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Comparing the Environmental Footprint of B.C.'s Farm-Raised Salmon to Other Food Protein Sources

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Prepared for:

BC SALMON FARMERS ASSOCIATION

Contents

1. Executive Summary

This paper examines the evidence from the literature on the environmental impact of ocean net-pen farm-raised salmon versus other protein sources and, based on the evidence, develops estimates of the overall environmental footprint of farm-raised salmon in B.C. compared to production of other food proteins. Since over 90% of salmon raised in BC are Atlantic salmon, the paper focuses on this particular species. However, it should be noted that BCSFA members also raise Certified Organic Chinook salmon, steelhead salmon, Coho salmon, and sablefish.

Environmental Impact Measures

The most common metric used to determine the sustainability of food production systems is life-cycle assessment (LCA). LCA employs a number of objective indicators, such as energy use (measured in mega joules per kg of meat produced), greenhouse gas emissions (measured in carbon dioxide equivalents per kg), eutrophication potential (measured in grams of phosphate per kg), water use (measured in litres per kg), and land use (measured in m^2 per kg). Results from the literature for each of these indicators are summarized in the table below.

Estimated Environmental Impacts per kg of B.C. Farmed-Raised Salmon and Livestock

	Energy (MJ)	Greenhouse Gases (kg CO_2eq)	Eutrophication (g of PO_4-eq)	Water (litres)	Land (m^2)
B.C. Salmon	31.7	2.2	47.4	1,400	4.3
Beef	44.8	37.2	55.0	15,400	68.3
Poultry	23.1	5.1	5.0	4,300	9.9
Pork	23.6	6.4	12.7	6,000	11.5

Summary of Results:

- **Energy Use:** Over 90% of cumulative energy use for farm-raised salmon is from feed production. Overall, the evidence indicates that the life-cycle energy intensity for farm-raised salmon is better than beef.
- **GHG Emissions:** GHG emissions for B.C. farm-raised salmon lower than beef, poultry and pork.
- **Eutrophication Potential:** Evidence suggests that B.C. farm-raised salmon has lower eutrophication potential than beef.
- **Water Use:** B.C. farm-raised salmon was found to have consistently lower water use than other types of animal farming, using only a small fraction of the water compared to other species.
- **Land Use:** Over 90% of land use for farm-raised salmon is from feed production. Overall, studies have found that production of feed for B.C. farm-raised salmon requires much less land than used in the production of most other species.

Comparing Environmental "Costs"

Estimates of the value of environmental impacts of B.C. farm-raised salmon and other animal protein sources show that B.C. farm-raised salmon imposes much lower environmental impact values. Estimated prices for environmental impacts were set at $30 per tonne of CO2-eq for GHGs (current value of B.C.'s Carbon Tax), $126 per $1000m^3$ for water use (FAO Economic Valuation of Water: Irrigation Price, based on estimates for the U.S.) and $7.3 per kg of PO^4-eq for eutrophication potential (UNEP, Economic Valuation of Waste Water, at 4-6 euros per kg of PO^4 to clean up).

Based on these prices, the estimated "cost" of environmental impacts of B.C. farm-raised salmon is $0.59/kg. At $0.73/kg, the environmental "cost" of chicken is 24% higher than B.C. farm-raised salmon. Pork ($1.04/kg) is 76% higher, and beef ($3.45/kg) is 486% higher than B.C. farm-raised salmon.

Cross-country Comparison

Based on a limited number of cross-country comparisons in the literature, it appears that the environmental footprint of B.C. farm-raised salmon is comparable to Norway, and better than U.K. or Chile.

- Energy use related to net-pen farming in B.C. is comparable to Norway, but lower than the U.K. and Chile.
- GHG emissions appear slightly higher than Norway, but lower than U.K. and Chile.
- Eutrophication potential is comparable to Norway, and lower than the U.K. and Chile.

Feed Conversion Ratios (FCR)

Another key element in assessing the sustainability of food animal production systems, such as fish, poultry, pork and beef, is the feed conversion ratio, or FCR. FCR measures the efficiency of food production in terms of the amount of feed an animal requires to gain a kilogram of body weight. For farm-raised salmon, the FCR averages about 1.3:1 worldwide. For B.C. farm-raised salmon, the FCR is estimated to be 1.2:1. This means that to produce 1 kg of B.C. farm-raised salmon, 1.2 kg of feed is required.

B.C. farm-raised salmon's feed conversion ratio of 1.2:1 has decreased dramatically from previous decades, and is significantly lower than the FCRs for other sources of food protein: poultry (1.7:1 to 1.9:1), pork (2.8:1 to 2.9:1) and beef (6:1 to 9.1:1). In terms of FCR, B.C. farm-raised salmon are the most efficient of all the commercially raised farm-fed animals.

Fish In – Fish Out (FIFO)

Another aspect of the sustainability of farm-raised salmon is the amount of wild fish meal and fish oil used in feed. Since 1990 the ratio of marine protein to produce 1kg of salmon protein has dropped from 3.8kg of fish meal and 2.8kg of fish oil to only 0.7kg of fish meal and 0.5kg of fish oil.

However, FIFO is not a rigorous indicator for the overall environmental or ecological sustainability of salmon farming. More sophisticated measures, such as forage fish dependency ratios (FFDR) for both fishmeal and fish oil, are being adopted worldwide by groups such as the Aquaculture Stewardship Council (ASC). In B.C., the average FFDRs have decreased over the years, and are well below the standards set by the Aquaculture Stewardship Council, indicating a continuing shift in B.C. farm-raised salmon away from reliance upon wild marine resources in feed.

The nutritional efficiency measures above show that B.C. farm-raised salmon are much more efficient converters of feed to flesh than other widely-consumed food animal, and use of fish meal and fish oil in feed is becoming more and more sustainable. And recent advances in research into alternative and novel raw materials for feed have enabled fish feed companies to develop salmon feed formulations that are completely fishmeal-free while delivering equal performance in terms of fish growth and health.

2. Background

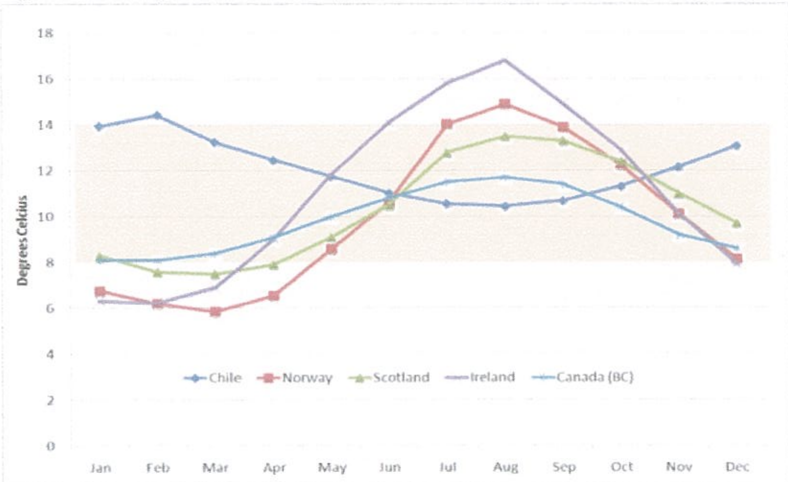
This paper examines the evidence from the literature on the environmental impact of farm-raised salmon versus other protein sources and, based on the evidence, develops estimates of the overall environmental footprint of farm-raised salmon in B.C. compared to production of other food proteins.

2.1 Farm-Raised Salmon: A Very Efficient Food Protein

Compared to terrestrial animals, farm-raised salmon are a very efficient source of food protein due to the following factors:

- Salmon are cold-blooded so do not expend energy maintaining a constant body temperature. They do not have to swim against strong water currents or devote biomass to reproduction unlike wild salmon. Farm-raised salmon are the most efficient of all the commercially raised farm-fed animals (DFO, 2012).
- Seawater temperature is one of the most important natural competitive advantages that BC has compared to the other salmon farming regions in the world. Figure 1 compares average water temperatures for major salmon farming regions in 2014. In BC, ambient seawater temperatures are more optimal than other regions, ranging from 8° C to just below 12° C over the course of 2014. For 2015, measurements in B.C. across a limited number of farming sites indicate that water temperature range from about 8.8° C to about 13.8° C, which is still within the optimal range for farm-raised salmon (BCSFA, 2016).

Figure 1: Average Seawater Temperatures in Major Salmon Farming Regions



Source: Marine Harvest (2015).

- Fish are practically weightless in the water and do not need to expend energy for carrying their body weight or opposing gravity, and a weightless animal does not need a strong and heavy skeleton.
- The processing yield of farm-raised salmon is relatively high compared to domestic animals:
  - Atlantic salmon also deposit most of the fat in the muscle, giving a higher slaughter yield compared to fish that deposit lipid (fatty acids) in the liver. Slaughter yields (bled and gutted) vary between 86% and 92%.
  - The relative low weight of the skeleton gives edible yields in the range of 60% and 68%, thus compared to edible yields of pork (52%), poultry (46%) and beef (40%), Atlantic salmon yields were substantially higher.
- Farm-raised salmon feed has a high energy content and is highly digestible, and farm-raised salmon are more efficient at utilising the protein in the feed compared to other farmed animals. The protein retention, which is a measure of protein utilisation, can be as high as 45 per cent in salmon, while corresponding figures for poultry and pork are 18 and 13 per cent respectively. As more of the proteins in the feed are converted into meat, the high protein retention gives farm-raised salmon an ecological advantage compared to other meats.

These factors, as well as others such as feed conversion ratio (discussed in Section 4), all contribute to the advantages of farm-raised salmon over other food protein sources in terms of environmental impact.

2.2 Ecological/Environmental Impact Measures

As James Diana wrote in paper on aquaculture and biodiversity, "No food production system now in use is truly sustainable from an energy and biodiversity perspective—all food production systems generate wastes, require energy, use water, and change land cover." (Diana 2009, p. 28)

However, it is possible to compare different food systems based on several objective environmental measures. Life-cycle analysis (LCA) is a tool to measure environmental impacts of food systems. They are an ISO standardized method for measuring specific environmental indicators and they take a "cradle-to-farm gate" approach across the animal or crop's life. Not every LCA covers every indicator, area, or species, although the estimation methods are standardized. The most common indicators, presented per kg of protein produced, are:

- Energy use: The total energy from sources such as electricity and fuel used in production, measured in Megajoules (MJ) per kg

- Greenhouse gas emissions: Greenhouse gases released in production from sources such as fuel use or methane release in feces, measured in carbon dioxide equivalents (CO_2-e) per kg
- Eutrophication potential: The artificial release of fertilizing nutrients, such as phosphate and nitrogen, into the environment, measured in grams of phosphate (PO_4) equivalents per kg
- Water use: Water used for drinking, feed production, and other uses, measured in litres per kg
- Land use: Land used to care for the animals or to produce feed, measured in m^2 per kg

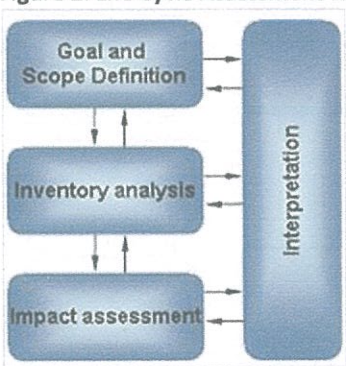
These measures are not an exhaustive list of environmental impacts, so some discussion to the various advantages and disadvantages of different livestock systems compared to aquaculture is given below.

2.3 What is a Life-cycle Assessment?

The United Nations Environmental Programme (UNEP) defines a life-cycle assessment as "a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. LCA provides an adequate instrument for environmental decision support. Reliable LCA performance is crucial to achieve a life-cycle economy." (UNEP)

LCAs are a standardized method for measuring the full environmental impact of a product across the whole life-cycle of a product: from production to end-user. The methods for doing an LCA are standardized under the International Organisation of Standards ISO14040.

Figure 2: Life Cycle Assessment Flowchart



Source: UNEP. What is Life-cycle Assessment? http://www.unep.org/resourceefficiency/Consumption/StandardsandLabels/MeasuringSustainability/LifeCycleAssessment/tabid/101348/Default.aspx

Caveats

Not all environmental impacts are necessarily captured in an LCA, although energy, GHGs, acidification, eutrophication, and biotic resource use are commonly included. Furthermore, the scope of LCAs often varies. For instance, some studies only estimate the environmental impact from "cradle-to-gate" – from birth to when the animal leaves the farm – while others go further and include the impacts of distribution and the consumer. Additionally, the estimated impacts are sensitive to an author's assumptions. Each LCA often requires authors to make decisions on potentially hundreds of variables across farmed species. As a result, despite the standardized methodology, the environmental impact estimates from LCAs can vary considerably. Estimates of farm-raised salmon environmental impacts are particularly sensitive, because the B.C. industry has experienced a rapid change in inputs in the last two decades, leading authors of LCA studies to make quite different assumptions.

3. Summary of LCA Results from the Literature

The following literature review was compiled from various life-cycle assessments (LCAs) or meta-analyses of LCAs across different species.

3.1 Energy Use

A 2006 study prepared for the UK Department for Environment, Food and Rural Affairs (Foster et al. 2006) estimated that 400g of farm-raised salmon takes 23 MJ of energy per kg of fish compared to 46 MJ/kg of beef. The study authors, however, founded their estimate on the assumption that 3 to 5kg of wild fish are required to produce 1kg of salmon. As stated previously, wild fish ratios have dramatically fallen and feed conversion ratios have improved in the past 20 years in B.C. salmon farming.

A desk top study of aquaculture energy, produced for the Organisation for Economic Cooperation and Development (OECD), reviewed energy estimates for various farmed species and countries. The authors found similar energy requirements compared to the U.K. Department of Environment, Food and Rural Affairs (DEFRA) study across studies (Hornborg and Ziegler 2014). Furthermore, they found that most studies reported that farm-raised salmon was slightly more energy intensive than pork or chicken, but much less intensive than beef, although land-based recirculation systems require higher energy.

In a Canadian specific study, Ayer and Tyedmers (2008) found that net-pen farm-raised salmon required 26.9 MJ/kg of fish; which was lower than farm-raised salmon from bag-based systems (37.3 MJ/kg), and significantly lower than for farmed-raised salmon from land-based flow through systems (132 MJ/kg) and land-based recirculating systems (233 MJ/kg).

Table 1: Summary of Studies on Energy Use in Livestock and Salmon Farming (MJ per Kg)

	Salmon	Beef	Poultry	Pork
Hornberg and Ziegler	31		17	23
Devries		34-52	15-18	18-45
DEFRA study	57.5	44	12	17
Pelletier (2008, 2009, 2010a,b)	31.2	38.2	14.95	9.7-11.9
Mungkung et al.	66	40	55	16.9
Tuomisto et al.	26.6	71.8	23.3	37.5-47.6

Ayer and Tyedmers also noted that 93% of cumulative energy use for farm-raised salmon is from feed production. Overall, the evidence indicates that the life-cycle energy intensity for farm-raised salmon is comparable to beef farming, but somewhat higher than poultry and pork.

It is important to note that much of the energy use data from the literature is out of date, and relies on assumptions that are no longer accurate for B.C. farm-raised salmon. B.C. fish farmers report much lower energy use rates than shown in Table 1, particularly for net-pen systems. B.C. salmon farmers also continue to develop sophisticated energy tracking and reporting tools to meet Aquaculture Stewardship Council (ASC) standards.

3.2 GHG Emissions

A 2011 study from ESU Service (Buchspies et al. 2011) compared GHG emissions across a variety of wild caught species, farm-raised salmon, and several livestock species. Overall, GHG emissions per kg of farm-raised salmon were slightly above those of capture fisheries, poultry and pork, but far lower than beef. The authors noted that "this large difference is caused by the significant amount of methane that cattle produce when digesting" (pg. 4).

In fact, a number of studies on the GHG impact of Canada's net-pen farms found even lower GHGs. A 2009 LCA of GHG emissions for various countries with salmon farming supposed that Canada salmon farming produced only 2.3kg of CO_2-e per kg live weight (Pelletier et al. 2009). Pelletier et al. also noted that on average, farm-raised salmon had markedly lower emissions than Swedish pork or Belgian beef, but was higher than poultry or capture fisheries. Comparatively, Western Canadian beef farming was estimated to produce 22kg of CO_2-e per kg of beef, nearly 10 times the Pelletier et al. estimate for Canadian farm-raised salmon (Beauchemin 2010). In an LCA of alternative aquaculture systems in Canada, Ayer and Tyedmers (2009) found that GHG emissions per kg of net-pen salmon were 2.0kg.

Table 2: Summary of Studies on GHG Emissions in Livestock and Salmon Farming (kg of CO_2-eq per kg)

	Salmon	Beef	Poultry	Pork
Buchspies et al.	6.6	16	4.5	5
Devries		14-32	3.7-6.9	3.9-10
Tuomisto et al.	1.5	40.97-55	8.9	6.88-14.25
Nijdan et al.	3-15	9-129	2-6	4-11
Pelletier (2008, 2009, 2010a,b)	2.4	14.5	1.4	2.47-3.05
SINTEF study	2.9	30	2.7	5.9
Stonerook	4.2	28.4	6.12	5.78

Nijdam et al. (2012) reported that GHG estimates for aquaculture ranged from 4kg to 75kg of CO_2-e per kg of protein, compared to 40kg to 650kg CO_2-e per kg of beef. Although the studies used different methodologies, they show that GHG emissions for farm-raised salmon are comparable to pork and poultry, but far below those of beef.

3.3 Eutrophication Potential

Eutrophication refers to an ecosystem's response to the addition of artificial or natural nutrients, such as phosphates (P) and nitrogen (N), through detergents, fertilizers, or sewage, to an aquatic system. Land-based livestock systems result in eutrophication of nearby water sources when nutrient rich organic matter (e.g. manure) leaches into surrounding water bodies. Aquaculture eutrophication can result when excess fish food and faeces add nutrients to the water.

A 2007 comparative review of environmental assessments of aquaculture and other livestock systems found that "comparatively, N and P retention efficiency are much greater in fish than in cattle" (Soto et al. 2007). The authors review reported that in Canada, cattle and diary N efficiency is 17% compared to 41% for Atlantic salmon. Furthermore, they noted that the improving FCR of salmon over the past two decades has substantially improved the N and P retention efficiency of salmon farming. The authors found that the ecosystem impacts varied greatly for both cattle and salmon, depending on the size of the relevant ecosystem.

Table 3 below summarizes results from a number of cross species comparisons of eutrophication potential. Similar to the caveats for the energy use section above, data from the literature on eutrophication potential is dated, and is based on assumptions that do not reflect current practices in B.C. fish farming. Stonerook (2010) observed that eutrophication estimates for farmed salmon are very dependent on feed quality (i.e. digestibility) and farm management strategies, such as fallowing. We also note that FCR's have greatly improved over time, marine ingredient use has decreased, feed formulations and feeding practices have changed. These improvements are not reflected in the studies cited in Table 3, and would have a significant impact on the estimates of eutrophication potential of B.C. farm-raised salmon.

Table 3: Summary of Studies on Eutrophication Potential in Livestock and Salmon Farming (grams of PO4-eq per kg)

	Salmon	Beef	Poultry	Pork
Devries and Boer		10-25	1-12	5-20
Pelletier (2008, 2009, 2010a,b)	74.9	104-142	3.9	15.9-20.8
Stonerook	8.7	24.4	4.6	7.1
Lane et al. (grams of N per kg)	55	170	45	65

3.4 Water Use

Verdegem et al. (2006) stated that marine aquaculture uses "negligible amounts of non-feed-associated fresh water" and could serve as a way to protect freshwater resources because of its lower feed conversion ratios, which they estimated to be below 2kg of feed per kg of aquaculture product for most types of aquaculture, compared to around 7kg of feed per kg of beef. Salmon farming and other aquaculture have far lower feed conversion ratios than livestock.

Overall, salmon farming was found to have consistently lower water use than other types of animal farming, although the magnitude varies considerably between methodologies and studies. Studies by Marine Harvest and Stonerook (2010) in particular stated that aquaculture used only a small fraction of the water compared to other species.

Land-based livestock production relies on available local water sources to sufficiently water animals. However, the bulk of water use in animal husbandry comes from feed. The UNESCO Institute for Water Education (Mekonnen and Hoekstra, 2010) estimated that 98% of water use came from feeds. Although they did not study aquaculture, they did report that large ruminants with higher feed conversion ratios had far higher water use footprints.

Using a similar methodology to Mekonnen and Hoekstra, Marine Harvest (2015) estimated that salmon farming required about 2,000 litres per kg[1], although Mekkonen and Hoekstra included non-consumptive water use and, as a result, have significantly higher estimates than either Stonerook or the Lane et. al which only compared consumptive water use.

A cross-country review of resource intensiveness of aquaculture systems also reported that sea based marine aquaculture had very low water use, using 0 to 100 litres per kg of product (Akvaplan and VGREEN, 2009). Most of the fresh water use was a result from refilling evaporated water in land-based systems.

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1 This figure reflects traditional smolt production in plants with water flow through. Recirculation plants, which are being implemented to an increasing extent, requires significantly less fresh water (up to 99% of the fresh water is recycled (Marine Harvest, 2015, p. 15). The 2016 report shows a figure of 2,000 litres, which reflects total water footprint for farmed salmonid fillets in Scotland. (Marine Harvest, 2016, p. 15).

Table 4: Summary of Studies of Water Use in Livestock and Salmon Farming (m^3 per kg)

	Salmon	Beef	Poultry	Pork
Lane et al.	190	1,000	225	350
Marine Harvest	1,400	15,400	4,300	6,000
Stonerook	720	19,500	7,240	10,310

Aquaculture water use is significantly lower than other kinds of livestock, even once water used for feed production is factored in. An EU study on the sustainability of aquaculture (sourcing Welch et al. 2010) found that water use was under 200 litres of consumptive water use per kg of salmon compared to nearly 1,000 litres per kg of beef. Stonerook (2010) estimated even a more dramatic difference in consumptive water use.

3.5 Land Use

Production of farm-raised salmon also compares favorably to terrestrial animal protein production in terms of land use. Both terrestrial livestock and farm-raised salmon require the production of grain (e.g., corn) and oilseed (e.g., soybeans) for feeds. For terrestrial livestock, the animals' diets are largely based on the direct feeding of these products; for farm-raised salmon, grains and oilseeds are key ingredients in the production of aquafeeds. Overall, studies have found that production of feed for farm-raised salmon farming requires much less land than for feed used in the production of most other species.

An EU study on the sustainability of aquaculture based on Welch et al. (2010) found that land use was just over $6m^2$ per kg of salmon compared to nearly $12m^2$ per kg of beef (Lane et al. 2009). In a meta-analysis of land use comparing various animal husbandry methods, Nijdam et al. (2012) stated that salmon farming land use ranged from $13m^2$ to $30m^2$ per kg of protein, well below those of other types of livestock, like beef which ranged from $37m^2$ to $2100m^2$ per kg of protein.

Estimated for the amount of land by species varied considerably across studies. Salmon farming was estimated to use as little as $0.2m^2$ to $7m^2$, but estimates for beef were consistently higher and varied more from $12.5m^2$ to as much as $420m^2$.

Table 5: Summary of Studies of Land Use in Livestock and Salmon Farming (m^2 per kg)

	Salmon	Beef	Poultry	Pork
Nijdam et al.	2-6	7-420	5-8	8-15
Devries		27-49	8.1-9.9	8.9-12.1
Mungkung et al.	6	33	12.5	5.9
Lane et al.	7	12.5	7	10.2
Tuomisto et al.	0.2	13.5-75.2	12.4-14.6	15.7-22.4

3.6 Cross-Country Comparisons

With the exception of Pelletier (2009), most meta-analyses did not make a distinction between Canadian production of farm-raised salmon and other countries, such as Norway or Chile. The Pelletier study did, however, show that salmon farming across the world is quite similar. Canada's salmon farming environmental impacts were found to be around the world-average. Greenhouse gas production and energy use was found to be in the middle of the global comparison.

Table 6: Cross-country Comparison of the Environmental Effects of Farm-Raised Salmon (per kg)

	Energy (MJ)	Greenhouse Gases (kg CO_2eq)	Eutrophication (g of PO_4-eq)
Canada	**31.7**	**2.2**	**47.4**
Pelletier (2009)	31.2	2.37	74.9
Ayer (2008) - Net Pen	26.7	2.1	35.3
Ayer (2008) - Bag	37.3	2.25	31.9
Norway	26.2	1.79	41
U.K.	47.9	3.27	62.7
Chile	33.2	2.3	51.3

The Pelletier comparison and the Ayer study both included the fact that British Columbia production relies more on hydroelectricity – a relatively clean source of energy – than other countries. The Pelletier study did not find that Canadian salmon resulted in much different GHG emissions per kg. British Columbia-specific studies like Ayer et al. found very similar energy use and GHG values to Pelletier, although Ayer et. al estimated a significantly lower eutrophication potential level.

4. Other Measures

4.1 Feed Conversion Ratio and Fish In – Fish Out

What is FCR?

A key sustainability measure in food production is the Feed Conversion Ratio (FCR). The FCR measures the efficiency of food production in terms of the amount of feed an animal requires to gain a kilogram of body weight. The FCR is the mathematical relationship between the input of the feed and the weight gain of the animal. FCR is calculated as follows: Feed given / Animal weight gain. The lower the FCR the more efficient an animal is in retaining the protein and energy from the feed and converting it into food for humans (i.e. meat and fillets).

FCR values affect a number of key environmental/ecological footprint measures, including land use, eutrophication potential, and water use. For example, a lower FCR means that per kilogram, the animal requires less water, because the water use per kg is almost entirely based on the amount of water required to grow crops to produce feed.[2]

Estimates of FCR

For farm-raised salmon, the FCR averages about 1.3:1 worldwide (GSI, 2015).[3] This means that to produce 1 kg of salmon, you need around 1.3 kg of feed. Other sources of food protein have higher FCRs: poultry (1.7 to 1.9), pork (2.8 to 2.9) and beef (6 to 9.1).

FCR estimates in the literature for farm-raised Atlantic salmon vary by region, from about 1.103 in Norway, to 1.313 in Canada (1.2 in B.C.), 1.331 in the United Kingdom, 1.35 in Australia, and 1.493 in Chile (Torrissen et al, 2011). Torrissen et al suggest that regional differences are partly the result of differences in the national regulatory framework on feed composition. However, the U.N. FAO notes that FCR varies according to several factors, including the nutritional and physical quality of the aquafeed; environmental variants, such as temperature; the intensity of production; and other factors, including genetics (New and Wijkström, 2002).

B.C. farm-raised salmon's feed conversion ratio of 1.2 has decreased dramatically from previous decades (BCSFA 2016, Marine Harvest 2016).

Fish In – Fish Out (FIFO)

Over the last 20 years, salmon farmers have gradually substituted marine raw materials with vegetable raw materials, while sustaining the health benefits and quality of farm-raised salmon. This change in the dietary composition has reduced dependency on forage fish considerably in commercial feeds for farm-raised salmon, which now contain as little as 15% fishmeal and 15% fish oil. And recent advances in research into alternative and novel raw materials for feed have enabled fish feed companies to develop salmon feed formulations that are completely fishmeal-free while delivering equal performance in terms of fish growth and health.

Another aspect of the sustainability of farm-raised salmon is the amount of wild fish meal and fish oil used in feed. Fish meal and fish oil are harvested from sustainable stocks of fish for which there is little or no demand for human consumption (anchovy, mackerel etc) and also from trimmings left over from other fish processing. This fishery doesn't just supply meal and oil to farm-raised salmon, but also to other aquaculture species as well as the pork, poultry, and pet food industries.

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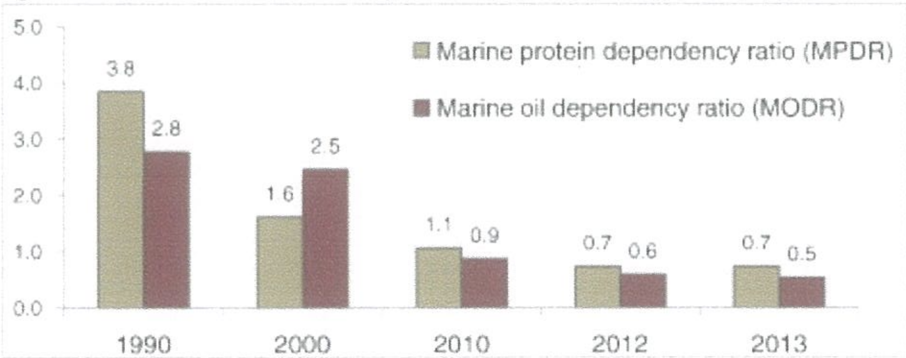
2 While most of the water use is driven by water required to grow feed, LCAs estimates of water use for aquaculture take into account any freshwater usage for tank-rearing, e.g. in hatcheries.

3 Unless otherwise noted, all FCR figures for farm-raised salmon are "economical FCR" or eFCR, which is higher than the "biological FCR". The eFCR takes fish mortalities and losses into account, and therefore reflects actual feed demand.

Historic estimates as high as 3, 5, 7 or even 10 kg of wild forage fish to produce one kg of farm-raised salmon have been published in the literature. The most commonly referenced figures come from Tacon and Metian (2008) which put forward a FIFO of 4.9:1 for farm-raised salmon, and Naylor et al. (2009) – who used 5:1. However, more up to date and accurate data indicate that the FIFO ratio is 1.4:1, meaning that it takes about 1.4 kilograms of wild fish to produce 1.0 kilogram of farm-raised salmon. At Norwegian salmon farms, wild fish per kg of salmon dropped from 4.4kg in 1990 to only 0.7kg in 2013 (Ytrestøyl et al. 2015). Since 1990 the ratio of marine protein to produce 1kg of salmon protein has dropped from 3.8kg of marine protein and 2.8kg of fish oil to only 0.7kg of marine protein and 0.5kg of fish oil.4 B.C. salmon farmers confirm that these figures are similar to those derived in their own internal FCRs and marine nutrient ratios.

Figure 3: Ratio of fish oil and marine protein to salmon farming protein by year, 1990 to 2013



Source: Ytrestøyl et al. 2015

While FIFO is useful to measure raw material usage in farm-raised salmon diets, some argue that it is not a rigorous indicator for environmental or ecological sustainability of salmon farming. Alternative measures to FIFO include the marine nutrient dependency ratio (MNDR), and more specifically, one for protein (MPDR) and one for oil (MODR). These measures are included as requirements under the Aquaculture Stewardship Council (ASC) Salmon Standard, with the acceptable Fishmeal Forage Fish Dependency Ratio (FFDRm) for grow-out at < 1.35 and the Fish Oil Forage Fish Dependency Ratio (FFDRo) for grow-out set < 2.95 (ASC, 2012).

In B.C., the average FFDR has decreased since 2013, and is well below the standards set by the Aquaculture Stewardship Council, indicating a continuing shift away from reliance upon wild marine resources in feed (BCSFA 2016).

4 Note: fish meal and oil are sourced from the same fish

The nutritional efficiency measures above show that B.C. farm-raised salmon are much more efficient converters of feed to flesh than other widely-consumed food animal, and use of fish meal and fish oil in feed is becoming more and more sustainable. Furthermore, nutritional efficiency measures drive a major portion of the environmental impacts and also account for some of the differences in results between various studies, some of which are based on FCRs and FIFO that are not currently representative.

4.2 Biodiversity

A widely cited study from the U.N. Food and Agriculture Organization (FAO) by Steinfeld et al. (2007) reports that livestock is now 20% of the earth's land animals and is spread over 30% of the earth's area. The authors went so far to say that "the livestock sector may well be the leading player in the reduction of biodiversity, since it's the major driver of deforestation."

Aquaculture has mixed impacts on biodiversity. A number of studies have reported that aquaculture can have beneficial impacts on pelagic fish around farm sites, but a negative impact on benthic species. James Diana (2009) reported positive and negative impacts on biodiversity of aquaculture systems. Those impacts relevant to B.C. are summarized below:

Negatives:

- Escapement and genetic alteration of wild stocks (not in B.C.)
- Effluents effect on water quality, particularly in fresh water systems
- Inefficient resource use (specifically, the use of fish and fish meal in aquaculture)

Positives:

- Reduces pressure on wild stocks
- Aquaculture can be used to stock depleted wild stocks
- Effluents and waste can increase local wild stocks of certain species

4.3 Trends in Environmental Impacts of Aquaculture

A 2014 paper from the World Resources Institute predicted that aquaculture will more than double by 2050 from 2010 levels. However, a trend towards replacing fish-based ingredients with crops based ingredients for salmonid species – without considering other trends in aquaculture resource use - would result in higher eutrophication potential and indirect land use, but reduced freshwater use and reduced GHG emissions.

In addition to improved FCRs, salmon farming and aquaculture in general has moved more towards using a higher percentage of vegetable-based feed ingredients. Swapping ingredients affects the life-cycle environmental impacts, because the feed source drives most of the impacts.

That said, a number of other trends in resource use in aquaculture will continue to reduce the impact on the environment, including:

a) improved efficiency in input use;
b) a shifting energy supply;
c) adoption of current best practices; and
d) replacing fished-based ingredients with crop-based ingredients

Table 7: Factor Growth in Global Aquaculture and Associated Environmental Impacts (2010 to 2050)

	Production	Land Use for Feeds	Wild Fish Used for Feed	Freshwater Consumption	Freshwater Eutrophication	Marine Eutrophication	Greenhouse Gas Emissions
Baseline	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Replacing fish-based ingredients (salmonids only)	2.3	3.9	0	2.3	2.7	3.6	2.2
Combined effects (see list in text)	2.3	1.9	1.5	2.1	1.9	1.9	0.8

Source: Waite et al. 2014. Figures refer to an x-fold increase in 2050 relative to 2010.

5. Overall Results

British Columbia salmon farming clearly exhibits lower environmental impacts than beef across all of the investigated environmental measures. Although energy use is quite comparable between beef and salmon farming, beef production has much higher GHG emissions per kg, primarily because of the additional methane released by cattle. Authors that compared several species found that beef had higher eutrophication potential than salmon, although they reported a wide range of values. Compared with chicken and pork, salmon farming has significantly better performance in GHGs, water use, and land use.

Table 8: Summary of the Environmental Impacts per kg of B.C. Salmon farming compared to Livestock

	Energy (MJ)	Greenhouse Gases (kg CO_2eq)	Water (litres)	Land (m^2)	Eutrophication (g of PO_4-eq)
B.C. Salmon	31.7	2.2	1,400	4.3	47.4
Beef	44.8	37.2	15,400	68.3	55.0
Poultry	23.1	5.1	4,300	9.9	5.0
Pork	23.6	6.4	6,000	11.5	12.7

Source: Estimates for BC salmon farming are based on Canada-specific studies. When a meta-analysis gave ranges of values for other livestock products, the middle value was used and an average of the studies taken. For the sake of consistency, the water values from the Marine Harvest report were used.

Valuing Environmental Impacts

Based on the valuation of greenhouse gases, water use, and eutrophication, B.C. salmon farming has a lower total environmental cost than beef, chicken, or pork.

For policy makers performing cost-benefit analysis, they must often quantify the value of environmental services in order to weigh the costs and benefits of a new regulation or program. Using these estimates, we can make a preliminary case for the relative total environmental impacts between salmon farming and other types of livestock. A crucial limitation of this analysis is that a lack of data or valuation estimates for environmental services limits what can be quantified.

Table 9: Valuation of Environmental Effects by Type ($2016)

Type	Value	Unit	Source
Greenhouse Gas Emissions	$30	per ton of CO_2-eq	Current value of B.C.'s Carbon Tax.
Water	$126	per 1000m^3	FAO Economic Valuation of Water: Irrigation Price, based on US estimates
Eutrophication	$7.3	Per kg of PO_4-eq	UNEP, Economic Valuation of Waste Water. Based on cost of 4 to 6 euros per kg of PO_4 to clean up.

Using the environmental effects values from Table 9 and the estimated environmental impacts from Table 8, the monetized values of environmental impacts by farmed species are compared in Table 10 below.

Table 10: Estimated Valuation of Environmental Impacts for B.C. Salmon Farming and Livestock ($/kg)

	Greenhouse Gases	Water	Eutrophication	Total
B.C. Salmon	$0.07	$0.18	$0.35	$0.59
Beef	$1.12	$1.94	$0.40	$3.45
Chicken	$0.15	$0.54	$0.04	$0.73
Pork	$0.19	$0.75	$0.09	$1.04

Table 10 shows that the value of environmental impacts of other protein sources are significantly higher than farm-raised B.C. salmon. At $0.73/kg, the environmental "cost" of chicken is 24% higher than B.C. farm-raised salmon. Pork ($1.04/kg) is 76% higher, and beef ($3.45/kg) is 486% higher than B.C. farm-raised salmon.

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