism (the focus of Chapter 4). Unfortunately, such data is no longer public and collection ceased in 2015.

The life cycle analysis (LCA) literature of food products is biased towards a few key foods of dietary importance from developed countries, though the rate of research has slowed down in recent years (Clune et al., 2017). Two key challenges with using LCAs is the lack of consistently reporting on discrete elements within a system. The LCA literature uses a number of different system boundaries; farm-gate, regional distribution centre, consumer, grave. Holding the production system, food product, and supply chain configuration constant, the embedded emissions estimates will be different for each system boundary variant. Such estimates are not directly comparable, and the discrete boundaries may not be reported upon resulting in less available data and greater uncertainty of such estimates.

Whilst my primary focus is this thesis has been on quantification of food wastage and embedded production-phase emissions, this research raises questions of the impact of food knowledge and behaviour of the Western consumer on wastage further upstream. Using fresh fruit and vegetables (FFV) as an example – does the knowledge of a typical consumer of how what they are buying could look, smell, and taste like at various stages of that food's life impact their behaviour? Does the consumer understand the degree of natural variation that safe, edible FFV may have, or when that FFV is at its optimal state? Taking that analogy further, we could investigate how the level of understanding of possible reuse or alternative uses of previously prepared food affects food wastage across different cultures and/or economic development.

These are but three avenues of further investigation into various aspects affecting our understanding of food wastage that could lead to mitigation pathways being identified.

6.7 Conclusion

In this thesis, I have identified and quantified several inefficiencies within the food supply system, at the global level and then focusing on Europe and the UK. It is clear there is a great deal of food wastage globally, occurring to a greater or lesser degree at every stage in the food supply chain. No global region is immune – developing countries lose similar proportions of their food supply as is wasted in developed countries, merely at different stages. The drivers for loss and waste are many and diverse – there is no 'one-size-fits-all' solution to addressing the issue. Tackling the FLW problem requires understanding of the food systems of specific locations and the up-/down-stream implications of policies and actions undertaken meant to address this problem. The CVA framework proposed in this chapter could be an aid in developing this understanding.

The embedded emissions of producing food that ultimately goes uneaten is a significant proportion of global emissions. In the near-term, the elimination of FLW could mitigate against such emissions if food production itself were reduced by a proportionate amount. Total supply of food that reaches the end consumer would remain the same yet require fewer inputs along the chain. Alternatively, food loss and waste may be eliminated whilst maintaining current production levels. There would not be any climate change mitigation in terms of total embedded emissions needed for food production, but total food supply would increase. Under such a scenario, the emissions intensity of food produced would fall.

Despite being a 'wicked problem', there is potential for meaningful climate change mitigation by tackling the food waste issue. It is a topic that seems to touch a nerve with the wider public when the size of the problem is put into terms they are familiar with. 'Climate change' or 'global warming' may not be the most relevant framework to use with respect to FLW. Perhaps the image of Wembley Stadium full to the brim with the UK's unsold 'wonky' veg provides a clearer call to action[10]. The climate will thank us for it either way.

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[10] I was 'fortunate' enough to experience this whirlwind first hand with the publication of Chapter 5. A bit daunting, but fun! And 4,500 kt of FFV, the amount of 'ugly veg' lost in the UK, would roughly fill Wembley's internal volume of 40 million m^3. That's a lot of veg!

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Appendix A
Supplementary Information for Chapter 3

A.1 Meta-analysis literature search: additional detail

I decided it would be most time efficient to take a ‘brute force’ approach to the literature search and review. This exercise was unlikely to be repeated at a similar scale in the near future, and I was not skilled in coding to automate the database search and cleaning functions for the resultant list of potential sources. Therefore, I manually reviewed the list of results from each database search separately. The number of unique results from the literature search is not known precisely as this approach would likely lead to some duplicates across the searches. For each database search, the following stepwise reviews were conducted to determine relevance of potential sources identified:

- title – exclude if obviously not relevant, otherwise move to next
- abstract – repeat as above
- full article for relevant loss/emission factor data
- Remove duplicate entries (based upon recording full bibliographic data of the source for each factor estimate uncovered)
- Convert factor data to a common base (e.g. retail weight and GWP) and study scope (i.e. cradle to farm-gate). Exclude if there is not sufficient granularity.

A.2 Supplementary tables

Table A-1. Mean emission factor values (in t CO_2e t^{-1}) for each food commodity-region pair.

Group & Commodity	Europe	Industrial Asia	North America & Oceania	Latin America	North Africa, West & Central Asia	Sub-Saharan Africa	South & South-East Asia
Cereals							
Barley	1.57 [1–3]	0.63 [1]	0.40 [1]	0.84 [1,4]	0.49 [1]	0.80 [1,4]	0.75 [1,4]
Maize	0.45 [1,2]	0.44 [1,5–7]	0.38 [1,8]	0.81 [1,4]	0.56 [1,4]	1.56 [1,9]	1.73 [1]
Millet	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]
Oats	0.61 [2,3]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]
Rice	2.88 [1,10–12]	1.43 [1,5–7,13,14]	1.77 [1]	2.58 [1,4]	2.36 [1,4]	5.23 [1,4]	1.91 [1,15–18]
Rye	0.46 [1,2]	1.02 [1]	0.50 [1,4]	0.76 [1,4]	0.69 [1]	0.38 [4]	0.70 [4]
Sorghum	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]
Wheat	0.61 [1–3,19–22]	0.62 [1,5,7]	0.36 [1,8,21,23–26]	0.60 [1,4]	0.61 [1]	0.46 [1,4]	0.46 [1,4,13,16,21,27]
Other Cereals	0.43 [2]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]	0.93 [4]
Fruit & Veg							
Apples	0.25 [1,2,20,28,29]	0.17 [1]	0.15 [1,28,30]	0.19 [1,4]	0.17 [1]	0.12 [1,4]	0.22 [1,4,16]
Bananas	0.35 [1]	0.56 [1]	0.28 [1,4]	0.30 [1,31]	0.51 [1,4]	0.54 [1]	0.45 [1,16]
Citrus	0.36 [1,2,32]	0.17 [1]	0.09 [1]	0.19 [1]	0.16 [1,4]	0.27 [1]	0.23 [1]
Grapes	0.42 [2]	0.62 [4]	0.67 [4]	0.67 [4]	0.55 [4]	0.40 [4]	0.62 [4]
Fruit Other	2.30 [1,2,11,19,20,28]	0.35 [1]	1.00 [1,30,33]	0.41 [1,4,34,35]	0.34 [1]	0.19 [1,4]	0.84 [1,15]
Vegetables	0.84 [1,2,20,28,36–38]	0.30 [1]	0.58 [1,30,33,39,40]	0.31 [1]	0.27 [1,41]	1.53 [1]	0.81 [1,15,16]
Marine							
Fish & Seafood	4.09 [2,42,51–53,43–50]	2.77 [4]	4.42 [4,39,46,47,51,54–56]	3.01 [4,42,47]	6.86 [4,57]	9.19 [4,58]	5.29 [4,15,16,46,51,59–61]
Meat							
Bovine	22.86 [2,19,68–71,22,28,62–67]	33.26 [4,66,72]	22.08 [4,39,79,66,72–78]	35.01 [4,28,62,66,80]	19.44 [4,66,76]	33.96 [4,66,76]	39.08 [4,66]
Mutton & Goat	23.89 [2,19,20,28,64,66,71,81]	15.45 [4,66] [4,66]	15.35 [4,24,28,39,66,72,78]	20.89 [4,66] [4,66]	20.29 [4,66]	16.89 [4,66] [4,66]	15.71 [4,16,66]
Pig	5.06 [2,11,19,63–65,82,83]	5.85 [4,84]	4.29 [4,39,85–88]	4.65 [4]	5.67 [4]	4.27 [4,89]	6.92 [4,15]
Poultry	3.58 [2,19,28,63–65]	12.06 [4,84]	4.39 [4,39]	3.38 [4,28]	4.55 [4]	4.89 [4]	4.68 [4,15,16]
Milk & Eggs							
Eggs	3.49 [2,19,64,65,90]	4.39 [4,84]	3.66 [4,39]	5.20 [4]	5.54 [4]	6.18 [4]	3.06 [4,16]

Milk	1.33 [2,19,95–100,20,22,64,65,91–94]	1.26 [4,84,94,97]	1.13 [4,39,105–107,93,94,97,98,101–104]	2.52 [4,94,97,98,108]	2.77 [4,94,97,98]	4.16 [4,94,97,98,109]	2.31 [4,16,94,97,98]
Oilseeds & Pulses							
Oilcrops	1.13 [1,2,19]	1.10 [1]	0.56 [1,8,110]	0.91 [1,4,111–113]	1.59 [1]	3.94 [1]	1.96 [1,16]
Pulses	0.93 [2,114,115]	0.37 [4,5]	0.44 [4,8,39]	0.15 [4]	0.71 [1,4]	0.12 [4]	0.34 [4,16]
Roots & Tubers							
Starchy Roots	0.25 [1,2,11,19,20,22,28]	0.19 [1]	0.17 [1,39]	0.18 [1,4]	0.15 [1,4,28]	0.52 [1,4,9]	0.16 [1,16]

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Table A-2. Mean values of loss factors (in %) by food group/commodity and FSC stage, grouped by region. (f) denotes loss factors for fresh produce and (p) is the equivalent for processed food.

a) Europe

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	4.3 [1]	3.8 [2]	10.5 [3]	3.0 [3]	27.0 [4]
Fruit & Veg	20.0 [5]	7.3 [2]	2.0 [3]	4.9 (f) [6–9] 2.0 (p) [3]	19.0 (f) [4] 15.0 (p) [4]
Marine	9.4 [3]	7.9 [2,3]	6.0 [3]	9.0 (f) [10] 5.0 (p) [3]	11.0 (f) [3,4] 10.0 (p) [3]
Meat			5.0 [3]	4.0 [7,10]	11.0 [4]
Bovine	2.3 [3]	0.6 [2,3]			
Mutton & Goat	10.0 [3]	0.6 [2,3]			
Pig	2.5 [3]	0.3 [2,3]			
Poultry	7.0 [3]	0.9 [2,3]			
Eggs	4.0 [11]	1.9 [2]	0.5 [3]	2.00 [3]	8.00 [4]
Milk	3.5 [3]	1.7 [2]	1.2 [12]	0.82 [8,12]	7.00 [4]
Oilseeds & Pulses	5.3 [13]	1.2 [2]	5.0 [3]	1.00 [3]	4.00 [4]
Roots & Tubers	20.0 [3]	7.6 [2]	13.8 [3,14]	7.00 (f) [10] 3.00 (p) [3]	17.00 (f) [4] 12.00 (p) [4]

b) Industrialised Asia (IndusAsia)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	3.92 [1,15]	4.24 [2,15,16]	11.8 [3,15]	2.00 [3]	13.65 [3,15]
Fruit & Veg	10.00 [3]	8.37 [2]	2.00 [3]	8.00 (f) [3] 2.00 (p) [3]	10.35 (f) [3,16] 8.00 (p) [3]
Marine	15.00 [3]	16.50 [2,3]	6.00 [3]	11.00 (f) [3] 5.00 (p) [3]	7.30 (f) [3,16] 7.00 (p) [3]
Meat			5.00 [3]	6.00 [3]	6.80 [3,16]
Bovine	2.30 [3]	0.55 [2,3]			
Mutton & Goat	10.00 [3]	0.81 [2,3]			
Pig	2.50 [3]	0.18 [2,3]			
Poultry	7.00 [3]	1.03 [2,3]			
Eggs	6.00 [11]	2.38 [2]	0.50 [3]	4.00 [3]	3.65 [3,16]
Milk	3.50 [3]	2.24 [2]	1.20 [12]	0.50 [12]	2.60 [3,16]
Oilseeds & Pulses	6.00 [3]	2.72 [2]	5.00 [3]	1.00 [3]	16.55 [3,16]
Roots & Tubers	20.00 [3]	4.85 [2]	15.00 [3]	9.00 (f) [3] 3.00 (p) [3]	7.15 (f) [3,16] 12.00 (p) [3]

c) North America & Oceania (NAmOce)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	7.17 [1,17]	3.25 [2,18]	10.50 [3]	9.00 [18–21]	23.99 [4,18–21]
Fruit & Veg	20.00 [5]	15.30 [2,18]	2.00 [3]	9.35 (f) [18–20,22,23] 4.75 (p) [18–20,22]	25.43 (f) [18–20,22] 14.60 (p) [18–20,22]
Marine	12.00 [3]	2.22 [2,3]	6.00 [3]	6.83 (f) [10,18–22] 5.50 (p) [3,18]	28.17 (f) [3,18–22] 14.00 (p) [3,18]
Meat			5.00 [3]	3.90 [10,18–22]	21.19 [4,18–22]
Bovine	2.30 [3]	0.31 [2,3]			
Mutton & Goat	10.00 [3]	0.80 [2,3]			
Pig	2.50 [3]	0.66 [2,3]			
Poultry	7.00 [3]	0.88 [2,3]			
Eggs	4.00 [11]	2.27 [2]	0.50 [3]	7.00 [18–22]	20.40 [18–22]
Milk	3.50 [3]	0.40 [2,18]	1.20 [12]	7.75 [12,18–22]	21.00 [18–22]
Oilseeds & Pulses	12.00 [3]	3.91 [2]	5.00 [3]	1.00 [3]	4.00 [4]
Roots & Tubers	20.00 [3]	5.83 [2,18]	15.00 [3]	8.00 [3,10,18]	15.00 [4,18]

d) Latin America (LatAm)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	6.00 [3]	7.46 [2]	9.00 [3]	4.00 [3]	10.00 [3]
Fruit & Veg	20.00 [24]	14.32 [2]	20.00 [3]	12.00 (f) [25] 2.00 (p) [25]	10.00 (f) [3] 1.00 (p) [3]
Marine	5.70 [3]	19.61 [2,3]	9.00 [26]	10.00 (f) [3] 5.00 (p) [3]	4.00 (f) [3] 2.00 (p) [3]
Meat			5.00 [3]	5.00 [3]	6.00 [3]
Bovine	5.00 [3]	1.32 [2,3]			
Mutton & Goat	10.00 [3]	1.04 [2,3]			
Pig	6.00 [3]	0.41 [2,3]			
Poultry	6.00 [3]	1.50 [2,3]			
Eggs	6.00 [3]	6.21 [2]	0.50 [3]	4.00 [3]	4.00 [3]
Milk	3.50 [3]	3.74 [2]	2.00 [3]	8.00 [3]	4.00 [3]
Oilseeds & Pulses	6.00 [3]	1.49 [2]	8.00 [3]	2.00 [3]	2.00 [3]
Roots & Tubers	14.00 [3]	10.39 [2]	12.00 [3]	3.00 (f) [3] 3.00 (p) [3]	4.00 (f) [3] 2.00 (p) [3]

e) North Africa, West & Central Asia (NAWCA)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	6.00 [3]	7.23 [2]	9.00 [3]	4.00 [3]	12.00 [3]
Fruit & Veg	11.33 [24,27]	11.30 [2]	20.00 [3]	15.15 (f) [24,27] 3.00 (p) [3]	13.00 (f) [24] 1.00 (p) [3]
Marine	6.60 [3]	22.46 [2,3]	9.00 [26]	10.00 (f) [3] 5.00 (p) [3]	4.00 (f) [3] 2.00 (p) [3]
Meat			5.00 [3]	5.00 [3]	8.00 [3]
Bovine	10.00 [3]	0.20 [2,3]			
Mutton & Goat	15.00 [3]	0.20 [2,3]			
Pig	8.00 [3]	0.23 [2,3]			
Poultry	8.00 [3]	0.90 [2,3]			
Eggs	6.00 [3]	4.89 [2]	4.50 [3]	4.00 [3]	12.00 [3]
Milk	3.50 [3]	3.32 [2]	2.00 [3]	8.00 [3]	2.00 [3]
Oilseeds & Pulses	15.00 [28]	2.80 [2]	8.00 [3]	2.00 [3]	2.00 [3]
Roots & Tubers	11.9 [27]	9.26 [2]	12.00 [3]	5.70 (f) [27] 2.00 (p) [3]	6.00 (f) [3] 3.00 (p) [3]

f) Sub-Saharan Africa (SSA)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	7.21 [3,29]	8.75 [2,29–33]	15.25 [3,34]	2.00 [3]	1.00 [3]
Fruit & Veg	13.47 [35]	17.71 [2,31]	25.00 [3]	34.13 (f) [35] 10.00 (p) [3]	5.00 (f) [3] 1.00 (p) [3]
Marine	5.70 [3]	21.94 [2,3,31]	9.00 [26]	15.00 (f) [3] 10.00 (p) [3]	2.00 (f) [3] 1.00 (p) [3]
Meat			5.00 [3]	7.00 [3]	2.00 [3]
Bovine	10.00 [3]	0.93 [2,3,31]			
Mutton & Goat	33.00 [3]	0.20 [2,3]			
Pig	10.00 [3]	0.23 [2,3]			
Poultry	25.00 [3]	0.90 [2,3]			
Eggs	8.00 [3]	8.01 [2]	0.10 [3]	3.00 [3]	1.00 [3]
Milk	6.00 [3]	8.20 [2,3,31]	2.00 [3]	10.00 [3]	0.10 [3]
Oilseeds & Pulses	12.00 [3]	8.18 [2,30,31]	8.00 [3]	2.00 [3]	1.00 [3]
Roots & Tubers	14.00 [3]	16.94 [2,31]	15.00 [3]	5.00 (f) [3] 2.00 (p) [3]	2.00 (f) [3] 1.00 (p) [3]

g) South & South-East Asia (SSEAsia)

Group / Commodity	FSC1 (Agricultural Production)	FSC2 (Handling & Storage)	FSC3 (Processing)	FSC4 (Distribution)	FSC5 (Consumer)
Cereals	6.00 [3]	6.59 [2,36,37]	7.00 [3]	2.98 [3,36]	3.00 [3]
Fruit & Veg	8.71 [27,35,38,39]	9.87 [2,35,36,38–40]	25.00 [3]	12.96 (f) [35,36,38,41] 10.00 (p) [3]	18.16 (f) [27,39] 1.00 (p) [3]
Marine	8.20 [3]	25.47 [2,3]	9.00 [26]	12.33 (f) [3,42] 10.00 (p) [3]	2.00 (f) [3] 1.00 (p) [3]
Meat			5.00 [3]	7.00 [3]	4.00 [3]
Bovine	10.00 [3]	0.21 [2,3]			
Mutton & Goat	10.00 [3]	0.20 [2,3]			
Pig	6.00 [3]	0.47 [2,3]			
Poultry	8.00 [3]	0.97 [2,3]			
Eggs	8.00 [3]	7.23 [2]	0.10 [3]	3.00 [3]	2.00 [3]
Milk	3.50 [3]	4.68 [2]	2.00 [3]	10.00 [3]	1.00 [3]
Oilseeds & Pulses	7.00 [3]	3.40 [2,36]	8.00 [3]	2.00 [3]	1.00 [3]
Roots & Tubers	8.15 [43]	12.11 [2,36,43]	10.00 [3]	10.78 (f) [43] 8.00 (p) [3]	3.88 (f) [43] 5.00 (p) [3]

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Table A-3. Country and region groups, based upon FAO definitions.

North America & Oceania (NAmOce)	
N.Am	Canada
N.Am	USA
Oceania	Australia
Oceania	New Zealand

Europe (Europe)	
E.Eur	Belarus
E.Eur	Bulgaria
E.Eur	Czech Republic
E.Eur	Czechoslovakia
E.Eur	Hungary
E.Eur	Moldova
E.Eur	Poland
E.Eur	Romania
E.Eur	Russia
E.Eur	Slovakia
E.Eur	Ukraine
E.Eur	USSR
N.Eur	Denmark
N.Eur	Estonia
N.Eur	Finland
N.Eur	Iceland
N.Eur	Ireland
N.Eur	Latvia
N.Eur	Lithuania
N.Eur	Norway
N.Eur	Sweden
N.Eur	United Kingdom
S.Eur	Albania
S.Eur	Bosnia Herzegovina
S.Eur	Croatia
S.Eur	Cyprus
S.Eur	Greece
S.Eur	Italy
S.Eur	Macedonia
S.Eur	Malta
S.Eur	Montenegro
S.Eur	Portugal
S.Eur	Serbia
S.Eur	Serbia & Montenegro
S.Eur	Slovenia
S.Eur	Spain
S.Eur	Yugoslavia
W.Eur	Austria
W.Eur	Belgium
W.Eur	Belgium & Luxembourg
W.Eur	France
W.Eur	Germany
W.Eur	Luxembourg
W.Eur	Netherlands
W.Eur	Switzerland

Industrialised Asia (IndusAsia)	
E.Asia	China
E.Asia	Japan
E.Asia	South Korea

North Africa, West & Central Asia (NAWCA)	
N.Afr	Algeria
N.Afr	Egypt
N.Afr	Libya
N.Afr	Morocco
N.Afr	Sudan
N.Afr	Tunisia
W.Asia	Armenia
W.Asia	Azerbaijan
W.Asia	Georgia
W.Asia	Iraq
W.Asia	Israel
W.Asia	Jordan
W.Asia	Lebanon
W.Asia	Mongolia
W.Asia	Saudi Arabia
W.Asia	Turkey
W.Asia	UAE
W.Asia	Yemen
C.Asia	Kazakhstan
C.Asia	Kyrgyzstan
C.Asia	Tajikistan
C.Asia	Turkmenistan
C.Asia	Uzbekistan

Latin America (LatAm)	
C.Am	Costa Rica
C.Am	El Salvador
C.Am	Guatemala
C.Am	Honduras
C.Am	Mexico
C.Am	Nicaragua
C.Am	Panama
C.Am	Panama
Carib	Cuba
Carib	Dominican Republic
Carib	Haiti
Carib	Jamaica
S.Am	Argentina
S.Am	Bolivia
S.Am	Brazil
S.Am	Chile
S.Am	Colombia
S.Am	Ecuador
S.Am	Guyana
S.Am	Paraguay
S.Am	Peru
S.Am	Suriname
S.Am	Uruguay
S.Am	Venezuela

Sub-Saharan Africa (SSA)	
E.Afr	Ethiopia
E.Afr	Kenya
E.Afr	Malawi
E.Afr	Mozambique
E.Afr	Rwanda
E.Afr	Tanzania
E.Afr	Uganda
E.Afr	Zambia
E.Afr	Zimbabwe
Mid.Afr	Angola
Mid.Afr	Cameroon
Mid.Afr	Central African Republic
Mid.Afr	Chad
Mid.Afr	Congo
Mid.Afr	Gabon
S.Afr	Botswana
S.Afr	Lesotho
S.Afr	Namibia
S.Afr	South Africa
S.Afr	Swaziland
W.Afr	Benin
W.Afr	Burkina Faso
W.Afr	Gambia
W.Afr	Ghana
W.Afr	Guinea
W.Afr	Guinea Bissau
W.Afr	Ivory Coast
W.Afr	Liberia
W.Afr	Mali
W.Afr	Mauritania
W.Afr	Niger
W.Afr	Nigeria
W.Afr	Senegal
W.Afr	Sierra Leone
W.Afr	Togo

South & South-East Asia (SSEA)	
S.Asia	Afghanistan
S.Asia	Bangladesh
S.Asia	India
S.Asia	Iran
S.Asia	Nepal
S.Asia	Pakistan
S.Asia	Sri.Lanka
SEA	Cambodia
SEA	Indonesia
SEA	Laos
SEA	Malaysia
SEA	Myanmar
SEA	Philippines
SEA	Thailand
SEA	Viet.Nam

Table A-4. Grouping of individual food commodities – FAO categories.

Group	Commodity	Group	Commodity	Group	Commodity
Cereals	Barley	Fruit & Veg	Apples	Meat	Bovine
	Maize		Bananas		Mutton & Goat
	Millet		Citrus		Pig
	Oats		Grapes		Poultry
	Rice		Other Fruit	Milk & Eggs	Eggs
	Rye		Vegetables		Milk
	Sorghum	Marine	Fish & Seafood	Oilseeds & Pulses	Oilcrops
	Wheat	Roots & Tubers	Starchy Roots		Pulses
	Other Cereals				

Table A-5. Mass of total FLW (in Mt) by region, and globally, at 10-year intervals.

Region	1961	1971	1981	1991	2001	2011
Europe	185	210	225	223	209	221
IndusAsia	100	131	163	216	347	443
NAmOce	78	93	115	134	161	167
LatAm	39	57	76	94	126	159
NAWCA	21	31	43	61	90	121
SSA	35	47	58	81	112	159
SSEAsia	79	103	144	190	258	355
World	536	673	824	1000	1302	1626

Table A-6. Per capita FLW by mass (in kg) at 10-year intervals by region and globally.

Region	1961	1971	1981	1991	2001	2011
Europe	285	296	298	281	286	298
IndusAsia	126	133	138	157	232	281
NAmOce	352	373	417	439	470	443
LatAm	175	198	208	211	240	268
NAWCA	178	199	214	232	230	259
SSA	180	193	181	192	205	225
SSEAsia	95	98	109	114	129	154
World	177	182	186	190	216	240

Table A-7. Mass of FLW (in Mt) by commodity group at global level in 10-year intervals.

Group	1961	1971	1981	1991	2001	2011
Cereals	150	192	248	306	336	378
Fruit & Vegetables	165	212	268	342	516	678
Marine	11	17	21	28	40	54
Meat	17	24	32	42	52	66
Milk & Eggs	49	58	71	78	99	129
Oilseeds & Pulses	27	37	50	64	88	123
Roots & Tubers	117	132	134	140	170	198
Total	536	673	824	1000	1302	1626

Table A-8. Mass of production-phase FLW-associated GHG emissions (in Mt CO_2e) by region, and globally, at 10-year intervals.

Region	1961	1971	1981	1991	2001	2011
Europe	216	277	315	329	273	289
IndusAsia	66	107	146	214	347	446
NAmOce	133	170	187	209	240	250
LatAm	66	87	128	160	212	267
NAWCA	24	32	47	62	99	142
SSA	53	74	98	130	170	254
SSEAsia	123	163	221	300	399	542
World	681	910	1141	1404	1740	2189

Table A-9. Per capita mass of FLW-associated production-phase GHG emissions (in kg CO_2e) at 10-year intervals by region and globally.

Region	1961	1971	1981	1991	2001	2011
Europe	333	391	417	414	374	389
IndusAsia	83	108	124	156	233	283
NAmOce	604	681	681	682	703	663
LatAm	299	301	349	360	402	448
NAWCA	197	206	231	236	253	302
SSA	277	302	305	305	312	359
SSEAsia	149	156	166	180	199	236
World	225	247	258	266	289	324

Table A-10. Mass of global FLW-associated GHG emissions (in Mt CO_2e) by commodity group at 10-year intervals.

Group	1961	1971	1981	1991	2001	2011
Cereals	141	189	244	302	342	400
Fruit & Vegetables	103	129	157	190	266	344
Marine	44	68	90	116	163	226
Meat	252	345	428	533	621	750
Milk & Eggs	83	103	131	150	198	267
Oilseeds & Pulses	30	42	56	75	103	146
Roots & Tubers	28	32	33	37	46	56
Total	681	910	1141	1404	1740	2189

Appendix B
Supplementary Information for Chapter 5

B.1 Supplementary tables

Table B-1. Loss factor (*LF*) ranges (in percent) and sources for fresh fruit and vegetables in the UK and European Economic Area (EEA). The 'central' estimate is: i) the average value provided in the source publication; ii) the midpoint of a given range where no average value is provided; or iii) the point estimate if only one value is provided in the source publication.

Crop	Region	Minimum	Central	Maximum	Sources
Apple	UK	5	15	25	1
	Europe	1	10	25	1–5
Broccoli + Cauliflower	UK	3	12	20	1,6
	Europe	3	12	20	1,2,5,6
Cabbage	UK	8	22	40	2,5,7
	Europe	8	22	40	2,5,7
Carrot	UK	24	31	50	6,8,9
	Europe	10	23	50	2,4–6,8–10
Lettuce	UK	5	26	50	6,9,11
	Europe	5	24	50	2,5–7,9,11
Onion	UK	9	15	20	1
	Europe	8	17	33	1,2,10
Pear	UK	10	11	12	2,5
	Europe	10	11	12	2,5
Potato	UK	3	19	40	1,9,12
	Europe	3	14	40	1–5,9,12,13
Strawberry	UK	1	12	35	1,6,8,9,11,14
	Europe	1	10	35	1,2,4–6,8,9,11,14
Tomato	UK	7	7	7	1
	Europe	1	3	7	1–3,5,7

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Table B-2. Emission factor (*EF*) ranges, in t CO_2e t^{-1}, and sources for fresh fruit and vegetables in the UK and European Economic Area (EEA). The 'central' estimate is the average all values provided in the source publication for a specific crop in Europe or the UK. The minimum and maximum values are the lowest and highest values for the specific crop in Europe or the UK.

Crop	Region	Minimum	Central	Maximum	Sources
Apple	UK	0.11	0.21	0.32	1–3
	EEA	0.03	0.17	0.43	1–11
Broccoli +	UK	0.29	1.12	1.94	1,2
Cauliflower	EEA	0.29	1.26	2.22	1,2,12
Cabbage	UK	0.22	0.22	0.22	1
	EEA	0.22	0.35	0.48	1
Carrot	UK	0.05	0.20	0.35	1,2
	EEA	0.02	0.17	0.50	1,2,5,9,12,13
Lettuce	UK	1.00	1.39	1.78	2,14
	EEA	0.26	1.01	1.78	2,14
Onion	UK	0.07	0.22	0.37	1,2
	EEA	0.04	0.23	0.48	1,2,5,12
Pear	UK	0.32	0.32	0.32	1
	EEA	0.20	0.32	0.43	1,4
Potato	UK	0.17	0.22	0.26	1–3,15
	EEA	0.09	0.19	0.51	1–3,5,9,13,15
Strawberry	UK	0.80	0.94	1.27	1–3,15
	EEA	0.30	0.78	1.27	1–3,15
Tomato	UK	2.07	4.34	9.40	1,3,15,16
	EEA	0.11	1.59	9.40	1,3,19–21,5,9,12,13,15–18

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Table B-3. Grade-out losses (in kt) of FFV crops for the UK and EEA.

		Grade-out Losses (kt)		
Crop	Region	Minimum	Central	Maximum
Apple	UK	11	37	69
	EEA	94	1,034	3,103
Broccoli + Cauliflower	UK	5	21	38
	EEA	72	319	585
Cabbage	UK	20	65	154
	EEA	332	1,078	2,547
Carrot	UK	229	325	724
	EEA	629	1,692	5,663
Lettuce	UK	6	38	107
	EEA	120	722	2,285
Onion	UK	39	69	98
	EEA	576	1,357	3,262
Pear	UK	3	3	3
	EEA	248	276	304
Potato	UK	151	1,147	3,259
	EEA	1,507	7,933	32,486
Strawberry	UK	1	16	64
	EEA	13	146	706
Tomato	UK	7	7	7
	EEA	70	216	525
Total	UK	472	1,728	4,523
	EEA	3,661	14,773	51,466

Table B-4. Embedded production-phase emissions (in kt CO_2e) of FFV grade-out losses in the UK and EEA. *LF* refers to loss factor and *EF* refers to emissions factor. There are three values for each factor (minimum, central estimate, maximum), which combine together to create nine possible embedded emissions scenarios.

		Embedded Production Phase GHG Emissions (kt CO_2e)								
Crop	Reg	Min_{LF}-Min_{EF}	Min_{LF}-Ctr_{EF}	Min_{LF}-Max_{EF}	Ctr_{LF}-Min_{EF}	Ctr_{LF}-Ctr_{EF}	Ctr_{LF}-Max_{EF}	Max_{LF}-Min_{EF}	Max_{LF}-Ctr_{EF}	Max_{LF}-Max_{EF}
Apple	UK	1	2	3	3	7	10	6	11	17
	EEA	3	16	40	28	158	400	70	396	1,001
Broccoli + Cauliflower	UK	1	5	9	5	20	35	9	34	59
	EEA	20	88	156	81	354	624	136	590	1,039
Cabbage	UK	4	4	4	11	11	11	20	20	20
	EEA	67	107	147	185	294	403	336	535	734
Carrot	UK	9	35	61	11	45	79	18	72	127
	EEA	11	96	283	26	221	651	57	481	1,416
Lettuce	UK	5	7	10	28	39	50	54	74	95
	EEA	30	115	203	143	554	976	297	1,154	2,034
Onion	UK	2	8	13	4	13	22	5	17	29
	EEA	21	122	254	45	259	540	87	503	1,049
Pear	UK	1	1	1	1	1	1	1	1	1
	EEA	45	71	96	49	79	106	54	86	115
Potato	UK	25	32	38	158	204	241	332	430	508
	EEA	132	278	746	614	1,296	3,479	1,754	3,703	9,941
Strawberry	UK	1	1	1	11	13	18	33	39	52
	EEA	4	10	17	39	102	166	138	358	583
Tomato	UK	14	29	64	14	29	64	14	29	64
	EEA	8	111	655	23	332	1,965	54	776	4,586
Total	UK	63	124	204	246	382	531	492	727	972
	EEA	341	1,014	2,597	1,233	3,649	9,310	2,983	8,582	22,498

B.2 Examples of aesthetic 'quality' standards for FFV

The following are a selection of EU CMO requirements related purely the aesthetics of three fruit and vegetable products (apples, potatoes, and strawberries). The complete set of requirements are found in Annex I, Part B of Commission Implementing Regulation (EU) No 543/2011. Also included is a summary of the private standards for strawberries applied to the case-study, as per personal communication with the case-study farmer.

B.2.1 Apples (CMO)

Minimum criteria for sale to consumer as fresh (per Annex I, Part B, Part 1, II.A)

- Intact
- Sound
- Clean, practically free from visible foreign matter
- Practically free from pests and/or damage caused by pests affect the flesh
- Free from serious watercore
- Free from abnormal external moisture
- Free from foreign smell and/or taste
- Sufficiently developed to:
    - Withstand transportation and handling, and
    - Arrive at destination in satisfactory condition

Table B-5. Apples: selection of CMO classification criteria when sold for fresh consumption in the EU.

Criteria	Extra Class	Class I	Class II
General	superior quality; stalk must be intact	good quality; stalk may be missing	
Colour	¾ red for colour Group A; ½ mixed red for colour Group B	½ red for colour Group A; 1/3 mixed red for colour Group B	
Shape	Free from defects, except very slight superficial defects	Slight defect permitted	Defects permitted provided recognisable as an apple
Skin	Free from defects, except very slight superficial defects such as very slight russeting	Bruising < 1 cm^2 and not discoloured; <2 cm in length; slight russeting	Bruising < 1.5 cm^2, slightly discoloured; < 2.5 cm^2 for all surface defects; <4 cm in length; slight russeting

B.2.2 Tomatoes (CMO)

Minimum criteria for sale to consumer as fresh (per Annex I, Part B, Part 10, II.A)

- Intact
- Sound
- Clean, practically free from visible foreign matter
- Fresh in appearance
- Practically free from pests and/or damage caused by pests affect the flesh
- Free from abnormal external moisture
- Free from foreign smell and/or taste
- For trussed tomatoes the stalks must be fresh, healthy, clean and free from all leaves and visible foreign matter
- Sufficiently developed to:
    - Withstand transportation and handling, and
    - Arrive at destination in satisfactory condition

Table B-6. Tomatoes: selection of CMO classification criteria when sold for fresh consumption in the EU.

Criteria	Extra Class	Class I	Class II
General	Superior quality Firm Free from greenbacks and other defects, except very slight superficial defects	Good quality Reasonably firm Free from cracks and visible greenbacks Slight defects permitted	Reasonably firm (but slightly less so than Class I) Not showing unhealed cracks
Shape & colour	very slight superficial defects	Slight defect permitted in shape, colour, and skin Very slight bruises	Defects in shape, and colour permitted provided variety remains recognisable Skin defects and bruising permitted provided they are not serious
Tolerance	Up to 5% by number or weight may be of Class I , and not more than 0.5% of Class II	Up to 10% by number or weight may be of Class II, and not more than 1% not meeting Class II For trusses, up to 5% may be detached from stalk	Up to 10% by number or weight may not meet Class II <2% affected by decay For trusses, up to 10% may be detached from stalk

B.2.3 Strawberries (CMO)

Minimum criteria for sale to consumer as fresh (per Annex I, Part B, Part 7, II.A):

- Intact, undamaged
- Sound
- Clean, practically free from any visible foreign matter
- Fresh in appearance, but unwashed
- Practically free from pests and damage caused by pests
- With the calyx; calyx and stalk must be fresh and green
- Free of abnormal external moisture
- Free of any foreign smell and/or taste
- Sufficiently developed to:
  - Withstand transportation and handling, and
  - Arrive at destination in satisfactory condition

Table B-7. Strawberries: selection of CMO classification criteria when sold for fresh consumption in the EU.

Criteria	Extra Class	Class I	Class II
General	Superior quality 'Bright' in appearance Free from soil Free from defects, except very slight superficial defects	good quality May have slight defects in shape or colour	Satisfy minimum criteria, but may have defects
Colour		White patch not more than 10% of surface	White patch not more than 20% of surface
Shape & Appearance	Free from defects, except very slight superficial defects	Slight defect in shape permitted; Superficial pressure mark	Defect in shape permitted Traces of soil Slight dry bruising
Size (diameter)	At least 25 mm	At least 18 mm	At least 18 mm
Tolerance	Up to 5% by number or weight may be of Class I , and not more than 0.5% of Class II	Up to 10% by number or weight may be of Class II, and not more than 2% total not meeting Class II nor minimum criteria, or affected by decay	Up to 10% by number or weight may not meet Class II or minimum criteria <2% affected by decay

B.2.4 Strawberries (private)

The following is based upon specific criteria from the case study supermarket as obtained during a site visit to the case study farm. The classifications are the supermarket's own and relate to decision making with respect to deliveries of fresh produce from a supplier such as the case-study farm.

Table B-8. Strawberries: example of private supermarket criteria used in the UK.

Characteristic	Reject	Improvement needed	Acceptable
Shape	More than 10% excessively misshapen	< 10% of fruit with fanned or flattened shape Brown or scorched calyxes	Fruit typical of classic strawberry shape All calyxes fresh with stems present
Size	More than 10% of fruit outside of size grade (25-50 mm)	Fruit between 25 and 50 mm but not in 10 mm bands. < 10% berries smaller than 25 mm or larger than 50 mm	Fruit between 25 and 50 mm, visually graded in approx 10 mm bands.
Appearance	>10% with dry bruise, rub marks, dull or tired looking >5% wet bruise, stalk, or pest damage	Up to 10% with dry bruise/wind-rub, healed cracks, dull or tired looking fruit Up to 5% with wet bruise	Bright fruit with good lustre, clean skin finish
Colour	White shoulder in excess of 10%. >10% green tips present >10% of berries higher than colour stage 6	Up to 10% of fruit with white shoulder or green tips Up to 10% of berries higher than colour stage 6	All berries pink/red colouration more than 90% of area All berries at or below colour stage 6
Firmness	Excessively soft	Slightly soft	Firm to touch