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Fisheries and aquaculture by-products: Case studies in Norway, United States, and Vietnam

David C. Love [a,b,*], Frank Asche [c,d,h], Jillian Fry [e], Mark Brown [f], Ly Nguyen [g], Taryn M. Garlock [c,h], Elizabeth M. Nussbaumer [a,b], Gabriela L. Sarmiento [a,b], Sigbjørn Tveteraas [d], Roni Neff [a,b]

[a] *Johns Hopkins Center for a Livable Future, Johns Hopkins University, Baltimore, MD 21202, USA*
[b] *Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205, USA*
[c] *School of Forest, Fisheries and Geomatics Sciences, University of Florida, Gainesville, FL 32611, USA*
[d] *Department of Safety, Economics and Planning, University of Stavanger, Norway*
[e] *Department of Health Sciences, College of Health Professions, Towson University, Towson, MD, 21252, USA*
[f] *Center for Environmental Policy, University of Florida, Gainesville, FL 32611, USA*
[g] *Department of Agricultural Economics, Texas A&M University, McAllen, TX 78504, USA*
[h] *Global Food Systems Institute, University of Florida, Gainesville, FL 32611,USA*

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ABSTRACT

Fishmeal and fish oil (FMFO) have historically come from capture fisheries, although supply from capture fisheries is constrained and demand for FMFO is increasing. Fish production losses and by-products are an alternative raw material for FMFO, however, there is little systematic data collected on the use of these raw materials and limited knowledge about barriers to their use in FMFO production. This study collected data on production losses and by-products from seven fisheries and aquaculture sectors that are important in supplying the US seafood market. From 2019–2021, quantitative surveys (n=47 businesses), semi-structured qualitative interviews (n=31 businesses), and secondary data were collected for the study period of 2014–2018. There was significant variation in utilization of production losses and by-products across sectors (range: 37–99 %), and overall, the aggregate utilization rate was 72 %. Scale appeared to be the most important factor leading to use of production losses and by-products. Aquaculture industries in this study had a large and relatively steady supply of by-products year-round, which made investments in FMFO plants worthwhile and led to moderate to high rates of by-product utilization. Wild-caught fisheries in this study had lower rendering rates due to short fishing seasons, smaller scales, operations in remote locations, and regulations that allow dumping of by-products. There were several examples of companies that invested in rendering plants because it was profitable to sell the rendered waste, while other sectors and industries require better coordination and policy supports to make use of this valuable resource.

1. Introduction

Fishmeal and fish oil (FMFO) can be made from three types of raw materials: i) whole captured fish, ii) by-products (i.e., offal, heads, tails, frames) from processing of human food fish, and iii) production losses (i.e., bycatch, discards, diseased or dead animals) from fisheries and aquaculture. FMFO has historically come from capture fisheries [1], however, this is shifting for economic, sustainability, and food security reasons. Global fishmeal production peaked in 1993 [2] and has been gradually declining partly due to declining stocks and landings [1], as well as switching of resources to human consumption due to improved fisheries management [3–5] (Fig. 1). The decline in FMFO production is somewhat surprising given the strong demand from aquaculture for aquafeed ingredients [6], although cost considerations have led to reduced use of marine ingredients in aquafeeds [7–9] as well as strong demand for marine ingredients in dietary supplements for humans [10].

About 20 % of marine capture fisheries production or about 16 million tonnes in 2020 was used to produce FMFO [2]. The bulk of that

* Corresponding author at: Johns Hopkins Center for a Livable Future, Johns Hopkins University, Baltimore, MD 21202, USA.
E-mail address: dlove8@jhu.edu (D.C. Love).

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came from small pelagic fisheries such as Peruvian anchoveta, Pacific sardine, Gulf and Atlantic menhaden, and several other species, but this supply is constrained by natural limits and management, and varies annually (i.e., due to *El Niños*). FMFO is also produced from larger pelagic species when profitable, however, these species are more readily used for human food, which poses a food security challenge in places like coastal West Africa [2,11,12]. The decline in FMFO production from small pelagic fisheries is even stronger than what is suggested by the aggregate numbers, as there is a growing FMFO industry using by-products from wild caught and aquaculture species [13] (Fig. 1). Hence, the strong demand for FMFO, primarily driven by growth in the aquaculture sector [2], provides incentives to use alternative sources of raw materials that do not compete with the human food supply [14,15].

By-products are useful raw materials for FMFO, as the filet yield for most species varies between 40 % and 60 % [16,17]. Despite their significant potential, by-products are often not fully utilized [18]. One study by Cao and colleagues estimated that half of China's demand for fishmeal in aquaculture feeds could be met by using domestic by-products from fish processing [19]. Moreover, with increased global aquaculture production [20,21], demand grows for by-products as a raw material. Still, there is little systematic data collection on this topic and limited knowledge about barriers to its use in FMFO production.

To shed light on potential opportunities and barriers, this article presents information about the usage of by-products and production losses in seven industrial fisheries and aquaculture sectors that are important in supplying the US, the world's largest seafood importer [22]. The seven sectors are located in three major aquatic food producing nations (Norway, United States, and Vietnam). We use qualitative interviews to understand the factors related to the generation of by-products and production losses, and explore policies that can promote greater use of by-products and production losses.

2. Methods and data

This study estimated utilization and byproduct use in the production and processing stages of the US aquatic food supply chain from 2014–2018, and was nested within a larger project to estimate the total energy and water use and food waste in the US seafood supply [23–26]. This study selected shrimp, salmon, Alaska pollock, catfish and pangasius for in-depth analysis, which are five of the top-10 species groups consumed in the US and accounted for 55 % of the US supply. Within each species group, representative production methods were identified based on the predominant methods (aquaculture, wild capture, or both) that supply the US market. Top production regions were identified for study based on an analysis of US import data, and a rapid feasibility assessment based on expert consultation and recruitment success. The seven sectors included in the study are reported in Fig. 2 and Table 1.

Businesses in each sector were recruited through trusted intermediaries and industry contacts, with an emphasis on the firm's being typical, although with the small sample, we recognize that these may not be representative. Quantitative surveys were completed in person from production centers or corporate headquarters in 2019. The surveys collected data on production, losses and byproduct generation among capture fisheries and aquaculture producers and processors. The utilization rate was defined as the amount of products for human consumption divided by the total production. The rendering rate was defined as the amount of production losses and byproducts rendered divided by the total production. These rates were empirically calculated based on data collected during the study. Semi-structured qualitative interviews were performed either in person or by phone from 2019 to 2021 using previously reported methods to complement the quantitative data collection [23,24,27]. Sample sizes are reported in Table 1. Secondary processing was not considered in this study if it was done at a separate processing facility, such as in another country. The project was approved by the Institutional Review Boards at Johns Hopkins School of Public Health (IRB# 8345) and University of Florida (IRB# 201901559).

National production statistics for species and sectors in the study were collected from government websites for each sector and reported in Table 1. These secondary datasets were used to scale-up utilization and rendering rates collected through surveys. The rendering rates used were averages for each industry, and given our small samples, it is a good sign that that the rates reported by our subjects were very similar. For aquaculture species, we estimated the biomass lost when

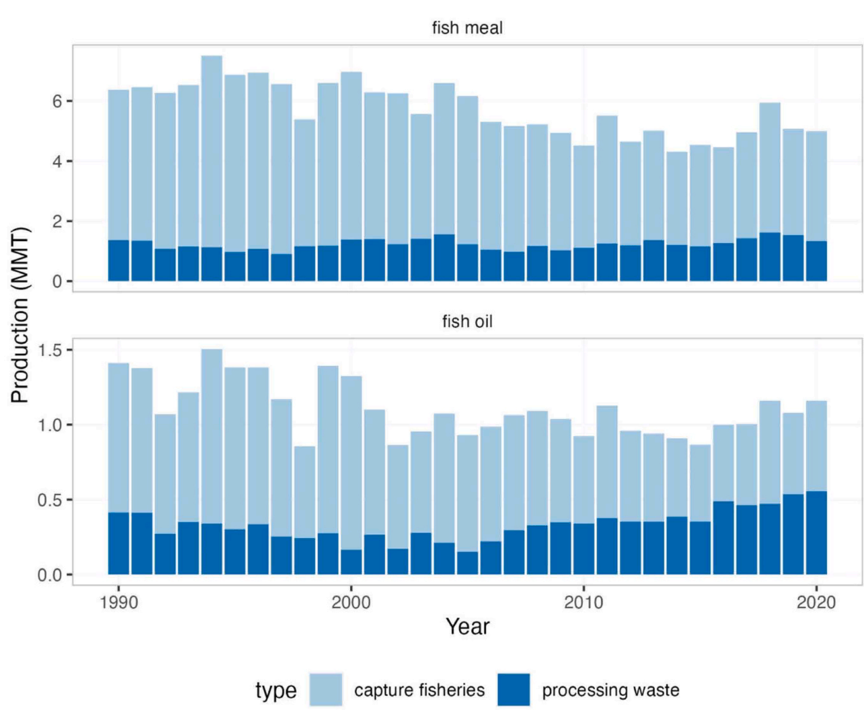

Fig. 1. Global fish meal and fish oil production from 1990 to 2020 (million metric tonnes). Source: [2].

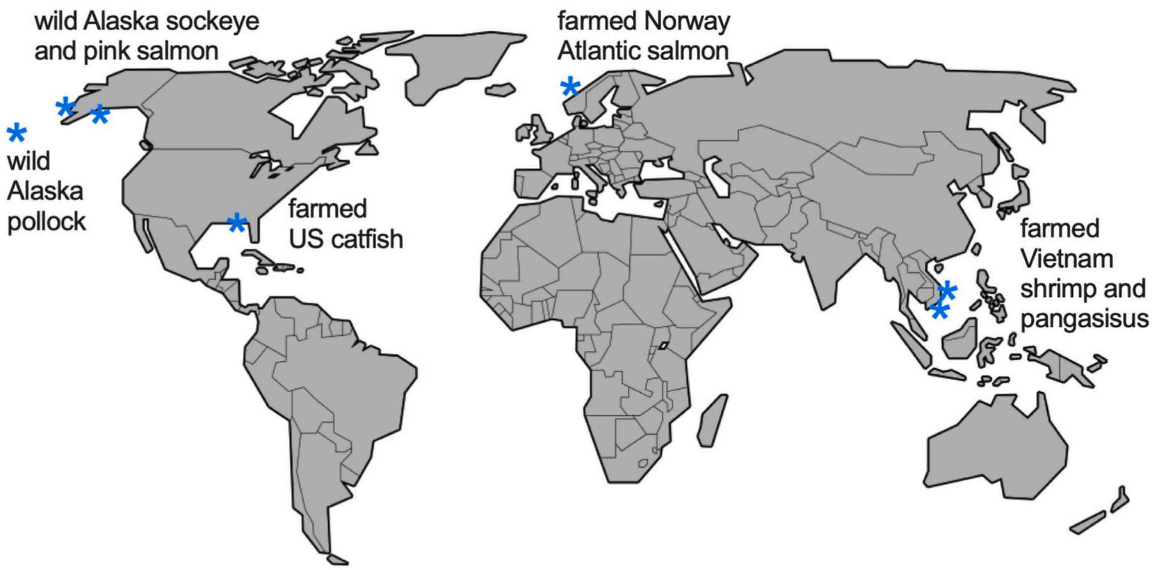

Fig. 2. Map of study sites.

Table 1
Sample size by sector (n = businesses surveyed or interviewed).

Species group	Location	Quantitative surveys		Qualitative interviews		Secondary data
		Production	Processing	Production	Processing	
Aquaculture						
Atlantic salmon	West coast, Norway	3	3	3	3	[30]
Catfish	Mississippi and Alabama, US	9	3	2	2	[31]
Shrimp	Mekong Delta, Vietnam	5	5	3	3	[32]
Pangasius	Mekong Delta, Vietnam	7	3	5	3	[33]
Capture Fisheries						
Alaska pollock[a]	Bearing Sounds, Aleutian Islands, Gulf of Alaska, US	n/a	n/a	n/a	n/a	[34]
Pink salmon[b]	Bristol Bay, Alaska, US	-	4	3	1	[35]
Sockeye salmon[b]	Prince Williams Sound, Alaska, US	-	5	3	3	[36,37]
Total		24	23	19	12	

[a] For wild Alaska pollock, surveys and interviews were not performed. Instead we used government reports and information from industry contacts about harvests.
[b] For wild Alaska sockeye and pink salmon, processors surveys including information about the production phase.

harvestable-size animals died before harvest as described previously [28]. Flow diagrams (i.e., Sankey plots) were produced using an online tool (SankeyMATIC) [29]. Quantitative and qualitative data were used to present overview findings, describe the situation in each sector, and highlight sector-specific factors shaping decisions about by-product recovery for FMFO.

3. Results

3.1. Overall results

The seven industrial fisheries and aquaculture sectors in this study combined for 4,961,000 tonnes/yr (round weight) of aquatic food production (Table 2). Of the production, 2,916,000 tonnes/yr or 59 % went to supply chains for human consumption and 2,032,000 tonnes/yr or 41 % was inedible or were once edible but were discarded as food loss.

Table 2
Production, processing, and by-product utilization among the study population, average of 2014–2018.

Country and species group	Production (tonnes)	Processing (edible yield, a)	Production losses and byproducts[b]		
			Total loss and by-products (tonnes)	Rendered (tonnes)	Rendered (%)
Aquaculture					
Norway Atlantic salmon	1,251,097	76 %	412,436	412,436	~99 %
US catfish	124,766	46 %	91,870	71,029	77 %
Vietnam shrimp	692,611	58 %	309,904	171,441	55 %
Vietnam pangasius	1,218,000	77 %	569,078	275,723	48 %
Capture Fisheries					
US Alaska pollock	1,495,063	33 %	1,008,521	802,595	80 %
US Alaska pink salmon	90,865	52 %	43,605	26,991	62 %
US Alaska sockeye salmon	88,951	70 %	26,603	9761	37 %
Total	4,961,353	59 %	2,462,017	1,769,977	72 %

(a) edible yield is the weight of the edible product after processing divided by the total live weight before processing
[b] Production losses include by-catch, discards, mortalities, and weigh-backs if they were not sold as human food.

Production losses and by-products from processing were, on average, 2,462,000 tonnes/yr and 72 % of that amount, or 1,770,000 tonnes/yr, was rendered (Table 2). Rendering rates ranged from 37 % to 99 %, with slightly higher rates in aquaculture (avg: 70 %, range: 84–99 %) than capture fisheries sectors (avg: 59 %, range: 37–80 %). The highest rendering rates were in Norway farmed salmon (99 %) and wild Alaska pollock (80 %) and the lowest rendering rates were in wild Alaska salmon (37 %) and farmed Vietnam pangasius (48 %).

Fig. 3 provides a generalized schematic of seafood production, processing, and by-product utilization among study participants. At the production stage, raw material for FMFO included bycatch, discards, weigh-backs (i.e., undersized and oversized animals), and diseased and dead animals, which were either saved for rendering or discarded, depending upon the sector and business. Rendering occurred both at-sea and in shore-side plants. At the processing stage, the rendering stream included by-products from processing, production culled before processing (ie., weigh-backs, mortalities), and edible products culled based on quality standards. By-products and production losses were mainly rendered into FMFO but also other sellable products. Next, we describe each sector in detail and opportunities and barriers for by-product utilization.

3.2. Norway farmed Atlantic salmon

Norway is the top producer of farmed Atlantic salmon with on average 1,251,000 tonnes/yr (round weight) harvested during the study period [30] (Fig. 4a). Production losses came principally from fish mortalities [38] that created 104,000 tonnes/yr of biomass lost and an additional 12,000 tonnes/yr of fish that were removed from pens for other reasons such as deformities (Fig. 4a). All dead or deformed fish removed from net pens are stored and sent to rendering (including silage) plants, which shows the extent that the Norwegian farmed Atlantic salmon industry seeks out raw materials for rendering.

On average, the edible yield among processors in this study was 76 % of production volume, which was high because it includes headed and gutted (H&G) fish that have higher edible yields than cuts such as filets. Fig. 4a shows the rendering stream includes 296,000 tonnes/yr of by-products from processing waste (72 % of total), 104,000 tonnes/yr of production mortalities (25 %), 12,000 tonnes/yr of fish not processed (i.e., deformed fish) (2.8 %), and nearly 1000 tonnes/yr of floor drops in processing plants (0.2 %) for a total of almost 413,000 tonnes/yr, with nearly all waste rendered into FMFO, pet food, and cosmetics. To our knowledge, the only part of the salmon that is not turned into a product is the blood.

3.3. US farmed catfish

The catfish industry is the largest aquaculture industry in the US [39] with on average 125,000 tonnes/yr produced from freshwater ponds, with almost all sold for domestic consumption (Fig. 4b). Production losses mainly come from mortalities which were 15,000 tonnes/yr on average. Mortalities from catfish ponds were removed individually or left to decompose in the pond and were not recovered for rendering. Another type of production losses are weigh-backs, which are harvested fish that have no or low commercial value and includes oversized or diseased catfish and non-target species (2300 tonnes/yr). The fact that the weigh-backs (which are discovered when the fish are harvested and accordingly come in a significant quantity) are rendered while individuals that die during the production process are removed individually and are not rendered provides a good illustration of the importance of scale in incentivizing the use of unsellable fish.

At processing plants, the edible yield for catfish was 46 % of the production volume, which reflects demand for filets that have lower yields. The edible yield varied based on the product mix at each plant, and historically, edible yields were above 50 % of production volume (avg: 2008–2012) [31] when filets made up a smaller share of the product mix. Therefore, demand for certain product forms, such as filets, can influence the quantity and type of processing waste that is available to render.

The catfish industry creates large amounts of by-products during processing and utilizes nearly 100 % of them. When factoring in production losses (i.e., mortalities) and by-products together, the overall utilization rate was 77 %. In total, over 68,000 tonnes/yr of processing waste by-products and 2300 tonnes/yr of weigh-backs were sent to rendering plants to make FMFO during the study period (Fig. 4b). Processors reported that oversized catfish were too large for mechanical

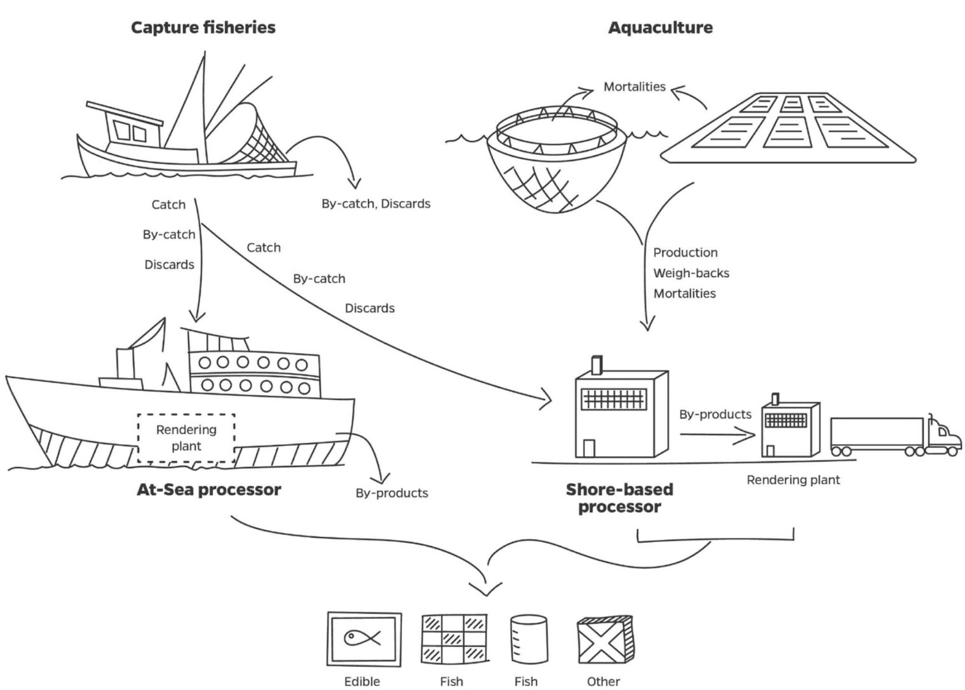

Fig. 3. Schematic of seafood production, processing, and by-product utilization among the study population.

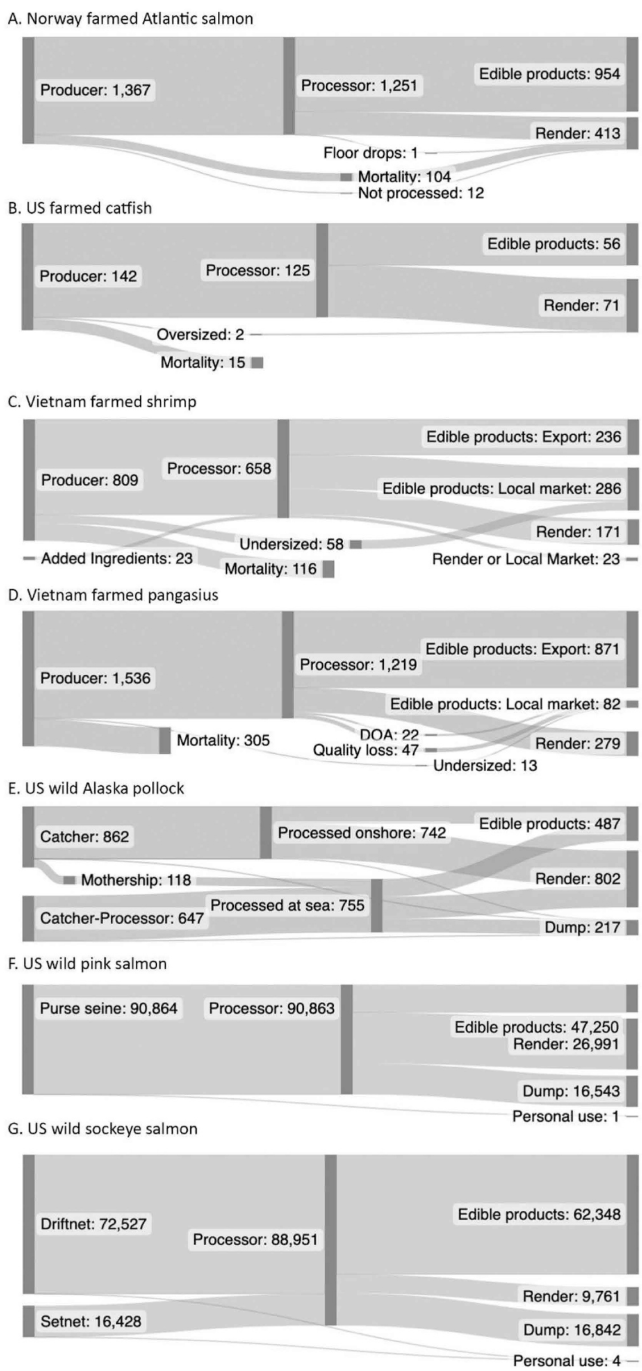

Fig. 4. Flow diagrams of production, processing and rendering among seven industrial fisheries and aquaculture sectors in Norway, United States and Vietnam (1000 tonnes/yr). Average of 2014–2018 for all sectors except Alaska pink salmon which was an average of odd-years (2015–2019). DOA = dead on arrival.

processing equipment and prices of these fish were too low to make it economical to process them all by hand, therefore, oversized fish were sold to rendering plants. Developing a value-added product for oversized fish would be one way to utilize these fish for human food if the right price points are reached, but currently they are sold to rendering plants for 0.13 $/kg after covering the cost of freight.

3.4. *Vietnam farmed shrimp*

Vietnam is one of the top countries for farmed shrimp production and produced on average 693,000 tonnes/yr during the study period (Fig. 4d). The survival rate among surveyed farms was 82 % and the biomass lost due to mortality was 116,000 tonnes/yr, which was not rendered. Weigh-backs (58,000 tonnes/yr) of undersized shrimp, were sold by processors to the local market as human food. At the processing plant, 20,995 tonnes/yr were not processed due to disease, deformed, spoilage, or other reasons. Processor floor drops and products unable to be processed were either rendered or sold to the local market, depending upon their quality. Roughly 88 % of processing waste by-products (171,400 tonnes/yr) was rendered, largely into animal feed. When considering all raw materials available for rendering, including production losses and by-products, the overall utilization rate was 55 %. Shrimp heads and shells are the main source of waste, and there is interest in using this raw material for more valuable food, biological, and cosmetic products.

3.5. *Vietnam farmed pangasius*

Vietnam is a leading exporter of pangasius which are raised in ponds along the Mekong River. An average of 1,218,000 tonnes/yr of pangasius were produced during the study period [33] (Fig. 4c). Producers reported concerns over high fish mortality rates which resulted in losses of 305,000 tonnes/yr of biomass that were not recovered for rendering. Weigh-backs were an additional but smaller source of loss for producers that on average was 13,000 tonnes/yr. Weigh-backs were mostly smaller fish <250–350 g for which processors pay half price and sell into the domestic market as human food.

At processing plants, the edible yield for pangasius was 77 % of production volume. This was higher than expected because a sizable portion of fish is sold as frozen H&G fish to China, which increases the overall apparent recovery rate and decreases the amount of by-products at this stage. Western markets prefer filets which have lower yields, while processors can sell fish skins, stomachs, and swim bladders for local snack makers and restaurants. Pangasius yields therefore vary depending on market and preference for different product forms. Processing yields ranged from 62 % to 90 % over the decade from 2009 to 2018, and the variation may be reflective of China's increasing market share, which in turn affects the quantity available to render.

Utilization of by-products from processing was high (100 %), but production losses (i.e., mortalities) were not captured for rendering, therefore the overall utilization rate was 48 % or 276,000 tonnes/yr. Lower quality products, floor drops, and fish dead on arrival to the processing plant were sold to local markets instead of rendering (Fig. 4c), which highlights an opportunity to keep products in the human food supply but also raises potential food safety concerns. At one processing plant, fish oil was being refined and sold as human-grade cooking oil, which requires more up-front investments in technology but also creates a higher value co-product.

3.6. *US wild Alaska pollock*

The US Alaska pollock fishery caught on average 1,495,000 tonnes/yr with roughly 49 % processed at shore-side plants and 51 % processed at-sea. The fishery had a very low rate of discards (0.79 % of total caught) and bycatch (0.04 %) [34] (Fig. 4e). Bycatch in the Alaska pollock fishery has been limited by gear modifications, closures at some times of the year, and changes to regulations. About half of all bycatch salmon and halibut was processed as human food through a bycatch donation program [40].

The main edible product forms were frozen filets, surimi, and roe. Overall recovery rates were 38 % and 40 %, respectively, for at-sea and shore-side processors, which is the ratio of all sellable products to the round weight of pollock catch. The edible yields were 33 % and 32 %, respectively, for at-sea and shore-side processors. These data suggest that shore-side processors were slightly more efficient than at-sea processors. Overall, 80 % (802,000 tonnes/yr) of by-products, including a small amount of discards and bycatch, was turned into FMFO and the remaining 12 % (217,000 tonnes/yr) was ground and dumped at sea. Un-utilized byproducts were explained by one of three reasons: scraps that fall off the conveyor belt were not rendered, some plants exclude bones from fish meal, and most importantly some at-sea processors (3 of 13 catcher-processor vessels) do not have rendering plants onboard.

3.7. US wild pink salmon

Pink salmon makes up 45 % of all salmon caught in Alaska by volume and 19 % by value, making them both abundant and inexpensive. The Prince William Sound fishery represents over half of the total catch of Alaska pink salmon [35] and was the focus of this study. Pink salmon are caught in greater numbers in odd years and our analysis focused on odd years from 2015 to 2019. During that period, Prince William Sound pink salmon production was on average 90,800 tonnes/yr (Fig. 4f). The edible yield of pink salmon was 52 % of production volumes. The edible product forms were frozen H&G (66 % of total production volume), canned salmon (27 %), roe (6 %), and filets (1 %), with a trend away from canned salmon and towards greater production of frozen H&G which was shipped to Asia for secondary processing. An average of 43, 600 tonnes/yr of by-products were generated during the study period with 62 % rendered and 38 % ground and dumped into Prince William Sound (Fig. 4f). This rate was lower than expected because some shore-based and floating processors were not fully utilizing all by-products.

3.8. US wild sockeye salmon

The Bristol Bay, Alaska sockeye salmon fishery is the largest sockeye fishery in the world. An average of 88,900 tonnes/yr of sockeye salmon was harvested from Bristol Bay during the study period, with 82 % coming from a fleet of driftnet vessels and the remainder (18 %) coming from shore-based setnet fishers [36] (Fig. 4g). Experts report that salmon discards and bycatch were rare. Most fish (86 %) are chilled immediately after harvesting, which improves quality [37]. Additional quality improvements included bleeding fish after harvest, shorter sets, salmon slides and deck mats to prevent bruising while harvesting fish, lower brailer weights, and vessel cleanliness/proper sanitation [37]. Many processors support quality improvement by giving bonuses to vessels that adopt these practices. As quality has improved, processors have shifted to fresh and frozen product forms, which are more valuable, and less canned sockeye salmon.

The main product forms are frozen H&G and filets (76 % of total), canned (17 %), fresh H&G and filets (6 %), and other forms including roe (2 %). At processing plants the edible yield for sockeye salmon was 70 % of production volumes. This high rate is explained by having a large share processed as frozen H&G. Of the 26,600 tonnes/yr of by-products, 37 % was rendered and 63 % was ground and dumped into Bristol Bay (Fig. 4g).

The economics of rendering salmon byproducts in Alaska are challenging because of the short fishing seasons, remote location, and high cost of building rendering plants given the limited quantity of product. Shore-side plants that operate under older permits are allowed to grind and dump all of their processing waste. One new shore-side processor was not permitted to dump waste and instead shipped frozen waste outside the region in place of building a rendering plant. Another shore-side processing plant was required to build a rendering plant as part of an environmental lawsuit, and now handles 100 % of its processing waste and accepts additional processing waste from other facilities. In addition to shore-side plants, some companies bring at-sea processors with onboard rendering plants into Bristol Bay. At-sea processors render most or all of the by-products they generate, depending upon the vessel.

4. Discussion and conclusions

Demand for FMFO continues to be strong, yet the amount of raw material from whole wild fish is constrained. Therefore, additional FMFO supply will have to come from by-products from processing and losses from capture fisheries and aquaculture. In 2020, 27 % and 47 % of global fishmeal and fish oil came from by-products and the remainder from whole wild fish [2]. The share from by-products is likely to continue to grow. However, as global FMFO production has been declining for almost three decades, increased production from alternative sources is still not making up for a transition to more wild fish for human consumption or what is lost due to poorly managed fish stocks.

In this study, we characterize the use of by-products and production losses from seven sectors that are important in supplying the US seafood market. Not unexpectedly, there is significant variation in the utilization of production losses and by-products, ranging from 37 % to 100 %. Overall, the utilization rate of these industries appears high (72 %) within the context of global FMFO production levels [2]. We found that aquaculture utilized a larger share of by-products and production losses compared to capture fisheries. Rendering seems to be more economically feasible for industrial aquaculture sectors because they generate a large and relatively stable year-round supply of raw material for rendering plants. Industrial aquaculture has a large scale for each unit which makes investments in handling by-products more likely to be profitable. The Norwegian farmed Atlantic salmon industry has developed mechanisms for capturing and rendering production losses, but other aquaculture sectors in the study leave most fish mortalities during production un-utilized.

Wild caught fisheries in this study had lower rendering rates than aquaculture for several reasons, including short fishing seasons, smaller scale, operating in remote locations, the cost of building and operating rendering plants that are not used year-round, and also regulations allowing dumping of processing waste [41,42]. As such, the shorter fishing season in many fisheries are not only causing a market mismatch [43], but are also leading to sustainability issues. In Alaska, there is significant regulatory push to utilize by-products in newer plants showing that this is feasible. Most likely it is not profitable for all companies, but the fact that they remain in business suggests that the cost is not prohibitive either. It is also notable that the by-product usage rate is significantly higher in the Alaska pollock fishery where the fishery, as well as the vessels, are larger and the fishing seasons are longer than in the salmon fisheries.

Our study was focused on industrial-scale sectors and may not be representative of the many small-scale fisheries and aquaculture sectors where capacity is a challenge, as discussed for example in Bangladesh [44,45]. However, our results offer perspectives that may help inform policies to increase by-product utilization. First, the importance of scale. Production of FMFO requires plants that constitute a significant investment and are more likely to be profitable with a steady and large supply of by-products. In both Alaska and Norway there are examples of collection systems for seafood by-products and production losses enabling scale to be reached, but where the threat of (or actual) government action may be necessary for the companies to engage in such a network. In sectors that are less industrialized, such systems are likely to be even more important, and in fisheries that have more seasonal production than aquaculture, it will be harder to succeed. It is also interesting that our cases provide several examples of firms that voluntarily invested in the capacity to render waste because they found it profitable. Additionally, a lack of coordination is a challenge that leads to under-utilization of by-products and production losses.

With a filet yield of between 40 % and 60 % for most seafood species, there is tremendous potential for increasing the global production of FMFO by rendering by-products, if no other uses can be found. Given the high demand for FMFO and constrained supply from capture fisheries, there should be a greater emphasis placed on reducing barriers to fully utilize production losses and by-products.

CRediT authorship contribution statement

Gabriela L. Sarmiento: Writing – review & editing. **Elizabeth M. Nussbaumer:** Investigation, Supervision, Writing – review & editing. **Taryn M. Garlock:** Writing – review & editing. **David C. Love:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Roni Neff:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing. **Sigbjørn Tveteraas:** Writing – review & editing. **Ly Nguyen:** Investigation, Methodology, Writing – review & editing. **Mark Brown:** Investigation, Methodology, Writing – review & editing. **Jillian Fry:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Frank Asche:** Conceptualization, Investigation, Methodology, Writing – original draft.

Data Availability

Data will be made available on request.

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