Environ. Sci. Technol. 2009 *43,* 8730–8736

Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems

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Received April 3, 2009. Revised manuscript received September 26, 2009. Accepted September 30, 2009.

We present a global-scale life cycle assessment of a major food commodity, farmed salmon. Specifically, we report the cumulative energy use, biotic resource use, and greenhouse gas, acidifying, and eutrophying emissions associated with producing farmed salmon in Norway, the UK, British Columbia (Canada), and Chile, as well as a production-weighted global average. We found marked differences in the nature and quantity of material/energy resource use and associated emissions per unit production across regions. This suggests significant scope for improved environmental performance in the industry as a whole. We identify key leverage points for improving performance, most notably the critical importance of least-environmental cost feed sourcing patterns and continued improvements in feed conversion efficiency. Overall, impacts were lowest for Norwegian production in most impact categories, and highest for UK farmed salmon. Our results are of direct relevance to industry, policy makers, eco-labeling programs, and consumers seeking to further sustainability objectives in salmon aquaculture.

Introduction

Food provision is a key driver of anthropogenic environmental change (*1*, *2*). Historically much research has focused on the proximate, ecological impacts of food production. Increasing awareness of the cumulative contributions made by food systems to macroscale environmental change through resource use and emissions is spurring a wealth of new research. This work contributes to the ongoing shift in thinking about environmental management in food systems from local through regional and global scales. It informs dialogues as diverse as the policy relevance of production-versus consumption-based regulation, product eco-labeling, and the identification of key leverage points for reducing food system emissions (*3*−*5*).

In recent decades, Atlantic salmon (*Salmo salar)* farming has become a thriving component of the global finfish aquaculture sector. In its early years the industry supplied high-end markets, serving out-of-season demand for capture fisheries products. Farmed salmon has since become a global supercommodity, as evidenced by its year-round, almost universal availability, product consistency, and high production volume (*6*, *7*).

Examining the macroscale environmental dimensions of producing farmed salmon requires consideration of the entirety of the interlinked series of industrial activities that comprise the salmon supply chain. This includes the production, processing, and transportation of diverse salmon feed inputs, as well as the production and on-farm use of material and energy resources (*4*).

Life cycle assessment (LCA) is an ISO-standardized biophysical accounting framework used to (1) compile an inventory of material and energy inputs and outputs characteristic of each stage of a product life cycle and (2) quantify its contributions to a specified suite of resource use and emissions-related environmental impact categories (*8*, *9*). The framework has been previously adapted and applied to evaluate crop agriculture, animal husbandry, fisheries, and aquaculture production systems (*10*−*22*).

Here, we report a subset of the cradle-to-farm-gate resource use and environmental impacts of salmon farming in each of the four major production regions as well as a weighted global average. Specifically, cumulative energy and biotic resource use, along with the greenhouse gas, acidifying, and eutrophying emissions associated with the production of one live-weight tonne of farmed salmon are reported. Drivers of environmental performance in each region are evaluated, and a suite of improvement recommendations is advanced. The level of resolution achieved represents a significant advance over previous analyses restricted to single regions and based on more limited data sets (*12*−*14*). The research outcomes are intended to inform the following: the optimization of supply chain environmental performance by salmon feed producers and salmon farming companies; environmental policy and regulation for the salmon farming industry; eco-labeling and consumer awareness campaigns promoting sustainable seafood production and consumption; and consumers of salmon products.

Methods

ISO-compliant life cycle assessment methodology (*8*, *9*) was used to evaluate the cumulative energy use (MJ), biotic resource use (net primary productivity as measured in C) (*23*), and greenhouse gas (CO_2-e), acidifying (SO_2-e), and eutrophying (PO_4-e) emissions associated with the cradle-to-farm-gate production of Atlantic salmon in Norway, the UK, Chile, and British Columbia, Canada (hereafter simply Canada). The system boundaries of our analysis appear in Figure 1.

Foreground data were collected directly from globally and regionally important salmon feed and farming companies. In each case, detailed questionnaires were distributed to head offices soliciting details of aggregate operational material/energy inputs and production associated with each company's operations in each region in 2007. Follow-up correspondence with key personnel in each region was undertaken to ensure clarity and consistency in reported data. To protect confidentiality, resulting data were compiled into production-weighted average inputs to operations in each region. As prior analyses indicate that infrastructure contributes neg-

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10.1021/es9010114 CCC: $40.75
Published on Web 10/23/2009

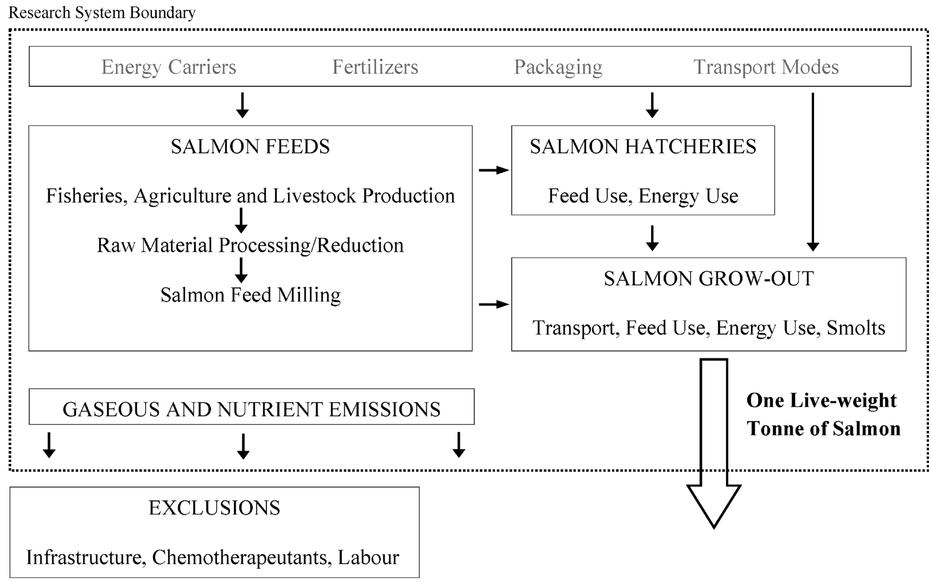

FIGURE 1. System boundaries for a cradle-to-farm-gate LCA of live-weight salmon production in Norway, the UK, Canada, and Chile (gray font denotes background system data derived from the EcoInvent database, modified as appropriate to conform to regional conditions).

ligibly to the life cycle impacts of salmon culture systems (*13*), we focused exclusively on quantifying operational inputs (direct material/energy use) at all stages of the production process. Chemotherapeutant use on salmon farms was also excluded as our analysis did not consider toxicological effects. Our industry engagement efforts yielded data representing ~70% and ~24% of 2007 global farmed salmon feed and Atlantic salmon production volumes, respectively, with at least 15% of production volumes represented for each region.

Background inventory data (i.e., for the provision of energy carriers, transport modes, and fertilizers, etc.) were derived from the EcoInvent database (*24*), and modified where appropriate to reflect regional conditions (for example, energy mixes underpinning electricity production, type and source of fertilizer mixes for agriculture, etc.). All other (foreground) processes, including feed input raw material production, processing and transport, hatcheries and farm-level inputs were modeled using inventory data and standardized assumptions as described in Supporting Information.

Life cycle contributions to cumulative energy use were calculated following the Cumulative Energy Demand method (*25*), which accounts for conversion efficiencies of energy carriers. Global warming, acidifying, and eutrophying emissions were quantified using the CML 2 Baseline 2001 method (*8*) and SimaPro 7.1.8 software (*26*). Biotic resource use, in which the net primary productivity required to sustain production of feedstuffs while accounting for their trophic level, yield,and carbon content, was quantified separately following the method described by Pelletier and Tyedmers (*12*). Gross chemical energy content was used as the basis for all coproduct allocation for crop-, fish-, and livestock-derived feed inputs (*27*). A full description of our modeling methods, inputs, and assumptions appears in Supporting Information.

All impacts were calculated per live-weight tonne of salmon or salmon feed produced in each region and also scaled up to estimate a 2007 production-weighted global average. Supply chain impacts were assessed to identify impact hotspots and key leverage points for environmental performance improvements within and between production regions. Sensitivity analyses and scenario modeling were undertaken to test the importance of key methodological assumptions and strategies to reduce impacts (see Supporting Information).

TABLE 1. Aggregate Life Cycle Inventory Data for Salmon Farming and Salmon Feed Milling in Norway, the UK, Canada, and Chile in 2007

	Norway	UK	Canada	Chile
inputs per tonne of salmon				
feed (t)	1.103	1.331	1.313	1.493
feed transport (t-km)	290.3	321.7	316.0	298.7
smolts (kg)	17.4	22.2	16.0	15.0
smolt transport (t-km)	1.2	3.9	3.2	3.0
total on-farm energy use (MJ)	646.8	904.0	933.7	1199.0
farm-level emissions (kg N/P)[a]	41.1/5.2	58.7/8.5	51.4/13.6	71.3/12.6
inputs per tonne of feed				
energy for feed milling (MJ)	902.6	1090.1	1393.2	1118.7
feed composition[b] (%)				
crop-derived meals/oils	35.3/6.1	32.3/1.1	43.4/5.1	36.9/5.8
animal-derived meals/oils	–	–	16.8/3.1	15.1/0
fish-derived meals/oils	33.1/25.5	40.5/26.1	20.9/10.7	25.1/17.1

[a] Calculated using nutrient balances based on N and P content of feeds and live-weight salmon. [b] For detailed region-wide feed inputs modeled see Table S1.

Results

Life Cycle Inventory Results. Detailed feed composition and inventory data sources for the production, processing, and transport of all feed inputs (including individual crop, fisheries, and livestock supply chains) are available in Supporting Information Tables S1–S4. Aggregate farm-level inputs and modeled nutrient emissions, inputs to feed milling, and coarse feed composition data for all four production regions appear in Table 1 (for details regarding energy use by type and transport distances by mode, see Supporting Information Tables S5 and S6).

TABLE 2. Life Cycle Impact Assessment (Both Total Impacts and Proportional Contributions) for the Production of One Live-Weight Tonne of Salmon in Norway, UK, Chile, and Canada in 2007, Including the Production-Weighted Global Average (For Breakdown of Values See Table S7)

	CEU (GJ)	BRU (kg C)	GHG Em. (kg CO_2-e)	Acd. Em. (kg SO_2-e)	Eut. Em. (kg PO_4-e)
Norway	26.2	111,100	1,790	17.1	41.0
UK	47.9	137,200	3,270	29.7	62.7
Canada	31.2	18,400	2,370	28.1	74.9
Chile	33.2	56,600	2,300	20.4	51.3
Average[1]	31.1	89,400	2,160	20.4	49.3

Feeds | Smolts | Farm Energy | Farm N/P Emissions

[1] Weighted average calculated using 2007 production volumes of 626, 386, 132, and 102 kilotonnes live weight for Norway, Chile, the UK, and Canada, respectively.

On-farm material and energy use is markedly different among regions (Tables 1, S5). Gross feed conversion ratios (FCR), the amount of feed used to raise a tonne of salmon accounting for all forms of feed loss, vary from 1.1 tonnes of feed per tonne of fish produced in Norway to nearly 1.5:1 in Chile. Farm-level energy use is also highly varied, with Norwegian operations the most efficient. Relative to Norway, on-farm energy use per tonne of salmon raised is 40%, 44%, and 85% higher on UK, Canadian, and Chilean farms, respectively. Modeled farm-level nutrient emissions also vary, and are influenced by FCR and the nitrogen/phosphorus content of feed ingredients. For example, the inclusion of relatively P-rich poultry coproduct meals in Canada and Chile explains the higher farm-level phosphorus emissions in these regions. Overall, Norwegian operations have consistently lower on-farm material/energy use and emissions (Tables 1, S5).

Not surprisingly, inputs to feeds vary markedly between regions (Tables 1, S1). Interestingly, marked heterogeneity remains even when inputs are aggregated according to origin-type (Table 1). Crop-derived inputs account for only one-third of UK diets but almost 50% of those milled in Canada. In contrast, the proportion of fish-derived ingredients is the lowest in Canada (31.6%) and Chile (42.2%), and much higher in Norway (58.6%) and the UK (66.6%). Livestock coproducts make small but noteworthy contributions to feeds milled in both Canada (19.9%) and Chile (15.1%) (Tables 1, S1).

Both the amounts and sources of energy used for feed milling also vary considerably among regions (Tables 1, S6). Norwegian feed milling is the least energy-intensive, whereas Canadian milling operations modeled required 50% more energy inputs per tonne of feed produced (Tables 1, S6).

Life Cycle Impact Assessment Results. Feed production dominates cradle-to-farm-gate life cycle impacts of farmed salmon production in all impact categories other than eutrophying emissions (Table 2). For the production-weighted global average salmon, feed accounts for 93% of farm-gate cumulative energy use, 100% of biotic resource use, and 94% of global warming and acidifying emissions (Table 2). In contrast, farm-level nutrient emissions contribute 85% of eutrophying emissions with the balance coming from feed production. Farm-level energy use is the second greatest contributor to cumulative energy use (4%), greenhouse gas (3%), and acidifying (3%) emissions (Table 2). These patterns are very consistent across regions (for a detailed breakdown of values see Table S7).

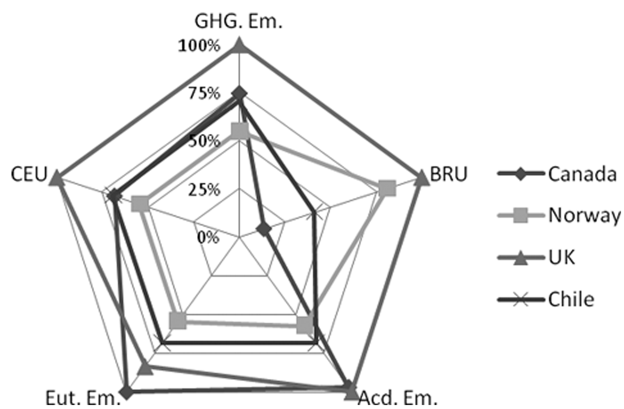

FIGURE 2. Comparative cumulative energy use (CEU), biotic resource use (BRU), greenhouse gas emissions (GHG. Em.), acidifying emissions (Acd. Em.), and eutrophying emissions (Eut. Em.) for the farm-gate production of farmed salmon in Norway, UK, Canada, and Chile in 2007 relative to the poorest performer (set to 100%) in each impact category.

Despite these similar patterns, differences in the scale of life cycle impacts among regions are pronounced (Table 2, Figure 2). In all impact categories besides biotic resource use, Norway has the lowest impacts per unit production, whereas impacts are consistently highest in the UK (Table 2). Given the predominant influence of feeds on overall impacts, these differences reflect variation in both FCR and feed composition among regions. Importantly, despite differences in FCR, this pattern is markedly different for biotic resource use, which is lowest in Canada, followed by Chile, Norway, and the UK (Table 2, Figure 2). Greater BRU in Norway and the UK results from higher inclusion rates of fish inputs (Table 1) together with their greater reliance on fish meals and oils derived from higher trophic level species such as blue whiting (*Micromesistius poutassou*) (Table S1). Also of note is the degree of variation in eutrophying emissions, which are markedly higher in the UK and Canada (Table 2, Figure 2). For the UK, this is due to the high inclusion rate of relatively phosphorus-rich fish-derived inputs, eutrophying emissions from fish reduction, and a relatively high FCR, while in Canada the inclusion of phosphorus-rich poultry meal (15% by mass) contributes over 50% of phosphorus emissions. For detailed life cycle impact assessment results for each region see Tables S7−S11.

In light of the critical role of feeds, it is worth considering the comparative life cycle impacts of feed production within and among regions, along with key drivers of environmental performance. In general, fish- and livestock-derived inputs contribute disproportionately on a per-unit mass basis when compared with crop-derived inputs. In Norway and the UK, fish-derived inputs contributed an average of 71% and 84%, respectively, across impact categories while only accounting for 58% and 66%, respectively, of the mass of the feeds milled. Similarly, in Canada and Chile, fish- plus livestock-derived inputs accounted for just over 50% of the mass of all feed inputs (Table 1) but an average of 75% of impacts up to the feed mill gate (Tables S8−S11).

There is, however, considerable variation in the impacts associated with specific ingredients (Tables S8−S11) with overlap between the most impact-intensive crop-derived ingredients (e.g., wheat gluten meal) and the least impact-intensive fisheries ingredients (e.g., fish meal made from menhaden (*Brevoortia spp.*)). Conversely, the production of meals and oils from mixed-whitefish trimmings in the UK are many times more impactful than soy meal largely because the fisheries that supply the raw material are fuel intensive and meal and oil yields from trimmings are low (Tables S8−S11). In general, raw material production and processing is much more important than transport of feed ingredients while feed milling contributes negligibly in all regions (Table 3).

The impacts of feed production are similarly variable among regions (Table 3). With the exception of biotic resource use, impacts per tonne of feed are lowest in Chile and highest in the UK. Canada has the lowest biotic resource use due to the lower inclusion rates and trophic levels of fish inputs.

Sensitivity Analysis and Scenario Model Results. We tested the importance of the field-level nitrous oxide emission factor used in our agricultural systems models by substituting extremes of the range of values (0.3−3.0% of total N applied) provided by the IPCC (*28*) for the recommended default value of 1% used throughout our analysis in all crop systems underpinning Norwegian salmon production. At the low end of the range (0.3%), estimated salmon farm-gate GHG emissions were 3.5% lower than in our base case analysis. At the high end of the range, estimated emissions were 14% higher than the base case (Table S12A).

Since feed use is a pivotal driver of environmental performance, we modeled the effect of lowering the FCR across all regions to that obtained in Norway, the region with the lowest feed use in 2007. Results suggest that global average greenhouse gas emissions per tonne of farmed salmon produced would decrease by 10% (Table S12B), effectively reducing cumulative CO_2-eq. emissions from salmon farming by over 260 kilotonnes per year based on 2007 production volumes. In such a situation, comparative impacts among regions would be much closer, with Chile emerging as the most efficient producer in all impact categories other than biotic resource use.

We also examined the impact of changes in feed composition over time within a region by substituting average inputs to feeds milled in Canada in 1997 and 2003 into our 2007 Canadian production model (Table S13). Interestingly, these older composite feed inputs resulted in modeled greenhouse gas emissions 16−21% lower per tonne of salmon produced than our year 2007 results (Table S12C) largely due to previously lower use of poultry products.

Finally, we explored potential greenhouse gas emission reductions through feed input substitution by modeling the replacement of all fish meals and oils used in 2007 Norwegian production with products with impacts equivalent to menhaden meal and oil (the least GHG-intensive fisheries ingredients evaluated) (Table S12D). Such a substitution would reduce farm-gate emissions by 57%.

Discussion

Our global-scale life cycle assessment of this food supercommodity yields a rich suite of information and insights relevant to informing how we conceive of and seek to further sustainability objectives in farmed salmon production. Of first-order interest is the striking variability in the quantity and nature of resources underpinning the production of this seemingly uniform commodity. Despite the high degree of ownership concentration and vertical integration in the salmon farming sector (*6*), as well as the standardized nature of net-pen production, our inventory data indicates considerable differences across the four major farming regions. Obviously different is the feed conversion ratio, which varies as much as 35% among regions (we should note that outbreaks of infectious salmon anemia in Chile in late 2007 may partially explain the high FCR in this region). Notable too is the diversity of inputs to feeds, with each region drawing from a suite of regionally and globally available crop-, fish-, and (in the case of Canada and Chile) livestock-derived inputs. Similarly striking are the variable energy requirements for feed milling and salmon farming operations. Understanding this variability is essential to interpreting inter-regional differences in the environmental performance of farmed salmon production.

Feeding Farmed Salmon. Consistent with previous research (*12*−*17*), we found feed provision to be the single most important contributor to resource use and emissions associated with the farm-gate production of salmonids cultured in net-pen systems. Given the wide range of impacts characteristic of the production of various crop-, livestock-, and fish-derived feed ingredients (*12*), it would thus appear that significant opportunities exist for dramatically improving the overall environmental performance of salmon production through a focus on the development of least-environmental-cost (as opposed to least-economic-cost) feed formulations. Certainly, this is evidenced by the dramatic decrease in farm-gate greenhouse gas emissions (57%) that could result from a hypothetical substitution of all higher-impact fish meals and oils in Norwegian production with less GHG-intensive products such as menhaden meal and oil (although stock capacities must also be considered). Such large differences are to be anticipated given the wide range of meal and oil yield rates between species and the fuel use intensities of fisheries that target them (*29*).

Although it is essential to maintain a nutritional profile most conducive to fish performance, the substitutability of ingredients within and between ingredient types has already been widely investigated and evidences considerable flexibility and opportunity (*12*). Of particular interest is the possibility of replacing fish and animal protein meals and oils with vegetable-based equivalents, which, in many cases, will reduce associated impacts (*12*). However, this requires

TABLE 3. Cradle-to-Mill Gate Life Cycle Impact Assessment for the Production of One Tonne of Average Salmon Feeds Milled in Norway, UK, Canada, and Chile in 2007, Including Contributions from the Production, Processing, and Transport of Crop-, Livestock-, and Fish-Derived Ingredients

	CEU (GJ)	BRU (kg C)	GHG Em. (kg CO_2-e)	Acd. Em. (kg SO_2-e)	Eut. Em. (kg PO_4-e)
Norway	**22.6**	**101,000**	**1,530**	**14.3**	**5.7**
Crop	5.5	212	443	5.9	1.9
Fisheries	15.6	101,000	1,030	8.2	3.6
Milling[2]	1.5	-	57	0.2	0.2
UK	**33.6**	**102,000**	**2,290**	**21.3**	**7.2**
Crop	4.1	137	306	4.2	1.3
Fisheries	27.3	102,000	1,860	16.8	5.8
Milling[2]	2.2	-	130	0.3	0.1
Canada	**22.4**	**14,100**	**1,710**	**20.4**	**6.9**
Crop	3.7	234	337	7.0	2.2
Fisheries	8.8	13,300	568	4.5	2.1
Livestock	8.0	564	716	8.7	2.5
Milling[2]	1.9	-	89	0.2	0.1
Chile	**20.5**	**37,900**	**1,430**	**12.8**	**4.8**
Crop	4.8	268	335	4.6	1.0
Fisheries	8.8	37,400	565	3.2	2.3
Livestock	5.2	193	426	4.7	1.4
Milling[2]	1.7	-	104	0.3	0.1
Average[1]	**23.3**	**70,900**	**1,590**	**15.0**	**5.6**
Crop	4.9	226	379	5.3	1.5
Fisheries	13.8	70,500	913	7.1	3.3
Livestock	2.5	116	215	2.4	0.7
Milling[2]	2.0	-	85	0.2	0.1

Production   Processing   Transport

[1] Weighted average calculated using 2007 production volumes of 626, 386, 132, and 102 kilotonnes live weight for Norway, Chile, the UK, and Canada, respectively. [2] Includes energy use for milling, and also packaging.

attention to the environmental performance of specific products. As a general rule, crop-derived ingredients are less resource and emissions intensive than fish- or livestock-derived ingredients, but there are clearly exceptions. For example, vegetable materials such as canola oil and wheat gluten meal are actually more resource and emissions intensive than the most efficient fisheries products considered (e.g., menhaden meal and oil).

The influence of feed composition on the environmental performance of salmon production is evident in the high degree of variability in the impacts of feeds produced in each region. It is also reflected in the marked differences in modeled GHG emissions associated with Canadian salmon production as a function of shifting inputs to feeds between 1997, 2003, and 2007, where emissions increased largely due to greater use of poultry products. Certainly, all regions would see marked improvements in environmental performance through the substitution of high-impact ingredients such as blue whiting meals/oils in Norway, mixed whitefish trimmings meals/oils in the UK, and poultry-derived meals and oils in Canada and Chile. However, the scale of potential substitution is ultimately constrained by alternative product availability on global markets (for example, menhaden stocks are insufficient to satisfy all fish meal demands). It is also influenced by certain (surmountable) cultural and regulatory factors. For example, the high rate of fish meal and oil use in UK production partially reflects the demands of some domestic retailers for salmon produced on a "natural" high fish diet and the dictates of product quality labels such as the French Label Rouge standard to which some UK fish are produced. A further example of a regulatory constraint is the ban on using animal processing coproduct meals in European production. This situation results in a number of seeming incongruities including that European salmon production is partially underpinned by Brazilian soy production, while Chilean salmon consume European poultry processing coproducts that were themselves produced using Brazilian soy.

It should also be noted that feed ingredient substitution may have environmental implications beyond the range of issues considered here. For example, increasing soy cultivation in Amazonia as a result of growing global demands for feed protein has been identified as a major driver of deforestation in the region as well as a contributor to greenhouse gas emissions associated with land-use change (not accounted for in our analysis) (*30, 31*). Substituting fish and poultry meals with soy meal in aquaculture may exacerbate these problems. The results of this analysis should therefore be used in concert with broader considerations of the proximate ecological and socioeconomic implications of alternative feed sourcing patterns.

Non-feed Composition Related Environmental Performance Drivers. Beyond feed composition, the importance of feed conversion ratio to cumulative impacts of farm-gate salmon production cannot be overstated. FCR's in salmonid production are notably lower than those characteristic of most terrestrial animal husbandry systems, since poikilotherms need not divert a substantial fraction of feed energy to maintain body temperature as is the case with homeotherms. However, considerable margin for improvement remains. Interregional differences in FCR (1.1−1.5:1) is a key factor in the overall patterns of environmental impacts observed for all impact categories besides biotic resource use, where the trophic level and inclusion rates of fish products are more important. If all regions achieved an FCR similar to that of Norway, where feed conversion ratios are lowest, the cumulative impacts of global salmon production would be much reduced. Moreover, the relative ranking of environmental performance among regions would change, with Chile moving to the fore in all impact categories other than biotic resource use. Given the scale of production of this global supercommodity, such improvements may have nontrivial implications for cumulative anthropogenic resource use and emissions. As FCR is influenced by a combination of factors including feed composition, feeding technology and feed loss, fish size, fish growth, disease, escapes, and mortality, continued improvements in all of these areas will be pivotal to improving the overall environmental performance of farmed salmon production worldwide.

Although feed provision is a central driver of environmental performance according to the criteria considered in this analysis, other aspects of the salmon production life cycle bear consideration. For example, our inventory analysis suggests a high degree of variability in energy use and emissions associated with feed milling between regions. While perhaps somewhat influenced by regional feed composition, these differences are more likely the result of technological variables such as equipment age and efficiency along with operational differences that can result from the number of feeds milled and the duration of milling runs. Given the increasing costs of energy, one would anticipate that companies, in the long term, would reap both economic and environmental benefit from transitioning to best available technologies and lowest-impact milling practices. Another area of significant variability among regions is the level of on-farm energy use and associated emissions, which are lowest in Norway and highest in Chile. Attention is required to streamlining production toward the most efficient performance potential.

Comments on Methods and Assumptions. We should also make note of our assumptions and their influence on the research outcomes. We have endeavored to model the diverse range of crop, fisheries, and livestock systems providing inputs to salmon feeds in a rigorous, systematic, and broadly representative manner—for example, by applying IPCC (*28*) default emission factors for field-level nitrous oxide emissions in agriculture across systems and regions. As suggested by our sensitivity analysis, the apparent farm-gate greenhouse gas intensity of farmed salmon production is roughly 14% higher when field-level nitrous oxide emissions for agricultural inputs are at the high end of the uncertainty range provided by IPCC. Nonetheless, given that feed inputs are purchased on commodity markets and drawn from a large pool of production systems, we are confident that our use of default emission factors to represent average conditions is defensible.

Also important is our choice of allocation principle. In feed input production systems yielding coproduct outputs, we have partitioned resource use and emissions according to the gross chemical energy content of coproduct streams. We believe that this principle accurately reflects the flows of material and energy, and associated emissions, attributable to the functioning of the product system, which is at its root motivated by the basic human need for food energy. Allocation according to energy content allows apportioning of burdens according to an inherent biophysical property of the raw material which is distributed between coproducts in a quantifiable manner (*27*). As such, this approach speaks directly to the efficiency with which the product system produces food energy and is consistent with ISO (*9*) recommendations that the allocation criterion be based on the function of the coproducts. For a full discussion of this and alternative allocation principles, see Ayer et al. (*27*) and Pelletier and Tyedmers (*12*).

Farmed Salmon in Perspective. Although our analysis indicates the possibility of substantial reductions in the life cycle resource use and emissions characteristic of net-pen salmon aquaculture worldwide, it should be noted that, based on the subset of environmental performance criteria considered here, farmed salmon products compare favorably to certain livestock products in some respects. For example, our results suggest that, on average, GHG emissions from salmon farming are lower than has been reported for some competing meat sources. At a global average farm-gate GHG emission intensity of 2.15 t CO_2-e/t, farmed salmon has markedly lower emissions than has been reported for either Swedish pork (3.3−4.4 t CO_2-e/t) (*19*) or Belgian beef (14.5 t CO_2-e/t) (*20*). In contrast, it is approximately 50% more GHG-intensive than U.S. poultry (1.4 t CO_2-e/t) (*22*) and 27% higher than average global capture fisheries (1.7 t CO_2-e/t) (*29*) (the latter estimate includes reduction fisheries and would hence be higher for fisheries for human consumption). This suggests that the application of carbon taxes might render farmed salmon more competitive than several alternative animal husbandry products. However, the environmental performance of farmed salmon may be relatively poor according to other measures. For example, biotic resource use will be substantially higher in salmon production due to the use of fish meals and oils—particularly those derived from high trophic level species. Haberl et al. (*32*) estimate that humans currently appropriate close to 23% of global net primary productivity and predict an increase to

50% by 2050. As pointed out by Imhoff et al. (*33*), this is a remarkable level of appropriation for a species representing only 0.5% of planetary heterotroph biomass, and has significant consequences for energy flows within food webs, the biodiversity that ecosystems can support, the composition of the atmosphere, and the provision of important ecosystem services. In this respect, producing farmed salmon (and other carnivorous species) may be considerably less eco-efficient than terrestrial livestock production.

It should also be noted that, given the diverse potential product forms and modes of distribution by which farmed salmon products may reach consumers (*34*), policies and regulations designed to further sustainability objectives in the salmon farming industry should take account of resource use and emissions associated with the full cradle-to-grave supply chain (publications forthcoming). Nonetheless, given the general importance of the production stage to food system supply chain environmental impacts, this global analysis of farm-gate salmon production provides information relevant to environmental supply chain management by producers and retailers of farmed salmon products, policy makers seeking to influence more sustainable practices, and consumer awareness campaigns designing and promoting sustainability assessments of salmon aquaculture.

Acknowledgments

This work was supported by the Lenfest Ocean Program of the Pew Charitable Trusts, the Esmée Fairbairn Foundation, the Oak Foundation; the Lighthouse Foundation, the Killam Trust, and the Natural Science and Engineering Research Council of Canada. It was made possible by the generous cooperation of our industry collaborators worldwide, and facilitated by the data collection efforts of Peter Bridson and Stephany Gonzalez in the UK and Chile respectively.

Supporting Information Available

Detailed discussion of model development and methods, results, and additional figures and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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ES9010114