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The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilisation

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Abstract

Since 2000, the use of wild fish inputs in the production of farm raised fish outputs, also known as the Fish In:Fish Out (FI:FO) ratio, has been a primary concern of the sustainability dialogue surrounding aquaculture production. Far less attention has been placed on the sustainability of downstream processing, including how byproducts are managed. This paper contributes new information on the current utilisation of aquaculture byproducts in a case study on the Scottish Atlantic salmon industry. The findings show that there is considerable potential to increase the sustainability of the industry through maximising human edible yield by strategically managing by-products. Supporting the movement towards the full utilisation of by-products, this paper goes a step further by emphasising the need to maximise their use in human consumption and select animal feeds, highlighting the economic, food security, and environmental benefits of doing so. Through exploratory scenarios based on the case study, the paper identifies that Scotland could increase food production from fish farming by over 60%, increase by-product revenue by 803%, and increase the industry bottom-line by over 5%, all without having to put any new cages in the water, or use any more marine resources. As the aquaculture industry moves into a new era of production and processing, where a diverse range of products can be produced from a single species, sustainability will be sought throughout the value chain. It is hoped that the ideas raised within this paper will encourage further discussion and collaboration on this topic going forward.

Keywords: Aquaculture; By-products; Marine resources; Fish In: Fish Out ratio; Scottish Atlantic Salmon; Food production

1. Introduction

With an estimated one-third of all food produced for human consumption being lost or wasted (Gustavsson *et al.* 2011), calls to limit waste and recover edible food are growing. The United Nations (UN) Sustainable Development Goals (SDGs) call for a reduction in food loss during production, and throughout the supply chain, through to consumption (UNDP 2017). The US Environmental Protection Agency's *Food Recovery Hierarchy* (Fig. 1*)* prioritises more sustainable food management practices through preventing and diverting wasted food grade products (US EPA 2017). Similarly, Article 4 of the revised EU Waste Framework Directive (2008) outlines a 'waste hierarchy' highlighting the financial and environmental benefits of reducing, reusing and recycling materials versus sending them to landfill (UK DEFRA 2014).

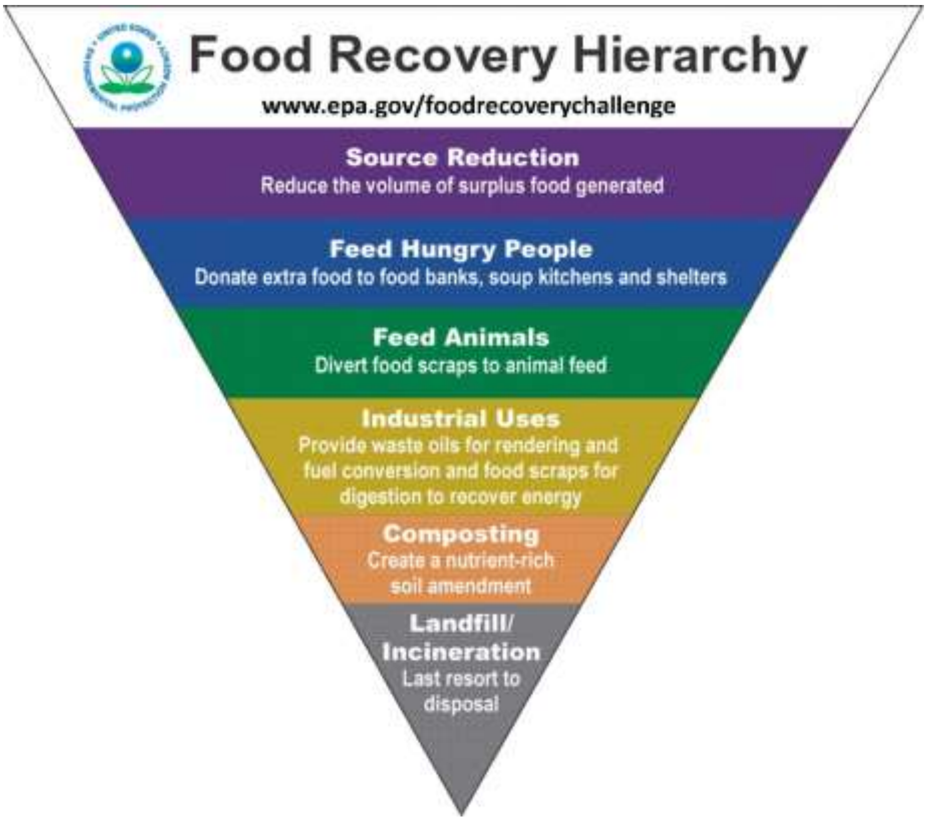

Fig 1. Food recovery hierarchy (US EPA 2017).

Aquaculture is a necessary industry to ensure future global access to seafood. There is increasing realisation that the success of aquaculture production goes hand in hand with adopting more sustainable practices. Sustainability, as used in this paper, refers to a process-driven journey of continual improvements that seeks to create more resource efficient products that maintain functional ecosystems (Tlusty & Thorsen 2017). Efforts are being made to increase the efficiency of aquaculture as a food production system by maximising the edible yield of products through genetic improvement, and better processing technology (Campos-Montes 2017, Vandeputte 2017, Tsai *et al*. 2015, Ytrestøyl *et al*. 2015, Mathiassen 2011, Rutten *et al*. 2005). However, there is a limit to these improvements, and in both seafood production and processing, use of aquaculture by-products is now increasingly considered to be important for improving economic and environmental efficiency, as well as food security (Ytrestøyl *et al*. 2015, Newton *et al.* 2014, FAO 2014, Ramírez 2007). Furthermore, in aquaculture, as in other food production sectors, slim processing margins mean that innovation in the utilisation of by-products becomes a key factor for remaining competitive and maintaining long-term profitability.

For this paper, by-products will be defined as all the raw material, edible or inedible, left over following the preparation of the main product (Gildberg 2002). For finfish, by-products typically include trimmings, skins, heads, frames (bones with attached flesh), viscera (guts) and blood (Fig. 2).

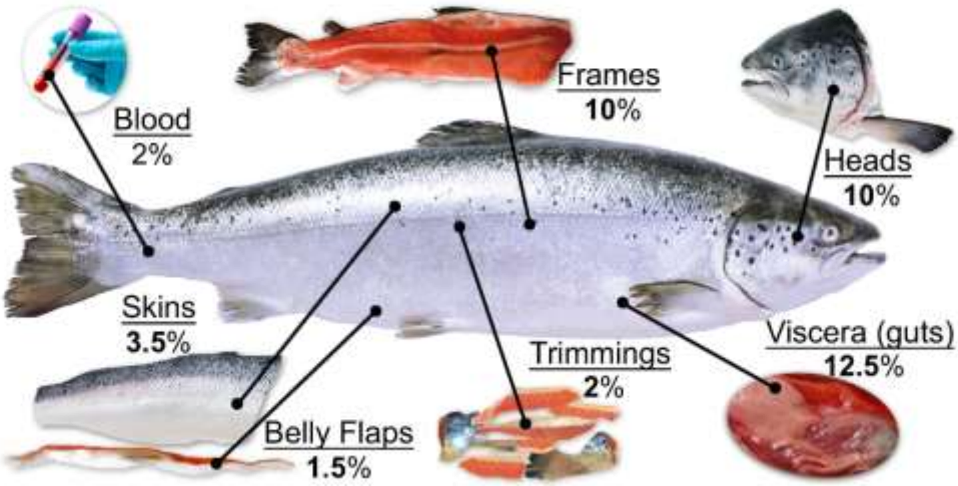

Fig 2. Atlantic Salmon By-product Fractions as a Percentage of the Total Wet Weight. Compiled from FAO (2014), Rustad (2007), Liaset et al. (2003), Sandnes et al. (2003).

While human consumption options for some by-product types, such as viscera, bones and blood remain limited, there are many avenues for value addition. Indeed, far from being 'waste', marine by-products have been found to contain valuable minerals, vitamins, protein and lipid fractions (Table 1), which can be applied in a range of products and markets (FAO 2014, Ramírez 2013, Archer 2005, Rustad 2003).

Table 1. By-Product Uses.

By-Product	Valuable Components	Current Uses
Heads	proteins, peptides, lipids, collagen, gelatine, minerals including calcium, flavour	food, fish meal, fish oil, food grade hydrolysates, animal grade hydrolysates, pet food, nutraceuticals, cosmetics
Frames (bones, flesh, fins)	proteins, peptides, lipids, collagen, gelatine, minerals including calcium, flavour	food, fish meal, fish oil, food grade hydrolysates, animal grade hydrolysates, pet food, nutraceuticals, cosmetics
Trimmings	proteins, peptides, lipids	food, fish meal, fish oil, food grade hydrolysates, animal grade hydrolysates, pet food
Viscera	proteins, peptides, lipids, enzymes such as lipases	food grade hydrolysates, animal grade hydrolysates, fish meal, fish oil, fuel, fertilisers
Skin (with belly flap)	collagen, gelatine, lipids, proteins, peptides, minerals, flavour	fish meal, fish oil, cosmetics, food, fish meal, nutraceuticals, cosmetics, leather, fuel, fertilisers
Blood	proteins, peptides, lipids, thrombin & fibrin	fuel, fertiliser, therapeutants
Mortalities	proteins, peptides, lipids, collagen, gelatine, calcium and other minerals, flavour	animal feed (fur animals), zoo animal feed, fuel, fertilisers

Ramírez (2013), Rustad (2003), Suresh and Prabhu (2012), Kurtovic and Marshall (2013), Rothwell *et al*. (2005), Sharp *et al.* (2012).

Within terrestrial livestock industries the value-addition of the ‘fifth quarter’ (processing by-products) has been integral to both traditional artisanal and industrial practice, with both financial and environmental benefits (Irshad & Sharma 2015, Walsh 2014, Mirabella *et al.* 2014). The processing expertise, technology and infrastructure developed by the poultry industry, provides useful insights for the aquaculture industry as it continues to refine its resource use throughout the supply chain (Asche *et al.* 2016).

Compared with its terrestrial counterparts, the seafood sector has been slow to reduce its discards. To facilitate improvement, there is a need for further infrastructure investment and policy support to incentivise resource efficiency, along with greater transparency on the current uses of by-products within the sector (FAO 2016). Nonetheless, there has been some promising movement toward a value-added approach with certain species and regions. In Iceland, Iceland Ocean Cluster has worked to create new products from fish processing waste, resulting in twice the value for 40% of the catch (Sigfusson 2014). Norway was one of the earliest countries to recognise seafood by-products as a resource, with laws encouraging their use as early as 1639, resulting in products such as fertilisers, animal feeds, and fish oil (Bekkevold and Olafsen 2007). Today, Norway has developed streamlined modern processing facilities to manage over 650,000 tonnes of seafood by-products each year (Olafsen *et al.* 2014), and the Norwegian Atlantic salmon industry utilises around 90% of its by-products (Ytrestøyl *et al*. 2015, Olafsen *et al.* 2014). In Vietnam, Pangasius by-products are well separated and directed to specific industries for value addition, and globally, growing interest is being placed on adopting strategies for other finfish and shellfish species (Newton *et al.* 2014).

Here, the strategic utilisation of aquaculture by-products is explored further, based on current practice in the Scottish salmon industry (SSI), assessing how it can achieve greater sustainability. The paper begins with a brief exploration of the history and development of the Fish In: Fish Out (FI:FO) concept, a common focal point in the dialogue on sustainable seafood and marine resource use. The paper reflects on the FI:FO concepts effectiveness as a driver in the current context, and proposes that the strategic management of aquaculture by-products should be an integral part of the sustainability dialogue going forward. The paper then develops a model of current and potential uses of processing by-products, based on case study data from the SSI, in which scenarios for additional economic value and food production can be achieved through strategic by-product management. Through the findings and recommendations presented, this paper aims to provide insights relevant to policy makers and industry stakeholders, and to encourage continuous improvement towards more responsible and sustainable practice.

2. Background and context

In recent years, aquaculture has been presented as both a solution to (Tidwell & Allan 2001), and a causative factor of (Naylor *et al.* 2000), the world's dwindling marine resources. While aquaculture can relieve pressure on wild fisheries through producing alternative fish for human consumption, the production of those fish often requires inputs from wild fish stocks in the form of feed ingredients. The paradox stems from the diversity of farmed species and husbandry systems. Species such as algae, shellfish, and herbivorous fish, typically require few inputs (Waite *et al.* 2014), whereas intensively raised higher trophic species, such as salmon, require complete feeds that have conventionally contained a high proportion of marine ingredients (Tacon 1997).

The Fish In: Fish Out (FI:FO) concept began as a way of highlighting the use of marine ingredients in aquaculture feeds (aquafeeds), aiming to increase awareness of their use through a simple metric and identify species and systems where their use was inefficient (Naylor *et al.* 2000). In 2000, findings showed that more than 3 times as much fish biomass was used in feed than was produced as salmon (Naylor *et al.* 2000), leading to calls for a reduction of wild fish inputs in aquafeeds, and for the aquaculture industry to implement more 'ecologically sound management practices'.

Different versions of the FI:FO concept have since emerged as a key metric for standards and assessment schemes aiming to stimulate better management and address environmental concerns and reassure consumers. The 'Jackson (2009) method' for calculating a FI:FO ratio, most closely resembles the requirements used by Global Aquaculture Alliance's Best Aquaculture Practices (BAP). Whereas the calculation used by Seafood Watch, known as the Feed Fish Efficiency Ratio (FFER), and the calculation used by Aquaculture Stewardship Council, known as Forage Fish Dependency Ratio (FFDR), are most aligned with that proposed by Tacon and Metian (2008). Based on Jackson (2009) and data from Shepherd *et al.* (2017), the current mean FI:FO ratio for salmon is approximately 1.31.

All versions of the FI:FO ratio calculations currently used by certifiers end at the farm 'gate' or production stage, and are unable to consider how fish are processed and subsequent by-products are utilised past this point (Ytrestøyl *et al*. 2015). As Figure 3 illustrates, the FI:FO concept leaves much of the value chain unconsidered.

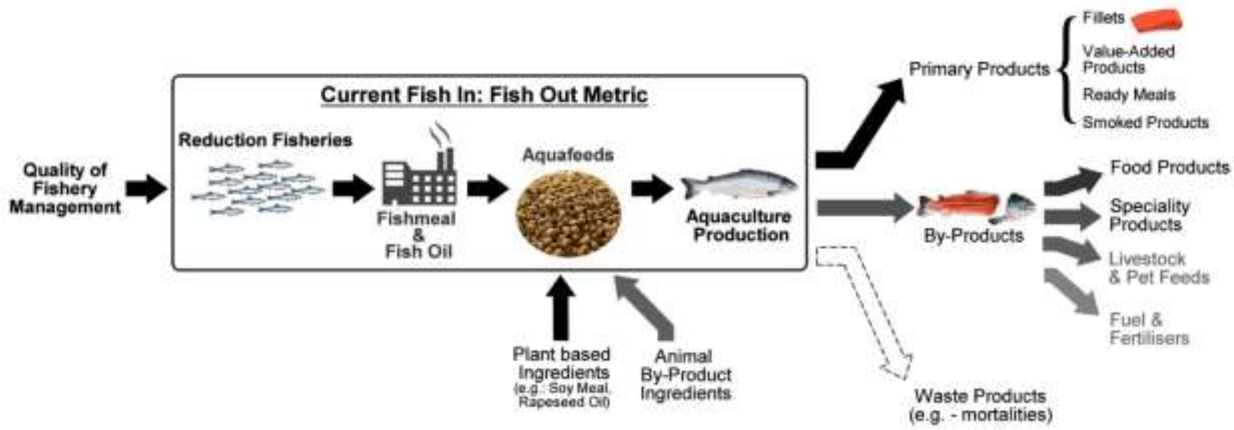

Fig 3. Thinking 'Outside the Box.'

Furthermore, while the FI:FO ratio provides a tool to predict trends and highlight areas for improvement within the industry, it has not demonstrated that increasing demand for aquafeeds has placed added pressure on wild fish stocks at any aggregate level. The growth in aquaculture production has had little correlation to fishmeal and fish oil production (Asche & Bjørndal 2011); although aquaculture output has doubled since 2000, the global production of fishmeal has fluctuated between 5 and 7 million tonnes per year over the same period (FAO 2014). Tacon and Metian (2008) found that FI:FO ratios progressively declined over the period 1995-2006 for the major species globally, with decreases being most dramatic for carnivorous fish species such as salmon. Data from Norway (Fig. 4) indicates there has been a decreasing trend in the inclusion of fishmeal and fish oil in the diets of farm raised Atlantic salmon, while the commodity price has been steadily increasing (Fig. 4). These trends reflect a lower inclusion of fishmeal and fish oil in aquafeeds and an improved feed conversion ratio (a critical factor determining FI:FO) as salmon has become commoditised (Tlusty 2012). As aquaculture grows, fishmeal and fish oil will likely become specialty ingredients, used selectively in key stages of production (FAO 2016).

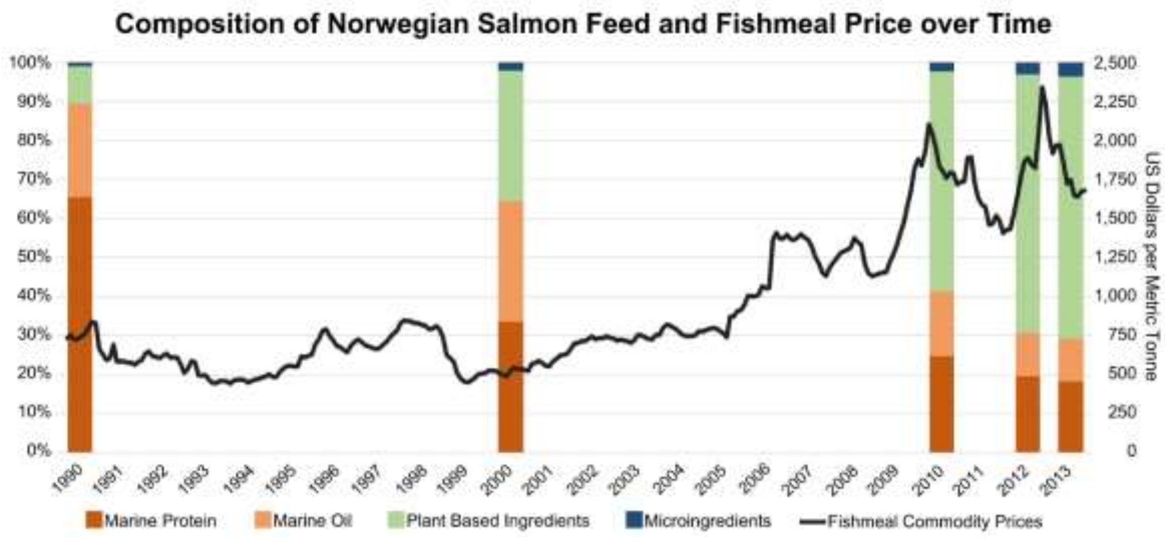

Fig 4. Composition of Norwegian Salmon Feed and Fishmeal Price over Time. Compiled from Ytrestøyl et al. (2015), and IndexMundi (2017).

In addition, a growing quantity of fishmeal and fish oil are now being derived from by-products sourced from both wild caught and farm raised fish (FAO 2016, Shepherd & Bachis 2014). Ytrestøyl *et al.* (2015) identify that 25% of fishmeal worldwide originates from fish by-products, with an even greater opportunity to gather raw materials for fishmeal and fish oil from the estimated 60 million tonnes of by-products produced around the globe from fisheries and aquaculture.

Increasingly, the focus among certifiers has moved towards scrutiny of the fisheries from which marine ingredients are sourced and on promoting improved fisheries management programs (Ytrestøyl *et al.* 2015, Merino *et al.* 2012, Asche & Bjørndal 2011), along with overall management of fed aquaculture operations (Merino *et al.* 2012, Tacon & Metian 2008). In a report for the United Nations Food and Agriculture Organisation (FAO), entitled *Salmon by-product proteins*, author Ramírez (2007, iii) states that:

> *"A responsible and sustainable use of fish resources, whether from capture fisheries or from aquaculture, foresees an efficient utilization of the whole fish including the use of the various by-products generated throughout the processing stage".*

This paper proposes that following the value chain to the processor, a step further than the current FI:FO concept allows (Fig. 3), and considering how the primary products and by-products are being utilised is critical to a more robust evaluation of resource use. Far from minimising the importance of aquafeed inputs, which remain a key factor in the sustainability of production, an examination of the other end of the value chain following the 'Fish Out' stage, sheds light on the sustainability of the industry as a whole. The case study presented in the following section examines aquaculture by-products from Scottish salmon production in 2015, providing new data on an often-overlooked aspect of the industry. Such insights will inform stakeholders and policy makers how aquaculture itself can better contribute to responsible marine resource use.

3. Case study: Scottish salmon aquaculture by-products

Production of farmed Atlantic salmon (*Salmo salar*, Linnaeus, 1758) in Scotland has attained important status, being the UKs largest food export (SSPO 2015). It 'holds a distinctive position in world markets' (Shepherd *et al.* 2017), despite its considerably smaller scale than global leaders, Norway and Chile. High animal welfare standards (RSPCA 2015) along with comparably higher levels of Omega-3 fatty acids in the marketed fish are points of differentiation (Shepherd *et al.* 2017). The main salmon products produced are head-on gutted (HOG), fresh and frozen fillets, and various value-added products (VAP).

3.1 Study methodology

The aim of this Scottish Case Study was to identify the types of by-products created, and the methods by which they are currently utilised. Prior to this research, there was little industry-wide data about the status of salmonid aquaculture by-product (BP) streams in Scotland. Both quantitative and qualitative data was collected between February and July 2016 using a mixed methods approach (Creswell 2014, DiCicco-Bloom & Crabtree 2006), and included a literature review, key informant interviews, processor surveys and interviews, along with basic nutritional analysis of BP samples.

3.2 Key findings from the 2015 Scottish salmon case study

The literature review highlighted that in Scotland, as in many other countries around the world, better utilisation of marine resources is being widely called for, both in terms of public preference, academic findings and regulatory policy (FAO 2016, Zero Waste Scotland 2015, Newton *et al.* 2014, Olsen 2014, Ramírez 2013, Archer *et al*. 2001). The National Marine Plan outlines the Scottish Government's commitment to sustainable development and its objectives for an Aquaculture industry that is, 'sustainable, diverse, competitive, economically viable and which contributes to food security whilst minimising environmental impact' (Scottish Government 2015). There is documented support, from a range of local stakeholders, outlining on-going commitment to a sustainable Scottish seafood sector and a reduction in seafood waste, including the *Code of Good Practice for Scottish Finfish Aquaculture*, which sets out industry standards and guidelines for responsible production (CoGP 2015). The reviewed literature also acknowledged Salmon BPs as sources of valuable raw materials (Ramírez 2013, Archer 2005, Rustad 2003). In its 2016 report, *State of the World Fisheries and Aquaculture*, the FAO identified that BPs may contain higher fatty-acid nutritional content than the fillet.

The nutritional analysis carried out as part of this study confirmed the presence of valuable protein and lipid components in the BP samples. In particular, the BP types sampled in the nutritional analysis (Table 2) showed combined EPA and DHA levels above 1.4g per 100g sample for each type of BP, which is higher than EPA and DHA levels recently reported in the main product, the fillet, at 1.36g in Sprague, Dick and Tocher (2016).

Table 2. Nutritional analysis of Atlantic salmon by-products 2016.

	Flesh % of total fraction	*SD n=3*	Crude Protein % of total fraction	SD *n=6*	Lipid % of total fraction	SD *n=4*	Fatty Acid % of total fraction	SD *n=4*	EPA g. 100g^{-1}	SD *n=4*	DHA g. 100g^{-1}	SD *n=4*
Atlantic Salmon												
Heads	25.13	±2.4	12.00	±0.53	21.96	±0.57	18.30	±1.59	0.86	±0.18	1.29	±0.36
Frames	32.37	±1.7	16.18	±1.27	15.61	±0.35	12.88	±1.56	0.56	±0.04	0.89	±0.05
Belly Flaps	26.61	±1.4	12.88	±0.73	19.93	±0.16	16.96	±0.36	0.80	±0.02	1.24	±0.01
Trimmings	40.99	±3.2	15.83	±0.77	18.89	±0.31	15.72	±1.78	0.67	±0.10	1.06	±0.12
Viscera	N/A		10.05	±2.95	26.27	±0.82	22.11	±0.46	0.88	±0.03	1.37	±0.28

3.3 Breakdown and discussion of case study findings

In 2015, 171,722 tonnes of whole Atlantic salmon were produced in Scotland (Munro & Wallace 2016). Farmed salmon are typically harvested and transported by well-boat to a slaughter station, where they are slaughtered and bled before being moved to a primary processor for evisceration. The resulting head-on-gutted (HOG) salmon are either processed on-site or transported to other processors, domestically or abroad, for secondary processing. The main BPs from secondary processing are trimmings, heads, frames, skins, and belly flaps (Fig. 2). The total volume of reported BPs in the Scottish Case Study was 76,052 tonnes. The largest BP category type reported by processors was in the form of 'mixed by-products', where various types of BPs were combined, rather than separated or sorted. All 34,400 tonnes of these mixed BPs were sent for rendering into fishmeal and fish oil.

Figure 5 shows that in 2015, there were three broad categories of salmon by-product utilisation in Scotland: *Food for Human Consumption*[1] represented 15% of total use, *Animal Feed* represented the major category of use with 75%, and *Fuel and Fertiliser Production* represented the remaining 10% of total use. The *Animal Feed* category could be further assessed as BPs used for producing more food (71% - livestock feeds and aquafeeds), and those that do not (29% - pet foods). Significantly, all reported BPs were used in some form; no processing BPs ended up in landfill.

[1] In this article, for illustration purposes, all fish by-products directed to human consumption are assumed to be edible, however, that is not always the case (e.g. bones in the fish head).

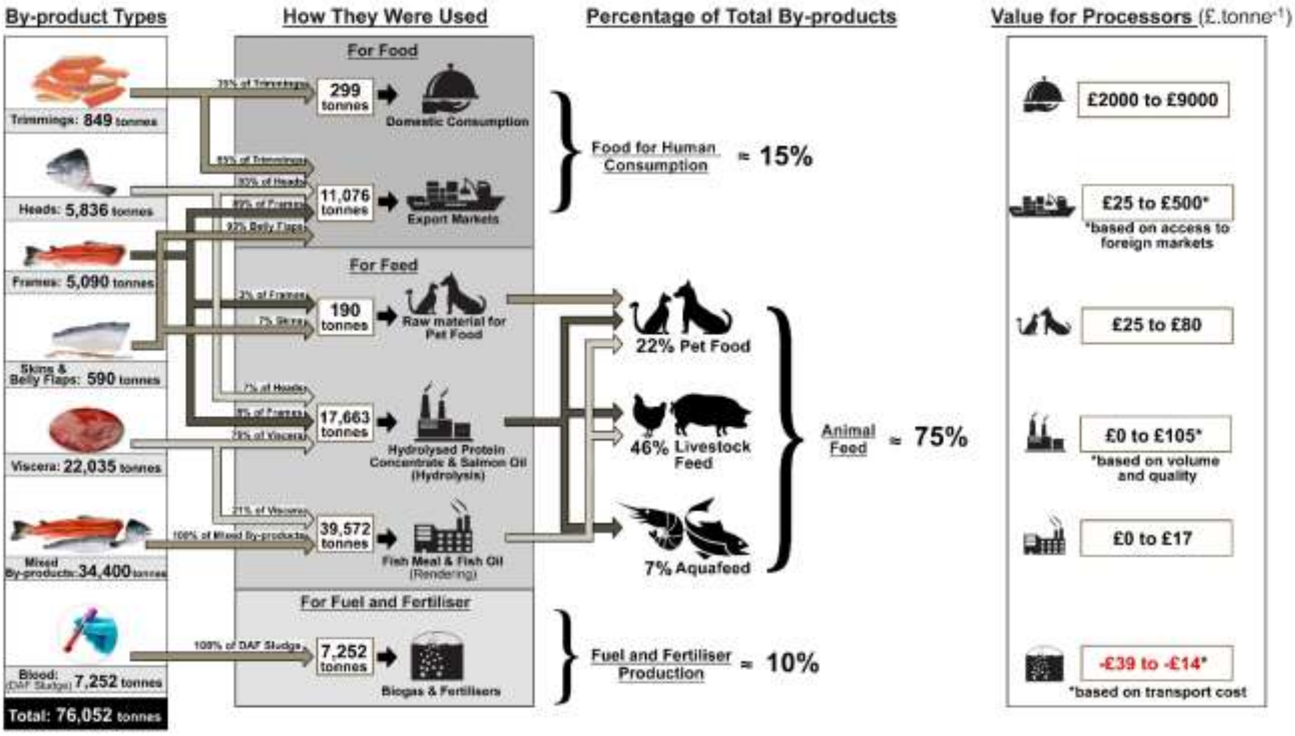

Fig 5. Salmon by-product utilisation in 2015 for Scotland.

These overall findings align with the commitment from Scottish industry stakeholders towards greater sustainability and are a result of a combination of factors, including (1) the increasing value of fish BPs in a competitive sector, (2) policy and regulation that restricts the disposal of BPs, and (3) a consolidated Scottish industry where there is growing infrastructure to manage BPs (i.e. FM/FO rendering facilities). However, while total utilisation of BPs can be seen as positive resource use, the *Food Recovery Hierarchy* (Fig. 1) along with other literature identifies that the best use of fish by-products to retain and add value, is as food or food ingredients (FAO 2016, Olsen *et al.* 2014, Rustad 2007). The study shows that, apart from the salmon 'blood-water' which at this time is not suitable for human or animal consumption (currently used for fuel and fertiliser production), the majority of processing BPs were downgraded from human grade, to category 3 Animal By-Products (as per EU ABP regulation (EC 2009, EC 2011)) and used as raw material for non-edible products. In the EU and UK, the regulatory considerations of how BPs are handled determines their categorisation, what makes a BP fit for human consumption can also be culturally and technologically mediated.

This study suggests that there exists a greater financial opportunity to use these raw materials in the production of value-added goods for human consumption. As shown in

Figure 5, the value for processors of one tonne of domestically consumed trimmings (£9000 to £2000) and exported BPs such as heads, belly flaps, and frames (£500 to £25) were generally much higher than those used for livestock and pet foods (£105 to £0). Despite the value for processors being the highest for domestic consumption of BPs, in 2015 this category of use represented less than 0.5% of total BPs, and was limited only to trimmings (Fig. 5). With seemingly clear financial benefits, what then were the limiting factors for directing more BPs towards human consumption?

A common theme reported by processors was in order to make human consumption of BPs viable and profitable, they needed access to markets. Processors reported that UK consumers, while generally amenable to regional food items made from livestock BPs, such as black pudding and haggis, have thus far been more conservative with fish BPs. The primary exception is in the form of trimmings, which can be used to generate many different value-added and smoked products. Key informants from the case study reported that with no current local demand for BPs like salmon heads, processors looked to export overseas to existing Asian and African markets.

In 2015, the majority of salmon BPs used for human consumption were transported to foreign countries, where they were either used directly for food production (fish head soup, barbequed belly flaps) or further processed for the food service or retail industries (surimi, pâtés, mousses, or for other value-added products). In some markets, canned salmon fins are considered a delicacy, and in both Japan and Taiwan the belly flaps of salmon are a popular foodstuff which can be barbequed or fried (Batista 2007, Tonsberg *et al.* 1996). On occasion, the price for BPs in these regions has been comparable to the fillet price (Batista 2007).

Countries with both high demand and cultural reliance on fish, are potential candidates for the marketing and sale of BPs, and range from low to high income economies. The sale of nutritious BPs to low income food deficit countries, can be viewed as enlightened self-interest. Improved storage, processing and distribution integrated with the broader fisheries sector could facilitate penetration of other global markets as demand grows; emergent trade in pelagic fisheries products with West Africa are already established.

Even with overseas demand, many processors did not direct their BPs to foreign markets for human consumption, let alone strive for domestic consumption. Processor interviews pointed to several limiting factors, including the need for suitable facility infrastructure, economies of scale, and transport networks. In order to maximise BP use for human consumption, and ensure the quality and safety of the raw materials is maintained, the handling of BPs must be managed and controlled in the same manner as the primary product (Ramírez 2013, Rustad *et al.* 2011, Ramírez 2007, Guerard 2007). To this end, the application of food safety and quality control systems, including Hazard Analysis and Critical Control Point (HACCP) and Good Manufacturing Practice (GMP) are imperative for retaining the suitability of BPs as sources of human grade food (Olsen *et al.* 2014).

With suitable infrastructure, BP types could be sorted, graded, stored, transported and used strategically, whereas currently, many processors tend to mix BP types and send them to local rendering and hydrolysate facilities (for animal feed). Processors reported that this practice, with its guaranteed yet lower payment, represents the most straightforward process within existing infrastructure. The results suggest processors could more than double the value of their BPs if they did not mix them, and instead sold them as the component parts: trimmings, heads, frames, viscera, skins, and belly flaps (see Fig. 2).

Sorting and grading BPs to be used for human consumption, will likely add the most value to large volume facilities producing high volumes of BPs. During processor surveys, a few large and medium Scottish facilities were identified as already implementing these innovative practices to increase value-addition of their BPs. However, the current sector profile of many small to medium sized processors with limited economies of scale is undoubtedly a constraint, coupled with the aforementioned infrastructure needs.

The literature and key informant interviews identified another area with the potential for increased financial return - one that was not reported as a current use by processors in Scotland - using aquaculture BPs for specialty and niche products for human use, such as human grade hydrolysates or salmon leather. In some instances, BPs diverted to this type of utilisation may have higher total possible value (e.g. fish skins - to leather - to handbags). To this end, the quality brand associated with Scottish salmon could be beneficial to the commercialisation of niche products, and the nature of aquaculture-raised salmon also means a reliable availability of BPs with consistent quality.

An issue regarding marketing of salmon BPs is that their origins are both local and imported. In Scotland, half of all salmon produced in 2015 was exported as premium head-on-gutted products, and a nearly equivalent amount of head-on-gutted salmon was imported to satisfy local demand. Thus, the salmon products and BPs available in Scotland and the UK derive from both Scottish and imported head on gutted salmon. As a result, the nutritional, potential use and provenance in value-added products are variable with implications for their value.

The current nutritional value of Scottish salmon BPs is high (Table 2), yet there is also the potential that this value could be undermined over time as the industry continues to reduce its use of omega-3 rich marine ingredients in the Atlantic salmon diet. The proportion of imported product with lower n-3 ratios also adds uncertainty. Sprague *et al.* (2016) found declining EPA/DHA levels in farmed Scottish Atlantic salmon between 2006 and 2015 linked to increasing use of vegetable oils in aquafeeds, this finding was supported by Shepherd and Bachis (2014). While this decline will need to be addressed by the industry in order to maintain its 'omega-3 rich' marketing, farmed Scottish salmon still provides more long-chain omega-3 fatty acids in comparison to most other fish species and all terrestrial livestock (Sprague *et al.* 2016).

Mortalities arising as a normal part of production, along with blood BPs from the slaughter stage, were not included in this study, as the data collection occurred at the processing stage. While there are niche biomedical uses for salmon blood (Sharp *et al.* 2012), in Scotland, as well as is in Norway, the extraction and utilisation of salmon blood is currently cost prohibitive. Based on the Zero Waste Scotland, *Finfish Mortalities in Scotland* (2016) report, mortalities are estimated to be 6.7% of Scottish production totals per annum, which equates to 11,272 tonnes for 2015. Mortalities are in-fact a production BP, which are included in FI:FO calculations through the eFCR. While there are no current avenues for the utilisation of mortalities in Scotland, as the industry grows, methods currently used in Norway such as ensilage to produce fuel and fertiliser may be applicable. Disposal of mortalities is a significant expense to the industry (over £2 million per annum), and innovation in this area would provide financial and environmental benefits (Zero Waste Scotland 2016).

With salmon production levels expected to increase in Scotland (SSPO 2016), there is potential for BPs to provide additional profitability and employment for the Scottish processing industry. Ongoing improvement in the use of BPs is relevant not only for local SSI goals to better utilise aquaculture by-products (Scottish Government 2016), but additionally contributes to global efforts, such as 'Goal 12: Responsible Consumption and Production' of the UN’s Sustainable Development Goals (SDGs), aiming to halve food waste by 2030.

4. Scenarios: adding value and food through aquaculture by-products

In this section, two scenarios are presented based on the 2015 Case Study findings exploring the potential outputs that might arise from aquaculture by-products when used strategically. The scenarios are by no means comprehensive, rather streamlined explorations intended to aid in future planning and initiate further dialogue. Scenario One: ‘Value Output’ focuses on potential financial gain, and Scenario Two: ‘Food Output’ focuses on the potential for food generation. These themes were chosen because they represent key drivers in the current market.

4.1 Value output

Scenario One (Fig. 6) takes the 76,052 tonnes of BP types from 2015, and the value of those individual BP streams and explores what the comparative value would be if they were managed strategically and directed towards their most profitable potential use. For example, BPs in the form of trimmings represent a 2% yield of the whole fish (Fig. 2), yet in 2015 only one tenth of trimmings went to domestic human consumption, despite this use offering the highest value of any BP. When the full 2% of this BP type is directed towards domestic human consumption as shown in Figure 6, the potential value in this case is £18,889,420, over a 1100% increase in value output from 2015. When BPs in the form of heads are redirected from their 2015 partial use in animal feeds, and maximum yield (10%) is diverted towards human consumption via the export market, there is a 300% increase in value output. There are similar value benefits seen for belly flaps and frames.

Overall, Scenario One demonstrates the potential for a total increase of 803% (£23.7M) in the total BP value output for 2015, assuming all high value BP types (heads, frames, trimmings and belly flaps) were managed for domestic and export food markets, and similar price points were achieved for all these available BPs. If compared with recently reported Scottish industry annual profits of £494M (SSPO 2015), this potential BP value could provide a 5.5% boost in industry revenue. Through prioritising use based on potential profit and therefore directing more BPs towards food for human consumption, Scenario One not only sees increased value output, but also more closely aligns with the *Food Recovery Hierarchy* (Fig. 1) which encourages reduction in wasted food, and ranks feeding humans and animals above industrial uses, composting and landfill.

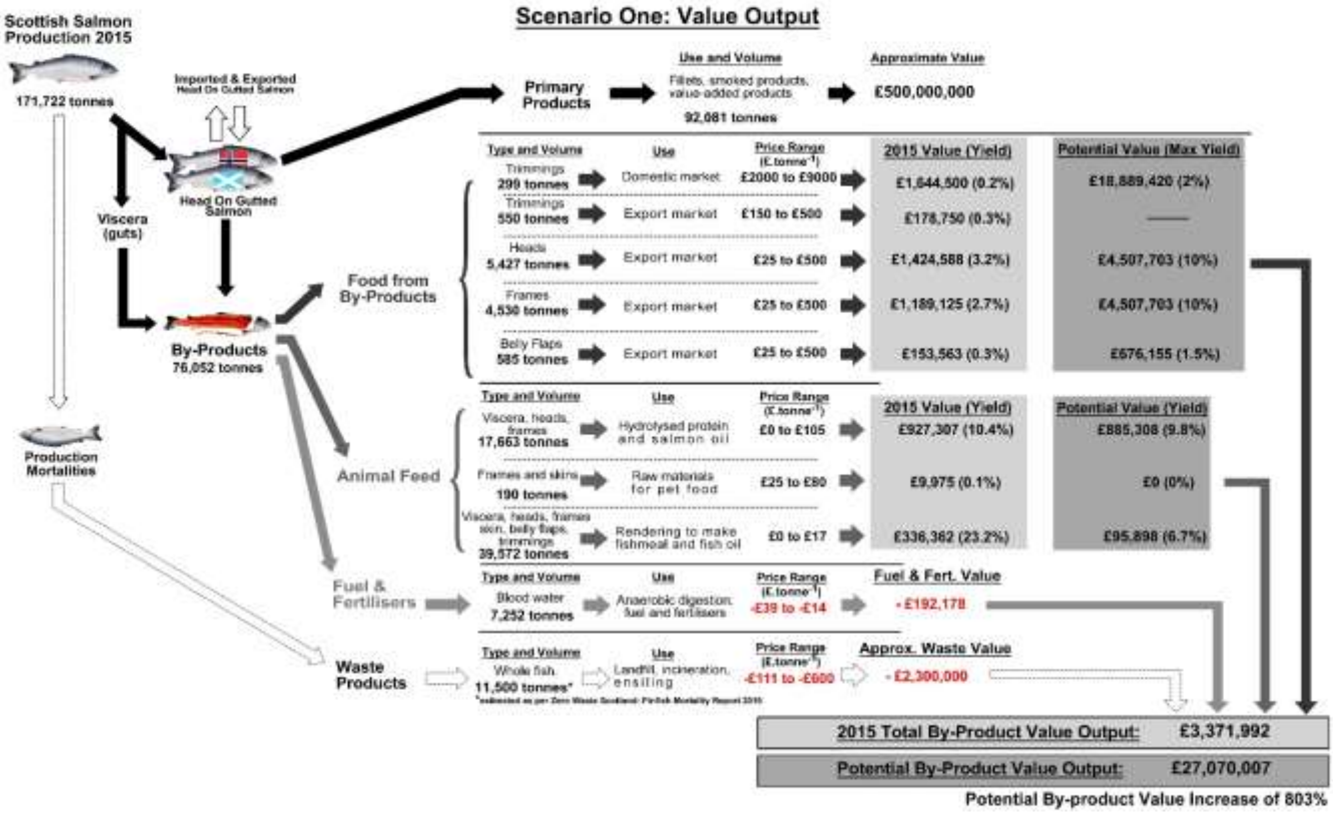

Fig 6. Scenario One: Value Output.

4.2 Food output

While financial incentives are key drivers for aquaculture business, food security and food production are equally relevant considerations for the efficiency of the overall system. The amount of food produced for human consumption can be explored through assessing edible yield. Roberts *et al.* (2015) developed a 'Fish In: Edible Yield Out' (FI:EYO) calculation based on the Jackson (2009) FI:FO method. When applied to the SSI study data, the FI:EYO ratio is calculated as 2.36 for the 2015 primary products alone, and 2.10 when the 15% of by-products directed to human consumption are added to the edible yield.

Although there is potential for a calculation based on edible outputs to advance sustainable resource use, it is limited in its ability to consider the various types of uses. As a hypothetical example: Processor A produces 75% edible yield (EY) and Processor B produces 70% EY. At first glance, Processor A appears to be the better option, however, if the remaining 25% of BPs from Processor A went to anaerobic digestion for fuel production, this outcome is ultimately less desirable than Processor B having 30% BPs remaining and directing those BPs to specialised aquaculture and livestock feeds. As such, an EYO ratio alone is not an adequate indicator of best practice for BP utilisation.

In order to advance our understanding, Scenario Two (Fig. 7) explores what the potential 'food output' could be from salmon production, through maximising BP use in human consumption and strategic BP use in aquafeed to produce more food for humans[2]. Scenario Two directs 77% of the annual whole fish production towards human consumption, combining the Case Study data on primary products (54% yield)[3] with the maximum potential BP food yield (~23%) seen in Scenario One (Fig. 6). This results in 132,171 tonnes of food. The remaining BPs, minus blood water (4.3%), are then utilised in the production of fishmeal and fish oil and used in aquafeed for farm raised marine species. European seabass and gilthead seabream were chosen for this scenario, as they are regionally relevant non-salmonid species. Directing BPs in this way increases food output by an additional 16,520 tonnes (or 10%) for only a single year's production of seabass and seabream. When BPs are strategically managed as shown in Scenario Two (Fig. 7), there is a 61% increase in food production above the original Atlantic salmon primary food products. The total outcome from Scenario Two is the generation of 148,691 tonnes of total food, 1.6 times more than the original production of 92,081 tonnes of salmon.

If Scenario Two were calculated using only the 2015 Case Study levels of total food for human consumption, not the maximum potential, approximately 12,000 tonnes less overall food is produced. This suggests a preferable means of maximising food output is to use as much as possible in the first generation for human consumption, and to utilise the remaining BPs for highly efficient aquaculture species with low FCRs (as shown here), or as specialist feed ingredients in livestock diets.

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[2] Scenario Two explores by-product use in aquafeed inputs as, generally, there is a better feed conversion ratio (FCR) in aquaculture species than in terrestrial livestock (Torrissen *et al.* 2011).
[3] The 54% primary product yield comes from the processing of both imported and domestically produced Atlantic salmon. In 2015, over 83K tonnes of Scottish salmon was exported, most as head-on-gutted salmon, and another 81K tonnes was imported as head-on-gutted salmon.

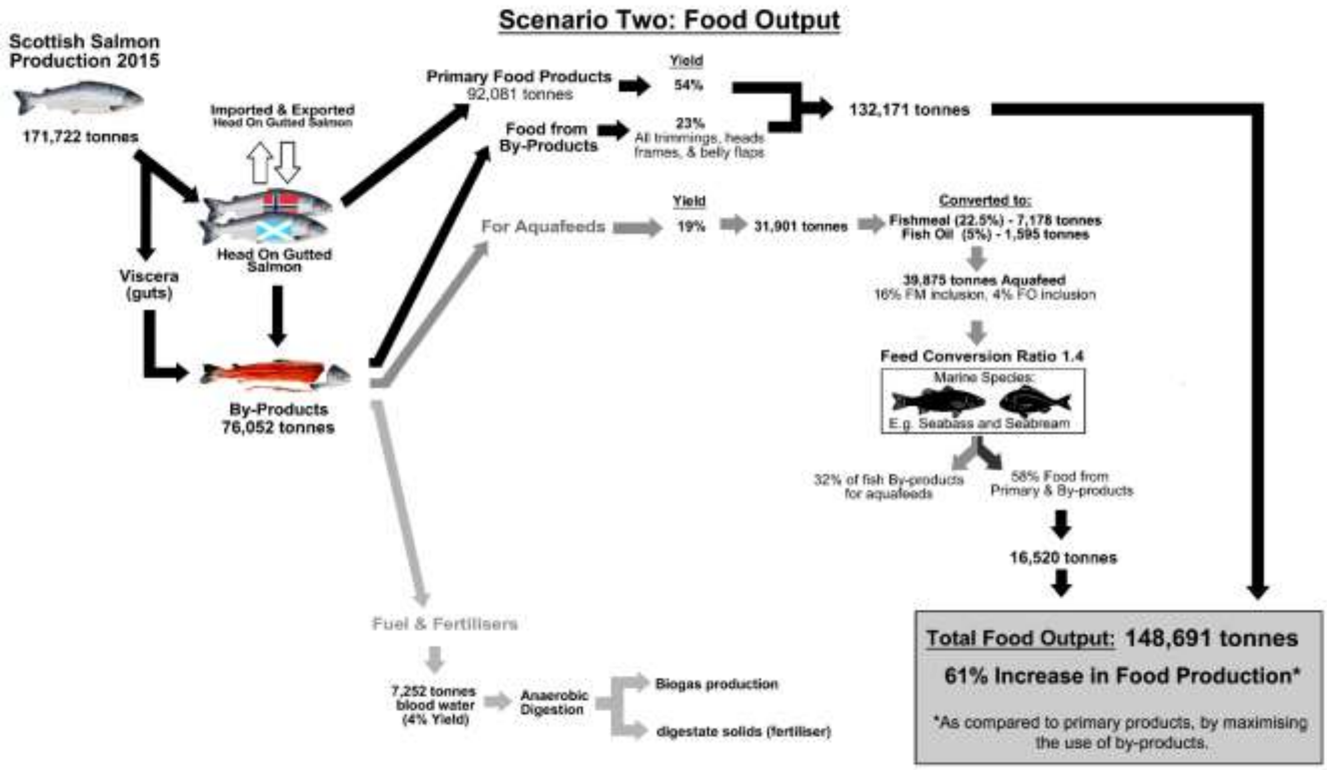

Fig 7. Scenario Two: Food Output.

5. Advancing aquaculture by-product utilisation

Incorporating the findings from the 2015 Case Study (Section 3) and the scenarios explored in Section 4 with the US EPA *Food Recovery Hierarchy* (Fig. 1), this paper offers The *Food Recovery Hierarchy for Fish By-Products* (Fig. 8). This adapted hierarchy proposes that environmentally, the most preferred way to utilise fish BPs, and indeed the most valuable way, would be to maintain their food grade quality and maximise edible yield – first as food in domestic and then export markets. The next tier in the hierarchy proposes processing BPs into high-value consumables for human use. For salmon, such consumables include products such as protein powders and hydrolysates, salmon oil supplements, collagen supplements, and niche products like salmon leather or pharmaceutical products extracted from salmon blood. These top two tiers of the hierarchy will require HACCP processing standards (Olsen *et al.* 2014).

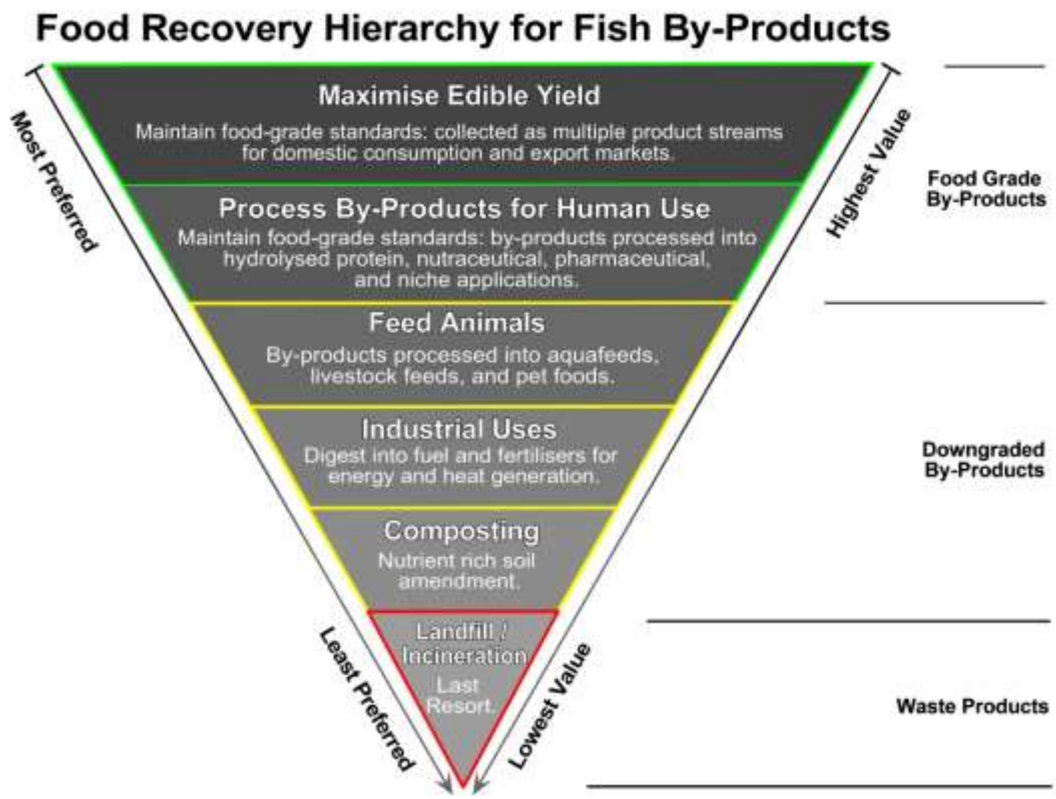

Fig 8. Food recovery hierarchy for fish by-products. Adapted from US EPA (2017).

The next level recommends using BPs to create feed for animals such as fish (excluding intra-species feeding), shrimp, poultry, and pigs. Strategic use in this area could result in more food for human consumption, and may benefit livestock in key developmental stages (Pike 1999). In this tier, fish BPs could also be used as pet feed because they can substitute for higher grade products which may be directed to human consumption. The next tier down in the hierarchy includes use in industrial fuels and fertilisers, followed by composting. While these options can be considered a significant downgrading of food grade BPs, they remain preferable to sending BPs to landfill, which is the least preferred and lowest value option.

Through addressing the use of valuable marine resources beyond the confines of the current FI:FO concept, the strategic utilisation of fish BPs outlined in the *Food Recovery Hierarchy for Fish By-Products* (Fig. 8) provides a tool that can aid the industry as it moves towards greater sustainability throughout the value chain.

5.1 Future Recommendations

As the aquaculture industry continues to mature, the sustainability dialogue regarding aquaculture must also mature. FI:FO was created as a concerted effort to improve resource use upstream of the aquaculture value chain, but downstream implications are equally relevant. Aquaculture BPs must become an integral part of the sustainability dialogue going forward if the industry wishes to make best use of the entire fish and realise the advantages available from such practices.

The study highlighted that only a select number of processing companies in Scotland are currently aware of the benefits of the strategic utilisation of BPs; companies who are already beginning to adopt this methodology and innovate in this area have an advantage in an industry with slim margins. Through sharing this information within a larger network of stakeholders, including producers and retailers, and highlighting tools such as the *Food Recovery Hierarchy for Fish By-Products* (Fig. 8), the industry can further advance in its movement towards improved sustainability.

There is clearly room for UK consumers to be encouraged to use more fish BPs in their cooking; encouragement could come from choice-editors such as celebrity chefs showcasing recipes with fish BP ingredients. Better use of BPs through trade with low income food deficient countries may have implications for food insecure areas of the world.

In light of the benefits of the strategic management of BPs, policy should be put in place to support BP innovation for businesses actively seeking to develop the necessary infrastructure to drive their use of BPs up the hierarchy (Fig. 8). As seen in the Scottish Case Study, policy and regulation that restricts the disposal of BPs (UK DEFRA 2014, EC 2008, EC 2009, EC 2011) can be a key driver for industry innovation.

Aquaculture certification schemes and standards that include processing facilities, such as GAA's BAP Facility Certification (GAA BAP 2015), could encourage, educate, and incentivise facilities in maximising the use of their processing BPs. As a next step for further consideration, there is scope to use the *Food Recovery Hierarchy for Fish By-Products* (Fig. 8) to create a ranking system to be included in facility certification. Similarly, due to the ongoing use of the FI:FO concept in certification schemes, we recommend that the hierarchy system is further explored for its application to the FI:FO ratio.

With future innovation, additional options for the strategic management of fish BPs will become available, and the hierarchy (Fig. 8) can be updated accordingly. While this paper addresses the sustainability benefits of maximising the use of BPs, there are other considerations, such as social and technological implications, as well as market analysis, which will require further examination.

Regarding the local industry in Scotland and the UK, it is recommended that further analysis on the broadening demand for domestic consumption of BPs be conducted, as it is an area with the potential for much higher returns. The stability of the export market price for BPs should also be analysed, as well as infrastructure requirements for enhancing strategic BP utilisation both locally and abroad. Since economies of scale are necessary to enter the export market and achieve higher returns on BP, small and medium scale processors may need to work cooperatively/collectively to manage the cold-storage of aquaculture BPs. Alternatively, there may be business opportunities available for outside companies to collect and export BPs from small and medium scale processors.

While the results of the 2015 Scottish Salmon Case Study may also be relevant in other contexts, each aquaculture species will have its own considerations, as will each region. It is highly recommended that similar case studies be developed for other key aquaculture sectors, such as the shrimp and shellfish industries whose BP utilisation will be different than that of the fin-fish sector. For each region in which stakeholders wish to implement strategic utilisation, it will be helpful to first identify local practices in BP management in order to establish the regions current baseline for development.

5.2 Conclusion

The 2015 Scottish Salmon Case Study (Section 3) presented in this paper, has given new insights into how by-products are currently being used within the value chain, and demonstrated positive waste reduction through the full utilisation of reported by-products. At the same time, the Case Study offered insights into the potential for even greater sustainability through further strategic management of by-products as valuable marine resources. Scenarios One (Fig. 6) and Two (Fig. 7), explored the financial and food security benefits of strategic by-product utilisation, where it was identified that through maintaining the food grade quality of by-products and maximising their use in human consumption, there was an opportunity to achieve an 803% increase in by-product revenue and up to a 61% increase in food production. Through the strategic management of by-products, as outlined in the *Food Recovery Hierarchy for Fish By-Products* (Fig. 8), the paper has outlined the ability for the aquaculture industry to produce more food and value from the same amount of resources.

In conclusion, there are economic, environmental and food security benefits that should be considered strong motivating factors in prioritising the strategic management of aquaculture by-products. With collaboration, investment and innovation from key stakeholders, the rise of aquaculture by-products will undoubtedly contribute to the sustainable development and future growth of the industry.

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