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Wasted seafood in the United States: Quantifying loss from production to consumption and moving toward solutions

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ABSTRACT

Based on the average level of seafood consumption in the United States (U.S.), the 2010 Dietary Guidelines for Americans encourages citizens to double their intake to improve the health of their diets. The future availability of seafood, however, is threatened by overfishing, unsustainable seafood farming practices, ocean pollution and acidification, and other factors. The growing global population and advancing ecological threats such as climate change are placing increasing demands and constraints on U.S. and global seafood supplies. Waste reduction has the potential to support increased seafood consumption without further stressing aquatic resources. It is essential to quantify waste levels in order to effectively target and design waste reduction interventions. Accordingly, we used previous multi-country regional research and updated datasets to calculate a country-specific (U.S.) estimate of seafood loss for the years 2009–2013. We estimate that 40–47% of the edible U.S. seafood supply went uneaten in this period. The greatest portions of this loss occurred at the levels of consumers (in and out of home) (51–63% of loss attributed to consumption), bycatch discarded by commercial fishers (16–32%), and in distribution and retail operations (13–16%). Based on conservative estimates, this waste represents 208 billion grams of protein, 1.8 trillion mg of eicosapentaenoic (EPA) and docosahexaenoic (DHA) acids (i.e., omega-3 fatty acids), and 1.1 trillion kilocalories. The seafood that is lost could fill 36% of the gap between current consumption and U.S. Department of Agriculture-recommended levels. As another way of understanding the magnitude of loss, this lost seafood could provide the total yearly target quantity of protein for 10.1 million men or 12.4 million women, EPA + DHA for 20.1 million adults, and calories for 1.5 million adults. The lost nutrition estimates we provide are meant to be illustrative of the issue's significance and magnitude. While a significant portion of the loss could be prevented or recovered for human consumption, we do not intend to suggest that all of it could or should become food for humans. Bycatch is generally best left in the water; some seafood loss is not culturally acceptable, marketable, nutritious or safe; and a portion of loss is also unavoidable. Instead, we discuss waste prevention strategies involving governments, businesses, and consumers that can be employed to reduce seafood loss and create a more efficient and sustainable seafood system..

1. Introduction

Fish, crustaceans, and shellfish (which we refer to as seafood or fish) play an important role in human nutrition as a source of protein and healthy fats (Gormaz et al., 2014). Historically, fish were an abundant source of food for many civilizations, though overfishing and habitat destruction over several hundred years have greatly reduced global fish stocks and damaged aquatic ecosystems (Jackson et al., 2001; Lotze et al., 2006). While global harvests of wild seafood have remained static since the 1990s, certain fisheries have collapsed and no longer provide a significant food source for humans (FAO, 2014b). For fish populations to rebound, it is necessary to reduce or avoid harvesting some fish species for a period of time (among other approaches) (Worm et al., 2009), thereby significantly reducing the amount of harvested wild seafood. Despite these challenges, global availability of seafood per capita has risen in recent decades due to growth in aquaculture production (FAO, 2014b).

Aquaculture, the rearing of aquatic plants and animals in controlled settings, grew at an annual rate of 8.6% from 1980 to

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2012, and now provides about half of all seafood consumed globally (FAO, 2014b). Aquaculture production methods vary greatly around the world and by species, and some methods are associated with ecological and/or public health concerns, including use of wild fish in aquaculture feed, occupational health risks, release of pollutants into the surrounding environment, disease transfer between farmed and wild animals, and fish escapes (Fry et al., 2014; Gormaz et al., 2014; Love et al., 2011). Seafood available to United States (U.S.) consumers (i.e., the edible seafood supply) includes a variety of wild caught and aquacultured species, both from domestic sources and imported from as many as 138 nations (Kirkley et al., 2006). Five of the top-ten most consumed species in the U.S. are sourced mostly from aquaculture (National Fisheries Institute, 2014; NOAA, 2013b).

The 2010 U.S. Dietary Guidelines for Americans recommend increasing seafood consumption to 8 ounces per person per week, and consuming a variety of seafood in place of some meat and poultry (USDA, 2010). In fact, the National Health and Nutrition Examination Survey (NHANES) data suggest that adults consume a median of only 3.0 ounces per person per week (Papanikolaou et al., 2014) from a U.S. edible seafood supply of 4.5 ounces per person per week (NOAA, 2014a). Jahns et al. (2014) determined that 80–90% of Americans were not meeting seafood recommendations; and women, young people, and people with lower incomes consumed less seafood. Achieving government-recommended consumption levels would require doubling the U.S. seafood supply and nutrition programs targeting specific groups of consumers. The amount of seafood available to U.S. consumers, however, has remained relatively constant for four decades. Increasing this supply places greater burden on marine ecosystems, and could contribute to food insecurity in low-income countries and coastal communities (Brunner et al., 2009; Greene et al., 2013; Jenkins et al., 2009).

Accordingly, interventions are being considered to ensure the viability and continuity of U.S. and global seafood supplies. In the fisheries and aquaculture sectors, there is ongoing work to address overfishing, minimize the ecological and public health risks in aquaculture, adapt to climate change, and build resiliency into the food system, though there are significant barriers to addressing these challenges on a global scale (Cochrane et al., 2009; Gormaz et al., 2014; Troell et al., 2014; Worm et al., 2009).

Given the many challenges of increasing supply, reducing loss is an attractive way to incorporate additional seafood into the domestic supply. For the purpose of this study, we used the U.S. Department of Agriculture (USDA) definition of food loss as "the edible amount of food, postharvest, that is available for human consumption but is not consumed for any reason. It includes cooking loss and natural shrinkage (for example, moisture loss); loss from mold, pests, or inadequate climate control; and food waste" (USDA, 2014b). USDA defines food waste as "the component of food loss that occurs when an edible item goes unconsumed, as in food discarded by retailers due to color or appearance and plate waste by consumers," (USDA, 2014b) however for simplicity we refer to both food loss and waste as "food loss." Current estimates suggest that in the overall U.S. food system, 31–40% of the post-harvest food supply is lost (Buzby et al., 2014; Hall et al., 2009). While a slightly higher proportion of seafood than of other food types is lost at the consumer level (Buzby et al., 2014), the total amountof loss from chicken, beef, or pork, for example, is larger due to a larger supply of these animal products (Fig. 1) (USDA, 2014a). We identified two prior estimates of lost seafood in the U. S., although those estimates were based on studies limited to certain segments of the supply chain, or representing larger geographic regions. Buzby et al. (2014) at the USDA estimated that at the retail and consumer levels, 39% of seafood in the U.S. is lost; they estimated per capita seafood loss based on this quantity (Fig. 1). Gustavsson et al. (2011) reported that the North America and Oceana region (Canada, U.S., Australia, and New Zealand) had the highest fraction of seafood loss (50%) of any region in the world. According to their research, losses were primarily attributable to bycatch (when fishers catch and discard non-target species) and consumers. Stakeholders and researchers have been using these regional estimates as a proxy for U.S. seafood loss (Gunders, 2012). Our study refines and extends our understanding of U.S. seafood loss by providing estimates focused on the entire U.S. supply chain, using the most recent fisheries data, reporting data variability and data quality, and estimating lost nutritional value. Developing improved loss quantifications provides a baseline that can be used to measure progress in loss reduction, establish valuable evidence to inform intervention design, and enable better-targeted loss prevention programs and policies.

Of all foods that are lost, we focus on seafood for multiple reasons. First, there was a need for improved country-specific data on seafood losses. We have described seafood's important nutritional role in the human diet, the limited availability of aquatic resources, and concerns about alternate strategies for increasing seafood supply, and the high proportion of wastage. In addition, seafood has several characteristics that may make it particularly prone to wastage. These include: (i) fishing methods (e.g., bottom trawling) that lead to bycatch (some of the non-target

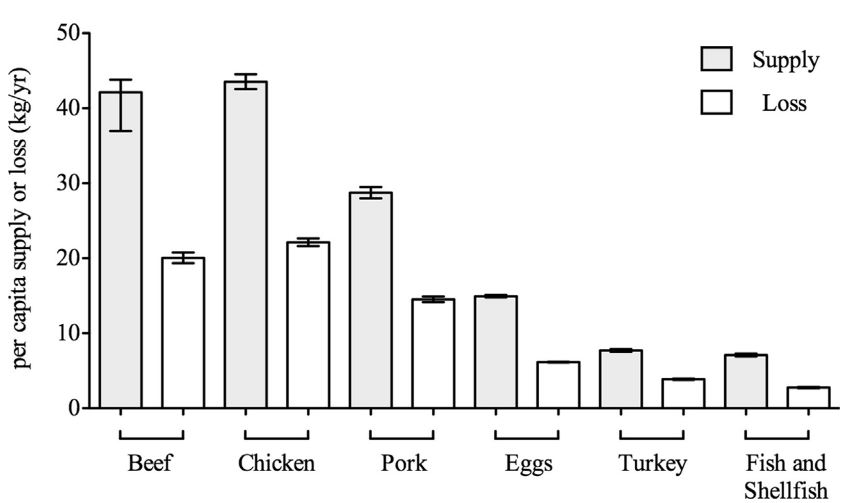

Fig. 1. Per capita meat supply (unadjusted for loss) and loss from 2000 to 2012 in the United States. Bars are median values and error bars are minimum and maximum values. Data from (USDA, 2014a).

species caught and discarded are edible); (ii) fish spoil quickly due to digestive enzymes, microbial spoilage, and oxidation, which change the odor, flavor and texture of fish (Ghaly et al., 2010); (iii) the different microbial and chemical food safety risks from seafood than from other meats, including histamine or scombroid food poisoning due to spoilage; (iv) strong odors that are not always associated with food safety risks, but may raise safety and quality concerns among retailers, food service providers and consumers.

In addressing food losses, responses should be prioritized according to the U.S. Environmental Protection Agency's "Food Recovery Hierarchy" (EPA, 2014). In this model, preventing loss at the source is prioritized, followed by feeding hungry people, feeding animals, industrial uses, composting, and landfilling or incineration. In the case of seafood, canned products, particularly tuna, can be donated because these items have a long shelf life. Byproducts (heads, bones, offal) at the production and processing levels are often rendered into fish meal and oil which are ingredients in animal and pet feed and fertilizer (Tacon and Metian, 2008). Beyond that, it seems likely that most uneaten seafood at the consumer, food service and retail levels goes to landfills. Deepening our understanding of how and why seafood is lost can indicate opportunities to move up the food recovery hierarchy.

The aim of this study was to estimate the amount of seafood that is lost annually at each stage of the U.S. seafood supply chain and at the consumer level. This information can be used to inform strategies to reduce lost seafood from production to consumption, and could boost efficiency and supply without using additional aquatic resources. In addition, it is valuable to quantify loss levels in order to most effectively target and motivate loss reduction actions. We compare our estimates to other national and regional estimates of lost seafood, discuss the implications of lost seafood for public health and nutritional status of the U.S. population, and identify potential strategies to reduce seafood loss and create a more efficient and sustainable seafood system.

2. Materials and methods

2.1. Seafood loss

We conducted Internet searches to identify government websites, reports, and peer-reviewed papers that document the quantity of seafood and fraction lost at various steps of the seafood supply chain and at the consumer level. We did not conduct a systematic review of seafood loss, but instead used a type of chain sampling approach where we explored the references listed in prominent reports and peer-reviewed papers and followed those reference to new references, and so on to identify pertinent literature. Only English-language reports were considered, which included data sources from other countries. Next, we cataloged all data sources and discrete data elements in Excel (Microsoft). The Supporting information (SI) document contains a detailed description of each data element reviewed for this study. In Table S1, we report all data elements used in the study, the units, available date range, data collection methods, and text description. We describe data limitations, and score data quality and generalizability on a scale (low, medium, high) based on our assessment. In Table S2, we describe all data reviewed but ultimately not used, and the reasons for not using these sources. Table S3 presents US National Marine Fisheries Service (NOAA, 2013a) raw data for annual aquaculture and fisheries production and trade and the US seafood supply by product form (fresh and frozen, canned, cured). Tables S4 and S5 report the loss fractions used in calculations and references for each loss fraction. After reviewing the available data on seafood supply and loss we selected the year range 2009–2013 as the most recent five-year range with high quality data available from most sources.

The amount of seafood lost in the U.S. supply chain and at the consumer level was calculated based on multiplying the total edible seafood supply (Table S3) by the fraction lost in specific steps of the supply chain (Table S4, S5). High and low estimates of loss were extracted from data sources and used to provide a yearly range of loss-adjusted seafood supply (Table S6) and seafood loss (Table S7). Many of these food loss calculations were drawn from the above-described UN FAO report on lost food estimates for regions of the world, including "North America and Oceania" (U.S., Canada, Australia and New Zealand) as one region (Gustavsson et al., 2013, 2011). We applied those fractions and newer loss estimates to the U.S. seafood supply to develop a more specific U.S. estimate, and combined the information with U.S.-specific bycatch and food loss data. Using the complete 2009 to 2013 dataset, we calculated the 25th, 50th (median), and 75th percentile loss estimates and the range for the loss-adjusted seafood supply (Table S8) and seafood loss (Table S9). We divided the total loss by the sum of the supply and the loss to calculate the percent lost through the supply chain. We report seafood loss to two significant figures to indicate that these are not precise measurements. Calculations for seafood loss at each step of the supply chain are presented in the SI text.

This study focuses on seafood loss associated with the U.S. seafood supply, which includes the portion imported from other countries. We include bycatch as part of seafood loss and define bycatch as non-target aquatic species caught by fishing gear and presumably discarded dead or injured into the ocean. Bycatch loss estimates were based on the total bycatch of fish from the U.S. seafood supply after accounting for exports. Imported bycatch loss was calculated based on the assumption that 50% of imported seafood comes from wild capture fisheries (with bycatch estimates) and half from aquaculture (bycatch is not applicable) (NOAA, 2013b). Consistent with previous reports, we assume that 50% of bycatch fish were inedible (bones, viscera, tails, heads, etc.) (Gustavsson et al., 2013), and these fractions were not included as food loss because these parts are not typically consumed in the U.S. Our bycatch estimates did not include marine mammals and birds impacted by commercial fishing because these animals are not typically consumed in the U.S.

2.2. Nutrition

We modeled the nutritional content of lost seafood based on the assumption that the nutrient content of seafood that is lost roughly parallels that of the most commonly consumed species in the U.S. Given that we do not know the actual mix of species lost, it is not possible to approximate nutrient content more closely. For each of the top ten seafood types (National Fisheries Institute, 2014), we obtained estimates of protein, eicosapentaenoic (EPA) and docosahexaenoic (DHA) acids (i.e., omega-3 fatty acids), and calories per pound (cooked edible portion) (SeafoodHealthFacts.org, 2008; USDA, 2010). When ranges of nutritional values were provided in reference data, those were preserved. Nutritional values for Pangasius catfish were not available, so we set the values equal to U.S. channel catfish due to the similarities between the two fish (Little et al., 2012). For the "other" category, representing 8.3% of seafood consumed, we created ranges for each nutrient reflecting the lowest and highest values across the top ten seafood types. Finally, nutritional estimates for each seafood type were multiplied by the cooked poundage of that seafood type that would be lost if loss distribution matched consumption distribution (per the above-noted assumption). Cooked poundage was obtained by multiplying amount lost by 0.8 to account for moisture loss (USDA, 2011). Importantly, by removing shrinkage, we diverge from the

USDA loss definition. For our purposes, this modification was important because water weight does not contribute to lost nutritional value. Moisture loss would differ based on the protein and fat content of the seafood item, but 0.8 is a commonly used estimate. Nutrients are reported in the most commonly used measurements (e.g., grams of protein, mg of EPA + DHA, and kilocalories). We summed these results to estimate overall nutrient loss due to lost seafood.

Lastly, we assessed the lost nutritional value in population terms. We calculated the proportion of the gap between recommended (suggested in the 2010 Dietary Guidelines for Americans [protein: Female 46 g, Male 56 g; EPA + DHA 250 mg (USDA, 2010)] and actual consumption that could be filled by lost seafood, by dividing the total quantity of seafood wasted per capita (2012) per week, by the size of the gap between the USDA-recommended 8 oz/capita/week, and actual median seafood consumption among those aged 19 and above based on NHANES data (3.01 oz/week) (Papanikolaou et al., 2014). As an additional way of illustrating the extent of nutrition lost, we also divided the protein and EPA + DHA estimates by target adult intake levels and kilocalories by the commonly recommended target of 2000 daily kilocalories, and then multiplied by 365 days to calculate an estimated number of person-years of nutrition lost in each category. We report the findings using the low-end estimates, even though these were often substantially lower than the median or high-end estimates. We made this conservative decision because the findings are not based on the actual distribution of seafood types lost, which is unknown. Raw data and calculations for nutrients in seafood loss are reported in the Supporting information section Tables S12–20.

3. Results

3.1. Seafood production

From 2009 to 2013, 8.4 million metric tons (MMT) of edible seafood entered the U.S. from imported (4.8 MMT) and domestic (3.6 MMT) sources (Fig. 2). Over one third of the U.S. supply (2.9 MMT) was exported to as many as 157 other countries (Kirkley et al., 2006), and the remaining 5.7 MMT comprised the U.S. edible seafood supply. These data reflect "round weight," which include the whole weight of the products (including heads, bones, and viscera). The National Marine Fisheries Service (NMFS) divides the U.S. edible seafood supply into the inedible and edible fractions, and the latter is called the "fillet weight" or "edible weight." From 2009 to 2013, the edible weight of the U.S. edible seafood supply reported by NMFS was 2.1 MMT (range: 2.1–2.2 MMT), which was not adjusted for loss, and serves as the starting point for seafood loss calculations in Fig. 2.

3.2. Bycatch

Standard commercial fishing activities routinely involve catching some amount of bycatch. Accounting for these fish is an important, and often overlooked, component of assessing lost seafood, because these species are part of the aquatic food web and losses reduce the food supply for other aquatic animals. We estimated there was 0.26 MMT of edible bycatch (range: 0.14–0.41 MMT) associated with the U.S. seafood supply (Fig. 2, Supporting information Table S9). Edible bycatch from domestic and imported harvests were 0.05 MMT and 0.21 MMT, respectively. U.S. bycatch estimates were not reported by region, however, some regions of the U.S. have very low bycatch rates while others, such as the Southeast, are exceptionally high due to bycatch during shrimp fishing (Supporting information Table S11).

3.3. Seafood loss

Loss at each stage of the supply chain is reported for all years in Fig. 3 and by year in Fig. 4. Throughout the supply chain loss was largest in production (due to bycatch, reported above) and consumption (median: 0.59 MMT; range: 0.50–0.68 MMT) (Fig. 3a). Depending upon the year and the loss estimates, bycatch represented 16–32% of total loss. The imported bycatch losses were

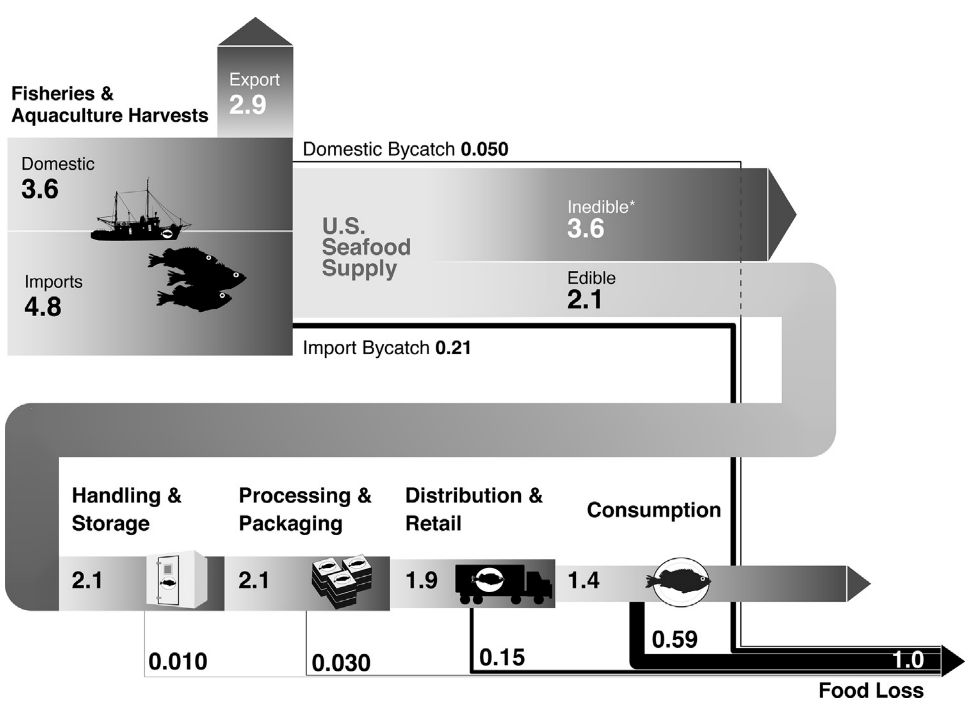

Fig. 2. Loss in the United States seafood supply from production to consumption. Units are million metric tons. Data are median values of loss from 2009 to 2013. (*) Inedible portions exist throughout the supply chain but for ease of viewing they are reported in one place. See Supplemental Tables S8 and S9 for data used in this figure.

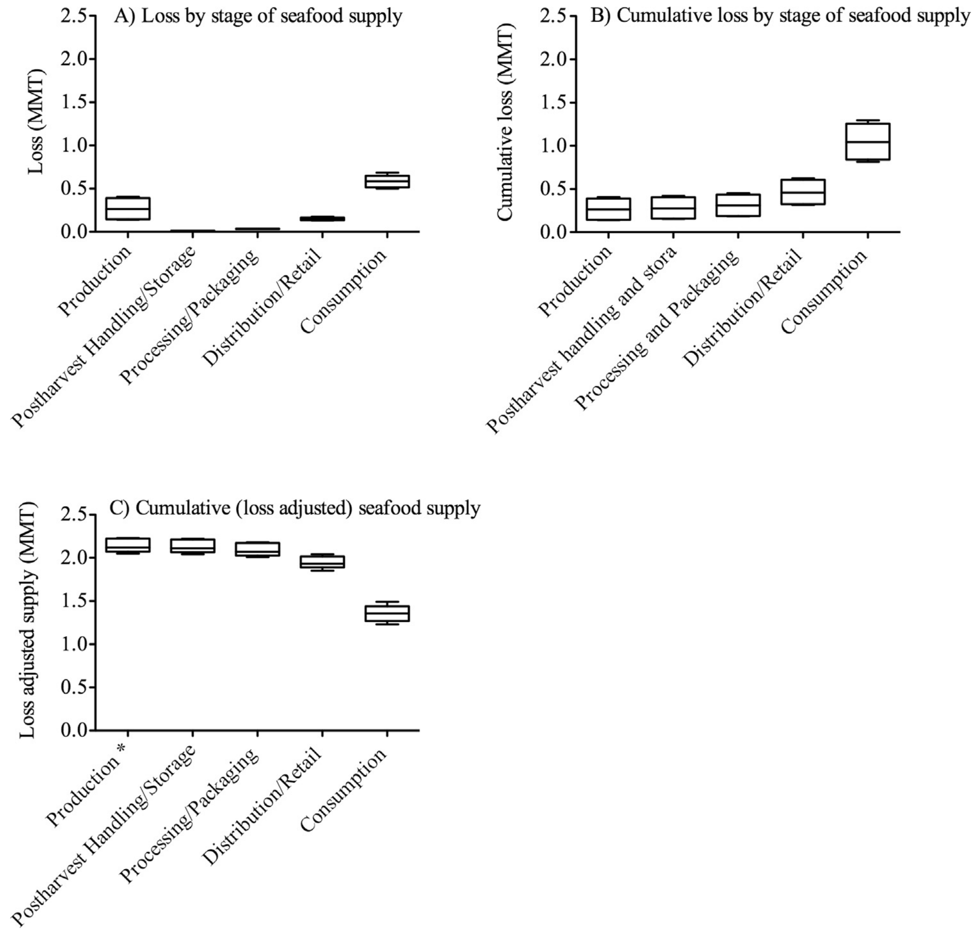

Fig. 3. Boxplot of (A) loss by stage of supply, (B) cumulative loss, and (C) cumulative loss-adjusted supply from 2009 to 2013 in the United States. Boxplots present 25th, 50th (median), and 75th quartiles, and minimum and maximum values. (*) In part C) bycatch estimates were not included as seafood production (which is consistent with other reports (USDA, 2014a)), however, bycatch was considered as food loss in parts (A) and (B). Variation comes from fluctuations in seafood harvests, changing dietary preferences for seafood products and product forms, and variation among high and low loss estimates. See Supplemental Tables S6 and S7 for data used in these figures.

70–85% of all loss associated with bycatch, because the vast majority of the U.S. seafood supply is imported. Consumption represented 41–56% of total loss. At the consumption level, 87–90% of loss came from fresh and frozen seafood and the remainder came from loss of processed seafood.

The total loss along the supply chain was 1.0 MMT (range: 0.82–1.3 MMT) (Fig. 3b). Based on the total loss and total supply,

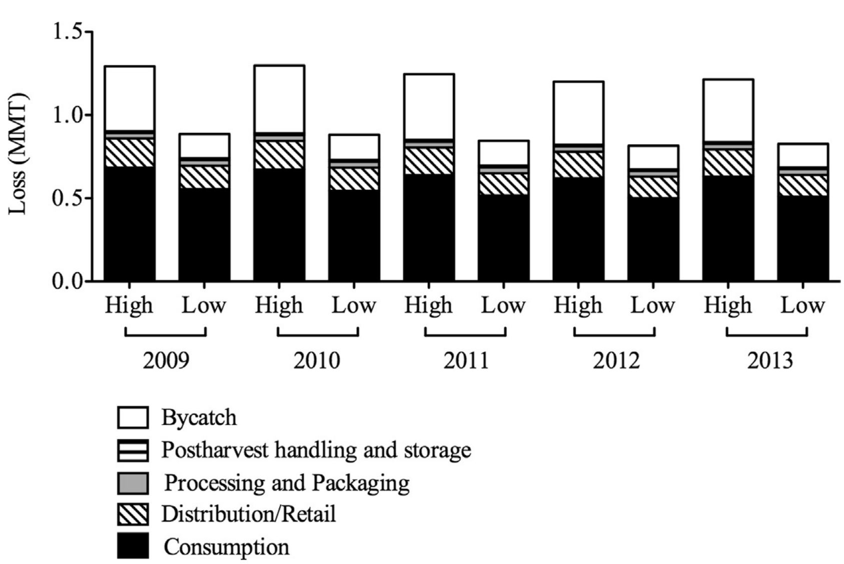

Fig. 4. Loss in the seafood supply chain in the United States from 2009 to 2013. High and low loss estimates were used to develop a range of loss. See Supplemental Table S7 for data used in this figure.

Table 1
Per capita loss-adjusted seafood supply and loss in the United States from 2009 to 2013.

Year	Per capita supply (kg)[a]		Per capita loss (kg)[a]	
	Our study (range)	USDA[b]	Our study (range)	USDA[b]
2009	4.31–4.84	4.31	2.89–4.21	2.84
2010	4.28–4.80	4.36	2.85–4.20	2.81
2011	4.08–4.57	4.13	2.71–4.00	2.66
2012	3.91–4.43	3.90	2.60–3.83	2.55
2013	3.97–4.45	n/a	2.62–3.84	n/a

[a] US population based on data from July 1 of each year.
[b] Data from (USDA, 2014a)

we estimated that 44% of the edible U.S. seafood supply (range: 40–47%) was lost annually from 2009 to 2013. We were unable to account for non-bycatch seafood losses during the production phase (including aquaculture and wild caught seafood) due to lack of available data.

3.4. Loss-adjusted seafood supply

The loss-adjusted seafood supply was 1.4 MMT (range: 1.2–1.5 MMT) from 2009 to 2013 (Figs. 2 and 3c). The wide range in the loss-adjusted supply was caused by fluctuations in annual seafood production, gradual changes in consumer preferences for seafood product types with different loss rates, and the use of high and low loss estimates. It appears the loss-adjusted supply has been decreasing slightly from 2009 to 2013, primarily due to decreases in seafood production (Table 1). When comparing our loss-adjusted supply to the USDA loss-adjusted supply (USDA, 2014a), our data provides a range of values that spans the USDA point value for most years (Table 1).

3.5. Data quality and generalizability to the U.S.

The data sources we used varied widely in their data quality and generalizability to the U.S., which affects our ability to accurately and confidently estimate loss at each stage of the supply chain (Fig. 5). In general, production level data was of good quality and highly generalizable to the U.S., while data along the supply chain and consumption was of low to moderate quality and low to moderate generalizability. We scored seafood export data as low quality, primarily because data were not reported by species or other key factors. Data quality on bycatch varied; the most recent domestic bycatch estimates from NMFS was the only source to quantitatively assess their own data quality as part of the estimate. Postharvest handling and storage and processing and packaging are two areas where better loss estimates are needed for the U.S. Loss estimates for distribution and retail were of medium quality for fresh and frozen seafood. No loss estimates currently exist for processed products and therefore expert opinion was used. Consumer loss estimates for seafood were of low quality because the methods used to develop loss estimates were imprecise and relied on proxy data in some cases. The methods were, however, nationally representative in scope. A complete list of the limitations of each data source is presented in the Supporting information section Table S1.

3.6. Nutrition

We estimated the nutritional content of lost seafood as an illustrative example of the magnitude of loss, and not to imply that all lost seafood could or should be eaten. Conservative (low end) estimates indicate that the above-described loss of seafood in the U.S. supply meant losing 208 billion grams of protein, 1.8 trillion mg of EPA+DHA, and 1.1 trillion kilocalories in 2012 (Table 2). For EPA + DHA levels, the high-end estimate is 6.3 trillion mg – more than triple the low-end estimate – due to the broad ranges of values for some species. Modeled results could change as more information about the specific species lost becomes available.

Our analysis found that the lost seafood could fill 36% of the weekly gap between median seafood consumption (among adults) and USDA-recommended levels. As another way to understand the volume of nutrients lost, we also found that the seafood that is wasted could conservatively provide the equivalent of the total yearly quantity of protein for 10.1 million men or 12.4 million women, EPA + DHA for 20.1 million adults, and calories for 1.5 million adults.

4. Discussion

We estimate that 40–47% of the U.S. seafood supply was lost annually from 2009 to 2013. Lost food has important implications for public health, natural resource use, and resiliency in the face of climate change (Cuellar and Webber, 2010; Dorward, 2012; Lewison et al., 2011; Parfitt et al., 2010), and the issue is gaining traction among a wide range of stakeholders. The ideal way to reduce loss of seafood is through prevention. Loss prevention

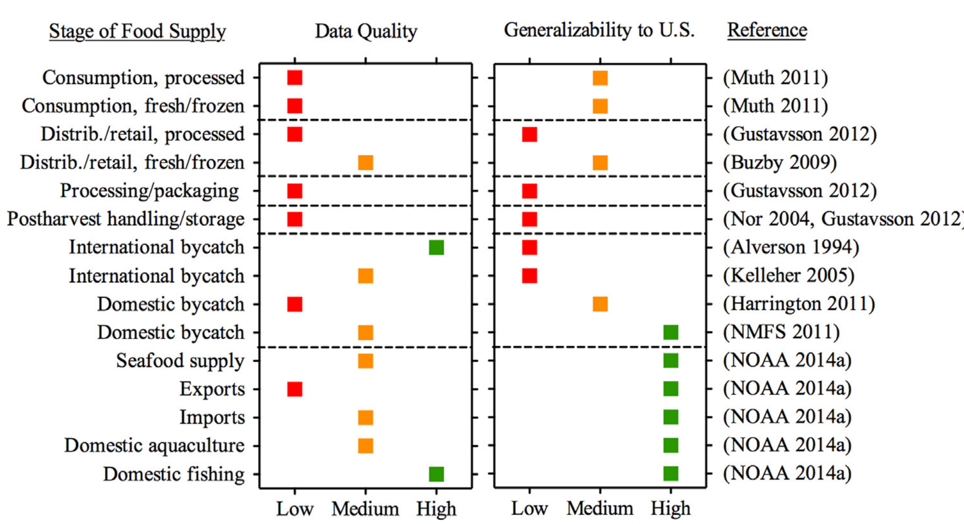

Fig. 5. Assessment of data quality and generalizability to the United States of data sources used to generate seafood loss estimates. References: (Alverson et al., 1994; Buzby et al., 2009; Gustavsson et al., 2013; Harrington et al., 2005; Kelleher, 2005; Muth et al., 2011; National Marine Fisheries Service, 2011; NOAA, 2014a; Nor, 2004).

Table 2
Estimated annual nutrients lost to the U.S. food supply due to seafood loss, based on median waste estimates from 2009 to 2013.

Nutrient	Quantity lost[c]	# Person-years nutrition lost[c]
Protein, g[a]	2.08×10^{11}–2.18×10^{11}	10,157,762–12,967,384
EPA + DHA, mg[a]	1.83×10^{12}–6.25×10^{12}	20,087,524–48,920,752
Kilocalories[b]	1.09×10^{12}–1.27×10^{12}	1,489,916–1745,832

[a] Targeted daily intakes of protein = 46 g (Female) and 56 g (Male); EPA + DHA = 250 mg. USDA Dietary Guidelines for Americans, 2010, Appendix 5 (averaging M, F); Appendix 11

[b] 2000 kcal is a widely used estimate averaged across age, sex and activity level categories

[c] High and low end estimates reflect range of possible nutrient content by seafood variety, based on the top 10 seafood items in the US food supply, 2009–2013 plus "other."

would reduce unnecessary production and harvesting, which would improve the ecological sustainability of fisheries and aquaculture, contribute to increased future food security, and reduce the carbon and energy (Cuellar and Webber, 2010) used in production and trade per unit of seafood consumed.

In our study, the bycatch rate from domestic fisheries was higher than bycatch rates from imports, however, 90% of the U.S. seafood supply is imported (NOAA, 2014b), which makes imported seafood a larger fraction of total bycatch. The actual bycatch rate for imported seafood may in fact be higher; the U.S. government has made monitoring and reducing bycatch a priority, while others have not. U.S. monitoring finds that some fisheries are still reporting unsustainable levels of bycatch; for example, roughly three-quarters of the catch brought aboard shrimp trawling vessels in the Gulf of Mexico is discarded as bycatch (Supporting information Table S11) (National Marine Fisheries Service, 2011). Fish caught as bycatch in this region include flounder, croaker, sole, halibut, hake and other species which are edible and considered fisheries in their own right (National Marine Fisheries Service, 2011).

From a nutritional standpoint, seafood assumes particular importance among types of lost food due to its high protein and omega-3 fatty acid content. We found that seafood lost from the U.S. food supply contains vast quantities of protein and omega-3 fatty acids. Consumer-targeted loss prevention efforts can help make this nutrition available to consumers who have already chosen to bring the seafood into their homes. If all the lost seafood along the supply chain were instead eaten, it would fill over 1/3 of the gap between USDA-recommended and actual consumption with no increase in fishing or aquaculture production. We are not advocating, however, that all seafood loss should be turned into human food. What is lost may undermine current bycatch limits and/or not be culturally acceptable, marketable, nutritious or safe. Some loss is unavoidable including due to the high perishability of seafood, changing circumstances after sellers and households make procurement decisions, and the reality of variation in demand. We present these estimates to help stimulate dialogue about the significance and magnitude of seafood loss.

A variety of tools are available to government, businesses, and consumers seeking to reduce the amount of seafood lost. To our knowledge, these have not been evaluated in the literature, but Table 3 provides examples and our qualitative assessment of potential costs, impacts, and limitations. Overarching approaches include:

i) creating positive and negative incentives to support reducing loss;
ii) designing production, processing and distribution processes and infrastructure with loss-reduction as a central goal;
iii) helping businesses and individuals become aware of the quantities they lose, and providing targeted strategies; and
iv) educating businesses and consumers about food safety in order to reduce unnecessary discards.

Government can play an important role by supporting the incentives needed to reduce loss of seafood at all levels of the supply chain and at the consumer level, and providing education and communication to consumers and others.

Strategies aimed at increasing utilization of aquatic animals that would otherwise be discarded as bycatch must be carefully considered. Creating markets for bycatch species runs the risk of incentivizing their capture and creating fishing pressure for species currently viewed as bycatch. One could envision, for example, fishers labeling otherwise marketable fish as 'bycatch' to circumvent catch limits, which are restrictions to prevent overfishing. In fact, the most effective strategies for addressing bycatch would not focus on incorporating the animals into the human food supply, and instead on keeping non-target species from ever being caught by commercial fishers. To reduce loss from bycatch, the U.S. government should expand monitoring and strengthen regulations to reduce and/or utilize bycatch in domestic and international fisheries (Keledjian et al., 2014). Domestic fishery regulations aimed at addressing bycatch could be expanded primarily through the reauthorization of the Magnuson–Stevens Fishery Conservation and Management Act. Another potential policy avenue for addressing bycatch and loss of seafood is the U.S. Presidential Task Force on illegal, unreported, and unregulated fishing and seafood fraud (NOAA, 2014c). International monitoring and utilization of bycatch can be increased through trade policy, especially because the U.S. is the second largest seafood importer in the world, with imports worth $17.6 billion in 2012 (FAO, 2014a). Private sector solutions, including third party certification of loss reduction strategies and marketing bycatch to consumers, can also play an important role. For example, the Marine Stewardship Council includes bycatch as part of their sustainable fisheries certification system (Marine Stewardship Council), and Louisiana Foods Total Catch Market has been selling fresh fish caught in the Gulf of Mexico that would otherwise be considered bycatch to chefs and consumers since 2011 (Louisiana Foods Total Catch Market, 2015).

From an environmental and greenhouse gas reduction perspective, preventing losses late in the food chain is particularly impactful, because at that point seafood includes all the embodied energy used in harvesting, processing, distribution, and preparation, and most importantly, cooling throughout the food chain. Referring to non-seafood products, Thomson estimates that by the consumer level, food contains about triple the embodied energy of food at the farm level (Thompson, 2011).

5. Limitations and future research

There were some limitations in our ability to attribute loss to specific species, so instead we attributed loss based on categories of products (fresh and frozen; and processed). Loss at the production level was limited to bycatch and did not include other types of loss associated with wild caught seafood due to a lack of data. In addition, low levels of monitoring may result in considerable uncertainties in bycatch data (Keledjian et al., 2014). National estimates of aquaculture processing loss were not available, however, this area deserves further attention. For example, most catfish processing plants typically reject a small fraction (1–3%) of each live truckload of fish. These "weigh-backs" are docked from the gross weight because i) some catfish do not meet the size requirement for mechanized processing, and ii) there may be other fish commingled with catfish. These other fish include gizzard and threadfin shad, grass carp, bluegill, and green sunfish, which are common in commercial catfish ponds practicing polyculture and are considered bycatch during catfish harvests. On

Table 3
Approaches to reducing food chain waste, and potential costs, impacts, and limitations.

Stage of food chain	Approaches	Approach Potential (qualitatively assessed)		
		Cost	Impact	Limitations
Seafood harvest and aquaculture [see also: (Keledjian et al., 2014)]	Bycatch utilization: develop strategies, such as marketing plans or boats with adequate refrigerated storage	Low-medium (marketing)	Low-medium	Could increase incentive to catch protected fish; boat storage depends on individual operator investment; bycatch may not be edible, culturally accepted, or safe to eat
		Low-medium (refrigeration on boats)		
	Regulation: Limit the percent of bycatch that can be caught	Low-medium (enforcement)	High	Requires enforcement capacity
	Incentives: Provide financial or tax incentives for bycatch reduction	Medium	Depends on incentive size	Political barriers
	Ban types of equipment known to trap substantial bycatch (e.g., drift gillnets, bottom trawlers)	Low	High	Political barriers; Requires enforcement capacity
	Require devices to exclude unwanted species such as turtles	Low-medium (already widely used)	Low (excluder equipment does not protect small animals)	Requires enforcement capacity
	Third party certification of loss-reduction strategies	Low	Low-Medium	Dependent on monitoring and on purchaser level of incentive, especially if price is higher; impact undermined if market remains for uncertified seafood products
	Improve bycatch monitoring and reporting, and support efforts to improve international fishery bycatch monitoring, reporting, and reduction	Low	Medium	Political barriers; Benefits are indirect
Seafood processing	Package seafood into smaller portion sizes for consumers	Low	Unknown*	Potential business concerns about reducing amount sold
	Consider use of new labeling technologies that track a product's time-temperature exposure and provide indicators that it may have become unsafe	Medium	High, if sensor is trusted	Technology not yet in wide commercial use
Seafood distribution including retail	Track waste using tools such as those provided by LeanPath	Medium	High	Each independent seller must decide to invest in process
	Include storage and freezing information on packages	Low	Medium	Consumer information utilization will vary
	Provide accurate information to consumers about when seafood becomes unsafe, and about how and when to freeze seafood	Low	Medium	Limitations of education for behavior change
Seafood consumption by individuals and in restaurants	Encourage consumers to create shopping lists, perform meal planning, including assessment of portion size, and use leftovers	Low	Medium*	Limitations of education for behavior change
	Encourage purchase of frozen seafood	Low	Low-medium*	Once defrosted, risk of waste might be same as for fresh
	Promote the idea of consuming parts of fish not commonly eaten in the U.S., such as soups from made from fish heads	Low	Medium	Could increase incentive to catch protected fish; Limitations of education for behavior change

*Unknown impact, because no information is available regarding how much this issue contributes to seafood waste burden.

occasion catfish seine crews will salvage the larger bream for personal use, which suggests these products are valued by some as a food source (Gregory N. Whitis, personal communication).

In the absence of data about the specific fish types lost in the U. S., the nutritional estimates were calculated based on the distribution of fish types consumed in the U.S. (Supporting information Table S13–15). The nutritional findings are strengthened by averaging results across ten seafood types, and we present the low-end figures as conservative estimates. These estimates would be higher if we included the nutritional value of parts of fish eaten elsewhere, but commonly rejected in the U.S., such as heads.

We note that in our study, as in most other national-scale research, loss was modeled by applying pre-determined percentages, based on research, to the overall supply. Thus, the loss estimates will change as the food supply changes, but will not rise or fall as loss reduction behaviors improve, unless the underlying loss percentages are modified based on findings from further research.

Important areas for future research include: robust monitoring of bycatch domestically and abroad to determine overall levels and specific types of seafood lost; monitoring loss in aquaculture production; understanding key determinants of lost seafood across the food supply chain and at the consumer level using research methods such as diaries where people describe the food they discard, and trash sorts where actual discards are categorized; identifying and developing appropriate interventions to reduce loss, and increasing Americans' receptivity to consuming parts of fish currently discarded.

6. Conclusions

This study finds that 40–47% of the U.S. seafood supply is lost. We detail the enormous nutritional implications of this loss, which is particularly troubling in light of the 2010 USDA Dietary Guidelines recommendation to more than double seafood intake. The loss exacts financial costs up and down the supply chain, and causes unnecessary losses to fisheries and other parts of our ecosystem needed for food security and our long-term survival. A portion of the loss of seafood is unavoidable, especially because seafood can spoil quickly compared to other foods, but continuing to treat our aquatic resources as though they are limitless is unsustainable and detrimental to the environment and public health. Reducing loss of seafood will require complex and diverse actions by many different participants in the supply chain, from production to consumption, and future research can serve to monitor and evaluate these efforts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.08.013.

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