HOOKED ON FOOD WASTE: CHARACTERIZING POST-PRODUCTION SEAFOOD LOSSES AND THEIR LIFE CYCLE IMPACTS ALONG VARIOUS SEAFOOD SUPPLY CHAINS

By

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ABSTRACT

Food waste is an increasingly important phenomenon in public and academic discourse. In my thesis, I set out to explore this topic by reviewing published literature examining the efficacy of food waste reduction in achieving positive social, economic, and environmental outcomes. In parallel, I also undertook my own analysis of the environmental implications of food waste and food waste reduction, conducting a life cycle assessment of exemplary seafood supply chains delivering product to retail setting in Toronto, Canada. Outcomes of both these research processes highlight the importance of developing food waste reduction strategies that 1) focus on high-impact products (i.e. beef), and 2) require low additional resource investment (i.e. addressing overconsumption and plate waste by reducing portion size). Notably, both the literature review and analysis of seafood supply chains indicate that data on food losses are limited in quality and quantity, suggesting that additional research is needed in this area.

LIST OF ABBREVIATIONS USED

AP	Acidification potential
BC	British Columbia
CBA	Cost-benefit analysis
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent
DEFRA	Department for Environment, Food, and Rural Affairs
EEIO	Environmentally-extended input output
EP	Eutrophication potential
EU	European Union
FAO	Food and Agriculture Organization
FCRN	Food Climate Research Network
FGS	Food Guide Serving
FSC	Food supply chain
FW	Food waste
FWR	Food waste reduction
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
GWP	Global warming potential
HDPE	High density polyethelene
IEA	International Energy Agency
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram(s)
km	kilometer(s)
kWh	kilowatt hour(s)
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LDPE	Low density polyethelene
MEXT	Ministry of Education, Culture, Sports, Science, and Technology
NGO	Non-government organization
NIA	Net impact assessment
PO_4 eq.	Phosphate
PS	Portion size
SDG	Sustainable Development Goal

SO_2 eq.	Sulphur dioxide
UK	United Kingdom
UN	United Nations
US	United States
WRAP	Waste and Resources Action Programme
WWI	World War I
WWII	World War II

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CHAPTER 1. INTRODUCTION

1.1 Background

Food systems have evolved considerably over the past century, markedly improving technological inputs, increasing food yields, and growing total global volumes of food production (Gordon et al., 2017; Reynolds et al., 2017; Ramankutty et al., 2018). Though these advances have allowed global levels of undernourishment to be reduced in the past (FAO, 2018), room for improvement in current and future food systems is significantly more limited, constrained by a set of interconnected, intensifying environmental challenges, to which food production activities themselves make notable contributions (Foley et al., 2011; Gordon et al., 2017; Poore & Nemecek, 2018; Ramunkutty et al., 2018). These environmental concerns are further compounded by forecasts of population growth and changing dietary patterns, which reveal that demand for food products will rise considerably (perhaps by up to 110% by 2050 from 2005 levels), particularly for animal-derived products which will become increasingly accessible as the global gross domestic product (GDP) per capita grows (Keyzer et al., 2005; Godfray et al., 2010; Kearney, 2010, McMichael et al., 2007). Meeting these demands will place substantial pressure on natural resources, a dilemma which has drawn increasing concern from the academic community and society writ large (Alston et al., 2009, Hubert et al., 2010; Tillman et al., 2011; Baldos & Hertel, 2014). Clearly, the path to achieving equitable and sustainable development cannot be navigated without addressing these challenges.

The pivotal role of food systems in the pursuit of social and environmental goals has been widely recognized globally and reflected in governance documents such as the United Nation’s (UN) Sustainable Development Goals (SDG), wherein food can be aligned directly or indirectly to many, if not all, of the global goals set by the UN General Assembly (Stockholm Resilience Centre, 2016; FAO, 2018). Contemporary concern for the environmental implications of food systems resonates particularly with SDG #12: Ensure sustainable consumption and production patterns (UN General Assembly, 2015). The concept of sustainable production and consumption has emerged over the past few decades, coming into international policy focus at the 1992 Earth Summit in Rio de Janeiro wherein the status of production and consumption patterns at the time was identified as “one of the most serious problems now facing the planet” (UN Conference on Environment and Development, 1992, p. 3). Sustainable consumption and production have since gained significant attention within national and international domains of environmental governance. Examples of high level documents that call for sustainable production and consumption include the Oslo Symposium on Sustainable Consumption (1994), the European Union (EU) Sustainable Development Strategy (2001), the World Summit on Sustainable Development (2002) (Fuchs & Lorek, 2005; European Commission, 2018). Within many of these documents, definitions of sustainable production and consumption remain vague, leaving room for them to be liberally interpreted and applied in practice (Lorek & Fuchs, 2013; Stoner, 2013).

Despite the widespread and long-standing recognition that sustainability can only be realised through efforts that address both production and consumption challenges, within food and other economic sectors, efforts to date have been overwhelmingly targeted to address production side challenges (Mont & Pleplys, 2008; Tukker et al., 2008; IPCC, 2014; Creutzig et al., 2016), leaving unsustainable consumption patterns largely unaddressed and upholding the “myth that we can achieve sustainable development without fundamentally affecting people’s lifestyles” (Dowdeswell, 1995). The transformation of consumption practices remains an equally, if not more acute part of the puzzle, and requires that technological advances on the production side be matched by changes to consumption patterns (Garnett, 2011; Bryngelsson et al., 2016; Poore & Nemecek, 2018). Operationalizing these changes, however, first requires sustainable consumption patterns to be delineated and differentiated from unsustainable ones. This is a substantial undertaking that presents obvious methodological challenges given that the line between “sustainable” and “unsustainable” will be relative to the efficiency and scale of consumption practices and the limits of the Earth’s carrying capacity (Rockstrom et al., 2009).

Within discussions of food systems, what constitutes sustainable food consumption remains a point of debate (Hamm, 2009; Garnett, 2011; Garnett, 2013; Heller et al., 2013; Freidberg, 2016). This is, to a great extent, understandable considering the inherently political nature of this task as well as the uncertainties that continue to prevent conclusions within fields of dietary health and environmental assessment from being definitive. In spite of and indeed *because of* these challenges, it is crucial for research efforts to continue exploring, defining, and guiding sustainable food consumption.

Dialogues and research efforts attempting to define sustainable food consumption have drawn attention to the importance of dietary patterns, suggesting that environmental dimensions need to be factored into dietary-related decision-making processes in order to shift high-impact diets to low-impact ones (Carlsson-Kanyama et al., 2003; Hallström et al., 2015; Freidberg, 2016, Hallström et al., 2017). This research has been possible through the efforts of hundreds of scholars over the last 30 plus years assessing the environmental performance of food systems (for compilations see: Nijdam et al., 2012; Notarnicola et al., 2017; Hilborn et al., 2018, Poore and Nemecek 2018). Results of this research reveal the substantial variation in impacts both between and amongst major food production systems (Poore and Nemecek, 2018). However, it is increasingly clear that the environmental consequences of animal product production, and in particular those derived from ruminants, outweigh those of their plant-based counterparts across a wide range of resource depletion and environmental concerns (Audsley et al., 2009; Carlsson-Kanyama & Gonzalez, 2009; Gonzalez et al., 2011; Nijdam et al., 2012, Poore & Nemecek, 2018). Various studies have carried out these comparisons at the dietary level, often arriving at a similar conclusion that plant-based diets can meet nutritional requirements at significantly lower environmental costs than those that include high amounts of animal-based products (Berners-Lee et al., 2012; Masset et al., 2014; Bryngelsson et al., 2016).

Ranking at the high-impact end of the animal-product spectrum, beef has been particularly marked as an unsustainable product within food systems literature (Pelletier & Tyedmers, 2010; Poore & Nemecek, 2018). On the other hand, certain seafood species and chicken products have been identified as, generally speaking, less impactful forms of animal protein (Tilman & Clark, 2014; Poore & Nemecek, 2018). Importantly, however, dietary studies indicate that within the average Western diet, consumption of animal protein often surpasses human nutritional requirements (Young & Nestle, 2002; Walker et al., 2005; Westhoek et al., 2014), a pattern which "is responsible for increased rates of heart disease, stroke and some cancers" (Walker et al., 2005: p. 354). This indicates that though the choice of food products matters, so too does the level at which they are consumed (Garnett, 2011; Stoner, 2013). Conceptually, this observation aligns with the strong sustainable consumption theory, which asserts that improvements to eco-efficiency must be accompanied by reductions to the scale of consumption in order for human life to remain inside of the ecological boundaries within which it can safely operate (Rockstrom et al., 2009; Garnett, 2011; Lorek & Fuchs, 2013). This stands in contrast to the weak sustainable consumption approach that posits that the consumption of efficiently-produced goods is sufficient to comprise sustainable consumption (Lorek & Fuchs, 2013).

One suggested route to achieving sustainable scales of food consumption is by addressing food waste, levels of which have been recently reported as high – amounting to up to 30% of the global food supply (Gustavsson et al., 2011; Conrad et al., 2018; Poore & Nemecek, 2018; Springmann et al., 2018). Read by many as an unsustainable, irrational use of both food products and natural resources, food waste has recently attracted significant attention within the academic community and wider society (Smil, 2004; Lucifero, 2016; Mourad, 2016; Campbell et al., 2017; Xue et al., 2018). Concern for this issue certainly predates the conceptualization of sustainable consumption (see food waste campaigns carried out in North America during World War (WW) I and II (Bentley, 1998; Veit, 2007; Witkowski, 2003), yet interest in it seems to have surged in the last decade or so, a trend that can be observed in the rise of academic and mainstream media articles containing the terms "food loss" or "food waste" (Mourad, 2016). Through both these outlets, food waste has been implicated in many environmental issues currently facing the global community (Hall et al., 2009; Venkat, 2011; FAO, 2013; Scholz et al., 2015; Song et al., 2015; Reutter et al., 2016; Vittuari et al., 2016; Brancoli et al., 2017; Poore & Nemecek, 2018). In this context, non-governmental organization (NGO)-led campaigns, corporate programs, and national and international policies have put food waste reduction on the global sustainable development agenda, in a literal sense considering that the UN included a food waste reduction target in SDG #12 (UN General Assembly, 2015).

Evidenced by its inclusion in SDG #12, the reduction of food waste has been formally tied to the pursuit of sustainable production and consumption patterns. In theory, there is great merit to this ambition, considering that, depending on where along the food supply-chain the loss occurred, the waste of edible food results in the waste of environmental resources that were used to produce, process, transport, store, and cook that food (Corrado et al., 2017). Within both grey- and peer-review literature, many have sought to characterize such environmental consequences (Hall et al., 2009; Venkat, 2011; FAO, 2013; Scholz et al., 2015; Song et al., 2015; Reutter et al., 2016; Vittuari et al., 2016; Brancoli et al., 2017; Poore & Nemecek, 2018). More often than not, studies have approached the quantification of environmental impacts from a top-down perspective, producing high-level understandings that speak to the environmental importance of reducing food waste (Hall et al., 2009; FAO, 2013; Reutter et al., 2016). Unfortunately, results of these top-down assessments are often too coarse to inform and guide specific waste reduction strategies. Finer-scale, more focused assessments enable exploration of practical issues such as how environmental impacts of food waste differ along nodes of supply chains and between product type and form. Such insight is necessary to target food waste initiatives on stages of supply chains and/or specific product types and forms wherein waste results in relatively high scales of environmental impacts.

Applying a bottom-up, focused approached to capture the life cycle impacts of specific products and processes, the environmental assessment tool or analytical framework of life cycle assessment (LCA) presents opportunities to capture details missed by top-down approaches and to produce environmental characterizations of food waste that are product- and node-specific. Yet, because food LCAs have been predominantly focused on production-level impacts of food systems, many, but certainly not all, extant studies have omitted from their analyses downstream supply chain stages and consequently, have seldom characterized the life cycle impacts of food waste that occurs post-production (Corrado et al., 2017). Various studies have reported high rates of losses within post-production stages, especially at the retail and consumer level within wealthier, industrialized country settings while in developing countries losses appear to occur earlier along supply chains (Buzby et al., 2012; Gustavsson et al., 2011), underscoring the need for LCAs to extend their analyses downstream. In doing so, food LCAs could 1) provide more comprehensive coverage of the life cycle impacts of food products and resultantly, be used to reveal post-production activities that contribute large shares of environmental impacts, and 2) provide further insight on the environmental impacts of food waste which could be helpful in decision-making processes related to food waste reduction initiatives (Corrado et al., 2017).

1.2 Research Aims and Objectives

Certainly, addressing food waste has a role to play in achieving sustainable development, but, given some of the issues discussed above, there has been an insufficient amount of critical investigation into the nature and extent of that role and the possible tradeoffs that may arise through successful food waste reduction initiatives. In this context, I set out within this thesis project to advance understandings of the environmental significance of food waste, with the overarching goals of exploring and ultimately, informing more sustainable food consumption patterns. Achieving these goals requires methods of measuring and understanding the environmental impacts of consumption practices to be critically questioned, applied, and improved. Accordingly, I aimed to further outline some of the nuances and complexities associated with measuring and addressing food waste, those of which are not frequently unpacked within food waste literature. Secondarily, I intended to explore ways forward: 1) to investigate ways in which food waste can be addressed to achieve more sustainable food systems, and 2) to identify important methodological issues and knowledge gaps which must be attended to in future food waste research in order for the environmental implications of this phenomenon to be better understood.

Flowing from the aims described above, I wanted to 1) explore how both food waste and food waste reduction are treated within published literature and 2) perform my own analytic work in order to assess the impacts of food waste and possible food waste reduction strategies. In the literature review, I systematically searched for, and selected for further analysis, articles that explicitly quantified the social, economic, and/or environmental outcomes of food waste reduction. In my analysis of these articles, I set out to achieve the following:

1) To characterize the potential outcomes of food waste reduction that have been determined by extant literature
2) To identify patterns in both methods and results of extant literature that has explored outcomes of food waste reduction
3) To identify the extant literatures' methodological shortcomings and suggest improvements for future research in this area

The analytical part of this research project was comprised of an exploration of the environmental impacts of seafood losses occurring along a set of example seafood supply chains. An analysis of activities of post-production stages (including food consumption activities such as food waste) of select seafood supply chains was carried out using the tool and framework of LCA. The objectives of this exercise were as follows:

1) to estimate the extent to which post-production losses occurring along seafood supply chains determine the life cycle impacts of consumed seafood products

2) to explore potential strategies (i.e. frozen storage and portion size adjustment) to reduce seafood losses and reduce the life cycle impacts of seafood supply chains

    a. to evaluate the effectiveness of these strategies in reducing seafood losses

    b. to evaluate how the application of these strategies to seafood supply chains determines the life cycle impacts of consumed seafood products

1.3 Overview of Food Waste Literature

As discussed above in Section 1.1, food waste is widely discussed and problematized within academic literature and society generally. As noted by Campbell and colleagues (2017), “compared to only a few years earlier, food waste has become a site of action. It is increasingly being measured, evaluated and subject to normative statements that morally position food waste as bad” (p. 171). Value systems underlying the contemporary concern surrounding food waste are various, and are certainly not exclusive to the environmental reasons motivating this research project. Importantly, these different value systems frame the ways in which food waste is interpreted, measured, and managed. Many activists and authors tie the occurrence of food waste to the presence of food insecurity, a framework that has led many to posit food waste reduction as a path to improving individual and collective nutritional outcomes (Chaboud & Daviron, 2017). A logical corollary to this, the management of food waste has been associated with the reduction of food insecurity; this is exemplified in Philip and colleagues, 2017, wherein an assessment of a food bank in Israel revealed that food gleaning projects that rescue perishable foods from being wasted, though “costly and complex”, improved the nutritional contents of items on the food bank’s shelves. Another dominant narrative ties food waste to disciplines of industrial ecology and waste management, motivating research efforts that investigate ways in which scraps of food waste can be diverted away from waste streams and revalorized as sources as chemicals, energy, feedstock for traditional (e.g. swine) or novel (e.g. insect) animal agriculture and/or materials (i.e. Han & Shin, 2004; Zhang et al., 2007; Esteban & Ladero, 2018). These are two very distinct framings that highlight 1) how understandings of the term "food waste" vary, and 2) how these varied understandings shape and are shaped by different disciplines of research within food waste literature.

Notable effort has been dedicated to outlining the distinct ways in which food waste has been framed, defined, and measured (Figure 1.1). As noted by Chaboud and Daviron (2017), different terminologies have been devised to refer to certain types of food waste; for example, some authors have restricted their use of the term "food waste" to retail and consumer stages of the food supply chain (FSC), wherein occurrences of food waste are presumed to be caused by unsustainable management and behaviours. Under this same framework, the more neutral term of "food loss" is applied to earlier supply chain stages (i.e. post-harvest storage and transport), wherein the perceived sense of responsibility is shifted away from actors and towards infrastructure and technology (Gustavsson et al., 2011). Though this system of terminologies has been widely adopted, its moral tone has been criticized by some who argue that it places unnecessary and unproductive blame on the consumer (Figure 1.2) (Evan et al., 2012; Chaboud & Daviron, 2017).

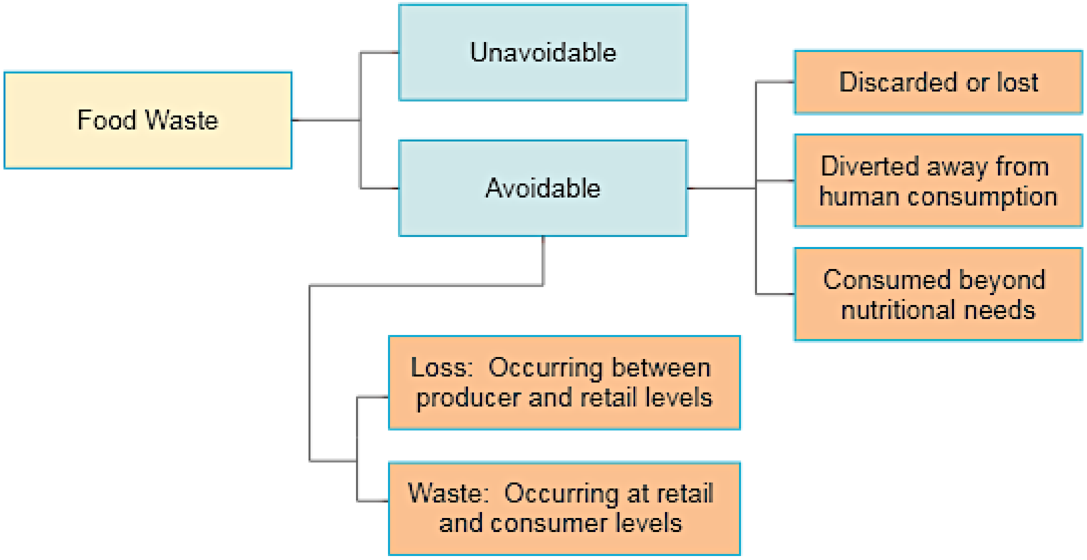
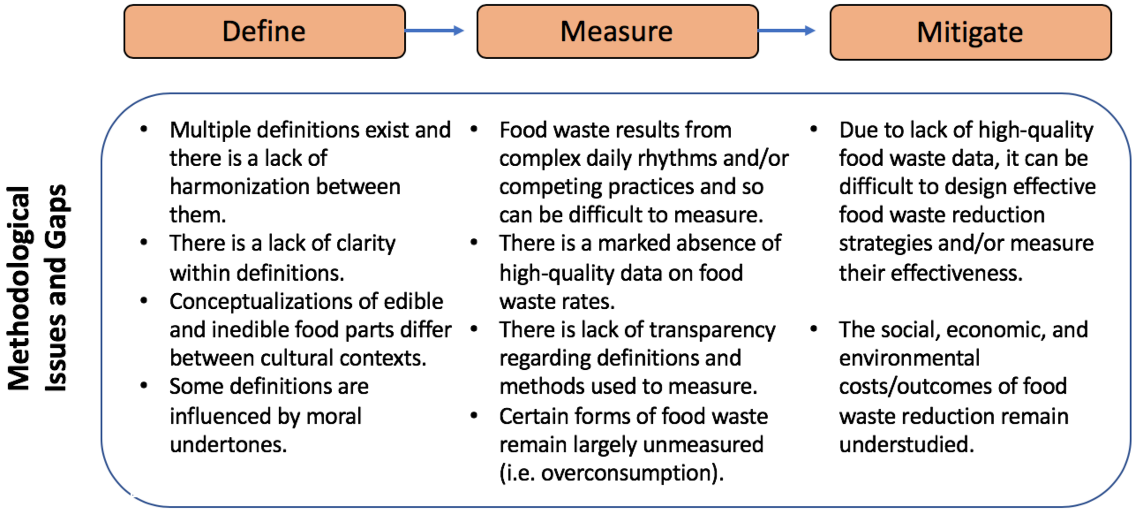


Figure 1.1 Conceptual hierarchy demonstrating the various definitions of food waste and the relationships between them that were found within food waste literature



- Multiple definitions exist and there is a lack of harmonization between them.
- There is a lack of clarity within definitions.
- Conceptualizations of edible and inedible food parts differ between cultural contexts.
- Some definitions are influenced by moral undertones.

- Food waste results from complex daily rhythms and/or competing practices and so can be difficult to measure.
- There is a marked absence of high-quality data on food waste rates.
- There is lack of transparency regarding definitions and methods used to measure.
- Certain forms of food waste remain largely unmeasured (i.e. overconsumption).

- Due to lack of high-quality food waste data, it can be difficult to design effective food waste reduction strategies and/or measure their effectiveness.
- The social, economic, and environmental costs/outcomes of food waste reduction remain understudied.

Figure 1.2 Overview of the methodological issues and gaps associated with efforts to define, measure, and mitigate food waste that can be found within and/or are discussed within food waste literature.

Another framework that has been applied to conceptualize distinct forms of food waste as well as to guide food waste management is the waste hierarchy (see Figure 1.3) (Papargyropoulou et al., 2014). Food rescue initiatives, such as the Israeli example discussed above, fall under the category of "re-use", which lies one level below the most environmentally preferable option "prevention", as depicted in Figure 1.1. The second narrative discussed above, which characterizes food waste as a resource through which energy/chemicals can be extracted for purposes other than human or animal nutrition, ranks near the bottom of the food waste hierarchy within the recovery level, which is characterized as only environmentally preferable to "disposal" of food waste in a landfill.

Though the food waste hierarchy can help prioritize actions to address food waste in the most economically and environmentally efficient way, it does not allow for the actual economic, environmental, and social outcomes to be known. In order to discern these impacts, analysis of the economic and/or resource investment associated with food waste reduction strategies is necessary. Importantly, some have noted the absence of such analyses from food waste literature (Koester, 2015; Reutter et al., 2016; Shafiee-Jood & Cai, 2016; Chaboud & Daviron, 2017), suggesting that additional research is needed to characterize the economic, environmental, and social outcomes of food waste (Figure 1.3).

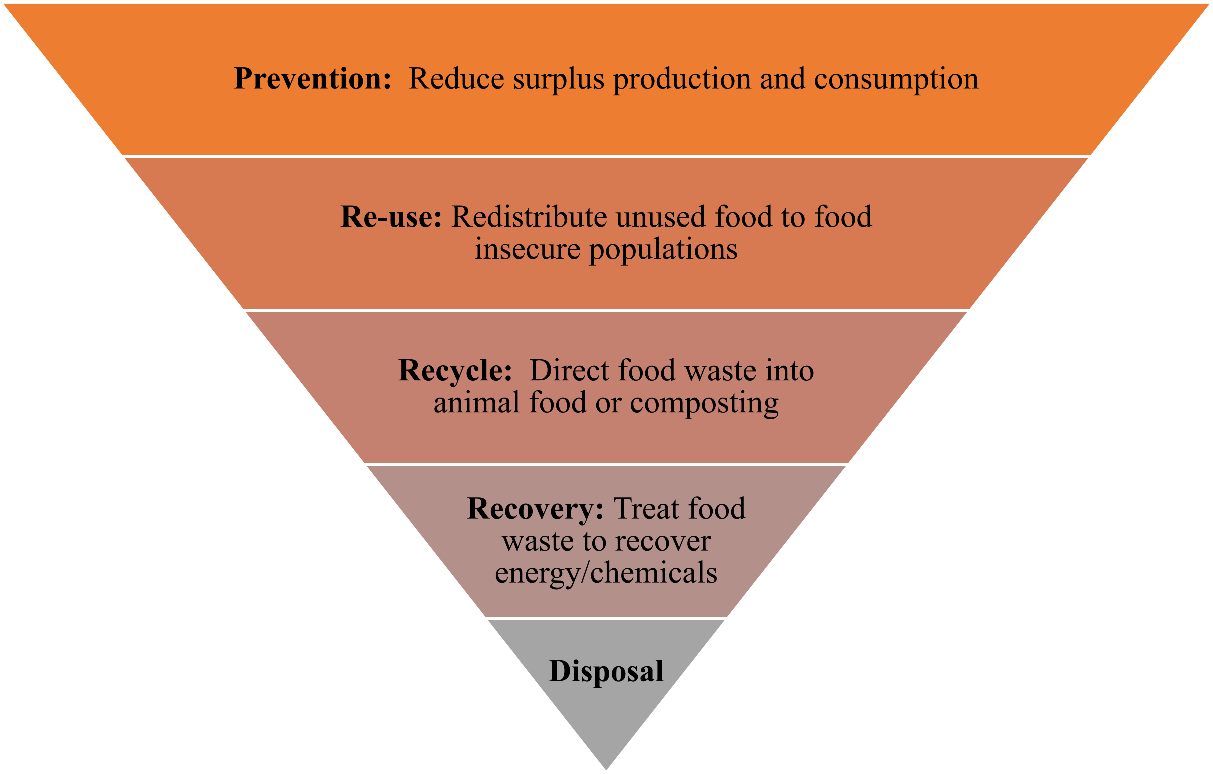


Figure 1.3 Food Waste Hierarchy

(Adapted from Papargyropoulou et al., 2014)

An important distinction has also been established between food waste that is "avoidable" and "unavoidable" (Figure 1.2), with the latter pertaining to parts of food that are considered inedible (e.g. meat bones and egg shells) and the former comprising of edible food parts (WRAP, 2009) (Figure 1.2). Between these two ends of the spectrum lies the category of "possible avoidable" food waste, "food and drink that some people eat and others do not (e.g. bread crusts)" (WRAP, 2009, p. 4). Reflecting on this, some authors have questioned the rigidity of these separate categories, noting how the line between edible and inedible food is strongly influenced by cultural preference (Figure 1.3) (Chaboud & Daviron, 2017). Within the category of avoidable food waste, Parfitt and colleagues (2010) observed three conceptually unique definitions, the first of which can be traced back to an FAO report published in 1981, wherein food waste is defined as edible product intended for human consumption that is discarded or lost (p. 3065). The second definition, developed by Stuart (2009), expands beyond the first to capture food that has been diverted away from the human FSC, such as edible by-products of processing activities that have been used in animal foods (Parfitt et al., 2010). Taking this conceptualization even further, the last definition, credited to Smil (2004), also classifies over-nutrition, "the gap between energy value consumed per capita and energy value of food needed per capita", as waste (Parfit et al., 2010, p. 3065) (Figure 1.2). Each of these definitions take issue with a different form of unsustainable consumption patterns; where the FAO (1981) definition implies that only the discard of edible food should be reduced, the other two definitions call for more substantial structural and sociocultural changes to food systems (i.e. reduction to scale of consumption levels, particularly of animal products).

Generally speaking, most attempts to measure levels of food waste have limited their analysis to the FAO definition and consequently (Figure 1.2), the second two definitions listed above (Smil, 2004; Stuart, 2009) are not frequently explored within food waste literature. Scope is sometimes cited as the reason preventing authors from tackling food waste arising from by-product diversion and overconsumption (Corrado et al., 2017). Certainly, the task of quantifying overconsumption poses additional challenges to the researcher, including determining both 1) current levels of food intake, and 2) nutritionally appropriate levels of food intake. There is limited data to support estimations of these parameters and researchers will be required to "make assumptions about relationships and processes" involved in overconsumption, also termed as "luxus consumption" (Blair & Sobal, 2004, p. 65). Furthermore, the decision to quantify overconsumption encroaches on sensitive social territory (Stoner, 2013, Food Climate Research Network [FCRN], 2019), probing the environmental and nutritional consequences of cultural norms that inform individual and collective social identities (Lindsay, 2010). In spite of these issues, overconsumption should not be overlooked considering that it may prove a key point of leverage through which scales of consumption can be reduced.

Excluding overconsumption from the food waste framework does not preclude a researcher from grappling with sociocultural complexities, considering that many observational studies have found household food waste to be the result of a food provider's navigation of daily rhythms (such as work schedules) and competing social beliefs/practices (making it difficult to both measure and address this phenomena) (Evans, 2012; Watson & Meah, 2013; Wang et al., 2017). Nor can researchers avoid dealing with imperfect, limited data; this problem is pervasive within food waste literature (Chaboud & Daviron, 2017). Some authors have attempted to characterize the nature of these data limitations, for example, Xue and colleagues (2018), reviewed the then available literature that quantified food waste and found the collective body of research to be fraught by: 1) a narrow spatial coverage (focused largely on developed countries and on retail and consumer stages), 2) predominant reliance on secondary data, some of which is outdated but still used, and 3) the use of assumptions in the absence of first-hand or secondary observations (Figure 1.3). Though noting that these shortcomings were consistent throughout the literature, Xue and colleagues (2018) found that the opposite was true in regards to studies' choice of system boundaries, methods, and definitions, making "systematic comparison and verification of food loss/waste data between countries, stages, and commodities often difficult" (p. 6619). These issues have great consequence for our collective ability to utilize the food waste literature, undermining the certainty of estimations of food waste levels as well as any research efforts or policy initiatives that rely on them to make additional assessments (i.e environmental assessments of the impacts of waste) or to take action on food waste (Xue et al., 2018) (Figure 1.3). In light of this, ample work remains to more effectively measure rates of food waste and their consequential environmental, social, and environmental impacts.

1.4 Overview of Seafood Sustainability

The environmental impacts of seafood systems have been historically addressed through single-stock management programs and regulations and more recently, through ecosystem-based management regimes (Ziegler et al., 2016). As the detrimental impacts of overfishing have become evident through the over-exploitation and in some instances collapse of important regional and global fisheries, consumers, particularly in Europe and North America, have played a more active role in these processes (Jacquet & Pauly, 2007). Many sustainable seafood labeling systems have been developed to aid consumers in making purchasing decisions that will support sustainable seafood production practices while discouraging unsustainable ones (Ziegler et al., 2016). According to the leading fishery-focused certification and labeling scheme, Marine Stewardship Council, for a seafood to be considered sustainable, it has to have been fished in a responsibly managed marine area, from a fish stock with a healthy population, and have resulted in minimal impact to the marine environment (Marine Stewardship Council, n.d.). Expanding this definition to aquaculture, a Canadian national program, Sea Choice, describes sustainable seafood as products that have been either "caught or farmed in a manner that can be sustained over the long term without compromising the health of marine ecosystems" (SeaChoice, n.d.). For farm-produced species, meeting this standard requires that the following impacts of production be considered and minimized: marine resources used in feed, risk of escapes, disease and parasite transfer to wild stocks, risk of pollution and other habitat effects (SeaChoice, n.d).

Notably, the myriad seafood certification schemes and government policies that comprise the contemporary sustainable seafood regime remain focused on a limited set of typically highly localized resource depletion or environmental issues attributable to production-level activities within fishery and aquaculture systems (Ziegler et al., 2016; Ocean Wise, 2019). These localized concerns are indeed well-founded and there is great merit to addressing them, yet they are, arguably, too narrowly focused and thus overlook other important issues that play a role in the realization of sustainable food systems (Pelletier & Tyedmers, 2008, Ziegler et al., 2016). Within the domain of LCA scholarship, researchers have drawn attention to an additional set of environmental concerns not historically considered within the sustainable seafood movement and conventional fishery- and aquaculture-related research (Pelletier & Tyedmers, 2008, Henriksson et al., 2012). The environmental issues studied within this field largely manifest on a global-level (e.g. contributions to climate change, acidifying emissions), or regionally (e.g. eutrophying emissions). This focus on global environmental challenges is due to the nature of LCA practice which uses standardized, defensible methods to connect locally occurring activities of a defined system, such as fuel use, to broad-scale issues such as climate change and abiotic resource use (Pelletier et al., 2007).   Thus, through the lens of LCA, for a seafood product to be considered sustainable it must not only have limited impact on marine and aquatic resources and environments but also make minimal contributions to these various global environmental challenges.

Early seafood LCA research observed that a large share of these broad-scale environmental impacts could be attributed to fuel use in the case of fisheries and feed production in the case of aquaculture (Hospido and Tyedmers, 2005; Thrane, 2004;

Grönroos et al., 2006; Aubin et al., 2009). As the body of seafood LCAs has grown, these early observations have been largely upheld (Parker, 2012) except in atypical production settings (Ayer and Tyedmers 2009, Ziegler et al. 2011). Importantly, though, various review papers have observed that seafood LCAs have remained largely focused on a limited part of seafood supply chains (the production level) and a restricted set of environmental dimensions (climate change, eutrophication, acidification) (Henriksson et al., 2012; Parker, 2012; Avadí & Freón, 2013; Cao et al., 2013). LCA studies that have expanded their analysis beyond the production level have identified other supply chain activities as environmentally significant, such as the extraction and processing of metal in the production of canned seafood products or the airfreighting of seafood products along international fresh seafood supply chains (Winther et al., 2009; Almeida et al., 2015). Consumer level activities (i.e. transportation, storage, and cooking) in particular have been seldom studied, though when they have been included in life cycle analyses of seafood products, their contribution to life cycle greenhouse gas emissions has been observed as non-trivial (Vazquez-Rowe et al., 2013).

Within the various disciplines of research and practice discussed above, imbalanced attention to the production side of sustainability can clearly be observed. Consumption practices have been largely interrogated from a weak sustainable consumption standpoint, exemplified in the design of consumer-facing seafood label schemes, which do not require nor imply changes to *scales* of seafood consumption (Stoner, 2013). Not surprisingly, post-production occurrences of waste and overconsumption have garnered little attention amidst the work of LCA researchers, fisheries scientists, and consumer activists alike. Resultantly, there has been relative omission of these two phenomena from seafood-related research, programs, and policy (Tacon & Metian, 2009, Stoner, 2013). Taking issue with this important knowledge gap, Stoner (2013) compiled first and secondary observations in order to produce preliminary estimates of post-production seafood losses occurring along fresh and frozen supply chains. Examining the issue of losses from a nutritional perspective, Love and colleagues (2015) presented seafood waste reduction as a pathway to reduce pressures on natural resources and increase the supply of important nutrients (i.e. omega-3 fatty acids) to the United States' population. Using extant food waste data sets, they determined that seafood losses in the United States amounted to 40-47% of seafood supply between the years 2009-2013. In another study, James and colleagues (2011), highlighting the environmental and economic importance of seafood losses, mapped out seafood losses along select UK seafood supply chains in order to characterize their cumulative carbon and economic impact. A message woven through each of these studies: sustainable consumption practices (i.e. the reduction of losses) are crucial to addressing the local- and global-scale environmental issues engendered by the production and provisioning of seafood products.

1.5 Thesis Structure

In the following section, the structure of the thesis chapters and their contents are briefly described. Chapter 2 follows this introductory chapter with a focused food waste literature review. In this review, systematically selected studies that assessed the economic, environmental, and/or social outcomes of food waste reduction were critically analyzed and their findings, methods, and limitations were summarized and discussed. This chapter has been written as a submitable manuscript to *Journal of Cleaner Production* and will include committee members as co-authors. Chapter 3 reports results of my analytical work exploring the potential impacts of seafood losses along supply chains, through which the objectives listed above in Section 2 were fulfilled. This chapter has been similarly prepared as a submitable manuscript to the *Journal of Cleaner Production*, within which committee members were listed as co-authors. The analytical work performed within this chapter takes a form similar to that of many of the studies assessed within the literature review of Chapter 2; resultantly, these two pieces of work are highly complementary. The themes and high level insights that run through both of these chapters will be summarized in the final concluding chapter (Chapter 4).

CHAPTER 2. REDUCING FOOD WASTE: BY WHAT MEANS AND FOR WHAT ENDS?

2.1 Increased Concern for Food Waste

Food waste (FW) has re-emerged as a topic of great public concern over the last decade. This increased attention is reflected by a rapid proliferation of national and international FW policies, a trend that is exemplified by the 2015 commitment of the United Nations and its member countries to reducing FW by 50% by 2030 (UN General Assembly, 2015) as well as the 2016 ban against retail FW in France (Mourad, 2015). The upsurge in national and international FW policy has occurred alongside the implementation of corporate programs seemingly aimed to address the challenge (such as the promotion of ugly fruit and vegetables in retail settings, such as Imperfect Produce, 2018) as well as the emergence of dedicated FW campaigns organized by non-governmental organizations across much of the global North (for example, the consumer outreach efforts performed by Waste and Resources Action Programme in the United Kingdom) (WRAP, 2009).

The increasing problematization of FW within political and civic realms has been mirrored by a recent rapid growth in academic work focusing on this phenomenon. Indeed, searches of the Web of Knowledge for articles in which either "food loss" or "food waste" appear, indicate that over the past decade there has been an approximate 800% increase in the number of articles published annually containing either of these terms (Figure 2.1). An informal assessment of the abstracts of FW related articles within the database suggests that themes generally explored within the literature include the quantification and characterization of FW as well as the exploration of drivers of, and potential solutions to, food waste. Consistent with the substantial volume of recent work produced within this field, approaches to understanding, defining, and quantifying waste are both numerous and diverse (which some have noted thwarts the capacity of this growing body of literature to effectively inform FW initiatives (Chaboud, 2017; Xue et al., 2018).

2.2 Seeming Importance of Food Waste and Food Waste Reduction

The rise of societal concern regarding FW is understandable at a certain level given the centrality of food to human existence. The primary source of nutrition, a symbol and creator of wealth (or lack thereof), an informant of individual and collective identity, food is, and has been, integral to the survival of humanity and the development of human society and culture (Fischler, 1998; Keil & Beardsworth, 2002; Coleman, 2012; Anderson, 2014). In this context, FW can be read as equating to a waste of social and cultural values attributed to food, as illustrated by the body of literature that quantifies the foregone nutrients within wasted food (Cuéllar & Webber, 2010; Love et al., 2015; Vittuari et al., 2016; Spiker et al., 2017; Khalid et al., 2019).

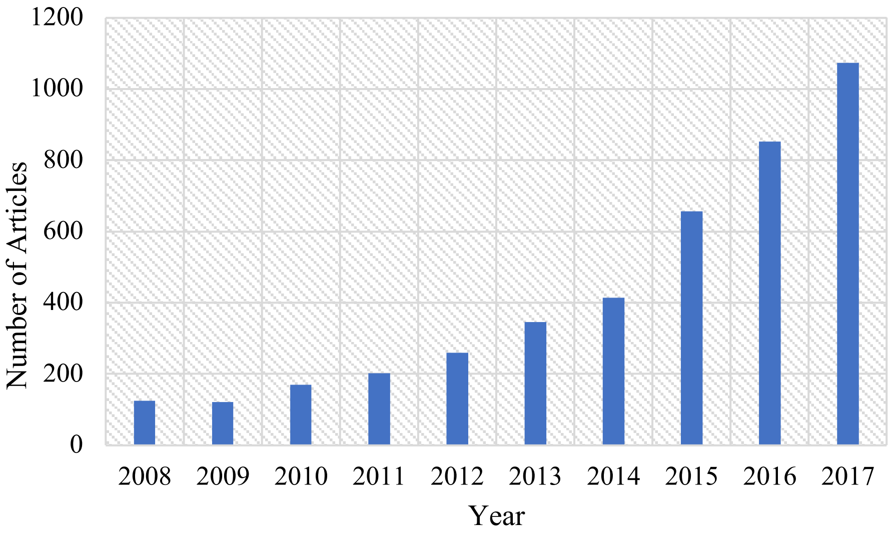


Figure 2.1 Frequency of articles published and tracked within Web of Knowledge in which one or both of the terms "food loss" or "food waste" appear: 2008-2017

Representing an apparent wasteful use of nutrients in the face of food-related issues such as under- and malnutrition, FW has been characterized by some as an unethical act, (Stuart, 2009), referred to as an “offensive demonstration of human irrationality” (Smil, 2004, p. 17) or an “intolerable contradiction” (Lucifero, 2016, p. 287). Consistent with this association, consumers have reported that they attribute feelings of guilt to the act of discarding edible food (Evans, 2012; Ganglbauer et al., 2013; Quested et al., 2013; Parizeau et al., 2015, Neff et al., 2015). Food consumers and producers alike have also related a sense of economic loss to FW, which makes sense considering that food is often a substantial economic expense for consumers and a source of revenue for supply chain actors (Mena et al., 2011; Nahman & de Lange, 2013; Stoner, 2013; Mavrakis, 2014; Mourad, 2016; Commission for Environmental Cooperation, 2017).

FW appears particularly problematic in the face of mounting environmental challenges, to which food production activities make significant contributions (Gordon et al., 2017, Poore and Nemecek, 2018). In this context, FW represents an apparent needless expenditure of natural resources and contribution to environmental degradation. On a global-scale, the environmental consequences of FW have been estimated as substantial, with global FW-related greenhouse gas emissions (GHG) amounting to the equivalent of 3.3 gigatons of CO_2 - an amount surpassed only by the world's two largest nation-state carbon emitters: China and the United States (FAO, 2013). It is thus understandable that FW has more recently been framed within academic literature and society at large as an environmental issue to be analyzed and addressed (Hall et al., 2009; Venkat, 2011; FAO, 2013; Scholz et al., 2015; Song et al., 2015; Reutter et al., 2016; Vittuari et al., 2016; Brancoli et al., 2017).

Against this background, food waste reduction (FWR) has been painted by some as a panacea, a means through which "we can reap the tremendous social benefits of alleviating hunger, the environmental benefits of efficient resource use, and the financial benefits of significant cost savings" (Gunders, 2012, p. 5). Adhering to this conceptual framework, governmental and non-governmental organizations have mandated FWR targets without considering the possible costs and consequences that may result (Hertel & Baldos, 2016). The investigation of possible outcomes of FWR has been similarly neglected in FW literature (e.g. Martindale, 2017), as many researchers have focused on problematizing FW rather than the potential impacts that could arise as a result of FWR efforts (Reutter et al., 2016).

This widespread disregard for the consequences of FWR efforts is disconcerting, given that FWR strategies are likely to require non-trivial investments of time, money, and/or natural resources (Koester, 2015; Parry et al., 2015; Shafiee-Jood & Cai, 2016; Reutter et al., 2016; Chaboud & Daviron, 2017). Additionally, any successful large-scale FWR initiatives may upset the current economic status-quo (and hence prices paid and received by consumers and producers, respectively) that results from the current overproduction and overconsumption of food (Britz et al., 2014). While such a disruption is necessary in order for the current global food system to be replaced with a more sustainable and equitable one, it is crucial to ensure that this process does not incidentally re-entrench or shift inequities and environmental degradation.

In light of these concerns, it should not be assumed that FWR is unconditionally desirable and will produce environmentally, economically, and socially beneficial outcomes. In order for FWR to serve its intended end(s) of increasing the economic and/or environmental efficiency of food provisioning, FWR targets and actions should be motivated not by potentially misguided popular beliefs but by research efforts that assess both costs associated with FWR strategies as well as potential consequences of economic transformations that may result from changes to food production and consumption patterns.

While some have drawn attention to research of this nature (Schott & Canóvas, 2015), no systematic review has thus far been undertaken. Given the need for such research to support informed FWR policies and practices, here we undertake a systematic review of extant literature that quantitatively analyzes outcomes of FWR strategies beyond simply assessing a reduction of FW in volume or value. In doing so, we aim to provide not only an overview of the outcomes of FWR determined by these articles but to also critically assess the ways in which research in this area has been conducted. The objectives of this literature review are as follows:

1) To characterize the potential outcomes of FWR that have been determined by extant literature
2) To identify patterns in both methods and results of extant literature that has explored outcomes of FWR
3) To identify the extant literatures' methodological shortcomings and suggest improvements for future research in this area

2.3 Methods

Consistent with the food waste hierarchy conceptualization of FW prevention/reduction as superior to and distinct from FW rescue and FW management, here we strictly focus on studies that evaluated the outcomes of FW reduction/prevention, wherein food waste is prevented from occurring and as such does not need to be rescued, recovered, or managed (Gentil et al., 2011; Papargyropoulou et al., 2014). While the terms “reduction” and “prevention” are both used to describe this level of the food waste hierarchy, this paper will use the latter term “reduction” to refer to it throughout the remainder of this review.

A systematic search of the literature published between 1900 and September of 2017 within the Web of Knowledge database was initially conducted using the terms “food loss” and “food waste”. We then searched within the resulting body of literature for only those studies that also contained the terms “reduce” or “prevent”. All abstracts of resulting studies were then read and articles were further excluded for one or more of the following reasons:

1) The research did not assess FWR but rather other levels of the FW hierarchy (i.e. food rescue or FW management),
2) The research analyzed a quantity of FWR but not the social, environmental and/or economic outcomes of it, or
3) The research carried out was descriptive/qualitative rather than analytical/quantitative.

The above criteria were initially used to exclude studies based on a reading of their abstracts and then were applied again upon a closer reading of the remaining studies. Additional potentially relevant studies were then identified from the reference lists of remaining studies. These potential additional studies were then also assessed against our criteria and, as appropriate, were added to the body of work for review. Upon determining the final selection of articles, we collected data on and analyzed the following characteristics of each study:

1) Temporal/geographic context,
2) Perspective of concern (i.e. economic, environmental, and/or social),
3) System boundaries (i.e. nodes of food supply chains considered),
4) Methods employed in the research, and
5) Results of the research.

Data collected on these characteristics were analyzed in order to identify general patterns in methods and results as well as methodological shortcomings and gaps requiring further research.

2.4 Results

The initial screening of “food waste” or “food loss” articles within Web of Knowledge returned 3,864 articles published between 1900 and September 2017. Applying the terms ‘reduce’ or ‘prevent’ to this literature winnowed the body of work to be screened in detail to 385 articles. After reviewing all abstracts, and excluding those that met the exclusions criteria, 51 were selected for further scrutiny. Under closer reading of the full studies, a further 16 were eliminated on the basis of the exclusion criteria while six additional studies were identified from the reference lists of selected studies and were added to those to be reviewed. As a result, a total of 41 studies met all our criteria and were then analysed further. In some of the selected studies, multiple strategies were evaluated (i.e. home composting or dietary changes) but due to the goal and scope of this paper, only strategies related to reduction/prevention of FW were evaluated.

2.4.1 Framework & Context of Studies

The studies assessed food waste reduction efforts from one or more of their economic, environmental, and social aspects, consistent with the different values of interest that various authors attributed to or prioritized in association with FW. Interestingly however, rather than limiting their frame of analyses to one perspective, many studies (n=21) incorporated multiple ones (Fig 2). From a temporal perspective, the analyses were largely static; tying both their data collection and conclusions to the relatively recent past. Geographically, the analyses were largely European focused (n = 29) with far fewer studies set in North America (n = 2), Asia (n = 2), Africa/Middle East (n = 2), or on a global level (n = 6). Of the studies analysing outcomes of FWR globally, two paid particular attention to impacts within developing countries. Many studies restricted their analyses to one level of the food system: the consumer level (n = 16), the retail level (n = 7), or the distribution level (n=1) with the remainder addressing losses at multiple levels of the supply chain (Table 2.1). Only one study – Manfredi et al., 2015 - analyzed the outcome of reduction at one level of the supply chain while also accounting for life cycle impacts of FW occurring at other life cycle stages.

Table 2.1. Framework and Contexts of Reviewed Papers

Reference Code	*Reference*	*Perspective*	*FSC Level of Focus*	*Location of Study*	*Type of Food*	*FW Solution Assessed*	*Methods Framework*
				Solution-Based Papers: Net Impact Assessments			
1	*Banasik et al., 2017*	Economic	Retail	Netherlands	Bread	Partial-baked bread (frozen and then baked in store)	Cost benefit analysis (CBA)
		Environmental	Retail	Netherlands	Bread	Partial-baked bread (frozen and then baked in store)	Exergy analysis
2	*Belavina et al., 2017*	Environmental	Consumer	US	All foods	Online grocery retail	Life Cycle Assessment (LCA)
		Economic	Consumer	US	All foods	Online grocery retail	CBA
3	*Brown et al., 2014a*	Environmental	Consumer	UK	Normally refrigerated foods (plus carrots, apples)	Lower refrigerator temperatures	Energy monitoring & LCA
		Economic	Consumer	UK	Normally refrigerated foods (plus carrots, apples)	Lower refrigerator temperatures	CBA
4	*Brown et al., 2014b*	Environmental	Consumer	UK	Normally refrigerated foods	Increased use of freezer	Energy monitoring & LCA
		Economic	Consumer	UK	Normally refrigerated foods	Increased use of freezer	CBA
5	*Conte et al., 2015*	Environmental	Consumer	Italy	Cheese	Multilayer packaging	LCA
6	*Dobon et al., 2011a*	Environmental	Retail	Netherlands	Pork chops	Flexible best-before-date packaging	LCA
7	*Dobon et al., 2011b*	Social	Retail	Netherlands	Pork chops	Flexible best-before-date packaging	Life cycle costing (LCC)
		Economic	Retail	Netherlands	Pork chops	Flexible best-before-date packaging	Willingness to Pay Survey
8	*Eriksson et al., 2016*	Environmental	Retail	Sweden	Cheese, deli, dairy, meats	Lower refrigerator temperatures	LCA
		Economic	Retail	Sweden	Cheese, deli, dairy, meats	Lower refrigerator temperatures	CBA
9	*Guillier et al., 2016*	Environmental	Retail, consumer	France	Ham	Lower refrigerator temperatures, better menu planning, consumption closer to use-by-dates	Energy consumption model
		Social	Retail, consumer	France	Ham	Lower refrigerator temperatures, better menu planning, consumption closer to use-by-dates	Bacteria growth modelling
10	*Gutierrez et al., 2017*	Environmental	Retail	Italy	Cheesecake	Improved packaging	LCA
		Economic	Retail	Italy	Cheesecake	Improved packaging	CBA
11	*Manfredi et al., 2015*	Environmental	Consumer	Europe	Milk	Active packaging	LCA
12	*Pezzuto et al., 2015*	Social	Consumer	Europe	Cheese	Active packaging	Microbial and chemical analysis, sensory evaluation, and silver migration test

Reference Code	*Reference*	*Perspective*	*FSC Level of Focus*	*Location of Study*	*Type of Food*	*FW Solution Assessed*	*Methods Framework*
13	*Rijpkema et al., 2014*	Economic	Distribution	Egypt to Belgium	Strawberries	Expedited transport	CBA
14	*Willersinn et al., 2017a*	Environmental	Production, supply chain, consumer	Switzerland	Potatoes	Pesticides against wire worms, improved sorting at farms, no quality sorting at farms, sale of unwashed potatoes, sale of unpacked potatoes	LCA
15	*Willersinn et al., 2017b*	Economic	Production, supply chain, consumer	Switzerland	Potatoes	See Willersinn et al., 2017a	Full-cost calculation scheme
		Social	Production, supply chain, consumer	Switzerland	Potatoes	See Willersinn et al., 2017a	Consumer survey
16	*Zhang et al., 2015*	Environmental	Retail	Europe	Beef	Active packaging	LCA
17	*Zhu, 2017*	Economic	Wholesale, retail	China	Fruits and vegetables	Radio frequency identification packaging	CBA
				Solution-Based Papers: Envelope Assessment			
18	*Wikström & Williams, 2010*	Environmental	Consumer	Europe	Bread	Improved packaging	LCA
19	*Wikström et al., 2014*	Environmental	Consumer	Europe	Yogurt, rice	Improved packaging	LCA
20	*Williams & Wikström, 2011*	Environmental	Consumer	Europe	Beef, cheese, ketchup, milk, bread	Improved packaging	LCA
Reference Code	*Reference*	*Perspective*	*FSC Level of Focus*	*Location of study*	*Type of Food*	*FW Outcome Assessed*	*Methodological framework*
				Outcome-Based Papers: Microeconomic Consequential Analyses			
21	*Chitnis et al., 2014*	Socioeconomic, environmental	Consumer	UK	All foods	100% reduction of avoidable FW	Environmentally-extended input output analysis (EEIO)
22	*Martinez-Sanchez et al., 2016*	Socioeconomic, environmental	Consumer	Denmark	All foods	100% reduction of avoidable FW	LCC, LCA, EEIO
23	*Salembdeeb et al., 2017*	Socioeconomic, environmental	Consumer	UK	All foods	1) 60% reduction of avoidable FW, and 2) 77% reduction of avoidable FW	Hybrid LCA & EEIO
				Outcome-Based Papers: Macroeconomic Consequential Analyses			
24	*Britz et al., 2014*	Socioeconomic	Consumer	Netherlands	All foods	Not specified	General equilibrium model
25	*Campoy-Muñoz et al., 2017*	Socioeconomic	All levels except processing	Germany, Spain, Poland	All foods	Reduction of avoidable FW	General equilibrium model
26	*Christis et al., 2015*	Socioeconomic	All levels	Belgium	All foods	Intensification of FWR	EEIO

Reference Code	*Reference*	*Perspective*	*FSC Level of Focus*	*Location of study*	*Type of Food*	*FW Outcome Assessed*	*Methodological framework*
27	*Hertel & Baldos, 2016*	Socioeconomic, environmental	All levels	Developed Regions/Sub-Saharan Africa	All foods	FW in rich countries reduced by 50%, post-harvest losses in Africa reduced to levels in Latin America (28% to 18%)	Partial equilibrium model
28	*Munesue et al., 2015*	Socioeconomic, environmental	Post-harvest levels	Global w/ focus on developing countries	All foods	50% reduction of FW in developed countries	Partial equilibrium model
29	*Rutten & Kavallari, 2016*	Socioeconomic	Production, post-harvest handling and storage	Middle East, North Africa	All foods	100% reduction of FW	Partial equilibrium model
30	*Rutten & Verna, 2013*	Socioeconomic	Production, processing, distribution	Ghana	All foods	50% reduction of FW	General equilibrium model
31	*Rutten et al., 2013*	Socioeconomic, environmental	Retail, consumer	Europe	All foods	1)30% reduction of FW, 2), 40% reduction of FW, and 3) 50% reduction of FW	General equilibrium model
32	*Stehfest et al., 2013*	Environmental	All levels	Global	All foods	15% reduction of FW	Partial and general equilibrium model
Outcome-Based Papers: One-to-One Analyses							
33	*Bellarby et al., 2013*	Environmental	All levels	Europe	Animal-derived products	Reduction of FW rate to 2.4-3.9%	Partial equilibrium model
34	*Schott & Andersson, 2015*	Environmental	Consumer	Sweden	All foods	100% reduction of avoidable FW	LCA
35	*Bryngelsson et al., 2016*	Environmental	All levels	Sweden	All foods	50% reduction of avoidable FW	LCA
36	*Costello et al., 2017*	Environmental	Consumer	United States	All foods	100% of avoidable FW	Waste reduction model (WARM) (LCA informed)
37	*Hamilton et al., 2015*	Environmental	Processing, wholesale, retail, consumer	Norway	All foods	100% reduction of FW	Multi-layer substance flow analysis
38	*Jalava et al., 2016*	Environmental	All levels	Global	All foods	1) 50% reduction of FW and, 2) Lowest loss rates at each level of the supply chain in any global region are also achieved in all other regions	Water footprint assessment
39	*Kummu et al., 2012*	Environmental	All levels	Global	All foods	Lowest loss rates at each level of the supply chain in any global region are also achieved in all other regions	Water footprint assessment, cropland and fertilizer use
40	*Martin & Danielsson, 2016*	Environmental	Retail, consumer	Europe	All foods	1) 60% reduction of FW by 2030, and 2) 85% reduction of FW by 2050	LCA
41	*Matsuda et al., 2012*	Environmental	Consumer	Japan	All foods	5% reduction of avoidable FW	LCA

All but seven studies assumed perfect linearity between FWR and food demand and hence food production - a conceptual framework that was referred to as "the green-consumption approach" by Salemdeeb and colleagues (2017 at p. 443). Amongst the seven exceptions were studies that assumed large-scale FWR would reduce food prices and consequently, increase consumption and reduce levels of undernourishment within developing countries (Table 2.1; studies #[27,28,29,30,31,32]). Similarly, in their assessment of the outcome of price markdowns within the retail setting, Zhu, 2017 assumed that reduced food prices would increase purchasing and consequently, increase consumption of food within households.

2.4.2 Categories of Studies

Two conceptually distinct categories of studies emerged from the detailed content review of the 41 articles. Papers fell into either: 1) solution-based assessments (n=20) or 2) outcome-based assessments (n=21) (Figure 2.2). Within the former group, articles first identified one or more particular potential solution(s) to reduce FW of a specific form or at a specific node along a supply chain. They then went on to quantitatively assess the potential of the solution(s) identified to reduce FW as well as to improve environmental and/or economic outcomes. The second category of studies, outcome-based assessments, did not account for the transaction costs of specific FWR measures

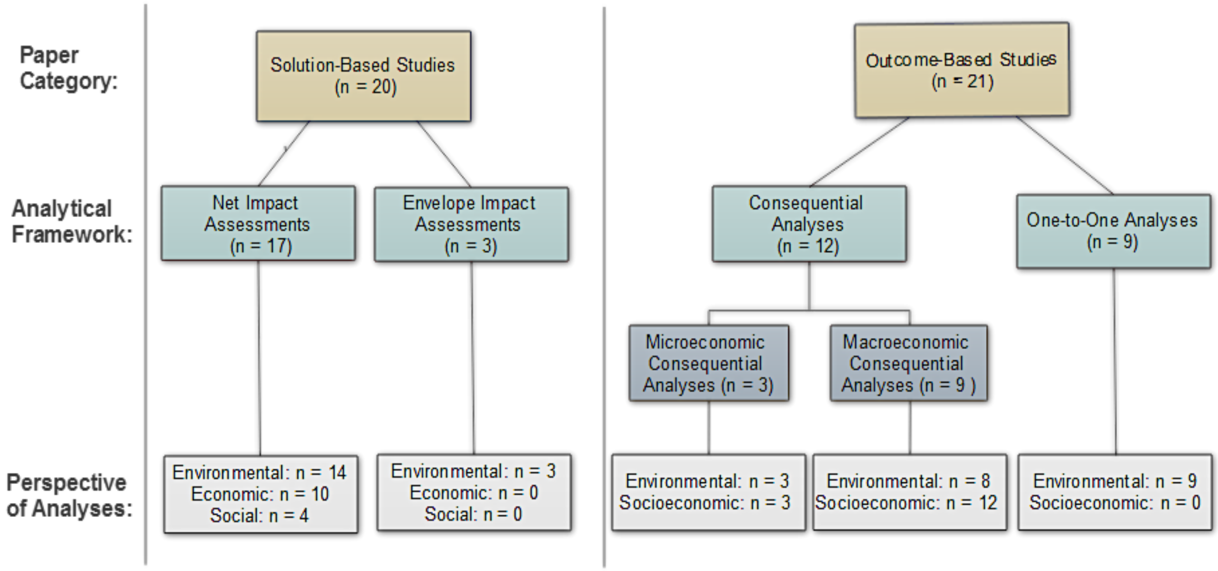
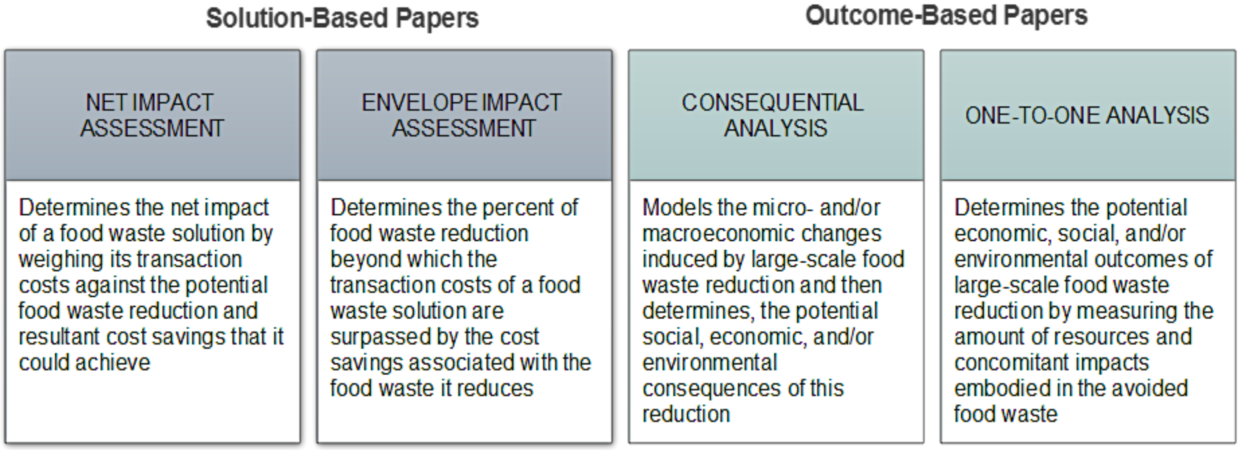


Figure 2.2 Hierarchy of Analytical Approaches Used Amongst 41 Food Waste Reduction Impact Studies Reviewed Based on the Analytical Framework Employed within the Reviewed Literature

but rather attempted to forecast the social, economic, and/or environmental outcomes of partial reduction and/or complete prevention of food waste at national (n=11) or international scales (n=10) (Table 2.1).

2.4.3 Solution-Based Studies

Within the group of solutions-based studies, two distinct analytical approaches were employed by researchers. Most authors performed what will be referred to as a net impact assessment (NIA) (n=17). In this form of analysis, the transaction costs (financial, social, or environmental) associated with a reduction strategy were weighed against the savings in resource investment and concomitant impacts that it could achieve by reducing FW. From this analysis, a net impact (of the FWR) was determined. In the second form of analysis, referred to as envelope-based assessment, the transaction cost (either financial or environmental) of a FW solution was similarly quantified (n=3).



Solution-Based Papers		Outcome-Based Papers	
NET IMPACT ASSESSMENT	ENVELOPE IMPACT ASSESSMENT	CONSEQUENTIAL ANALYSIS	ONE-TO-ONE ANALYSIS
Determines the net impact of a food waste solution by weighing its transaction costs against the potential food waste reduction and resultant cost savings that it could achieve	Determines the percent of food waste reduction beyond which the transaction costs of a food waste solution are surpassed by the cost savings associated with the food waste it reduces	Models the micro- and/or macroeconomic changes induced by large-scale food waste reduction and then determines, the potential social, economic, and/or environmental consequences of this reduction	Determines the potential economic, social, and/or environmental outcomes of large-scale food waste reduction by measuring the amount of resources and concomitant impacts embodied in the avoided food waste

Figure 2.3 Description of the Four Analytical Frameworks Discerned Amongst 41 Reviewed Food Waste Reduction Impact Studies

Distinct from the NIA, these studies then went on to delineate the quantity of FW that had to be reduced in order for the benefits associated with the reduction to surpass the costs of the FW solution at hand (Figure 2.2 & 2.3). Generally speaking, the solutions applied were designed specifically to reduce waste of a certain type of food at a specific stage of the supply chain, leading the analyses to be focused on a single food product (e.g. pork chops) or a single product category (e.g. commonly refrigerated foods) at a single supply chain level (e.g. retail).

Amongst solution-based studies, FW solutions assessed fell into the following categories: 1) shelf-life extension, 2) improved inventory management, and 3) portion size adjustment (Table 2.1). Shelf-life extension strategies assessed included: lowering refrigerator temperatures, increasing use of the freezer, employing alternative packaging designed to prevent bacterial growth (such as active packaging) and/or efforts to conserve freshness. Improved inventory management solutions assessed included: strategic menu planning within households, smart packaging technologies that measure and communicate the remaining shelf-life of a product, improved quality sorting, and distribution improvements such as expedited transport. Far outnumbered by the former two categories of solutions, portion size adjustment solutions included packaging that was designed to "contain the correct quantity" or be easy to dose into the correct quantity (Wikström et al., 2014).

2.4.4 Outcome-Based Studies

Unlike the solution-based studies, outcome-based assessments largely treated FW as a single unit, assuming that reduction efforts considered would reduce all types of FW proportionally (i.e by 50%). Some outcome-based papers performed a "one-to-one analysis" (following Rutten et al., 2013), assuming that benefits achieved from reducing FW would be equivalent to the total investment of resources both used and embodied in the prevented FW. Others, referred to as consequential analyses, took a more nuanced approach, modeling economic changes that would occur as a result of FW and then quantifying the consequential environmental, social, and economic outcomes of these economic changes (Figure 2.2 & 2.3). The latter approach can be further disaggregated into microeconomic analyses and macroeconomic analyses (Figure 2.2). Within the category of microeconomic analyses, studies sought to characterize the environmental outcomes of household monetary savings resulting from FWR efforts. Macroeconomic analyses forecasted national and international consequences of FWRs, such as changes to food prices and supply and demand patterns.

In a limited number of outcome-based studies, the outcomes of FWR were compared to a business-as-usual trajectory of global patterns in food production and consumption (Table 2.1; studies #[27,29,30,31,32,35,40]). Incorporating changes to population, productivity, and food preferences (such as increased demand for meat), these studies anticipated how the global economy would evolve over the period of time during which the FWR strategy was achieved; in doing so, they were able to compare the socioeconomic and environmental outcomes of FWR to a temporally appropriate counterfactual. The remaining outcome-based studies did not model projections of future economic and societal changes but rather drew conclusions based on previously produced reports of national and global food production and consumption patterns (Table 2.1).

2.5 Analysis of Methods Employed within Studies

Given the nature of the studies reviewed, the majority (n=39) entailed the estimation or quantification of two critical parameters: 1) levels of FW before reduction intervention occurs; and 2) levels of FW after reduction intervention occurs. Beyond these two near universally assessed parameters, studies also needed to assess one or more additional parameters depending on the outcomes to be measured: 3) the environmental and/or economic value of resources dissipated or embodied in the avoided FW (n=26); 4) the environmental and/or economic resource investment (and concomitant impacts) associated with the strategies employed to achieve a reduction (n=20); and 5) the magnitude of macroeconomic changes driven by a reduction (n=12), and 6) the social and environmental outcomes associated with these economic changes (n=21) (see Table 2.2).

Focused on the effects of a specific FWR strategy, solution-based studies generally restricted data collection to the first four parameters (Table 2.2). Exceptions to this included Guillier et al., 2016 and Pezzuto et al., 2015, wherein only the *costs* of the reduction strategy (Parameter 4) were considered and no calculation of potential benefits associated with reduction of FW was executed.

As consequential analyses typically addressed macro-scale FWR, they generally did not attempt to account for the resource investments associated with the strategies required to achieve a FWR (see Table 2.2). Resultantly, they largely included only Parameters 1, 2, 5 and 6 (Table 2.1, studies [24,25,26,27,28,29,30,31,32]). Microeconomic consequential analyses, however, required the inclusion of Parameter 3 in the place of Parameter 5 (Table 2.1, studies [21, 22, 23]). Some macroeconomic analyses included both Parameter 3 and Parameter 5, seeking to understand the extent to which theoretical savings in natural resource use (Parameter 3) could be offset by the decrease in food prices and resultant increased demand for food products incited by large-scale FWR (Parameter 5) (Table 2.1, studies # [27,28,31,32]). The only consequential analysis to include Parameter 4 (transaction costs of reduction strategy) was Britz et al., 2014. One-to-one analyses that effectively assumed FWR had no transaction costs or economic consequences only attempted to quantify Parameters 1, 2, and 3 within their analyses (Table 2.1, studies #[33,34,35,36,37,38,39,40,41]). Methods employed to determine each of the parameters varied across and between the solution- and outcome-based studies.

2.5.1 Parameters 1 & 2: Food Waste Quantification

Remarkably, 37 of 41 studies reviewed, spanning both solution- and outcome-based studies, relied entirely on secondary data to characterize levels of FW prior to a reduction intervention (Parameter 1). Two exceptions (Schott & Andersson, 2015 and Costello et al., 2017) undertook primary waste composition analyses, while the remaining two articles did not attempt to characterize Parameter 1 (Pezzuto et al., 2015; Guillier et al., 2016).

Studies were significantly more diverse in their approach to estimating levels of FWR after strategies were deployed (Parameter 2). Within the solution-based group, one study assessed microbiological densities in cooked ham products before and after they were subjected to various FWR strategies (i.e. lower refrigerator temperature, eating food products closer to best-by-dates) (Guillier et al., 2016). Despite the empirical data generated, Guillier and colleagues did not anticipate how microbiological growth rates could translate into resulting FW rates (and thus did not quantify Parameter 2). Another three solution-based studies conducted a literature review on shelf-life of products under different conditions in order to estimate the theoretical reduction that could result from extending the shelf-life of the food item(s) under analysis (Brown et al., 2014b; Conte et al., 2015; Eriksson et al., 2016).

Unlike some of the solution-based studies, authors of outcome-based studies did not perform analyses to inform their estimates of Parameter 2. Instead, they selected hypothetical scenarios of FWR, some of which were informed by discussions within extant literature. Many opted to assess the consequences of a 100% reduction of FW (Table 2.1, studies #[21,22,29,34,36,37]) while others assumed that only a partial reduction in FW levels would occur (Table 2.1, Studies #[23,27,28,30,31,32,33,35,38,39,40,41]). Somewhat remarkably, authors of three outcome-based studies, while quantifying economic, social, and/or environmental outcomes of FWR, did not specify the percent of FW that they assumed would be reduced (Table 2.1, studies #[24,25,26]).

Table 2.2. Parameters and Their Associated Methods and Applications within the Papers

Parameter	Description	Typical Methods Used	Net Impact Assessment	Envelope Impact Assessment	Consequential Analysis		One-to-one analysis
					Micro	Macro	
1	FW rate before intervention	Literature review, compositional waste analysis	x	x	x	x	x
2	FW rate after intervention	Literature review, hypothetical scenarios	x	x	x	x	x
3	Resources and concomitant impacts embodied in or generated by avoided FW	Life cycle assessment, life cycle costing, cost-benefit analysis	x	x	x		x
4	Resource investment and concomitant impacts associated with FWR strategy	Life cycle assessment, life cycle costing, cost-benefit analysis	x	x			
5	Macroeconomic change(s) induced by large-scale FW reduction	Input-output tables, equilibrium models				x	
6	Social, economic, and/or environmental impacts resulting from micro- or macroeconomic changes	Environmentally-extended input-output tables, equilibrium models			x	x	

Notes: Micro = Microeconomic; Macro = Macroeconomic. This table demonstrates general patterns in parameters used by the different analytical frameworks and the methods used to estimate them, but does not reflect variations that exist within each analytical framework. For example, various macroeconomic consequential analyses also estimate Parameter 3, while social impact assessments (that have been binned within the net impact assessment category) do not estimate Parameter 1, 2, or 3, limiting their analysis to Parameter 4.

Considering that authors of all reviewed studies (within both outcome-based and solution-based categories) relied on theory and/or scenario modelling to estimate Parameter 2, it is clear that there is a striking absence of empirical evidence available on the efficacy of FWR strategies. Despite the lack of empirical evidence used to inform key parameters of their models, many authors of studies (n=19) did not use sensitivity or scenario analyses in order to estimate the sensitivity of their results to the uncertainty inherent to reliance on secondary data and/or assumption.

Implicit in the evaluation of FWR is the evaluation of the proportion of FW that is avoidable and accordingly, can be prevented. In fifteen out of the 41, authors of studies differentiated between avoidable and unavoidable FW (WRAP, 2009), quantifying the outcomes of a reduction of avoidable FW only (Table 2.1, studies #[3,21,22,23,24,25,31,33,34,35,36,37,39,40,41]). In the remaining studies, authors did not make this distinction, with some focusing on types of food and/or activities along the supply chain wherein waste is largely avoidable. An example of this is the research of Banasik and colleagues (2017), wherein bread that arrives pre-baked at the retail level is unlikely to produce unavoidable FW within the retail setting.

2.5.2 Parameters 3 & 4: Quantifying Resource Investment Associated with Food Waste Reduction

Methods used to estimate resource investment and concomitant impacts associated with both FW (Parameter 3) and the strategies used to achieve the reduction (Parameter 4) varied with the frame and perspective of the analyses. Within solution-based studies, life cycle assessment (LCA), an environmental accounting tool, was used to assess whether environmental impacts of the FWR strategy under review (such as the global warming potential associated with additional energy required to lower refrigerator temperatures) were surpassed by the environmental benefits that a given percentage of FWR could achieve (Brown et al., 2014a; Eriksson et al., 2016).

In some outcome-based studies, authors also relied on LCA to characterize Parameter 3, synthesizing and aggregating extant LCA data in order to estimate the regional- and global-level resource investments and environmental impacts associated with FW (Table 2.1, studies #[34,35,36,40,41]). Within other outcome-based studies, authors used environmentally extended input output (EEIO) models (Table 2.1, studies #[21,22,23,26,38,39]), and in one case, a partial equilibrium model (to be discussed further in Section 2.5.3) (Bellarby et al., 2013). Consistent with the EEIO method, these studies drew on nationally- or regionally-scaled economic databases in order to estimate the carbon or water footprint or land use associated with food waste. While authors of both solution-and outcome-based studies that employed LCA tended to include multiple life cycle stages (accounting for impacts of processes at the production level and along the supply chain), those that relied on EEIO accounted only for environmental impacts associated with the production level.

Parallel to the employment of LCA within environmental analyses, life cycle costing (LCC) or "full cost calculation" was used to inform the economic analyses of some solution- and outcome-based studies (Table 2.1, studies #[7,15,22]). Authors of the majority of solution-based studies, however, applied some form of cost-benefit (CBA) analysis in order to estimate the economic outcomes of the application of a FW solution (Table 2.1, studies #[1,2,3,4,8,10,13,17]). In some instances, the CBAs entailed a rather simple calculation, comparing the economic costs of the strategy (Parameter 3) against the economic savings (Parameter 4) it would achieve. Authors of other studies took a more nuanced approach by estimating the additional profit (Parameter 3) that would result from the increased product demand that the FW solution would generate (i.e. in Zhu, 2017 wherein optimally-timed retail price markdowns generated increased demand and prevented FW from occurring within retail stores).

Unlike economic and environmental analyses, assessments of social impacts of FW and FWR strategies did not take the form of NIA. In the few solution-based studies that attempted to quantify the social impacts of FWR strategies, some analyses relied on microbiological growth or chemical analyses of food quality in order to estimate the food safety implications of a given strategy (Pezzuto et al., 2015; Guillier et al., 2016). Authors of other studies used willingness-to-pay consumer surveys to determine the social acceptability of a given strategy (Dobon et al., 2011b; Willersinn et al., 2017b).

2.5.3 Parameters 5 & 6: Quantification of Consequences of Food Waste Reduction

As distinct from practice employed within the solution-based analyses, authors of the consequential analyses largely employed equilibrium models, which "[encompass] demand and supply interactions, intersectoral linkages, the substitution effects and the role of the price mechanism therein" (Campoy-Muñoz et al., 2017, p. 202-203) (Table 2.1, studies #[24,25,27,28,29,30,31,32]). The one consequential analyses that did not use an equilibrium model (Christis et al., 2015) employed a more static tool, input-output (IO) tables - the economic basis upon which the EEIO tables discussed above are constructed.

While IO tables similarly model interdependencies within national and regional economies, they do not capture the aforementioned parameters listed by Campoy-Muñoz et al., 2017 that equilibrium models do. Both of these tools were used to ascertain Parameter 5 – the potential changes that FWRs could cause within various economic indicators such as: household incomes, employment levels, import/export patterns, food supply/demand interactions, food prices, and GDP.

Many consequential analyses further attempted to assess the social and environmental outcomes associated with the economic indicators described above (Parameter 6). For example, certain studies incorporated food distribution models in order to estimate how reduced global food prices (incited by FWR) would lead to increased consumption of food and consequently, decreased levels of undernourishment within developing countries (Munesue et al., 2015; Hertel & Baldos, 2016). Calculations of food prices (Parameter 5) and their impact on under-nutrition differed between studies; where Munesue et al., 2015 accounted for the reduction to income that would result from reduced demand and reduced food prices, Hertel & Baldos (2016) considered how a country's degree of global market integration would condition food price changes within its borders.

Accounting for the environmental implications of food price changes (Parameter 6), authors of some studies estimated how the natural resources required to meet increased demand within developing nations resulting from lower food prices would limit the land use and carbon emissions savings that could be theoretically achieved through large-scale FWR (Parameter 3) (Table 2.1, studies #[28,29,31,32]).

Focused on a much smaller scale, microeconomic consequential analyses sought to predict how FWR within households would effectively increase disposable income (Parameter 3) and subsequently, allow for the increased consumption of material goods and services (referred to as the rebound effect). The increase in consumption of material goods and services subsequent to increased economic efficiency was modeled in various ways. On the one hand, Chitnis et al. (2014) and Martinez-Sanchez et al. (2016) employed Engels curves – which indicate "how the expenditure on a particular category of goods and services varies with total expenditure" (Chitnis et al., 2014, p. 14) – in order to forecast how increased income would transform household consumption patterns (Parameter 5). In contrast, Salemdeeb et al. (2017) developed various scenarios by which money saved from household FWR would be spent. Upon modeling changes in household consumption patterns resulting from FWR, all three studies then estimated resulting environmental outcomes using EEIO (Parameter 6), thus determining the extent to which the rebound effect diminished any environmental benefits associated with FWR.

2.6 Overview of Results of Studies

The results of the diverse methodological approaches described above indicate, generally, that FWR may not be desirable under all circumstances and/or may not benefit all actors within food systems equally. This was not the case within studies that did not account for the costs and consequences of reduction efforts; unsurprisingly, these studies found FWRs to be unconditionally beneficial (Table 2.1, studies #[33,34,35,36,37,38,39,40,41]).

Looking just at the reviewed studies that *did* incorporate transaction costs within their analyses, it is evident that the application of a FWR strategy does not always imply a net reduction in resource expenditure(s). Rather, as indicated by the solution-based studies, such an outcome is conditioned by: 1) the extent to which the FWR strategy reduces waste of the food product(s) considered, 2) the resources (financial and/or environmental) embodied in the waste of the food product(s), and 3) the transaction costs (financial and/or environmental) associated with the FWR strategy applied. See the Equation 1 below for an example of how this framework could be operationalized and used to calculate the net outcome (i.e. global warming potential) of a FWR strategy.

$$\text{Equation 1:} \qquad Net\ GWP = GWP_{FWRS} - (M_{FWR} * GWP_{FW})$$

Where: Calculation of Global Warming Potential (GWP) outcome of a FWR strategy. GWP_{FWRS} = GWP (kg CO_2 equivalents) directly associated with the application of the FWR strategy.
M_{FWR} = Mass (kg) of food waste reduction. GWP_{FW} = GWP (kg CO_2 equivalents) embodied in each kg of food waste that is reduced.

On a larger scale, the results of outcome-based studies suggest that the achievement of net economic, social, and environmental benefits depends on how FWR impacts food prices and consequently, the relationship between food supply and demand. Broadly applied FWR strategies are likely to lower food prices generally and drive increased consumption of foods within developing countries, thus improving levels of under-nutrition within those countries. This subsequent increase to food consumption, however, diminishes the potential scale of environmental benefits that would otherwise have resulted from the initial FWR efforts (Table 2.1, studies #[26,27,28,29,30,31,32]).

2.6.1 Insights from Solutions-Based Studies

If the outcomes of FWR are dependent on the amount of resource investment and environmental impacts associated with the FW that is reduced, it follows that FW with higher embodied resource investment and concomitant environmental impacts are most likely to produce net benefits if reduced. Supporting this hypothesis, Eriksson and colleagues (2016) found that lowering retail refrigerator temperatures in the interest of forestalling spoilage only produced net environmental and economic gains amongst products that had relatively high initial GHG emission intensities and price tags together with lower turnover rates (e.g. meat products). Conversely, applying this FWR strategy to retail products that had lower pre-existing waste rates, and lower embodied resources and impacts (such as dairy products) resulted in *increased* environmental and economic costs. In this scenario, the restoration of economic and environmental resources embodied within the saved dairy products was insufficient to offset the environmental and economic costs of the additional electricity use required to store products at lower temperatures over a longer period of time (Eriksson et al., 2016). A similar relationship between FWR and environmental outcomes was demonstrated by Wikström & Williams (2010), Williams & Wikström (2011), Williams et al. (2014), and Willersinn et al. (2017a). In the former three studies, the authors demonstrated that potential increases in GHG emissions of improved packaging matters very little if the packaging improvement reduces FW in products with relatively high associated GHG emissions (e.g. beef). In the latter study, the authors concluded that the relatively low resource investment associated with potato production made FW management alternatives (such as the use of uneaten potatoes as animal fodder) preferable to reducing the waste of potatoes (Willersinn et al., 2014). Results of these studies all suggest that product-specific rather than universal FWR strategies are needed.

The solution-based studies also indicate that the nature and extent of benefits of FWR depend on the transaction costs (financial or environmental) of the FWR strategy being considered. Costs of specific strategies are likely to vary depending on the context within which they are applied. For example, the economic and environmental outcomes of FWR strategies requiring additional electricity use will depend on the price of electricity and the environmental consequences of locally available electricity (Eriksson et al., 2016). Given that the handling of packaging materials is contingent on regional waste management schemes, the environmental and economic transaction costs of FWR strategies involving more elaborate packaging will also be regionally dependent. As demonstrated by Williams & Wikström (2011), increased GHG emissions associated with packaging solutions may be difficult to offset by reducing FW with low embodied GHG emissions (i.e. bread) if packaging is incinerated without heat recovery. Assessing the economic and environmental feasibility of online grocery programs, Belavina et al. (2017) similarly observed that the location of a FW intervention matters, noting that the financial and environmental costs of grocery delivery services depended on the geography and population density of the setting in which the program was applied.

2.6.2 Insights from Outcome-Based Studies

The macroeconomic consequential analyses demonstrate that broad FWR will distinctly affect different countries, regions, and individuals, depending on their position within the global political economy. Due to disparities that exist within and between national economies, the distribution of potential socioeconomic benefits of FWR is not likely to be equitable and will resultantly produce both winners and losers (Rutten et al., 2013, Britz et al., 2014, Munesue et al., 2015).

Whether global-scale FWR will reduce undernourishment within developing countries hinges, in part, on the extent to which those countries are integrated into the global food market (as observed by Hertel & Baldos, 2016). In the case that sub-Saharan African food economies remain partially segmented from the global economy, domestic reduction in post-harvest losses will produce greater reductions in under-nutrition than they would if the regions' economy was fully integrated into the global economy (Hertel & Baldos, 2016). The opposite effect would result from FWR within developed countries; under this scenario, market segmentation of the sub-Saharan African region would limit downward pressure on food prices and hence potential nutritional benefits to consumers in sub-Saharan African countries.

The extent to which lower food prices translate into individual and collective improved nutritional outcomes is also impacted by the downward pressure that these lower food prices may place on incomes of food producers and suppliers, an effect demonstrated within both Munesue et al. (2015) and Rutten et al. (2013. When Munesue and colleagues (2015) accounted for the impact of FWR in the Global North on income within the Global South, they found that improvements to levels of under-nutrition in developing countries were slightly muted (in most cases) or even reversed (in the case of Brazil) in comparison to simulations wherein the income effect was excluded from analysis.

Studies focusing on microeconomic impacts within developed countries found that due to the rebound effect, consumers could be expected to re-spend the additional income freed up by FWR on other food goods, material goods, or services (referred to in some studies as marginal consumption). The environmental impacts associated with this marginal consumption limited or even negated potential reductions in environmental impacts that theoretically could have been achieved if household savings from FWR were not re-spent (Christis et al., 2015; Martinez-Sanchez et al., 2016; Salemdeeb et al., 2017). Notably, the extent of environmental impacts caused by the re-spending of saved income was highly conditioned by the types of products or services that studies chose to model as the form of marginal consumption that would result. Salemdeeb and colleagues (2016), for example, observed a 23% rebound in environmental impacts when they modeled a low-impact marginal consumption scenario, wherein saved income was re-spent on less environmentally intensive consumption categories such as education services, real estate services, and communication services. A substantially larger rebound effect of 59% was observed when the authors modeled a high-impact scenario, wherein saved income was directed into consumption categories of wholesale trade, motor gasoline, petroleum and air transport service.

2.6.3 Trade-offs of Food Waste Reduction

The negative impact of FWR on the income of food producers described above signals an important theme raised in many of the articles: the trade-offs associated with FWR. Authors of many of the reviewed studies alluded to the tensions between economic, environmental, and social virtues that may arise through FWR. Most commonly observed was the discord between environmental and economic outcomes, which is implicit in large-scale FWR that actually reduces global levels of food production and resultantly, its associated economic activities (Christis et al., 2015; Reutter et al., 2016). This tension also arises further downstream in the supply chain, at the retail and consumer level, wherein a FWR strategy may provide economic benefits to retailers and consumers while increasing the environmental impacts associated with food provisioning (due to additional resource inputs and associated impacts arising directly from the FWR strategy) (Brown et al., 2014a; Brown et al., 2014b; Belavina et al., 2017). The realization of environmental benefits may also be at odds with the safety and/or sociocultural preferences of consumers (Dobon et al., 2011b; Guillier et al., 2016; Willersinn et al., 2017b). For example, Willersinn and colleagues (2017b) found that the most effective FWR scenario from an environmental perspective (pesticide application to potatoes to prevent worms) was deemed unacceptable by consumers in Switzerland. These examples demonstrate that the environmental, social, and economic virtues attributed to FWR may not always align, contrary to current rhetoric surrounding FWR (e.g. Gustavsson et al., 2011; Gunders, 2012; Hanson & Mitchell, 2017).

2.7 Analysis of Methodological Shortcomings of the Studies

Notably, many of the reviewed studies strove to answer questions that remain relatively unexplored within FW literature. Notwithstanding the novel nature of their inquiry, these studies repeated some of the troublesome patterns pervasive in the wider FW literature: focusing on a limited temporal frame and geographic area and a limited system boundary of the food system, and relying largely on uncertain secondary data to characterize and quantify FW (Chaboud, 2017; Xue et al., 2017). Thus, while the research executed within these studies points to the importance of problematizing not only FW but also the means and ends of FWR, various gaps and methodological shortcomings remain, and are explored below.

2.7.1 Incomplete Incorporation of Parameters

While collectively the studies evaluated each of the parameters listed in Table 2.2, none included every parameter and only one study (Britz et al., 2014) attempted to characterize both Parameter 4 (transaction costs of intervention strategy) and Parameters

5 and 6 (macroeconomic changes and the consequences of them). As a result, the vast majority failed in producing an analysis that considered both the costs *and* the consequences of FWR as well as how these parameters interact with one another to condition the outcomes of a possible FWR. Outcome-based studies that only included Parameter 1 (the pre-intervention rate of FW), Parameter 2, (the post-intervention rate of FW) and Parameter 3 (the resources embodied in FW) were the most problematically limited in their analyses, considering that any conclusions that they made about the outcomes of FWR ignored both potential transaction costs (Parameter 4) and indirect effects (Parameters 5 and 6) of large-scale food waste reduction. In overlooking these aspects, these studies (Table 2.1, studies #[33, 34, 35, 36, 37, 38, 39, 40, 41]) failed to eclipse the dominant narrative that paints FWR as a silver bullet solution that bears little to no cost.

The exclusion of the transaction costs of FWR within the consequential analyses is also problematic. Various studies (Rutten & Verma, 2013; Rutten & Kallavari, 2016) acknowledged this shortcoming, justifying it by clarifying that their conclusions on the apparent welfare gains that could result from FWR should be seen as the budgets or envelopes within which FW solutions must comply to deliver a net benefit. However, considering that the cost of food production and consumption influences the price of food, it is likely that any FWR strategy that entails a financial cost for either the producer or the consumer would also change food prices and therefore undermine the welfare gains forecasted by Rutten & Verma (2013) and Rutten & Kallavari (2016). This outcome was demonstrated in Britz et al., 2014, wherein the authors observed that when the labour and capital costs of FWR were accounted for, the improvements to welfare lessened and the distribution of these benefits between regions changed. Arriving at a similar conclusion, Hertel and Baldos, 2016, conceded that their exclusion of transaction costs probably "led [them] to overstate the ensuing [food price] decline, as well as the net social benefits" (p. 201) of reducing post-harvest storage losses in sub-Saharan Africa. Capturing the interdependent nature of food prices and the transaction costs of FWR thus proved a challenge that most consequential analyses were unable to overcome in their aim to quantify the macroeconomic outcomes of FWR.

Studies estimating the environmental outcomes of the rebound effect similarly neglected to account for the economic and/or environmental transaction costs of household level FWR. To the extent that consumers are able to reduce their household

FW without expending additional financial and/or environmental resources, the rebound in environmental impacts that these studies forecasted might hold true. However, as demonstrated by studies such as Brown et al., 2014a, Brown et al., 2014b, Dobon et al., 2011b, certain solutions – i.e. improving household storage conditions (thus, often increasing household energy use) and/or purchasing food with improved packaging technology – result in both increased costs and resource investments. When the FWR measures bear a cost to the consumer, the amount of money that consumers save and are then able to re-spend on other goods and services will be reduced, thus reducing the degree to which the redistribution of additional income to other environmentally impactful expenditures would counteract any environmental gains achieved through FWR. The reverse could also be true, however, if the strategies employed by consumers bear an environmental cost that adds to the environmental impacts associated with the rebound effect; this is likely to occur under measures that require additional energy use, additional car trips to the grocery store, and/or more resource-intensive packaging (Christis et al., 2015).

2.7.2 Insufficient Consideration of Product-specificity

Recognizing how the design and capacity of a given FWR measure is tied to the type of FW it intends to reduce, many of the solution-based studies focused their analysis on a specific product or product category. Outcome-based studies were generally less specific in their analyses (Table 2.1). Scenarios of partial and/or full FWR, such as those employed within the outcome-based studies, are inattentive to the likelihood that it may not be possible nor desirable to reduce all types of FW equally or that there are inexorably going to be increasing marginal costs to any strategy. Blanket application of FWR targets ignores the product-specific nature of waste occurrences, the product-specific potential for waste reduction to occur, and the product-specific resources and impacts embodied in food provisioning and hence waste. Departing from the one-size-fits-all approach, Kummu and colleagues assumed that “lowest loss and waste percentages achieved in any region in each step of the food supply chain could be reached globally” (2012, p. 477). While this method inspires the use of FWR targets that are theoretically achievable and specific to both food product category and stage of the supply chain, it still upholds the misguided assumption that every product category of FW at every stage of the supply chain should be maximally reduced.

The absence of product-specific analyses in some of the studies also hindered their characterizations of embodied resources and concomitant impacts of FW (Parameter 3). In various solution-based studies, an average GHG emission intensity of all foods was used as a surrogate when estimating the emissions associated with the specific FW at hand (Brown et al., 2014a; Brown et al., 2014b; Belavina et al., 2017). In another case (Chitnis et al., 2014), the authors assumed that a 12% reduction in volume of FW would equate to a 12% reduction in the environmental impacts of FW. These approaches effectively overlook 1) the differences in waste rates of different product categories (in the case of Chitnis et al., 2014 and Belavina et al., 2017) and 2) the marked disparities in environmental impacts engendered by different product categories (in the case of all four aforementioned studies). This latter oversight is particularly problematic, as, for example, the GHG emission intensities of food and beverage products can differ by orders of magnitude (Poore and Nemecek, 2018). Even within product categories, intensity of environmental impacts is highly variable (Poore and Nemecek 2018), an issue acknowledged by authors of studies that used a top-down approach - such as IO tables and equilibrium models - to model environmental impacts of FW (Munesue et al., 2015; Hertel & Baldos, 2016; Salemdeeb et al., 2017). Studies that employed top-down approaches failed to capture these nuances and consequently, were limited in their capacity to quantify the embodied resources of FW (Parameter 3).

2.7.3 Limited Spatial and Temporal Coverage

Given that the majority of studies focused on the retail and/or consumer level within Europe and that all but seven studies carried out a temporally static analysis, the current body of literature is lacking in its coverage of FWR efforts over time and in diverse settings. If global food production levels should continue to increase over the next few decades, FWR may not reduce total global food production levels nor reduce resource usage associated with food production systems. Rather, under forecasted trajectories of future food demands, FWR may reduce the rate and extent to which production expands to feed a growing global population. This is an important distinction that can significantly influence the conclusions of analyses aiming to quantify outcomes of large-scale FWR - an achievement that is likely to require a decade (or two) to realize. Outcome-based studies that did not consider how food production and consumption would expand, but at different rates, over the foreseeable future thus overlooked a key dynamic component.

Within solution-based analyses, conceptualization of time varied. While they all characterized the resource investment associated with strategies employed to extend product shelf-life (i.e. energy required to lower refrigerator temperature), all but one of the solution-based studies considered the indirect implications of extended shelf-life: the additional time spent within refrigerated or frozen storage and the consequential energy use implications (Eriksson et al., 2016). Studies such as Brown et al. (2014b), that only considered the initial energy investment – i.e. the energy dissipated by a freezer within the 24-hour period after a food item is inserted – fell potentially far short of capturing the full life cycle implications of the FWR strategy that they set out to characterize. Shelf-life extension could result in several additional days in cold storage or months/years in frozen storage – all requiring constant though different levels of energy input – and thus should not be discounted within environmental/financial analyses of FWR strategies.

Studies that used insight from LCA research to inform their analyses of FWR strategies were also constrained by their limited individual and collective coverage of various stages of the food supply chain. Focused largely on losses at the consumer and retail level, most solution-based studies centralized their focus on one stage, consequently neglecting the occurrence of losses at other levels of the supply chain. This may be reasonable as a first approximation of a likely reality but falls short in two ways: 1) it overlooks the contribution of upstream losses to the embodied life cycle impacts of losses occurring further downstream and 2) it misses the potential shifting of FW from one level, say retail, to the next, consumer. This latter methodological issue is particularly important, given that FWR strategies that cause losses to occur in up- or downstream stages would falsely appear to produce greater net benefits than would accrue in reality. Attending to this possibility, Willersinn et al. (2017a & b) projected how waste levels upstream or downstream from the level wherein a strategy was applied would increase or decrease (e.g. reduced sorting of potatoes at the retail level would result in increased waste at the consumer level). In contrast, when Zhu (2017) investigated how the implementation of radio frequency identification system packaging could reduce waste and improve the bottom line for retailers, they failed to consider how price markdowns at retail could shift waste to the consumer level, a not unlikely outcome according to various consumer studies (Mondéjar-Jimenez et al., 2016, Calvo-Porral et al., 2017). Leaving consumer waste levels unaddressed in pursuit of increasing profits at the retail level, this study not only illustrates the problematic outcomes of constraining life cycle analyses of FWR strategies to one level of the supply chain but also the tensions and conflicting interests that exist between actors within food systems (Mourad, 2016).

2.7.4 Limited Perspective

Tensions exist not only between actors within food systems but also between the values that inform and motivate different actors' assessment, management, and/or treatment of FW (Mourad, 2016), evidenced by the tradeoffs between environmental, social, and economic values discussed in Section 2.6.3 above. Studies that limited their analyses to one perspective (e.g. performed an economic assessment only) did not capture these tensions nor the potential problem-shifting that could result from the implementation of FWR strategies that are driven by myopic interests. The conclusions asserted by Rijpkema et al. (2014) attest to this methodological concern, as the authors affirmed that a shift from sea transport (a low GHG emission impact transport mode) to air transport (a high GHG emission impact transport mode) of strawberries could prove economically beneficial to food distributors; thus, their economically-driven assessment led them to recommend a solution that would dramatically increase net GHG emissions associated with strawberry transport and appreciably eclipse any possible GHG emission savings achieved through the reduction of losses (DEFRA, 2005). In another study, Martinez-Sanchez and colleagues (2016), included both an economic and an environmental analysis yet fumbled in their execution of the latter. Modeling the rebound effect of several FW management and/or prevention options within households, these authors accounted for the economic savings that consumers could achieve by preventing FW yet failed to do the same for their environmental analyses; as a result, their estimation of the rebound effect associated with FWR appeared much larger than it would have had the authors accounted for the potential environmental savings associated with the reduced FW. As illustrated by this example, it is important not only for multiple perspectives to be included but also that their analyses be executed with consistent rigor.

2.7.5 Data Uncertainties

All of the reviewed studies were challenged by an obstacle often encountered within FW research: quantification of actual levels of FW. Whether the environmental or economic savings generated by FWR efforts exceeds the resources spent on reduction efforts depends on the amount of FW that is actually reduced. Consequently, accurately predicting the outcomes of FWR efforts necessitates rigorous quantification of FW rates (both before and after intervention). With all but two studies relying on previous data to quantify Parameter 1 (starting levels of FW), the analyses performed throughout the body of literature reviewed are largely based on data plagued by inconsistencies, best estimates, and antiquated statistics, some of which date back to the 1970s (MacRae et al., 2016; Chaboud, 2017; Xue et al., 2017). Data used to characterize Parameter 2 (levels of FW after reduction) were similarly problematic, considering that zero empirical analyses were used to determine the extent to which a given solution could reduce FW levels. In spite of the problematic nature of data used to quantify Parameters 1 and 2, only 19 out of the 41 studies employed sensitivity or scenario analysis to explore the sensitivity of their conclusions to changes to FW data. Considering that the studies relied on FW data beset by uncertainties, their analyses should be considered exploratory and their conclusions preliminary.

The issue of data uncertainty also pertains to the quantification of resource investment and environmental impacts associated with food products (Parameter 3) and FW solutions (Parameter 4). Uncertainty is implicit in data informing techniques, such as LCA or EEIO, that are employed to quantify the resources expended over the life cycle of a given product or system (Lazarevic et al., 2012; Reutter et al., 2016; Notarnicola et al., 2017). While producing more product-specific estimates of environmental impacts than top-down methods such as EEIO (which rely on typically older data and inevitably smooth over the differences between and within product categories), LCA ideally requires highly detailed accounts of processes associated with the product or system under analysis (Reutter et al., 2016). In reality, these data are often incomplete, may not be directly determined and often necessitate assumptions and reliance on uncertain and/or temporally/geographically unrepresentative data. As such, the quantification of embodied resources performed within these studies is inherently tied up with the uncertainties troubling data used within both top-down and bottom-up approaches.

2.8 Discussion

2.8.1 Producing Targeted Food Waste Solutions

Given the variety of food products consumed at present and the distinct environmental impacts and economic activity that each one engenders, it follows that not all FW or FW solutions are created equal. Through the product-specific analyses executed in the solution-based studies, it becomes evident that different types of FW may produce different environmental, economic, and social outcomes when subjected to FWR efforts. In their review of environmental assessments of FWR, Schott & Canóvas (2015) similarly found that the type of FW under analysis strongly influenced studies' conclusions on the outcomes of FWR, a verdict that is unsurprising given the potentially vast differences in environmental impacts associated with different types of FW (as demonstrated by Williams et al., 2011 in their comparison of prevention of ketchup, milk, cheese, bread, and beef waste). FWR targets that treat all FW equally (i.e. the zero-waste program promoted by Canada's National Zero Waste Council (National Zero Waste Council Canada, 2018)) are inattentive to these differences and resultantly miss out on opportunities to optimize the social, environmental, and economic outcomes of FWR.

Confronted by narratives that deem FW an improvident behaviour, consumers attach feelings of guilt to the act that they find themselves unable to avoid in the context of complex household provisioning dynamics and variable rhythms of daily life, an observation that has been noted frequently within consumer observation and survey studies (Evans, 2012; Ganglbauer et al., 2013; Quested et al., 2013; Parizeau et al., 2015; Russell et al., 2017). Related to this, consumer level studies have also found a positive correlation between consumer's perceived sense of control over FW and their capacity to reduce it (Stancu et al., 2016; Visschers et al., 2016; Russell et al., 2017). With this relationship in mind, practices of FWR within households could be improved through the provision of advice that specifically targets types of FW that have high environmental impacts and represent large amounts of embodied resources such as many terrestrial animal protein systems (Poore and Nemecek 2018) and some fisheries (Parker et al. 2018).

Advice surrounding FW management should also be considerate of the transaction costs that FWR strategies may bear. Impact assessments involving LCC or LCA, such as those that were performed within the reviewed studies, are necessary to point to behavioral and managerial changes that are financially accessible, socially acceptable, and produce net positive environmental outcomes that outweigh the transaction costs associated with FWR strategies. Analyses of this sort should be regionally-focused, considering that transaction costs will be influenced by regionally specific conditions associated with electricity mixes, recycling systems, geographies, and/or population densities (Wikström & Williams, 2010; Eriksson et al., 2016; Belavina et al., 2017).

Similar to this study, a recent article (Cristóbal et al., 2018) stressed the importance of using research to inform and support FW initiatives. Within this article, the authors proposed a methodological framework (analogous to the one described here in Section 3.4) to evaluate the economic and environmental outcomes of FW solutions. Though including important components such as 1) the mass of FW reduced, 2) the environmental resources saved through the avoided FW, and 3) the economic costs associated with the applied solution, the authors assumed that FW prevention bore zero environmental transaction costs and thus omitted them from their framework. This exclusion is notable, considering that many of the studies reviewed here observed that environmental transaction costs of FWR strategies can be significant.

2.8.2 Improving Assessments of Food Waste Solutions

Given the scarcity of empirical evidence supporting the potential for FW solutions to reduce FW, the capacity of behavioural and managerial changes to reduce FW remains ambiguous, not unlike the uncertain nature of extant quantifications of both current FW rates and environmental impacts of food products. In this context, the reviewed studies' reliance on assumptions and uncertain data to support their quantification of outcomes of FWR undermines the capacity of their conclusions to support evidence-based, targeted FW solutions. Where studies constrained their theoretical, temporal and/or geographical frame of analysis - overlooking the possibility of FW to shift to another level of the supply chain and/or transform from an economic burden to an environmental or social one - the effectiveness of their conclusions to support sound decision-making was further blunted. With these weaknesses in mind, this paper proposes the following recommendations in order to improve future research in this field:

1) To improve quantity and quality of data relating to:
    a. Rates of post-production food losses, ideally resolved into major food groups, across supply chains but particularly those that occur at the consumer level;
    b. Life cycle impacts of food systems and in particular those: i) that contribute substantially to collective nutrition but are largely currently understudied (e.g. eastern European, Russian and Asian-based food systems), and ii) in which known impacts are high but also highly variable (e.g. beef); and
    c. Capacity of FWR measures to achieve actual FW reductions.
2) To be attentive to, and anticipate the sensitivity of results to data uncertainty by employing sensitivity analysis or, where knowledge of uncertainties permit, Monte Carlo simulations of model outcomes.
3) To holistically approach the quantification of outcomes of FWR:
    a. To account for the impacts of FW at all levels of the supply chain;
    b. To consider and carry out assessments from multiple perspectives (i.e. economic, social, and environmental); and
    c. To consider the temporal frame of the intended FWR and adjust the temporal frame of the analysis accordingly.
4) To be attentive to the different amount of resource investment and economic/environmental impact associated with different types of FW and to avoid:
    a. Applying blanket scenarios of FWR; and
    b. Using average economic or environmental impact values to characterize the respective economic or environmental impacts of FW.

2.8.3 Reducing Food Waste: An End or a Means?

In spite of their methodological limitations, the studies reviewed here make important strides in quantifying the outcomes of FWR, demonstrating not only the importance of executing quantitative analyses on complex issues such as FW but also the pitfalls and obstacles that can be encountered in the process. Beyond the technical lessons that can be learned from their methodological strengths and weaknesses, a more profound underlying message can be surmised: the ultimate goal of FWR is not to reduce FW. Rather, it is to reduce environmental impacts and improve socioeconomic outcomes of an industry and society writ large that is increasingly encroaching on, and in some cases surpassing the planetary and social boundaries within which human life can safely and justly operate (Rockström et al., 2009; Gordon et al., 2017; Raworth, 2017).

Whether or not these desired ends can be achieved depends, in part, on the magnitude and nature of the costs and consequences associated with large-scale FWR. Studies that do not consider these relationships effectively treat FWR as an end in itself, assuming that it will correlate with positive environmental and socioeconomic outcomes. From the reviewed literature, it is clear that such an assumption does not always hold true, or that it may hold true for some countries/regions/individuals but not others, or for socioeconomic interests but not environmental ones (or vice versa) (Mourad, 2016). As such, the desired ends of a FW intervention should be made explicit and their progress should be monitored rather than assumed.

Even if steps are taken to carefully evaluate the impacts of food waste reduction, a critical question remains: is addressing FW the most efficient means of achieving sustainable food systems? Current FWR efforts are largely devoid of any intention to dismantle the structures that engender inequitable access to food supply (Warshawsky, 2015; Warshawsky, 2016). Resultantly, some have argued that FWR is unlikely to be the most effective nor the most economically-efficient means to reducing food insecurity (Gjerris & Gaiani, 2013; Koester, 2015; Rosegrant et al., 2015; Chaboud & Daviron, 2017). This is similarly true for environmentally-focused goals, those of which could be more effectively realized if FWR was complimented by strategies that address other forms of unsustainable consumption. Dietary change, for example, has been shown to produce a significantly greater magnitude of environmental benefit than FWR (demonstrated within Rutten et al., 2013 and Brygelsson et al., 2016). In light of this, FW could be reconceptualized to include dietary patterns that exceed nutritional requirements and/or do not achieve optimal human health outcomes at the lowest environmental cost (as conceptualized in Smil, 2004; Blair & Sobal, 2006; Alexander et al., 2017).

Ultimately, achieving transformative change within food systems and society writ large requires problematic economic and social structures (such as those that contribute to the waste and overconsumption of food) to be acknowledged and addressed. Within the current global food system, economic structures continue to reward retailers who sell the most product (Mourad, 2016) while food prices and cultural norms encourage wealthy consumers to buy and eat only the freshest foods (Freidberg, 2004; Mavrakis, 2014; Neff et al., 2015). Subsidies to farmers within wealthy countries generate surplus food supply, which later manifests as FW within developing countries who have received it in the form of food aid that is ill-suited to their domestic needs (Gille, 2013). On the consumption side, FWR initiatives do not challenge wider unsustainable consumption patterns and resultantly, their application within households is not likely to lead consumers to reduce the scale of their consumption. A more likely outcome, consumers will re-spend economic resources freed up through household FWR on other food or material goods and services (as demonstrated within the reviewed rebound effect studies). Additional attention must be directed towards transforming the dominant growth-based economy and the culture of (over)consumption that it informs (Gille, 2013; Lucifero, 2016; MacRae et al., 2016; Mourad, 2016; Chaboud & Daviron, 2017). Previously cited policies that can be used to address unsustainable scales and patterns of consumption include the abolishment of food subsidies (which encourage overproduction and overconsumption) and the taxation of food products and other consumer goods in proportion to their environmental impacts (Priefer et al., 2016, Schanes et al., 2018). Applied on its own, the latter economic instrument may exacerbate issues of food insecurity and consequently, it should be accompanied by "carefully targeted compensation" to low-income households (Chitnis et al., 2014, p. 24).

2.9 Conclusion

As food production activities increasingly push natural systems beyond the boundaries deemed as safe to maintain human life (Rockström et al., 2009; Gordon et al., 2017), unnecessary production of food that is later wasted increasingly seems an "offensive demonstration of human irrationality" (Smil, 2004, p. 17). Indeed, the amount of natural resources and concomitant impacts associated with FW is not inconsequential (FAO, 2013). Yet FWR efforts, like food production and provisioning activities, requires the investment of economic and environmental resources, the consequences of which have been largely overlooked within academic literature and society writ large. In drawing attention to the body of literature that has attempted to quantify economic, social, and/or environmental outcomes of FWR, this review has shed light on the importance of not only problematizing FW but the ways in its reduction is understood and achieved. As revealed here and in the contents of the literature that was reviewed, understanding FW and outcomes of its reduction is inherently uncertain and complex, a result of numerous challenges ranging from data uncertainty to the varying values that underlie and motivate individual and collective desire to reduce FW, and indeed the very meaning of the term 'waste'. Ultimately, the pursuit of FWR should not be considered an end in itself, but rather a means to achieve favorable socioeconomic and/or environmental outcomes. Consequently, the type of work performed in many of the studies assessed here is necessary to understand whether or not FWR can achieve its desired ends and corollary to this, whether the environmental, economic, and/or human resources expended to achieve it are worthwhile.

CHAPTER 3. SUSTAINABILITY BEYOND THE SEA: LIFE CYCLE ASSESSMENT OF VARIOUS SEAFOOD SUPPLY CHAINS AND ANALYSIS OF THE IMPACT OF POST-PRODUCTION LOSSES AND OVERCONSUMPTION

3.1 Introduction

Providing essential nutrients for human consumption, driving economies, and informing cultures, seafood plays a crucial role in sustaining many lives and livelihoods globally (FAO, 2016). In coming decades, seafood will likely maintain its status as an important global industry and food category, experiencing increased demand as the global population grows towards 10 billion (FAO, 2016). Consequently, it is crucial that seafood resources and seafood production systems be sustainably managed, a reality underscored by historical examples of socioeconomic devastation that the collapse of seafood stocks can engender (i.e. the cod fishery moratorium in Newfoundland, Canada (Milich, 1999)).

Addressing unsustainable use of marine and aquatic resources while also meeting increasing demands for seafood products will prove a formidable challenge, given that just over 30% of the world's major capture fisheries' stocks remain overfished as of 2015 (FAO, 2018). Though global aquaculture is expected to continue to expand to meet future demands, it provides no simple solution to this dilemma (Merino et al., 2012). Not unlike capture fisheries, aquaculture systems contribute to serious local- and global-scale environmental challenges including climate change, habitat alteration, disease/parasite amplification, water pollution, and the depletion of wild seafood stocks (for the production of fish feed) (Naylor & Burke, 2005; Klinger & Naylor, 2012) that threaten to undermine not only seafood production systems but also planetary boundaries within which human life can be safely and justly sustained (Rockstrom et al., 2009; Gordon et al., 2017; Raworth, 2017).

As concern regarding environmental challenges associated with both capture fisheries and aquaculture systems has grown in recent decades, the concept of "sustainable seafood" has emerged (Gutierrez & Morgan, 2015) and is characterized by a wide-range of consumer-facing sustainable seafood certification schemes and NGO-backed ocean-health related campaigns (Sutton & Wimpee, 2008; Gutierrez & Morgan, 2015). Given the ocean-impact reduction focus that motivates much of the sustainable seafood movement, it is not surprising then that significantly less attention has been paid to post-production stages of seafood supply chains and the losses of seafood that may be occurring within them (Stoner, 2013). Considering that seafood losses have, however, been reported to account for 50% of total seafood supply (Gustavsson et al., 2011; Love et al., 2015), their environmental implications are likely significant and merit inclusion within conceptualizations of sustainable seafood systems and the methods used to understand, define and shape them (Stoner, 2013).

3.1.1 Contextualization of Losses within Seafood LCAs

Amidst mounting concerns for the sustainability of global seafood systems, LCA has emerged as a tool to explore, compare, and address global-scale resource-depletion and environmental impact contributions from seafood systems (e.g. climate change, acidification, abiotic and biotic resource use, etc). In this context, the body of literature dedicated to characterizing the environmental impacts of seafood systems using LCA has grown significantly in both size and diversity over recent decades (Parker, 2012). Within early seafood LCA work, production-level activities were identified as key 'hot spots', or substantial sources of emissions from many seafood supply chains derived from both fisheries and aquaculture (Ziegler, 2002; Eyjolfsdottir et al., 2003; Thrane, 2004; Mungkung, 2005; Grönroos et al., 2006; Ellingsen and Aanondsen, 2006; Ziegler, 2006). In light of this, it is not surprising then that a considerable proportion of subsequent seafood LCA research has focused primarily if not exclusively on production-related activities (Henriksson et al., 2012; Parker, 2012; Cao et al., 2013; Avadí & Freón, 2013). Where seafood LCAs have extended beyond the production stage (Vasquéz-Rowe et al., 2013), product losses have seldom been considered in these analyses. A notable exception to this pattern was research undertaken for the United Kingdom's Waste and Resource Action Programme (WRAP) that characterized greenhouse gas emissions of avoidable and unavoidable waste arising along post-production stages of seafood supply chains (James et al., 2011). Restricting their scope to processing and retail supply chain nodes, the authors of this report unfortunately excluded the consumer level, wherein the highest rates of seafood losses have been observed (Gustavsson et al., 2011; Muth et al., 2011).

The limited attention to post-production losses along food supply chains is not unique to seafood LCAs. Corrado and colleagues (2017) note that lack of attention to food waste afflicts food LCA research generally while also presenting important definitional and methodological challenges for this domain of research to overcome. These include the need to increase general transparency in the modeling of food waste within LCA studies as well as to improve consistency between studies and their treatment of different forms of food waste (i.e. avoidable food waste which pertains to edible food parts versus unavoidable food waste which results from the discard of inedible food parts) (Corrado et al. 2017). Though previous work has established overconsumption as a form of food waste (Smil, 2004; Parfitt et al., 2010), it has seldom been included within food waste studies. More commonly assessed forms of food waste have included the following: 1) food intended for human consumption that is "discarded, lost, degraded, or consumed by pests" (Papargyropoulou et al., 2014: p. 108; FAO, 1981); and/or 2) food intended for human consumption that is downgraded to animal feed or other by-products (Stuart, 2009). The relative absence of overconsumption from food waste literature is noteworthy, given that some authors have found overconsumption to cause a magnitude of loss equivalent to that of consumer level waste (Alexander et al., 2017). Additionally, various studies have observed that the occurrence of plate waste correlates with portion size (Freedman & Brochado, 2010; Quested et al., 2013). In light of these observations, overconsumption and the role of portion sizes therein appear crucial issues to explore.

Given the finite capacity of global capture fisheries and the various challenges associated with all seafood production systems discussed above, the limited extent to which post-production losses have been considered within seafood LCA research is problematic, particularly as reductions in post-production seafood losses may represent opportunities to maintain and expand global access to seafood as demand for animal protein grows (Love et al., 2015). To this end, additional LCA work is needed to explore the environmental significance of post-production losses and to devise environmentally efficient measures to address them.

3.1.2 Environmental Evaluation of Food Waste

The insufficient attention to post-production losses that characterizes much of current food LCA literature generally stands in stark contrast to the contemporary profile of food waste within the academic community and society writ large (Mourad, 2016; Xue et al., 2018), as activists and authors alike have increasingly sought to define, quantify, and reduce the occurrence of this phenomenon (WRAP, 2009; Lipinski et al., 2013). environmental terms, food waste has been read as a misappropriation of natural resources. This concern has driven various researchers to estimate the environmental impacts incurred through the discard of food product (Hall et al., 2009; Venkat, 2011; FAO, 2013; Scholz et al., 2015; Song et al., 2015; Vanham et al., 2015; Reutter et al., 2016; Vittuari et al., 2016). Many, though not all, of these studies have used top-down methods, such as environmental input-output tables, which provide only high-resolution understandings (for a review see Mifflin et al. in prep). Product-specific and process-focused, LCA is capable of capturing details that top-down methods may miss, suggesting that increased reliance on LCA within this domain could enhance estimations of the environmental impacts of food waste.

Not unlike food production and provisioning activities, food waste reduction measures (such as frozen storage or enhanced packaging) require technological inputs and, consequently, expenditure of natural resources (Reutter et al., 2016; Shafiee & Cai, 2016; Chaboud & Daviron, 2017). Designing efficient food waste reduction strategies requires that the environmental costs of such technological inputs and resource expenditure be considered and assessed (Mifflin et al. in prep). This is a step that has often been skipped within extant environmental evaluations of food waste reduction, as researchers often assume that any given volume of food waste reduction results in a proportional reduction to environmental impacts (see Kummu et al., 2013; Jalava et al., 2016; Martin & Danielsson, 2016; Costello et al., 2017; Springmann et al., 2018). In this context, the application of LCA to food waste reduction strategies (and their transaction costs) presents opportunities for the environmental outcomes of food waste reduction to be better understood (as demonstrated by Eriksson et al., 2016 and Willsersinn et al., 2017).

3.1.3 Objectives

Here we set out to address the dearth of attention to the environmental consequences of post-production losses along seafood supply chains. Our primary objective was to illustrate the potential impacts that post-production losses, including overconsumption, can have on life cycle impacts associated with prominent seafood products consumed in North America. Secondary to this objective, we aimed to evaluate the life cycle impacts of potential strategies to reduce seafood waste while also reducing resource investment and environmental impacts per unit of seafood consumed.

In order to achieve this secondary objective, we explored two potential waste reduction strategies. First, we compare environmental impacts of fresh seafood supply chains to those resulting from frozen or canned supply chains. Preliminary research has indicated that some modes of preservation (frozen or canned) can decrease the rate at which food products are discarded due to spoilage, resulting in part from the increase to shelf-life that is enabled by freezing or canning methods (Stoner, 2013; Martindale et al., 2014). Motivated by observations that animal proteins are being over-consumed throughout most affluent societies and at rates which cannot be safely and justly sustained within planetary boundaries (Young & Nestle, 2002; Alexander et al., 2017; Springmann et al., 2018), the second strategy to address losses that we explored was the impact of portion size adjustment.

3.2 Methods

3.2.1 Life Cycle Assessment

We employed LCA to quantify the environmental implications of post-production seafood losses. As its name implies, the analytical and methodological framework of LCA is applied to understand, capture, and estimate the environmental impacts of a good or service over its life from "cradle to grave" (Duda & Shaw, 1997; Klöpffer, 1997; Baumann & Tillman, 2004). LCA analyses can encompass multiple product life cycle stages (i.e. production, processing, transportation, consumption, and waste management) and multiple resource depletion or environmental concerns (i.e. global warming, eutrophication, toxicity, resource depletion), collectively known as impact categories. Importantly, this comprehensive approach allows for trade-offs to be captured and for potential problem-shifting (between life cycle stages and/or environmental impact categories) to be understood and hence ideally avoided (Klöpffer, 1997; Baumann & Tillman, 2004).

The execution of an LCA occurs in a stepwise manner, starting with the "goal and scope definition" stage, wherein the LCA's purpose is defined and used to scope modelling specifications such as the system boundaries (i.e. the life cycle stages included), the types of environmental impacts considered, and the functional unit (e.g. 1 tonne of raw product, 1 unit of consumer ready product in packaging) to which the model inputs and outputs are related (Baumann & Tillman, 2004). The process of collecting data on the material and energy inputs and outputs associated with the product and it's sub-systems under analysis occurs in the second, life cycle inventory (LCI) stage (Baumann & Tillman, 2004). This is followed by the life cycle impact assessment (LCIA) stage, wherein inventory data are characterized into environmental impact potentials (Baumann & Tillman, 2004) using established peer-reviewed models. Outputs of the LCIA are then evaluated and used to inform conclusions or recommendations within the interpretation stage (ISO 14040: 2006). The application of these steps within this study will be discussed below in Sections 2 and 3.

3.2.2 Goal and Scope Definition

As our primary objective is to illustrate the potential scale of impacts of post-production losses in seafood supply chains, a suite of commonly consumed seafood products was first identified that conformed with the following criteria: 1) products were widely consumed in the North American context; and 2) previously published, robust LCA studies of typical commercial-scale production-level inputs and LCIA results were available that were also methodologically-consistent with one another in terms of key methodological issues including boundaries of analysis, cut-offs, and treatment of co-products. Selection was limited to a total of five seafood species in order to establish a feasible scope that was sufficiently sized to allow the study to achieve its objectives. For each seafood species, we constructed multiple supply chain case studies, which varied in their modes of preservation (e.g. fresh, frozen, and/or canned), modes of transportation (e.g. airfreight, seafreight), and rates of supply chain losses. Additionally, alternate scenarios were constructed in order to explore how variation of loss rates and supply chain parameters influenced the outcomes of the models. The functional unit selected for each case study and alternate scenario was 1 tonne of consumed product within Toronto, Canada, which encompassed all inputs and outputs of material and energy from the cradle to consumption stage (omitting the "grave" or waste management stage, a common scoping strategy used in food LCAs due to this stages' relatively small impact contributions (Schau & Fet, 2008)).

3.2.3 Production-related LCA Data and Onward Supply-chain LCI Data Collection

Identification of suitable production-level LCA data was informed by a previously produced report (Parker, 2012) that systematically summarized the methods and results of seafood LCAs published between 2000-2012. Employing the same methodology as Parker (2012), an additional review was conducted to assess and compare seafood LCAs published from 2012-2018. From results of these reviews, five recently published (< 10 years), methodologically robust and consistent LCAs that characterized typical commercial-scale operations of widely-consumed in Canada products were selected to inform production-level LCIA data for the seafood case studies (see Appendix A).

For all post-production supply chain activities, we modeled the simplest, most direct set of activities and pathways required as a proxy for reality. For example, all processing was modelled to occur once (no-reprocessing, with the exception of shrimp, see details below), and adjacent to the locale of production or landing. As well, industry-standard packaging materials, and shortest, mode-specific direct route distances were applied. Data on associated inventory inputs and outputs (e.g. forms and quantities of packaging, electricity, co-product production, etc.) were drawn from the literature (all LCI data appear in Appendix B). The resulting post-production LCI of the proxy supply chain activities was used to represent post-production material and energy inputs and outputs for most case studies. However, where existing LCA studies that were used to inform production-level impacts also characterized post-production stages including processing, these case-study-specific LCI data were used in place of the proxy LCI dataset. Intercontinental transportation distances were determined using mode-specific distance calculators (such as Google Maps). Mass allocation was applied in all cases wherein life cycle inventory items were shared between seafood items and their utilized co-products (following the rationale of Pelletier & Tyedmers, 2011).

Following the model used by Hoang et al., 2016 and Brown, 2014, energy efficiency profiles and volume dimensions of freezer and refrigerator products were used to estimate electricity inputs associated with cold storage at the retail and consumer level. It was assumed that percentage of available volume used was 50, 75, 70, and 70% for retail fridges, retail freezers, consumer fridges, and consumer freezers, respectively. Electricity from cold storage was then allocated to seafood products based on the volume of space they consumed (that which was determined using a stocking density of 500kg/m^3 as was done in Hoang et al., 2016). Duration of time in cold storage at the processing, retail, and consumer levels were informed by previous seafood LCA work and reasonable best estimates where data was unavailable (Thrane, 2004; Vasquez-Rowe et al., 2013) (see Appendix B for further detail). Previously published data on direct emissions from refrigerant leakages were compiled for only intercontinental transportation and retail levels, a decision motivated by previous studies which have demonstrated the insignificant nature of leakages at other levels (i.e. the processing stage wherein refrigerants typically used, e.g. ammonium, have low global warming potentials (GWP) or the consumer stage wherein leakages are typically reported as low) (Thrane, 2004; Evans, 2012).

3.2.4 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) was performed on LCI data using EcoInvent 3.3. unit processes. Within the original production-level LCAs, the choice of characterization model varied (four used CML baseline while one used ReCiPe). For methodological consistency, CML baseline and ReCiPe were each applied to the post-production stages of the seafood case studies according to the selected method of their respective production-level LCAs. For the case studies that used CML Baseline impact assessment models, global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) contributions were modeled. The first of these three categories, GWP, represents the *potential* contribution of a defined system to the warming of Earth's atmosphere. It is calculated as the sum of all greenhouse gas emissions, such as carbon dioxide, methane, and nitrous oxides, and is expressed in carbon dioxide equivalents (CO_2 eq.) (Stranddorf et al., 2005). AP represents the *potential* of a given activity to cause acidification within terrestrial and aquatic environments. Acidification occurs through the "release of protons into the terrestrial or aquatic ecosystems", which results from the leaching of anions or the emission of hydrogen ions (Stranddorf et al., 2005, p. 55). The consequences of this effect include inefficient growth of trees in forests or of shell-building organism in marine habitats (Ibid). AP is calculated as the sum of all acidifying emissions, such as sulfur, nitrogen oxides, and ammonia, and expressed in sulphur dioxide equivalents (SO_2 eq.) (Ibid). The last of the three impact categories considered, EP, represents the *potential* for a defined activity to cause eutrophication, a process wherein bioavailable nitrogen and/or phosphorus enter aquatic environments, increase algae growth, and ultimately decrease oxygen flow to aquatic organisms (Ibid). It is calculated as the sum of nitrogen and phosphorus derivatives, and expressed in the reference unit of phosphates (PO_4 eq.) (La Rosa, 2016).

Due to data constraints, only GWP was modeled for the ReCiPe case study. For the production of electricity in Canada, China, and Norway, national average emission intensities were used, based on data available in the EcoInvent 3.3 database. For Indonesia and Ecuador, a unit process for electricity-related emissions was created in EcoInvent 3.3. based on these countries' national mix of primary energy inputs to electricity grids reported in 2015 (see Appendix C). Along frozen supply chains, electricity requirements for cooling during transport phases were met through combustion of fuel as part of normal transport mode operations. We assumed that ice was used in transportation of fresh goods (250kg per tonne) and adjusted the emission-intensity/tonne-km of product transported accordingly.

3.2.5 Defining Losses

Before data collection on loss rates began, we defined avoidable seafood losses for the purpose of this study as: 1) seafood product intended for human consumption that is discarded; or 2) seafood product over-consumed beyond Canadian national nutritional recommendations as of 2018, reflecting the geographic setting of our point of final consumption. Unavoidable losses (WRAP, 2009) were defined as the parts of seafood that are typically not consumed within Western contexts and consequently are either discarded or directed to other industries (such as aquaculture feed production). These losses were not regarded as a loss of natural resources and concomitant environmental impacts within our models if they were deemed to be used productively in other industries. Our definition of avoidable losses included both 1) the discard of parts of seafood typically regarded as edible within Western contexts and 2) overconsumption. While the latter aspect of avoidable losses, overconsumption, is typically understood as the quantity of calories or nutrients that exceed(s) daily dietary requirements for energy and nutrient intake, here we defined it as the mass of uncooked fish muscle that exceeds the serving size recommendation provided for a specific food item (informed by Canada’s Food Guide). This distinction is due to the product-specific nature of this study. Previously devised frameworks have taken a different approach to defining overconsumption as they have been focused at the dietary level rather than on one product/specific dietary component (i.e. seafood) (Blair & Sobal, 2006; Alexander et al., 2017).

3.2.6 Data Collection on Loss Rates

Data on avoidable seafood losses were collected from extant quantifications of food waste within peer-reviewed and grey literature. Articles were retrieved through searches that were conducted in Google Scholar and Web of Knowledge using keywords “food”, “waste”, and “loss(es)”, “fresh”, and “frozen.” Additional potentially relevant studies were collected through reference lists of selected studies. Studies that a) did not provide seafood-specific data and/or, b) reformulated/manipulated previously published data were excluded. From the remaining studies, data on avoidable seafood loss rates were assembled. Unavoidable loss rates at the processing and/or consumer levels (e.g. discard of bones, etc.) were derived from edible yield reports (Bykov, 1985; Torry Research Station, 1989).

Attempts were made to augment the secondary data retrieved from the literature with primary reports of post-production loss rates at specific nodes along seafood supply chains. To this end, senior executives at processing and retail levels were contacted through personal networks of the researchers. In stages wherein neither primary observations or extant loss data were available, reasonable conservative assumptions of loss rates were used.

In order to determine overconsumption-related losses, a nominal portion size of consumption was estimated through a review of online seafood recipes. This method, “recipe analysis”, has been previously employed in dietary research as a strategy to estimate nominal intake rates of calories and macronutrients (Wasink & Payne, 2009; Church et al., 2015). From data derived from approximately 50 seafood recipes retrieved from the Food Network database (www.foodnetwork.ca), a mean portion size was calculated to serve as our nominal portion size typically consumed. Overconsumption was then calculated by determining the difference between the nominal portion size and the Canadian recommended food guide serving size (FGS) of 75 cooked grams as of 2018 (Dieticians of Canada, 2018). Importantly, all portion sizes drawn from recipes used were reported in raw (or wet) mass. As a result, this last step also necessitated data collection on the rate of mass yielded when raw seafood product is cooked. The former were derived from datasets provided by the Tory Research Station (1989) and Bykov (1985) and the latter data point was informed by various datasets including the Japanese Food Database (MEXT, 2015) and a seafood processing handbook (Silva & Chamul, 2000).

3.3 Results

3.3.1 Case Studies

Details of the five species selected for analysis appear in Table 3.1 and include three from farmed sources: Atlantic salmon (*Salmo salar*) from Norway, Nile tilapia (*Oreochromis niloticus*) from Indonesia, Whiteleg shrimp (*Litopenaeus vannamei*) from China; and two from fisheries: Atlantic cod (*Gadus morhua*) from Norway, and a set of mixed species of tuna (yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and bigeye (*Thunnus obesus*) from Ecuador (Appendix A). The source studies used to inform the production-level LCA data for each case study were largely methodologically consistent, except in their choice of impact characterization models used (Table 3.1). Avadí and colleagues (2015) used the ReCiPe characterization model whereas all other authors used the CML Baseline characterization model.

With the exception of shrimp and tuna, both fresh and frozen supply chains were modeled for each species. Additionally, we modeled a variant on frozen supply chains, wherein products remained frozen until the retail level, at which time they were thawed and sold as fresh. These seafood products, which will be referred to as refreshed case studies, were modeled as having the loss rates, form of intercontinental transport (seafreight), and storage conditions of frozen supply chains from the processing level to the retail level. At and beyond the retail level, they were assumed to experience the loss rates and storage conditions of fresh products. In the case of shrimp, no fresh supply chain was modeled given the predominance of frozen shrimp within North American markets. For tuna, while a fresh supply chain was modeled, a canned supply chain was modeled in place of a frozen supply chain given the relative prevalence of the former mode of conservation relative to the latter.

Table 3.1. Summary of seafood system production sources and data origins and Life Cycle impact assessment models used in original studies to characterize life cycle impacts of production

Species	Country of Origin	Production mode	Source LCA data and LCIA characterization model used	Life cycle impacts per 1 tonne live weight of product at dock/farm-gate		
				GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg PO_4 eq.)
Atlantic salmon (*Salmo salar*)	Norway	Farmed, net-pen	Pelletier et al. 2009, CML Baseline model used	1,790	17.1	41
	British Columbia, Canada	Farmed, net-pen	Pelletier et al. 2011, CML Baseline model used	2,370	28.1	74.9
Nile tilapia (*Oreochromis niloticus*)	Indonesia	Farmed, net-pen	Pelletier and Tyedmers, 2010, CML Baseline model used	2,250	13	2.82
Whiteleg shrimp (*Litopenaeus vannamei*)	China	Farmed, ponds	Cao et al. 2011, CML Baseline model used	1,517	20.2	47.8
Atlantic cod (*Gadus morhua*)	Norway	Fished, longline	Svanes et al. 2011, CML Baseline model used	5,280	43.9	63
Mixed species tuna	Ecuador	Fished, purse seine	Avadi et al 2015, ReCiPe model used	2,623	-	-

Notes: GWP = global warming potential; AP = acidification potential; EP = eutrophication potential; eq. = equivalents

Given the confounding effect that transport mode (i.e. seafreight versus airfreight) can have on product-form specific comparisons of the impacts of loss rates when perishable goods are transported long distances to markets, we modeled an additional set of salmon case studies in order to illustrate the effect of product form specific losses separate from transport mode. In these case studies, production of salmon occurred in

British Columbia, Canada in order to support a comparison between fresh and frozen supply chains wherein mode of long-distance transportation, trucking, was held constant (Table 3.1).

3.3.2 Avoidable Losses

The literature review of loss rates produced 11 sources reporting original data: five grey literature articles, four journal articles, and two theses (Appendix D). Methods employed within these studies largely consisted of semi-structured interviews, consumer surveys, and secondary data collection (Appendix D). Within these sources, country- or region-specific avoidable loss data were available for the following post-production stages: post-harvest storage and transportation, processing, retail, and consumer household (Table 3.2). Across all studies, seafood was treated as a single food category and resultantly, at each supply chain stage, a single, general value was used to characterize the loss rate for all seafood classes or species (this lack of species-specific data is reflected in Table 3.2).

Amongst the 11 reviewed studies, seven characterized loss rates of frozen products while one provided loss rates for canned products. The remaining studies did not disaggregate loss rates by product preservation form. As expected, studies that characterized the loss rates of different product forms/mode of preservation often observed highest loss rates among fresh products (in comparison to canned and/or frozen products) along supply chains (James et al., 2011; Muth et al., 2011; Stoner, 2013). However, the opposite was found to be true within two consumer-level focused studies, wherein the authors observed that loss rates of frozen seafood products slightly exceeded those of their fresh counterparts (Janssen et al., 2017; Martindale, 2017). Interestingly, one of these studies (Martindale, 2017) observed that frozen fish sticks experienced the lowest rate of losses at the consumer level (3%), though “other” frozen fish had a slightly higher loss rate (7%) than that of fresh fish (6%).

Reported loss rates associated with some supply chain nodes and product forms had high levels of variance either as a function of ranges reported within one study or resulting from divergent values provided by different studies for the same product form. For nodes for which loss rate variance was high, there was no systematic basis upon

Table 3.2. Supply-chain Node-specific Loss Rates for Seafood Supply Chain Case Studies Delivering Product to Toronto, Canada Determined from the Literature Review*

Species	Case Study Description	Product Form	Post-harvest Storage/ Transport Loss Rate	Processing Loss Rate	Distribution Loss Rate	Retail Loss Rate	Consumer Loss Rate	Over-consumption Rate
Atlantic Salmon	Fro. Salmon, Nominal PS	Frozen	0.5%[a]	6%[b]	1%[c]	1%[d]	33%[b]	19%[e]
	Fre. Salmon, Nominal PS	Fresh	0.5%[a]	6%[b]	2%[c]	5%[d]	33%[b]	19%[e]
	Ref. Salmon, Nominal PS	Refreshed	0.5%[a]	6%[b]	1%[c]	5%[d]	33%[b]	19%[e]
Atlantic Cod	Fro. Cod, Nominal PS	Frozen	0.5%[a]	6%[b]	1%[c]	1%[d]	33%[b]	19%[e]
	Fre. Cod, Nominal PS	Fresh	0.5%[a]	6%[b]	2%[c]	5%[d]	33%[b]	19%[e]
	Ref. Cod, Nominal PS	Refreshed	0.5%[a]	6%[b]	1%[c]	1%[d]	33%[b]	19%[e]
White-leg Shrimp	Fro. Shrimp, Nominal PS	Frozen	2%[a]	6%[b]	1%[c]	1%[d]	33%[b]	19%[e]
Nile Tilapia	Fro. Tilapia, Nominal PS	Frozen	2%[a]	6%[b]	1%[c]	1%[d]	33%[b]	19%[e]
	Fre. Tilapia, Nominal PS	Fresh	2%[a]	6%[b]	2%[c]	5%[d]	33%[b]	19%[e]
	Ref. Tilapia, Nominal PS	Refreshed	2%[a]	6%[b]	1%[c]	5%[d]	33%[b]	19%[e]
Tuna (Mixed Species)	Can. Tuna, Nominal PS	Canned	5%[a]	6%[b]	0%[a]	0%[a]	10%[f]	19%[e]
	Fre. Tuna, Nominal PS	Fresh	5%[a]	6%[b]	2%[c]	5%[d]	33%[b]	19%[e]

Notes:
Fre. = Fresh; Fro. = Frozen; Ref. = Refreshed; Can. = Canned; Nominal PS = Nominal portion size of 170grams of uncooked seafood
* Life cycle stages not included in this table are: 1) transport from processing to exporting port, and 2) intercontinental transport. In the absence of specific data a loss rate of 0.0001% was assumed for the former and 0.001% for the latter.
a. Assumed due to lack of specific data
b. Gustavsson et al., 2011; reports 33% losses at consumer stage. Here, this has been divided equally into pre-consumption (16.5%) and post-consumption losses (16.5%). Post-consumption losses, however, represent 20% of seafood available for consumption after pre-consumption losses are taken into consideration.
c. Stoner, 2013
d. James et al., 2011
e. Calculated using data collected on portion size and serving size
f. Muth et al., 2011

which an average or typical value could be identified given that they were executed at completely different scales on different products in different settings. Consequently, in all of these cases, the most conservative (lowest) loss rate value was selected and used to inform the models of each case study supply chain.

At the consumer level, the 33% loss rate reported by Gustavsson et al., 2011 (Table 3.2), functionally includes losses occurring in the home both prior to (e.g. spoilage) and during consumption (i.e. plate waste). As the intervening activity – cooking - entails additional energy inputs and associated impacts, the distribution of household-based losses needed to be further sub-divided. Consequently, it was assumed that these losses were evenly distributed between these two phases within the home, hereafter referred to as the pre-consumption and post-consumption stages, respectively (the loss rates of which were modeled as 16.5% and 20%, Table 3.2: Note B). Conservative loss rates (i.e. 0.1%) were used for life cycle stages where no extant data were available. In spite of the researchers' efforts to secure additional primary node-specific loss rate data from industry actors active at various stages in seafood supply chains no new data were forthcoming.

The review of online seafood recipes indicated that suggested portion sizes can also be highly variable, differing between and among seafood species. As a result, the most commonly suggested portion size of 6 wet ounces (~170 wet grams) was used to represent the nominal portion size for all seafood case studies. We chose not to differentiate portion size between different species or product form, as it was not our intention to discern which products were being consumed at higher rates but rather to characterize a reasonable first approximation of nominal seafood portion size. As such, though the reviewed canned tuna recipes recommended markedly lower portion sizes, the same nominal portion size of 170 grams was used within the canned tuna case study in order to ensure its comparability with the fresh tuna case study. In the conversion of raw to cooked seafood, a mass yield rate of 70% was applied (see Table E2 in Appendix E for data reporting wet to cooked yield rates assembled that ranged from 60% to 90% depending on the method of cooking and seafood product). Based on this, and the Canadian recommended serving size of 75 cooked grams, an overconsumption rate of 19% was determined. As a function of our model, larger portion sizes resulted not only in greater quantities of overconsumption but also plate waste (even though the post-consumption loss rate remained consistent, it resulted in a greater quantity of loss when applied to larger volumes of seafood product).

3.3.3 Unavoidable Losses

Between species, mean yield of edible product varied, with salmon and tilapia respectively having the highest and lowest rates of edible product yield for human consumption relative to live weight (Appendix E). Inedible processing residues were not considered unavoidable losses unless they were used unproductively (i.e. not diverted for further use as co-product). Evidence within the literature (Bekkevold & Olafson, 2007; James et al., 2011; Pelletier & Tyedmers, 2010; Avadí et al., 2015) indicated that processing residues were likely to be fully (or close to fully) utilized for all species, with the exception of Atlantic cod where one study found that only 77% of by-product was diverted for further use. In the shrimp case study, initial processing only removed the shrimp head (leaving the shell, legs, and tail intact), yielding a product that weighed 83% of its live weight counterpart (Cao et al., 2011). Additional processing was assumed to occur at the consumer level, where the product's mass was reduced further by 32% from its deheaded product form (yielding an overall edible from live yield rate of 56%). For all remaining products, it was assumed that removal of inedible parts occurred entirely at the processing level, beyond which only avoidable losses could then occur.

3.3.4 Life Cycle Impact of Seafood Losses

Including all unconsumed and consumed avoidable losses across all seafood supply chains effectively doubled life cycle contributions to global warming, acidifying and eutrophying emissions of seafood products as consumed relative to scenarios in which no losses occurred. Only the canned tuna supply chain with all losses included resulted in less than a doubling of GHG emissions relative to the no loss equivalent supply chain (Table 3.3). When just unconsumed losses were incorporated into the models (i.e. no overconsumption of final cooked products were considered), life cycle contributions associated with consumed seafood products increased by around 60% over the no loss scenarios (Table 3.3). Importantly, accounting for overconsumption

Table 3.3. Global Warming, Acidification and Eutrophication Potentials Associated with the Production through Consumption of 1 tonne of Consumed Seafood Products from Various Sources Destined for Toronto, Canada Conserved in Different Product Forms under both No Loss and Full Supply Chain Loss Scenarios

Species	Case Study Description	Product Form	Loss Scenario	Emission Contributions per tonne consumed		
				GWP (kg CO_2)	AP (kg SO_2)	EP (kg PO_4)
Atlantic Salmon	Fro. Salmon, Nominal PS	Frozen	No losses	3,250	26.4	44.5
			With losses	6,660	54.5	93.7
	Fre. Salmon, Nominal PS	Fresh	No losses	10,700	50.9	47.6
			With losses	22,400	108.2	104.8
Atlantic Cod	Fro. Cod, Nominal PS	Frozen	No losses	4,240	25.3	6.95
			With losses	8,142	52.2	14.1
	Fre. Cod, Nominal PS	Fresh	No losses	11,900	49.4	9.96
			With losses	25,200	105	21.1
White-leg Shrimp	Fro. Shrimp, Nominal PS	Frozen	No losses	11,200	89.7	99.0
			With losses	23,500	188	211
Nile Tilapia	Fro. Tilapia, Nominal PS	Frozen	No losses	3,900	41.5	53.1
			With losses	8,130	86.5	113
	Fre. Tilapia, Nominal, PS	Fresh	No losses	24,400	109	64.7
			With losses	51,000	231	143
Tuna (Mixed Species)	Can. Tuna, Nominal PS	Canned	No losses	9,050	-	-
			With losses	15,600	-	-
	Fre. Tuna, Nominal PS	Fresh	No losses	11,600	-	-
			With losses	25,100	-	-

Notes: Fre. = fresh; Fro. = frozen; PS = portion size; GWP = global warming potential; AP = acidification potential; EP = eutrophication potential; eq. = equivalents losses (i.e. food ingested in excess of recommended intake level) further amplified this effect, raising the life cycle impacts of consumed products by an additional approximately 30%. Notably, consumer-level unavoidable losses also influenced model outcomes in the one supply chain where they were modeled, the frozen shrimp product form. Here, consumer-level processing residues were responsible for 32% of the consumed products' increase in life cycle emissions across the three impact categories considered.

The bulk of life cycle emission increases result from losses occurring at the consumer level (encompassing pre-consumption, post-consumption and over-consumption losses), due to the relatively high loss rates used to inform the models (Table 3.2), the accumulation of post-production emissions, and the compounding effect of losses from previous stages. Within most case studies, the remaining post-production loss stages modeled each made relatively small contributions to life cycle emissions. Exceptions to this included 1) fresh product form case studies wherein intercontinental airfreight transportation required to move product to the destination market (Toronto) contributed a substantial proportion of these products' greenhouse gas and acidifying emissions (see Table 3.4), and 2) the canned tuna case study which experienced high impacts at the processing level due to the input of steel plate for packaging and vegetable oil (approximately 39% of GWP as consumed) (see Avadi et al., 2015 for details). In contrast to the fresh case studies, intercontinental sea freight transportation used along frozen supply chains contributed no more than 4% to the cumulative GWP of frozen seafood products, as consumed.

Across case studies, the AP and GWP contributions of post-production stages were non-negligible (Figure 3.1). In contrast, post-production activities (i.e. transportation and cold storage) were generally responsible for relatively minimal contributions to eutrophying emissions, but this was not the case for all case studies (i.e. the cod case studies). Because Norwegian-harvested Atlantic Cod had a very low EP at the production-level, the non-loss-related post-production activities of the fresh and frozen cod case studies appeared proportionally significant, contributing 32% and 35% to the EP of their functional unit.

Table 3.4. Life Cycle Contributions of Supply Chain Stages to the Global Warming, Acidification and Eutrophication Potentials of Frozen and Fresh Forms of Norwegian-farmed Atlantic Salmon and Norwegian-landed Atlantic Cod as Consumed (Including Supply Chain Losses and Overconsumption)

Case Study	Impact Category	Production	Post-Harvest Storage and Transportation	Processing	International Transport	Distribution	Retail	Consumer
Frozen Salmon	GWP	27%	1%	3%	4%	0%	7%	58%
	EP	44%	0%	3%	1%	0%	2%	50%
	AP	31%	0%	3%	8%	0%	3%	54%
Fresh Salmon	GWP	8%	0%	1%	37%	1%	3%	51%
	EP	39%	0%	3%	5%	0%	3%	49%
	AP	16%	0%	1%	29%	1%	3%	51%
Frozen Cod	GWP	32%	1%	3%	3%	0%	5%	56%
	EP	31%	0%	3%	9%	0%	3%	54%
	AP	25%	0%	3%	4%	0%	9%	59%
Fresh Cod	GWP	11%	0%	1%	33%	1%	3%	51%
	EP	15%	0%	1%	29%	1%	3%	51%
	AP	16%	0%	1%	27%	1%	3%	52%

The absolute (as opposed to relative) amount of emissions associated with 1 kg of edible product was found to be highly variable between seafood products and supply chain nodes (Figure 3.1). For example, a 1 kg loss of any product at the combined post-harvest storage/transport stage results in an order of magnitude lower life cycle impacts than what arises when 1 kg of product is lost at the post-consumption level (Figure 3.1); this pattern results from the fact that losses and their respective life cycle impacts accumulate along supply chains towards the consumer level. Importantly, however, patterns of loss-related impact differ between seafood supply chains (particularly with regard to mode of preservation) and between different impact categories. For global warming and acidifying emissions node-specific losses increase particularly rapidly along fresh supply chains for farmed salmon (produced in Norway), farmed tilapia (produced in Indonesia), and wild caught cod (landed in Norway), as beyond the intercontinental

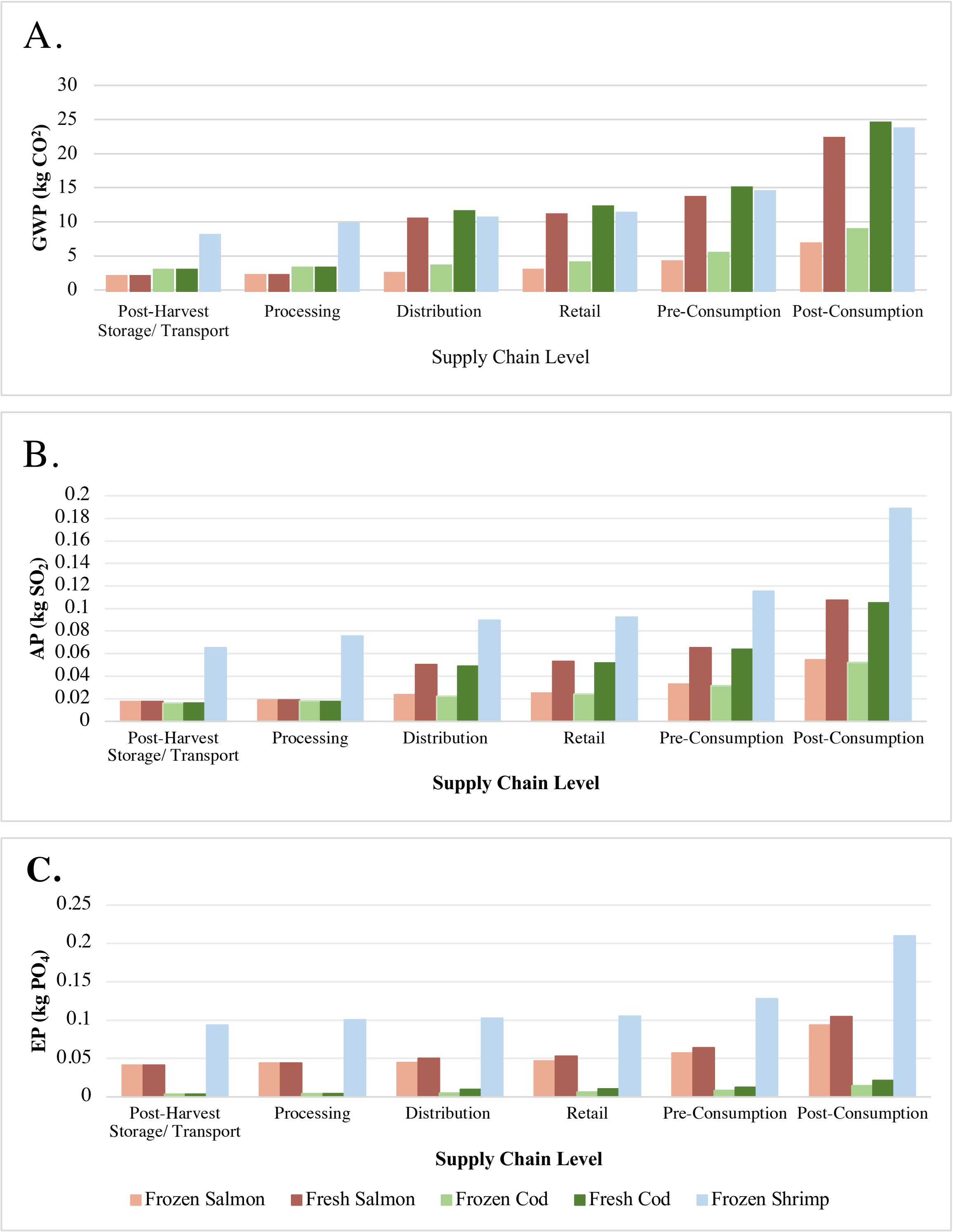


Figure 3.1. Life cycle A) global warming potential, B) acidification potential , and C) eutrophication potential emission consequences resulting from 1kg of product loss arising at specific nodes along five seafood supply chains delivering product into Toronto, Canada

transport stage, fresh losses also carry the burden of air transport (Figure 3.1). Where production-level impacts are high, the emissions per kg of loss are also high, a relationship exemplified by the frozen shrimp case study (Figure 3.1). As relative production-level emissions can vary markedly across impact category (Table 3.1), these differences will similarly be reflected in the emissions per kg of loss (i.e. GWP versus EP for the cod case studies in Figure 3.1).

3.3.5 Impact of Mode of Conservation

Amongst the five primary case studies modeled, frozen options were found to have substantially lower global warming and acidifying emissions than their fresh counterparts (Table 3.3). This finding is, however, an indirect result of the mode of product conservation given that five of the locales of seafood production modeled (Table 3.1) are located on different continents from the location of final consumption with four of the five separated by an ocean. Consequently, intercontinental transport of fresh seafood necessitates the use of fast and highly greenhouse-gas- and acidifying emission-intensive transportation, airfreight, giving rise to the great disparity between the GWP and AP impacts of fresh and frozen supply chains. In contrast, as airfreight makes a relatively trivial contribution to eutrophying emissions, the disparity between the eutrophying emissions associated with1 tonne of consumed fresh product and 1 tonne of consumed frozen product was much less substantial across the products modeled (Table 3.3).

Along the British Columbian-produced salmon supply chains, the distance between nodes of production and consumption (in Toronto) was shorter and located within the same continent, allowing for both fresh and frozen products to be transported using truck freight. Results of these supply chain options (Table 3.5) reveal that when mode of transportation is held constant, there are only minor differences between the respective global warming, acidifying and eutrophying emissions, with frozen British Columbia-sourced farmed salmon actually have a slightly higher (6%) modeled global warming emissions per functional unit when requisite additional cooling energy is accounted for (Table 3.5). Due to the low EP of frozen storage, this finding did not hold true in the case of EP (Table 3.5). Absent the additional cooling energy needed to maintain the lower temperature frozen cold chain in this scenario, the frozen case study would have appeared preferable to its fresh counterpart, with the higher modeled losses of fresh vs frozen salmon at retail (5% vs 1%) resulting in overall reductions of between 5 and 8% across the three impact categories considered (Table 3.5). Another example of this effect, refreshed seafood products, which were thawed and sold as fresh at the retail level, were found to have lower global warming emissions per functional unit than products that remained frozen through to the point of consumption in spite of the higher modeled losses of fresh vs frozen products at the retail level (5% vs 1%). This outcome is attributable to the significant energy investment and concomitant greenhouse gas emissions required to store frozen seafood products at a lower temperature and for longer periods of time than fresh products at the retail (3 weeks vs 4 days) and consumer levels (3 months vs 2 days).

Table 3.5. Difference in Greenhouse gas, Acidifying and Eutrophying Emissions Resulting from Fresh and Frozen British Columbian Farmed Salmon Trucked to Toronto Illustrating the Effect of Differential Loss Rates With and Without Additional Cooling Energy Requirements

Fresh Case Study	Frozen Case Study	Impact Category	Impact reduction/increase from fresh to frozen (additional cooling energy included)	Impact reduction/increase from fresh to frozen (additional cooling energy excluded)
BC Produced Salmon, Truck Transported, Portion Size: 170g, Retail Loss: 5%, Consumer Loss: 33%	BC Produced Salmon, Truck Transported Portion Size: 170g, Retail Loss: 1%, Consumer Loss: 33%	GWP	+6%	-8%
		AP	0%	-6%
		EP	-2%	-5%

Results of the Ecuadoran tuna supply chains with products delivered to Toronto also highlighted the importance of mode of transportation. The canned tuna supply chain, which relied on sea-freight for intercontinental transport (from Guayaquil, Ecuador to Toronto, Canada before transfer to road transport), resulted in global warming emissions 38% lower than those arising from the fresh tuna supply chain (Table 3.5), wherein airfreight was the modeled mode of intercontinental transport. This improvement, while substantial, was much lower than the 62-84% reduction in greenhouse gas emissions modeled for other frozen case studies relative to their fresh counterparts (Table 3.5) with the exception of the BC salmon frozen case study wherein no improvement was observed (Table 3.5). Though canned tuna products experienced lower consumer level loss rates (other than those associated with overconsumption) (Table 3.2), and needed no cold storage beyond the processing level, they required the input of GHG-intensive packaging materials (i.e. steel plate). As a result, the canned tuna case study did not produce a GWP reduction (in comparison to the fresh tuna case study) to the same extent that the frozen case studies did relative to their fresh counterparts (with the exception of the BC salmon case studies).

3.3.6 Impact of Portion Size

Using the case studies as base cases, additional scenarios were developed to reflect how changes to consumer portion size could impact model outcomes. In one scenario, portion size was reduced from 170 grams of uncooked seafood to 130 grams. This resulted in the elimination of overconsumed losses; rates of plate waste (or post-consumption waste), however, remained unchanged (Table 3.6). In the other scenario, portion size was reduced to the Canadian FGS serving size of 104 grams of uncooked seafood (based on 75 grams of cooked seafood and assuming a cooking mass yield of 70%). Because portion size was equivalent to the recommended serving size in this latter scenario, both plate waste and overconsumption were reduced to rates of 0%.

Because the life cycle emissions of overconsumed losses were proportionally greater than those arising from losses occurring in previous stages and because larger portion sizes also resulted in greater quantities of plate waste within our models, overconsumed losses represented a greater proportional opportunity for environmental impacts to be reduced in comparison to unconsumed losses occurring along the supply chain and at the consumer level. Further to this, and unlike the application of frozen storage or canning, portion size reduction does not entail any additional resource investment or environmental burdens. As a result, portion size adjustment resulted in substantial reductions to life cycle emissions. When the nominal portion size was reduced from 170g to 130g (a portion size which would allow for the Canadian FGS to be met in the presence of plate waste) the GWP, EP, and AP of the seafood products, as consumed, were reduced by around 24% (Table 3.6). When this same scenario was modeled without plate waste, potential environmental impact reductions increased further to about 39% relative to the GWP, EP, and AP of the functional unit for all case studies.

Table 3.6. Difference in Greenhouse Gas, Acidifying and Eutrophying Emissions Resulting from Various Scenarios/Case Studies of Frozen Farmed Salmon Shipped to Toronto Illustrating the Effect of Differential Loss Rates

Base Case	Alternative Scenarios/Case Studies	Scenario Description	Impact Category	Impact Reduction /Increase Potential from Base Case
Norwegian-Produced Frozen Salmon Portion Size: 170.1g, Retail Waste: 1%, Consumer Waste: 33%	Reduction of Portion Size to meet Canadian recommended food guide serving size (with plate waste)	Portion Size: 130g Retail Waste: 1% Pre-consumption Waste: 18% Plate Waste: 20% Overconsumption: 0%	GWP EP AP	-24% -24% -24%
	Refreshing of Frozen Product at Retail Stage, Increase in Retail Waste Rate	Portion Size: 170g Retail Waste: 5% Pre-consumption Waste: 18% Plate Waste: 20% Overconsumption: 19%	GWP EP AP	-12% +0.25% -3.6%
	Reduction of Portion Size to Canadian Food Guide Serving Size, Elimination of Consumer Plate Waste	Portion Size: 104g Retail Waste: 1% Pre-consumption Waste: 18% Plate Waste: 0% Overconsumption: 0%	GWP EP AP	-39% -39% -39%

3.3.7 Sensitivity Analysis

The generation of the supply chain models required the use of low-quality secondary data and, in various instances, assumption. In light of these issues, the GWP results of select case studies (Norwegian produced salmon case studies) were tested for sensitivity to a 20% increase to the values of the following parameters: all transport distances, duration of cold storage at the retail and consumer levels, and all loss rates (including overconsumption) applied throughout the supply chain stages. Having a significantly lower GWP than the fresh case study, the frozen salmon case study was slightly more sensitive to changes across all parameters. For both case studies, the increase to truck transport distances had minimal impact (less than 1% Δ in resulting

GWP, AP, and EP emissions) on model outcomes. The increase to airfreight transport distance along the fresh supply chain, however, resulted in a 15% increase to the GWP per functional unit; this is not a surprising outcome considering the large amount of greenhouse gas emissions that result from airfreight transportation. Changes to the duration of cold storage had little consequence for model outcomes of fresh salmon, but did have a slight impact on those of the frozen case study (sensitivity to 20% increase was 1.23% for retail storage duration and 1.9% for consumer level storage duration). Aside from the airfreight transport distance, parameters with the greatest sensitivity to the 20% increase were: pre-consumption loss rates, post-consumption loss rates, and overconsumption loss rates, which respectively resulted in a 4%, 7%, and 6% increase to the fresh case study outcomes and a 4%, 7%, and 7% increase for the frozen case study. Outcomes of this analysis highlight the need for future research to focus on consumer level occurrences of loss and overconsumption.

3.4 Discussion

3.4.1 Limitations and shortcomings

As suggested by the outcomes of the sensitivity analysis, the results of this study must be considered in the context of the various limitations encountered in the research process. The study relied exclusively on extant knowledge (and where necessary, assumptions) to characterize the myriad activities that manifest along seafood supply chains. An inevitable outcome of this, the models inherited any uncertainties associated with each secondary data point collected from the literature and each assumption made by the researchers. Reviews of food waste literature have noted the many issues that undermine the certainty of extant quantifications of food loss rates, including but not limited to researchers' use of out-dated, low-quality data and/or assumptions in the absence of first-hand or secondary observations (Love et al., 2015; Chaboud & Daviron, 2017; Xue et al., 2017). Further to this, robust data on mode of conservation-specific losses along supply chains is very limited, an issue which bears on the certainty of the comparisons that we made between fresh, frozen, and canned supply chains.

The issues that trouble extant quantifications of food waste stem, in part, from the complex, variable, and (sometimes) invisible nature of this phenomena which often takes place outside of the public sphere (James et al., 2011). Attempting to delineate and make visible its occurrence carries political weight, considering the heightened contemporary concern surrounding food waste (Mourad, 2016). In this context, methodological challenges abound, evidenced by the difficulties that we encountered when we attempted to obtain primary observations of loss rates from supply chain actors. Similar challenges have been reported at the consumer level, wherein bias is inherently introduced to data collection as consumers' become aware that their wasteful behaviours are being observed (Höjgård et al., 2013).

Within this study, the consumer level was found to be a source of great uncertainty for various reasons. Within any given household, the acts of food purchasing, preparation, and consumption can materialize in innumerable ways. Resultantly, in characterizing these acts, the use of assumption could not be avoided (i.e. cooking method, cold storage technology, duration of cold storage, and volume of cold storage spaced used). Previous LCA-based studies have cited these challenges as reason for excluding the consumer level from their analyses (Foster, 2005; Dobon et al., 2011). Because overconsumption has also often been excluded from food waste studies, a lack of data and methodological frameworks were available to define and measure this phenomenon. Under these circumstances, it was necessary to develop novel methods to quantify over-consumptive losses. Consequently, the rate of overconsumption that we determined is highly subjective to this study and highly uncertain considering the variation observed surrounding important parameters such as: 1) the uncooked portion size suggested within recipes, and 2) the estimated rate of mass yielded during the cooking process.

Excluding the waste management stage from consideration, this study did not capture the environmental implications of waste disposal, composting or recycling. These activities have potential to reduce life cycle impacts, particularly if resource-intensive packaging such as tinplate has been used (Dubreuil et al., 2010). For example, in their life cycle analysis of canned packaging, Poovarodom and colleagues (2012) found that metal recycling at the consumer level offset the GWP of their functional unit (85 grams of tuna in a can) by 33%. Considering the environmental benefit that can result from the recycling of canned products, it is important to note that the inclusion of the waste management stage within this study could have reduced the environmental impacts attributed to the functional unit of the canned case studies when tinplate is recycled.

In light of the various issues discussed above, the supply chains modeled here were not designed to represent any one specific reality. Rather, they represent a feasible model of reality, through which the researchers of this study were able to explore relationships between supply chain activities and environmental outcomes. Herein, the conclusions of this research process should not be read as definitive but rather illustrative of key insights, those of which will be discussed below.

3.4.2 Environmental Implications of Seafood Losses

The results of this study signal the environmental importance of post-production seafood losses, as their inclusion within the supply chain models more than doubled the environmental impacts of seafood products, as consumed for the three impact categories considered. Keeping in mind the uncertainties underlying loss rates (both unconsumed and overconsumed) used within this study, this observation is not necessarily indicative of the actual magnitude of environmental impacts engendered by seafood losses. Yet, it does reveal how losses, particularly those occurring towards the end of supply chains (i.e. consumer level plate waste and overconsumption), function as crucial levers within life cycle models, greatly influencing the quantity of material and energy inputs and outputs associated with each life cycle stage that precedes seafood consumption. This insight urges reconsideration of the typical approach of seafood LCAs and other forms of seafood sustainability assessments (and more generally those of other food systems): to limit analyses to the production level (Henriksson et al., 2012; Parker, 2012; Avadí & Freón, 2013; Cao et al., 2013). Certainly, production-level impacts of seafood products and differences between production practices can be substantial and consequently, they are important to quantify and address. Yet, this research clearly demonstrates that subsequent efforts to reduce production-level impacts could be easily negated without consideration of post-production losses, suggesting that LCA practitioners should make more concerted effort to include them within their analyses. Further to this, these results demonstrate the crucial need for additional research to address the uncertainty surrounding post-production loss rates.

Though it is clear that, in environmental terms, seafood losses matter, it should be noted that some forms of seafood losses matter more than others. Indeed, contributions to impact categories modeled per kilogram of loss can differ by orders of magnitudes depending on the supply chain stage in which it arises (Figure 3.1). This suggests that food waste reduction efforts should be targeted at high-impact supply chain nodes, such as the consumer level (should future research confirm the relatively high levels of consumer loss modeled here). This highlights the utility of bottom-up environmental assessment tools, such as LCA, within the domain of food waste research as more common top-down assessments of food waste impacts (i.e. Hall et al., 2009; FAO, 2013; Reutter et al., 2016) overlook node-specific consequences of losses. This finding further suggests that environmental evaluations of food loss should disaggregate the impacts of losses by supply chain level in order for these impacts to be meaningfully understood and addressed.

Another insight that the results reveal is that product-specific impact of losses is sensitive to more than just production-specific differences (Figure 3.1). When comparing emission contributions per kg of loss between seafood types, not surprisingly, products with higher environmental impacts at point of production will experience higher environmental impacts/kg of post-production loss, so long as impacts arising at subsequent supply chain stages are roughly equivalent. However, within our models, this latter condition was not always met. For example, at the point of consumption, GHG emissions of the fresh cod supply chain exceeded that of the frozen shrimp supply chain (Table 3.3) despite the former having a lower production-level GWP than the shrimp case study. This arose because of the substantial additional GHG emissions resulting from intercontinental transportation required in the fresh cod supply chain. This demonstrates that impacts of loss are specific not only to a product's impacts at its point of origin but also to the impacts that accumulate along the way to its point of consumption. Previous research has pointed to this complexity in the relationships between node-specific sources of impacts. For example, in their carbon footprint assessment of seafood losses, James and colleagues (2011) observed "high variability between the impacts of different supply chains" and consequently concluded that "it is not possible to assign a simple figure for the average carbon…impact of a tonne of seafood waste, or even a tonne of waste of one specific species" (p. 7). Observations such as these suggest that loss/waste reduction initiatives that treat all types of food waste equally (i.e. the 50% reduction of all food waste proposed within SDG 12.3) are expending efforts inefficiently. Rather than assuming that one reduction target or strategy fits all, a more nuanced, product-specific approach is likely to be far more effective in achieving actual reductions in environmental impacts.

3.4.3 Mode of conservation as an impact reduction strategy?

Consumers have been increasingly encouraged to use their freezers or other forms of food preservation to extend the shelf-life of their groceries and prevent household food waste (see the Make Toast Hate Waste Campaign in WRAP, 2018). Earlier research results indicate that such advice may indeed achieve food waste reductions (Janssen et al., 2017, Martindale, 2017). Yet, more often than not, food waste reduction is not the end goal of food waste research, schemes, or campaigns. Rather, food waste reduction is often motivated to address socioeconomic concerns related to access or, more recently, due to concerns for the environmental consequences of food production and provisioning (Mourad, 2016). Notably, some authors have presumed that the realization of food waste reduction in itself is sufficient to achieve environmental benefits. Yet, surprisingly very few have actually carried out environmental assessments to test out this hypothesis (see Mifflin et al. in prep for an analysis of studies that have conducted environmental assessments of waste reduction strategies). One author, Martindale, 2017, asserts that an environmental assessment of frozen storage is not necessary, claiming that a reduction of food waste amongst frozen food products is sufficient to prove that environmental impacts have been reduced.

The results of this study clearly demonstrate that the solution to food waste-related environmental impacts may not be as simple as the application of a preservation technology such as freezing or canning. Within the context of this study, the environmental advantages of the frozen and canned case studies relative to their fresh counterparts were mostly attributable to the distinct modes of intercontinental transport used along fresh and frozen supply chains (Table 3.5 and 3.6). When mode of transportation was held constant (the BC-sourced farmed salmon case studies, Table 3.5), the relative environmental advantages of the frozen supply chains were diminished, and in some cases (within GWP and AP impact categories) reversed due to the modeled energy resources investments required for frozen storage. In order to offset the GWP and AP transaction costs of frozen storage at the retail and consumer level, frozen products would have to experience significantly lower loss rates than their fresh counterparts at the consumer level and /or be kept in frozen storage for shorter periods of time at various levels of the FSC, and/or the greenhouse gas and acidifying emissions of the Canadian electricity mix would have to be reduced. The realization of these lower consumer loss rates seems uncertain at best, considering the results of the literature review discussed above (which indicated that frozen products may be discarded at a higher rate than fresh products at the consumer level).

It is important to note that the transaction costs of frozen storage did not similarly affect the EP results of the case studies (Tables 3.5 and 3.6). This finding highlights the following key insight: for environmental dimensions wherein impacts are borne largely at the production level and are not likely to be increased substantially by food reduction strategies such as frozen storage (such as EP or other local-scale impacts to marine habitats), the reduction of post-production losses is more likely to produce a net benefit. The corollary, however, is that waste reduction efforts may present environmental tradeoffs. Importantly, only some of these tradeoffs are amenable to analysis using LCA due to its focus on global-scale rather than local-scale environmental impacts (Pelletier et al., 2007).

The environmental implications of food preservation have been explored elsewhere within LCA literature. Characterizing the carbon footprints of fresh and frozen meals, Evans (2012) similarly found that the lower loss rates experienced by frozen chicken products were insufficient to outweigh the additional electricity required to store them. Other studies have also noted the substantial environmental costs of canning seafood (Avadí et al. 2014; Almeida et al. 2015). In light of these findings and those observed within this study, it is evident that the design of informed, efficient waste reduction strategies necessitates proper accounting of their environmental transaction costs. Extant environmental evaluations of waste reductions (see Kummu et al., 2013; Jalava et al., 2016; Martin & Danielsson, 2016; Costello et al., 2017; Springmann et al., 2018) that have neglected to consider such costs have overlooked a significant source of environmental impact and likely overestimated the environmental benefits that can be realized through food waste reduction efforts.

3.4.4 The environmental importance of portion size

According to the strong sustainable consumption theory (Lorek & Fuchs, 2013), realizing sustainable development requires that unsustainable scales of consumption be addressed, because improvements to the eco-efficiency of consumption practices are insufficient, on their own, to prevent the global population from surpassing the social and ecological boundaries within which it can safely operate (Rockstrom et al., 2009; Garnett, 2011). Thus far, many researchers and activists alike have approached the scale of seafood *consumption* uncritically. An indication of this, the UK fisheries industry and sustainability-oriented organization, SeaFish Industry Authority, describes an appropriate individual seafood portion size as ranging between 170-200 grams of uncooked fish (Seafish, 2019), which is significantly larger than the 75 grams of cooked fish per serving (or 104 grams of uncooked fish) that the Canadian FGS recommends (as of 2018) and was used within this study. Consistent with the strong sustainable consumption theory, this study found a strong positive relationship between portion size and the environmental impacts of seafood consumption, with portion sizes greater than 75 grams of cooked fish resulting in functional overconsumption. With this relationship in mind, it is essential for portion size to be included within conceptualizations of both sustainable seafood and food waste. Further to this, structural changes (for example, carbon taxes or the pre-portioning of seafood servings within retail settings) should be considered and evaluated as means of achieving portion size adjustment and relatedly, food waste reduction (Whitmarsh et al., 2011).

The variation that can be observed between recommended seafood portion sizes (i.e. Canadian FGS versus the SeaFish Industry Authority suggestion) raises other important concerns. Seafood nutritional contents vary by seafood type, origin, method of cooking, and even between different datasets (Persson et al., 2018, Hallstrom et al., 2019). Individual human need for the nutrients contained within seafood products is similarly variable, contingent upon aspects such as age, gender, life stage, and diet (Bauer et al., 2013; Golden et al., 2016). These factors clearly complicate attempts to determine nutritionally appropriate scales of seafood consumption, those of which may differ from socially appropriate scales which have been established through sociocultural practices and beliefs (Lindsey, 2010; Macdiarmid, 2013; Horgan et al., 2016; Wang et al., 2017). With the state of the world's fisheries and aquaculture in mind, perhaps a more relevant and fundamental question to ask is: what scale of seafood consumption can be supported within planetary boundaries (Rockstrom et al., 2009; Garnett, 2014) and how widely can the resulting nutritional benefits be shared? The answers to such an inquiry will inevitably reveal the tension between human and environmental health, as some researchers have suggested levels of seafood consumption should actually be lower than those recommended by nutritional guidelines (Garnett, 2014). In this sense, though it does not directly require additional investment of natural resources and concomitant environmental impacts, addressing portion size does carry social transactions costs, as it means acknowledging and navigating nutritional and environmental tradeoffs as well as considering how global seafood resources can be distributed equitably to best meet the nutritional needs of the global population (Garnett, 2014).

3.5 Conclusion

From the insights and issues discussed above, it can be discerned that the issue of post-production seafood loss is complex and should be treated as such. Though the environmental implications of these losses are likely significant, they are highly unique to the seafood species and origin, the product form, the node of the supply chain, and the environmental impact category under analysis. These distinctions should not be discounted, as they suggest that waste reduction strategies should be carefully designed according to the activities and impacts that are particular to specific products and supply chains. Uncertainties and variation surrounding post-production loss rates leave both the extent of the environmental problem to be addressed and the effectiveness of solutions meant to address it (such as canned or frozen storage) unknown. What remains evident is that post-production losses and overconsumption matter, in environmental terms, and additional research should be dedicated to better understanding these phenomena. Another crucial message that can be surmised is the importance of considering the life cycle impacts of waste reduction strategies, as overlooking them may cause the environmental problem created to shift from one life cycle stage or activity to another. As revealed within this study, the reduction of overconsumption through portion size adjustment shows great promise to reduce seafood waste and its environmental impacts without directly requiring additional material or energy inputs (in contrast to solutions involving canning or frozen storage). This outcome is not surprising, considering that previous research has stressed the gravity of not only increasing the efficiency of but also reducing the scale of consumption (Lorek & Fuchs, 2013). Ultimately, attempts to address the environmental impacts of seafood losses will be less effective so long as the nuances and insights discussed above are not considered.

CHAPTER 4. CONCLUSION

4.1 Overview

Throughout the previous chapters of this thesis, various questions were posed to explore the socioeconomic and environmental impacts of food waste and food waste reduction (particularly that of seafood products). Seeking answers within extant literature, the systematic literature review performed within Chapter 2 called into question the widespread assumption that food waste reduction bears no costs or consequences. In Chapter 3, this project's primary research questions (as outlined in Chapter 1) were explored through a life cycle assessment of select seafood supply chains. Within this final concluding chapter, high level insights attained through both of these investigations will be discussed and their practical implications explored. Following this, the limitations of the research carried out within Chapter 3 will be discussed and opportunities for improvements/future research will be explored.

4.2 High Level Insights

4.2.1 It's Not All About Production: Consumption Patterns Matter

Though the results reported within Chapter 3 are certainly not definitive, they clearly demonstrate the environmental importance of post-production stages and the losses occurring within them. Consideration of unconsumed post-production losses alone amplified the life cycle emission impacts of the seafood products as consumed by around 60% over those emissions would have occurred in the absence of losses. From this finding it can be surmised that, from an environmental standpoint, food losses *do* matter and that the recent public concern regarding food waste is not necessarily undue. This claim is, of course, well-supported within extant food waste literature and is in agreement with the findings of many previous studies (Hall et al., 2009; Venkat et al., 2011; Song et al., 2015; Vittuari et al., 2016). Similarly using LCA to study the impact of losses along food supply chains, Willersinn and colleagues (2017) found potato losses responsible for 31% of the consumed product's GWP. Unfortunately, there are few other examples of studies that have evaluated the environmental impact of losses through a cradle-to-consumer LCA approach (as was done in this study). Yet, the results of studies that have performed broader top-down assessments also indicate that the environmental impacts of food waste are non-trivial (see Hall et al., 2009; Venkat et al., 2011). An observation less discussed within wider food waste literature, this study found consumer level losses to be the most significant source of life cycle impacts, compared to impacts incurred by losses occurring at other levels. This is not a particularly surprising finding, considering the high rates of losses at the consumer level that have been previously reported at the consumer level, particularly within developed countries such as Canada (Gustavsson et al., 2011, Muth et al., 2011; Kranert et al., 2012; Stenmarck et al., 2016).

Perhaps a more novel and interesting outcome of Chapter 3's analysis was the environmental impacts that arise from *overconsumed* losses. Unlike the types of losses described above (those of which have been discussed extensively within the field of food waste literature), overconsumed losses have received relatively little attention (Blair & Sobal, 2004; Alexander et al., 2017). Yet, within the context of this study, they too accounted for a considerable fraction of the life cycle impacts of consumed seafood products. While the issue of overconsumption has been studied elsewhere (see Blair & Sobal, 2006; Alexander et al., 2017), no other efforts to date have taken a product-specific approach to assessing the environmental impacts of this phenomenon. In Alexander and colleagues (2017), the authors used commodity balance sheets in order to determine the net primary productivity consumed by global food losses and overconsumption (measured by the amount of energy and protein consumed beyond daily requirements). They observed "over-eating to be at least as large a contributor to food system losses as consumer food waste" (Alexander et al., 2017; p. 190). The authors also noted that the production and consumption of animal products, such as meat and dairy, represented substantial sources of inefficiency within the global food system, suggesting that harvested crops fed to animals could be more efficiently used if directly consumed by humans. The results of both this analysis and the one performed within Chapter 3 indicate that the phenomena of overconsumption (particularly of animal proteins such as seafood) and the excessive portion sizes through which it transpires represent significant points of environmental concern along supply chains and within food systems. Ultimately, these observations and those discussed above point to the environmental importance of food consumption patterns and volumes. With regards to seafood systems in particular, the research findings of Chapter 3 are indicative of the misleading nature of conceptualizations that depict seafood sustainability as something that happens explicitly ‘on the water’ rather than also within other life cycle stages, such as the consumer level (Stoner, 2013).

4.2.2 The Devil Is in the Details

Recognition of the environmental impacts of food waste prompts the question of how a seeming inefficient use of limited natural resources can be addressed. Not surprisingly, many within the academic community and society at large have asked, how can we reduce food waste? (Whitehair et al., 2013; Lazell, 2016; Rossaint & Kreyenschmidt, 2015; Martins et al., 2016; Jagau & Vyrastekova, 2017; Lorite et al., 2017). Though well-intended, these sorts of investigations have not properly framed and perhaps have oversimplified the environmental problem that they seek to solve (see specifically Martindale, 2017). The heart of this issue lies not in food waste itself but in the inefficient use of natural resources that is caused by food waste. So, from a resource management perspective, any attempt to address this phenomenon should actually be inquiring, *if* and *how* food waste reduction can result in a net increase to the environmental efficiency of a defined food system? Asking these very questions, many of the solution-based studies analyzed in Chapter 2 answered yes, it is possible to achieve environmental gains through food waste reduction (Dobon et al., 2011; Conte et al., 2015; Manfredi et al., 2015; Zhang et al., 2015). Importantly, however, such an outcome is conditional upon: 1) the extent to which the food waste reduction strategy reduces waste of the food product(s) considered, 2) the environmental resources embodied in and concomitant impacts generated by the waste of the food product(s), and 3) the environmental transaction costs associated with the measures applied to achieve the food waste reduction.

As discussed within Chapter 2, the environmental impacts generated by food waste differ between and within food categories (Wikström & Williams, 2010; Williams & Wikström, 2011; Wikström et al., 2014). This is because, as many scholars have previously noted, the resource investments and environmental impacts of food are highly variable, influenced by the methods by which a food product has been produced down to the detail of the mode of transportation by which it has been moved (Nijdam et al., 2012; Notarnicola et al., 2017; Poore & Nemecek, 2018). To state simply that food waste is an environmental problem is thus equivalent to effectively saying that food has an environmental impact. Surely, there is truth to both these statements, but they do not provide the level of detail necessary to inform effective strategies to reduce the impacts of food systems. For this reason, product-focused environmental assessments are necessary to understand and differentiate the impacts of different types of food and food waste. Various studies analyzed within Chapter 2, for example Williams & Wikström, 2011; Wikström et al., 2014; Eriksson et al., 2016, provide examples of just this sort of product-specific approach. Through their analyses, the authors of these studies arrived at the logical conclusion that the waste of higher impact products (i.e. beef) results in higher environmental and economic consequences than lower impact products (i.e. ketchup), an observation also noted by Scholz et al., 2015 and Dreyer et al., 2019.

To date, very few other environmental assessments have analyzed and described the environmental impacts of post-production losses to the same level of detail provided within Chapter 3. The results reported therein very clearly demonstrate the remarkable degree (by multiple orders of magnitude) to which the environmental impacts of food waste can vary within a single food category (though the widespread tendency to treat seafood as a single product category seems illogical if one considers the wide variation in impact that exists between seafood species, Tlusty & Lagueax, 2009). Like the studies discussed above (Williams & Wikström, 2011; Wikström et al., 2014; Eriksson et al., 2016), the analysis in Chapter 3 revealed a correlation between the production-level impacts of a defined product and its relative impact if wasted within post-production stages. Providing even further insight, it identified product mode of preservation as another important predictor of the relative environmental impact of seafood losses (with intercontinental fresh supply chains generating considerably higher impacts than their frozen counterparts at distribution, retail, and consumer levels as a result of their reliance on a resource intensive mode of international transportation – airfreight). Another key component noted was the accumulative nature of both losses and environmental impacts along supply chains. A logical outcome of this, the relative environmental impacts of consumer level seafood losses were found to severely outweigh those of losses at other stages of the same supply chain. Observations such as these underscore the highly heterogeneous nature of food waste and its environmental impacts.

Another point of concern for the environmental efficiency of food waste reduction initiatives is the environmental impact associated with measures taken to realize specific food waste reductions. As observed within both Chapter 2 and 3, food waste reduction strategies are not cost free, contrary to popular assumption. The successful reduction of food waste requires the input of time, labour, money, and/or natural resources (referred to as transaction costs). Cases wherein food waste reduction is achieved by means of shelf-life extension likely require inputs from the technosphere – such as plastic (i.e. packaging) or electricity (i.e. cold storage). If the natural resource use and concomitant environmental impacts of such inputs exceed those embodied within the avoided food waste, net environmental *costs* rather than benefits could be incurred. This outcome was observed within Eriksson and colleagues (2016), wherein the authors found that the additional expenditure of electricity used to reduce retail refrigeration temperatures and consequently reduce waste only proved worthwhile, from a greenhouse gas and financial perspective, in the case of high impacting losses of pork and beef (and not in the cases of dairy, cheese, or deli products). A similar pattern was noted within Chapter 3; there my analysis of select seafood supply chains revealed that it did not make sense, from a global warming perspective, to keep seafood products in frozen storage through to the point of consumption, even if it meant that losses could be reduced from 5% to 1% at the retail level. Overlooking the transaction costs of food waste reduction strategies could thus lead to 1) environmental problem shifting from food waste to food waste reduction activities or, even worse, 2) a net decrease in the environmental efficiency of a defined food system.

From the findings discussed above it can be discerned that the global warming implications of certain food waste reduction strategies (i.e. those involving cold storage) may be non-trivial depending, in part, on the emission intensity of electricity used to effect the loss reduction. The same cannot necessarily be said of other environmental dimensions, such as eutrophication, wherein impacts largely arise at the production level and are thus unlikely to be exceeded by the transaction costs of food waste reduction strategies (an effect noted within Chapter 3 and other studies such as Williams & Wikström, 2011). Such nuances should not be overlooked, as they signal not only that a multi-dimensional approach is needed to understand the outcomes of food waste reduction but also that environmental tradeoffs are likely implicit in successful food waste reduction strategies. The decision to reduce food waste is thus a value-laden one that requires certain environmental objectives to be prioritized over others.

Transaction costs of food waste reduction strategies vary not only across environmental dimensions but also time and space. This is because the nature and magnitude of life cycle impacts associated with the technological inputs used to reduce food waste can differ greatly between geographic regions (Wikström & Williams, 2010; Eriksson et al., 2016; Belavina et al., 2017). As mentioned, the mix of resources used to generate electricity, for example, is geographically specific but can also be modified over time to include more renewable sources of energy (International Energy Agency [IEA], 2017). Under circumstances wherein the greenhouse gas emissions associated with an electricity mix are very low, electricity-based food waste solutions (i.e. cold storage) seem more promising as opportunities to reduce the environmental impacts of food systems. This was demonstrated in Eriksson et al., 2016 wherein the authors observed that if a greener electricity mix was used in Sweden, lowering refrigerator temperatures to reduce retail spoilage would result in net benefits across all the food departments considered within their analysis. Geography also factors into the transaction costs associated with packaging-based food waste solutions, a result of the geographically distinct nature of waste management regimes. Certain waste management approaches may thwart the capacity of food waste solutions to achieve net environmental gains. For example, in Wikström & Williams research (2010), the authors observed that if plastic bread packaging was incinerated without heat recovery "there is an obvious risk of an increase of the total global warming impact if the global warming impact of the packaging increases, even if bread waste is reduced" (p. 409). Through observations such as these, as well as the many discussed above, it can be surmised that food waste, food waste solutions, and their respective environmental impacts are numerous, diverse, and nuanced. The key to answering the question posed above (*if* and *how* food waste reduction can result in a net increase to the environmental efficiency of a defined food system?) is thus in the details that make each occurrence of food waste and each attempt to reduce food waste unique.

4.2.3 Getting to the root of the problem

The research performed within Chapter 2 and 3 ties into broader discussions that call for a restructuring of the economic, political, and social systems that encourage food consumption beyond nutritional needs and/or beyond levels that the planet can safely and justly sustain. Under the dominant economic system, global production and consumption of material goods and services are organized around tenets of profit and growth rather than ecological limits (Altvater, 2007; Magdoff & Foster, 2011). This is reflected in current governance of food production practices; for example, within the Global North, national governments subsidize the overproduction of food (a practice which began in the 1950s) (Campbell et al., 2017). Resulting, in part, from these sorts of food policies, food is relatively cheaper and more widely available than it has been previously (compared, for example, to WWWI and WWII eras wherein experiences of food scarcity led to heightened concerns surrounding food waste (Evans et al., 2012)). It is within this economic context that food waste has been seemingly deprioritized (Campbell et al., 2017) and that conceptions of appropriate portion sizes have, in some but not all cases, eclipsed the amounts recommended by national health organizations (Young & Nestle, 2002). The same economic policies responsible for food overproduction in the Global North have also contributed, in part, to the occurrence of food waste within developing nations, wherein farmers, in some circumstances, have found themselves unable to sell their produce locally as their domestic markets have been flooded with food surpluses arising in and passed off as food aid by wealthier nations (Gille, 2013). Considering such political and economic complexities, the phenomena of food waste and overconsumption should be regarded as symptomatic of larger systemic problems.

Encouraging consumers to “love food hate waste” (WRAP, 2018) does nothing to make visible and dismantle the economic and political systems that uphold unsustainable levels of food production and consumption. Though large-scale food waste reduction may result in lower global food prices, it does not address inequitable relationships that exist both within food systems and the global economy at large and thus, cannot be expected to resolve food insecurity (see Rutten et al., 2013; Munesue et al., 2015). Nor does it challenge the deeply-ingrained, widely espoused ethos of economic growth that is at odds with the planet’s limited natural resources and capacity to justly sustain human life (Rockstrom et al., 2009). Rather than disrupting the status quo of boundless material consumption, successful reduction of food waste effectively frees up economic resources and allows them to be spent elsewhere (referred to as the rebound effect and explored within Chistis et al., 2015; Martinez-Sanchez et al., 2016; Salemdeeb et al., 2017).

Because no commodity can be produced without the input of natural resources (Alfredsson, 2004), any consumption that is subsequent to food waste reduction efforts will inevitably have environmental impacts. This means that, depending on the products or services comprising consumption that arises as a result of food waste reduction, the rebound effect could reverse any gains achieved through the avoidance of food waste (Salemdeeb et al., 2017). Thus, to assume that the problem starts and ends with food waste is to be blind to these inextricably linked economic and environmental realities. Achieving meaningful environmental change requires not only that symptomatic issues such as food waste be addressed but also that economic beliefs, the institutions that uphold them, and the social norms they engender be restructured to support sustainable and equitable scales of consumption.

4.3 Practical Applications

The practical applications of this work are various. For proponents of sustainable seafood systems (including researchers and activists alike), the message of the analysis performed within Chapter 3 is clear: efforts to conserve marine habitats and limit the environmental impacts associated with seafood production should not be limited to activities "on the water." The role of key supply chain activities and consumer behaviours should be emphasized within seafood sustainability campaigns to the same extent that production-level activities are. Forms of intercontinental transport, for example, could be communicated to consumers, considering that this supply chain activity proved to be a key predictor of the final global warming and acidifying emissions of seafood products once consumed. This would, of course, also require that seafood labelling schemes trade in their current environmental assessment approach for one that includes not only local-scale impacts on aquatic systems but also global ones such as climate change (Pelletier and Tyedmers, 2008; Madin & Macreadie, 2015). Separate from this form of communication, retailers could also play an important role in signaling appropriate portion size to consumers. At points of purchase, seafood could be cut and packaged into portion sizes according to the recommendations of national health bodies. This could help to prevent plate waste and overconsumption from occurring at the consumer level, both of which were found to significantly contribute to the life cycle impacts of seafood products.

For the myriad individuals and groups set on reducing food waste, this research also serves great purpose. Narratives that underlie concern for food waste paint it as immoral or bad, therein mandating its elimination in service of the common good (Campbell et al., 2017). Moving beyond such simplistic and essentializing rhetoric, this thesis provides a detailed and thoughtful perspective on the phenomena of food waste and overconsumption. The outcomes of this research process suggest that proponents of food waste reduction take a similarly thorough approach. Persons with influence over food waste narratives, researchers for example, should call into question simplistic constructions rather than support and re-embed them within their work (see Springmann et al., 2018 for example). Food waste initiatives led by governmental or non-governmental organizations should be informed by assessments such as those reviewed in Chapter 2 and performed within Chapter 3 and should target high impact losses (i.e. those occurring amidst airfreighted seafood products at the retail and consumer level). This approach is likely to prove more environmentally and economically efficient than waste targets that are universally applied to all food categories (i.e. the UN's SDG of 50% reduction of all food waste by 2030). In order to avoid environmental problem-shifting, it is imperative for proponents of food waste reduction to thoughtfully weigh the costs of food waste reduction against its benefits in order to determine if an intervention is necessary and/or desirable.

Ultimately, due to the structural issues discussed above in Section 2.3, thoughtfully designed and assessed food waste reduction strategies, while important, are insufficient to achieve the transformative type of change that is necessary to keep human systems within ecological limits. In this sense, the amount of contemporary concern surrounding food waste seems myopic and misdirected; why should food waste take on a connotation of guilt and immorality when other unsustainable forms of consumption do not? It is important for those in favour of food waste reduction to explore such questions and to ultimately recognize food waste as a symptom of larger systemic problems, those of which cannot be solved through food waste reduction. In light of this, the energy, money, and time dedicated to food waste reduction by activists, consumers, politicians, and researchers alike could be pointed, in addition, towards transforming the social norms and economic institutions through which unsustainable forms and scales of consumption arise. Food waste organizations could expand their platforms to address structural issues.

They could campaign consumers not only to reduce food waste but also their consumption of animal proteins. Consumers and activist organizations alike could lobby politicians to remove subsidies to food production and/or to implement policies, such as carbon taxes, that will help to limit total scales of consumption, particularly of greenhouse gas intensive products (i.e. certain animal proteins such as beef).

4.4 Research Challenges

Throughout the course of this work, many issues concerning data availability or data quality arose. As noted by many previous food waste review papers, a great amount of uncertainty surrounds extant data on food waste rates (Garrone et al., 2014; Chaboud & Daviron, 2017; Xue et al., 2017). Some of this uncertainty can be attributed to the inherently variable nature of food waste; it takes many forms, occurs throughout the supply chain but differently between nodes and sectors, and can be generated through and motivated by a myriad of values and processes, each of which vary between time and place or from person to person (see Stoner, 2013). In other ways, the lack of high quality food waste data stems from epistemological uncertainty, for example, at the consumer level wherein observational or survey-based studies introduce bias into respondents' answers (Höjgård et al., 2013). In light of these issues, attempts were made to supplement secondary data with primary observations of seafood waste rates, but they were ultimately unsuccessful; this outcome was in part due to the researcher's limited time and resources but also due to the seeming unwillingness of supply chain actors to participate in any form of data collection on waste that could put their reputation at risk. Due to these circumstances, reliance on existing and arguably low quality secondary data could not be avoided – an undesirable but inevitable conclusion, one which many LCA practitioners often arrive at in their "quest for complete and credible information" along diverse, disarticulated, and dynamic supply chains (Freidberg, 2013, p. 589). As a result, the data points used to inform loss rates within the supply chains modeled in Chapter 3 represent a source of uncertainty, the extent of which is likely significant but could not be quantified, once again, due to the lack of complete data. Ultimately, resolving the many unknowns associated with seafood losses and other activities along seafood supply chains required subjective methodological decisions to be made, which effectively rendered the version of reality depicted within Chapter 3, though feasible, highly subjective.

Within the sources of secondary data used to inform loss rates, very few reported loss rates for both fresh and frozen products, and those that did relied on small sample sizes (see Stoner, 2013) and/or conducted their interviews/surveys within specific geographic contexts (i.e. the Netherlands or the UK) that are likely not representative of patterns within North America, the nominal setting in which my modeled seafood consumption occurred. These issues undermine Chapter 3's comparison of the environmental impacts of fresh and frozen seafood supply chains and ultimately, leave unclear the potential of frozen storage to reduce seafood losses. This latter concern is certainly not unique to this study. As noted in Chapter 2, there is a general lack of empirical evidence to support the efficacy of food waste reduction strategies, which limits the capacity of environmental assessments to characterize the outcomes of food waste reduction and to discern whether or not the transaction costs of a reduction strategy can be offset.

The study of overconsumption is similarly troubled by a paucity of data (Blair & Sobal, 2006). Relatively few studies have sought to define or measure this phenomenon. As a result, this area of research is marked not only by a lack of data but also a lack of methodological frameworks to guide data collection. Novel methods had to be devised in order to frame and quantify overconsumption according to the goal and scope of Chapter 3's analysis. Though they are defensible, some of the methodological decisions made could be argued as problematic; even the decision to declare overconsumption as a form of waste could be (and has been) debated, considering the social stigma attached to overeating as well as the valuable social roles that food plays beyond its contribution of essential nutrients (Lindsey, 2010; Macdiarmid, 2013; Horgan et al., 2016; Wang et al., 2017; FCRN, 2019).

From a nutritional perspective, this study's use of Canadian recommended serving size (which has actually been eliminated since the start of this research process as part of Heath Canada's overhaul of its Food Guide) to represent appropriate scales of seafood consumption may also draw concern. Health recommendations for the general Canadian population may not align with individual nutritional needs, dependent on their age, gender, and dietary intake (Bauer et al., 2013; Golden et al., 2016). Further to this, portion size indicates volume of seafood consumption, but importantly, does not communicate the frequency at which those volumes are consumed on a daily/weekly/monthly basis. This latter issue is a critical limitation of using serving size to frame overconsumption. Though Canadians may consume seafood in excessive portion sizes, a survey conducted in 2011 indicates that they may not be meeting suggested weekly intake of seafood (RIAS Inc., 2013). Thus, framing seafood overconsumption on the basis of weekly recommendations rather than serving size recommendations would suggest the occurrence of under- rather than overconsumption of seafood products. Importantly, however, weekly underconsumption of seafood products could still result in the loss of *some* but not all nutrients. Canadians generally maintain a protein rich diet, so excessive seafood portion sizes are more likely to result in the overconsumption of protein rather than of omega-3 fatty acids, nutrients that are relatively scarcer in the Canadian diet and that *may* metabolize at a slower rate than amino acids (may is the key word here, considering that research efforts are ongoing to determine the rate at which fatty acids are metabolized and stored (C. Golden, personal communication, February 16, 2017)). Recognition of such complex nutritional relationships and tradeoffs is implicit to delineating sustainable scales and patterns of food consumption from unsustainable ones (Garnett, 2011; Freidburg, 2017).

4.5 Future Research

As indicated in the discussion above, many important data gaps remain within the study of both food waste and overconsumption. There is a clear need for extant data on food waste rates to be updated and improved through the collection of additional primary observations, specifically within regions of the world wherein characterizations of food waste have been largely based on assumption (i.e. in the developing world) (Xue et al., 2017) as well as within food categories and/or stages of supply chains wherein food waste occurs at a high rate and/or has a high environmental impact. Future data collection on food waste rates should also strive to provide higher data resolution, differentiating in particular between product forms (i.e. fresh, frozen, dried, canned) in order for mode of preservation to be evaluated, with greater certainty, as a potential solution to food waste. Further disaggregation of waste rates at the consumer level (i.e. between waste that happens before, during, and after consumption) is also needed to inform the design of food waste solutions. Additional environmental (and socioeconomic) assessments of the costs and outcomes of food waste solutions should be performed, those of which could be greatly improved if future research efforts were also dedicated to empirically testing the effectiveness of proposed food waste reduction strategies. With regards to overconsumption, future research could be dedicated to better understanding the relationships between food consumption patterns and human health outcomes. The nature of these relationships remain clouded with ambiguities, debates, and unknowns. For example, as discussed above, dietary studies have not been able to discern the rate at which many essential nutrients are metabolized. Improving knowledge in this area could better allow for nutritionally (and thus, environmentally – if the purpose of food production is to meet nutritional needs) inefficient dietary patterns to be discerned and addressed.

4.6 Personal reflection: Room for Improvement?

At the outset of this thesis project, I was under the ambitious assumption that I could collect data in ample quantity and quality in order to answer my research questions. Upon realizing that this was not the case, I was overcome with feelings of doubt: how could I possibly complete this project with incomplete data? Answering this question required me to come to terms with the many imperfections of the data available to me and resultantly, the limitations of my own research (as discussed above). Over the course of my degree, I learned that this is not an uncommon experience for researchers, especially those (such as LCA practitioners) working from secondary observations to understand complex issues. This is perhaps the most important insight that I gained through my thesis project. I became more comfortable with uncertainties and was able to recognize them as implicit to the study of human activities and the environmental impacts of them.

Within the context of my project, some uncertainties could not be avoided and were out of my scope and power to change. Improving upon consumer level loss rates, for example, would have required the implementation of household surveys, a process which certainly did not align with the time and resources available to me. In other cases, I believe that I could have done more to improve upon the data quality of loss rates. Perhaps, with more commitment to engaging with supply chain actors, I could have obtained primary data on loss rates for the retail, distribution, and processing levels. More concerted effort could have also been dedicated to seeking answers to the questions that I had surrounding the relationship between seafood consumption and human nutrition. Though I spent ample time within the literature, I could have reached out to a nutritionist who perhaps could have shed more light on these issues or pointed me in the direction of somebody who could do so. Ultimately, I do not regret the significant amount of time that I spent within food waste and wider food systems literature, as it led me to think about food waste and food waste reduction in ways that I could not have conceived before. Though I relied only on extant data and literature, I believe that I was able to present novel observations and insights on the topics of food waste and overconsumption. My work is imperfect, but that does not detract from the significance of the high level understandings reported throughout this thesis.

4.7 Final Concluding Thoughts

The work performed within this thesis explored the crucial yet too often overlooked relationship between food consumption practices (in terms of volume and patterns) and pressing global environmental challenges. The results reported here underscore the importance of both delineating and addressing unsustainable scales of consumption (Garnett, 2011; Lorek & Fuchs, 2013). This work further demonstrates that the solutions to contested and complex social and environmental challenges (such as food waste and overconsumption) are unlikely to be as simple or straightforward as many the researcher, activist, or politician would like to paint them. This is because food systems, the roles they play within society, and the environmental impacts they engender are numerous, diverse, and uncertain (Lindsay, 2010; Poore & Nemecek, 2018). My findings also make clear some of the issues that could arise if the concept of food waste reduction is oversimplified, as it often is within academic literature and society writ large (Reutter et al., 2016; Chaboud & Daviron, 2017). Through this project's consideration of the costs and consequences of food waste reduction, it is evident that food waste reduction is not synonymous with the realization of environmental, social, and economic gains. This is not to say that food waste reduction cannot play a role in achieving sustainable food systems, but that it is crucial for food waste reduction to be regarded as a means to an end rather than an end in of itself. Rigorous socioeconomic and environmental assessments are thus necessary to determine whether or not food waste reduction can achieve its desired ends.

APPENDIX A. Selected Production-Level Seafood LCA Studies

Table A1. Methods and Results of Production-Level Seafood LCA Studies

Source	Species/Class	Origin	Method of Allocation	Characterization Model	Life cycle impacts per 1 tonne live weight of product at dock/farm-gate		
					GWP	AP	EP
Pelletier et al., 2009	Atlantic Salmon	Norway	Energy	CML 2 Baseline 2001	1,790	17.1	41
Pelletier et al., 2009	Atlantic Salmon	Canada	Energy	CML 2 Baseline 2001	2,370	28.1	74.9
Svanes et al., 2011	Atlantic Cod	Norway	Mass	CML 2 Baseline 2000, CML 1992	2,250	13	2.82
Pelletier & Tyedmers, 2010	Nile Tilapia	Indonesia	Energy	CML 2 Baseline 2000	1,517	20.2	47.8
Cao et al., 2011	White-leg Shrimp	China	Mass & economic	CML 2 Baseline 2000	5,280	43.9	63
Avadí et al., 2015	Tuna (Mixed Species)	Ecuador	Mass	ReCiPe v1.07	2,623	-	-

APPENDIX B. Life Cycle Inventory (LCI) Data

Table B1. Frozen salmon (Norwegian-produced) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	558
Electricity, Freezing	Winther et al., 2009	kWh	133
Electricity - Frozen storage after processing	Thrane, 2004	kWh	21.7
Packaging - Polyethylene (LDPE)	Pelletier & Tyedmers, 2010	kg	12.5
Packaging - Cardboard	Winther et al., 2009	kg	80
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Refrigerated containership to Toronto (from Oslo)	ports.com	km	13,738
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	402
Refrigerant leakage - R404a	Evans, 2012	kg	0.015
Pre-Consumption Consumer Level			
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	474
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B2. Fresh salmon (Norwegian-produced) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	558
Electricity - Refrigerated storage after processing	Thrane, 2004	kWh	0.49
Electricity - Ice production for packaging	Brown, 2014 in Hoang et al., 2016	kWh	10.4
Packaging - Polystryrene	Winther et al., 2009	kg	25
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Air transport to Toronto (from Oslo)	worldatlas.com	km	5950
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.008
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B3. Frozen salmon (Canadian-produced) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	558
Electricity, Freezing	Winther et al., 2009	kWh	133
Electricity - Frozen storage after processing	Thrane, 2004	kWh	21.7
Packaging - Polyethylene (LDPE)	Pelletier & Tyedmers, 2010	kg	12.5
Packaging - Cardboard	Winther et al., 2009	kg	80
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Truck transport to Toronto (from Vancouver)	googlemaps.com	km	4,382
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.015
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B4. Fresh salmon (Canadian-produced) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	558
Electricity - Refrigerated storage after processing	Thrane, 2004	kW	0.49
Electricity - Ice production for packaging	Brown, 2014 in Hoang et al., 2016	kWh	10.4
Packaging - Polystryrene	Winther et al., 2009	kg	25
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Truck transport to Toronto (Vancouver)	worldatlas.com	km	6037
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.40
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.008
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B5. Frozen cod (Norwegian-fished) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	661
Electricity, Freezing	Winther et al., 2009	kWh	133
Electricity - Frozen storage after processing	Thrane, 2004	kWh	21.7
Packaging - Polyethylene (LDPE)	Pelletier & Tyedmers, 2010	kg	12.5
Packaging - Cardboard	Winther et al., 2009	kg	80
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Refrigerated containership to Toronto (from Oslo)	ports.com	km	13,738
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	402
Refrigerant leakage - R404a	Evans, 2012	kg	0.015
Pre-Consumption Consumer Level			
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	474
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B6. Fresh cod (Norwegian-fished) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Refrigerated truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	558
Electricity - Refrigerated storage after processing	Thrane, 2004	kWh	0.49
Electricity - Ice production for packaging	Brown, 2014 in Hoang et al., 2016	kWh	10.4
Packaging - Polystryrene	Winther et al., 2009	kg	25
Transportation to Destination Level			
Distance - Refrigerated truck transport to from processing to distribution	Estimate	km	75
Distance - Air transport to Toronto (from Oslo)	worldatlas.com	km	5950
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.008
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B7. Frozen tilapia (Indonesian-produced) LCI per 1 tonne of edible product (losses excluded

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	661
Electricity, Freezing	Winther et al., 2009	kWh	133
Electricity - Frozen storage after processing	Thrane, 2004	kWh	21.7
Packaging - Polyethylene (LDPE)	Pelletier & Tyedmers, 2010	kg	12.5
Packaging - Cardboard	Winther et al., 2009	kg	80
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Tilapia, Distance - Refrigerated containership to Toronto (from Tanjung Priok)	ports.com	km	27,300
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	402
Refrigerant leakage - R404a	Evans, 2012	kg	0.015
Pre-Consumption Consumer Level			
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	474
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B8. Fresh tilapia (Indonesian-produced) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Winther et al., 2009	kWh	661
Electricity - Refrigerated storage after processing	Thrane, 2004	kWh	0.49
Electricity - Ice production for packaging	Brown, 2014 in Hoang et al., 2016	kWh	10.4
Packaging - Polystryrene	Winther et al., 2009	kg	25
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Tilapia, Distance - Air transport to Toronto from Jakarta	worldatlas.com	km	15,836
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.008
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B9. Frozen shrimp (Chinese-Produced) LCI per 1 tonne of product with heads removed (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Deheading & Freezing	Cao et al., 2011	kWh	550
Electricity - Frozen storage after processing	Thrane, 2004	kW	2.89
Packaging - Polyethylene (LDPE)	Cao et al., 2011	kg	10.5
Packaging - Cardboard	Cao et al., 2011	kg	135
Transportation to Destination Level			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Refrigerated containership to Toronto (from Hainan)	ports.com	km	29,401
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	402
Refrigerant leakage - R404a	Evans, 2012	kg	0.015
Pre-Consumption Consumer Level			
Electricity - Frozen storage	Based on fridge specifications following Brown, 2014 calculations	kWh	474
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)*	Vázquez-Rowe et al., 2013	kWh	315

*Value provided for this inventory item represents 1 tonne of edible product (with shell, legs, and head removed; losses excluded)

Table B10. Canned tuna (Ecuadorian-fished) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport Level			
Electricity - Landing and storage	Avadí et al., 2015	kWh	124.2
Fuel Use - Landing and storage	Avadí et al., 2015	GJ	0.079
Distance - Truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Processing of fish for canning	Avadí et al., 2015	kWh	11.7
Fuel Use - Processing of fish for canning	Avadí et al., 2015	GJ	1.31
Refrigerant (R-22) - Processing of fish for canning	Avadí et al., 2015	kg	0.025
Vegetable Oils	Avadí et al., 2015	kg	268
Salt	Avadí et al., 2015	kg	5.46
Electricity - Canning and Sealing	Avadí et al., 2015	kWh	70.9
Fuel Use - Canning and Sealing	Avadí et al., 2015	GJ	2.81
Electricity - Packaging	Avadí et al., 2015	kWh	4.40
Packaging - Steel	Avadí et al., 2015	kg	393
Packaging - Polyethelene (LDPE)	Avadí et al., 2015	kg	12.4
Packaging - Cardboard	Avadí et al., 2015	kg	67.5
Transportation to Destination			
Distance - Truck transport to from processing to distribution	Estimate	km	75
Distance - Containership to Toronto (from Guayaquil)	ports.com	km	7348
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Electricity - Ambient storage	Estimate	kWh	0.00
Pre-Consumption Consumer Level			
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Preparation	Estimate	kWh	0.00

Table B11. Fresh tuna (Ecuadorian-fished) LCI per 1 tonne of edible product (losses excluded)

Inventory Item	Source	Unit	Value
Post-Harvest Storage/Transport			
Distance - Refrigerated truck transport from port to processing	Estimate	km	200
Processing Level			
Electricity - Filleting	Avadí et al., 2015	kWh	8.63
Electricity - Refrigerated storage	Thrane, 2004	kW	0.01
Electricity - Ice production for packaging	Brown, 2014 in Hoang et al., 2016	kWh	10.4
Packaging - Polystryrene	Winther et al., 2009	kg	25.0
Transportation to Destination			
Distance - Refrigerated truck transport to from processing to distribution	Estimate	km	75.0
Distance - Air transport to Toronto (from Quito)	worldatlas.com	km	4838
Distance - Truck transport to wholesale/retail	Estimate	km	100
Retail Level			
Packaging - Polyethylene (HDPE)	Almeida et al., 2015	kg	19.4
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	76.5
Refrigerant leakage - R404a	Evans, 2012	kg	0.008
Pre-Consumption Consumer Level			
Electricity - Refrigerated storage	Based on fridge specifications following Brown, 2014 calculations	kWh	10.5
Distance - Consumer level transport	Estimate	km	1000
Post-Consumption Consumer Level			
Electricity - Cooking (in oven)	Vázquez-Rowe et al., 2013	kWh	315

Table B12. Storage duration times for fresh and frozen products at the processing, retail, and consumer stages

Life Cycle Stage	**Storage Time**		**Source**
	Frozen Seafood	Fresh Seafood	
Processing stage	1 month	4 days	Assumed in the absence of specific data
Retail stage	3 weeks	4 days	Thrane, 2004
Consumer stage	3 months[a]	2 days[b]	a. Vázquez-Rowe et al., 2013 b. Assumed in the absence of specific data

APPENDIX C. Background Data for Electricity Emissions-Intensities in Indonesia and Ecuador

Table C1. Mix of Primary Energy Sources Used in Electricity Grid in Indonesia in 2015

Electricity Source	**Percent Used in Electricity Grid**
Coal	55.78
Oil	8.4
Gas	25.17
Biofuels	0.48
Waste	0.01
Hydro	5.87
Geothermal	4.29

Table C2. Mix of Primary Energy Sources Used in Electricity Grid in Ecuador in 2015

Electricity Source	**Percent Used in Electricity Grid**
Oil	34.53
Gas	12.66
Biofuels	1.58
Hydro	50.7
Solar PV	0.14
Wind	0.38

APPENDIX D. Literature Review of Seafood Loss Rates

Table D1. Methods, Place of Study, and Loss Rates Reported by Studies that Were Found to Quantify Seafood Supply Chain Losses

Source	Literature Type	Methods	Place of Study	Product Form	Post-Harv.	Proc.	Dist.	Ret.	Con.
Buzby et al., 2009	Grey literature	Secondary data on retail supply and sales	USA	Finfish				8.6 - 8.8%	
				Shellfish				9.2 - 9.4%	
Buzby et al., 2014	Grey literature	Secondary data on food supply	USA	Fish and seafood				8%	31%
Gustavsson et al., 2011	Grey literature	Secondary data on food supply and expert assumptions	North America	Fish	1%	6%		9%	33%
			Latin America	Fish	5%	9%	10%		4%
			Europe	Fish	1%	6%		9%	11%
			Industrialized Asia	Fish	2%	6%	11%		8%
James et al., 2011	Grey literature	Interviews with processors and retailers	UK	Fresh fish				5%	
				Frozen fish				1%	
Janssen et al., 2017	Journal article	Consumer surveys	Netherlands	Fresh battered fish					17%
				Frozen battered fish					17%
				Fresh unbattered fish					17%
				Frozen unbatterd fish					22%
Martindale, 2017	Journal article	Consumer surveys	UK	Fresh Fish					6%
				Frozen Fish					7%
				Frozen Fish Sticks					3%

Source	Literature Type	Methods	Place of Study	Product Form	Post-Harv.	Proc.	Dist.	Ret.	Con.
Mena et al., 2011	Journal article	Semi-structured interviews[1]	UK and Spain	Frozen fish				3%-7%	
Muth et al., 2011	Grey literature	Secondary data from previous consumer survey	USA	Fresh and frozen fish					33%
				Fresh and frozen shellfish					33%
				Canned salmon					10%
				Canned sardines					10%
				Canned tuna					10%
				Canned shellfish					10%
				Other canned fish					10%
				Cured fish					10%
Stoner, 2013	Thesis	Semi-structured interviews with a handful of seafood processors, distributors, and seafood counter managers	North America/ Europe	Fresh Finfish		<1%	0.1 - 2%	25%	
				Frozen Finfish		<1 %	0 - 1%	1%	
				Fresh Shellfish		<1 %	0%	29%	
				Frozen Shellfish		<1 %	0%	1%	
				Live		N/A	40-100%	6%	
Thrane, 2004	Thesis	Interview with retailer	Denmark	Frozen fish				1-2%	
Vázquéz-Rowe et al., 2013	Journal article	Interview?	Spain	Frozen fish blocks			9%		

APPENDIX E. Data for calculation of non-loss related mass transformations of seafood products

Table E1. Edible Yield and Co-Product Utilization Rates of Selected Seafood Species

Species	Ratio of Edible Weight to Live Weight	Ratio of Processing Residues Used as Co-Product	Source
Atlantic cod	0.47[a]	0.77[b]	a. Torry Research Station, 1989 b. James, Archer & Garrett, 2011
Mixed Species, Tuna	0.5[a]	1[a]	a. Avadí et al., 2015
White-leg Shrimp	0.57[a]	1[b]	a. Torry Research Station, 1989 b. Personal communication from Tyedmers
Atlantic Salmon	0.62[a]	1[b]	a. Bykov, 1985 b. Bekkevold & Olafson, 2007 in Winther et al., 2009
Nile Tilapia	0.37[a]	1[b]	a. Torry Research Station, 1989 b. Pelletier & Tyedmers, 2010

Table E2. Mass yield from raw to cooked form for selected species under various cooking method scenarios

Species	Cooking method	Raw Edible to Cooked Edible Weight Ratio	Source
White-leg Shrimp, Peeled	Tempura	0.77	MEXT, 2015
Kuruma Prawn, Peeled	Boiled	0.95	MEXT, 2015
Kuruma Prawn, Peeled	Baked	0.73	MEXT, 2015
Unspecified Shrimp, Peeled	Unspecified	0.6200	Silva & Chamul, 2000
Pacific Cod	Baked	0.65	MEXT, 2015
Atlantic Salmon Fillet	Baked	0.76	MEXT, 2015
Unspecified Tuna, Canned	N/A	0.77	Silva & Chamul, 2000
Unspecified Finfish	Unspecified	0.7	Silva & Chamul, 2000

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