Environmental benefits of novel non-human food inputs to salmon feeds

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Abstract

Global population growth and changing diets increase the importance, and challenges, of reducing the environmental impacts of food production. Farmed seafood is a relatively efficient way to produce protein and has already overtaken wild fisheries. The use of protein-rich food crops, such as soy, instead of fishmeal in aquaculture feed diverts these important protein sources away from direct human consumption and creates new environmental challenges. Single cell proteins (SCPs), including bacteria and yeast, have recently emerged as replacements for plant-based proteins in salmon feeds. Attributional life cycle assessment (ALCA) is used to compare salmon feeds based on protein from soy, methanotrophic bacteria, and yeast ingredients. All ingredients are modeled at the industrial production scale and compared based on seven resource use and emissions indicators. Yeast protein concentrate showed drastically lower impacts in all categories compared to soy protein concentrate. Bacteria meal also had lower impacts than soy protein concentrate for five of the seven indicators. When these target meals were incorporated into complete feeds the relative trends remain fairly constant, but benefits of the novel ingredients are dampened by high impacts from the non-target ingredients, Particularly, primary production requirements (PPR) are about equal and constant across all feeds for both analyses since PPR was driven by fishmeal and oil. The bacteria-based feed has the highest climate change impacts due to the use of methane to feed the bacteria who then release carbon dioxide. Overall, the results of this study suggest that incorporating SCP ingredients into salmon feeds can help reduce the environmental impacts of salmon production. Continued improvements in SCP production would further increase the sustainability of salmon farming.

Introduction

More efficient food systems are needed to feed a rapidly growing human population in environmentally sustainable ways. How to feed >9 billion people by the year 2050[1] is a major question, but doing so without further degrading or destroying natural ecosystems and their capacity to support food production adds a significant degree of difficulty. Our challenge is exacerbated by a clear trend indicating that as a country develops economically, and per capita income rises, there follows a shift in human behavior towards greater consumption of animal-based products, specifically meat-eating.[2,3] The FAO estimates that from 2010 to 2050 food production must increase by 70% and meat production in particular must increase ~100% to meet increased demand.[4,5] But animals must be fed to produce meat, and today most animal feeds are comprised of crop-based cereals, legumes, and seeds that require large tracts of land to grow. These crop-based feeds are also composed mainly of the same food stocks that much of the world's human population, located in the least developed countries, depend upon for their nutirition.[6,7] Clearly there is need to develop new sources of animal feeds that do not reduce our overall capacity to feed humans, and that minimize further demand on strained resources.

Seafood is an important source of protein that can help alleviate some of the major challenges facing food production systems. Wild fisheries have historically provided most of our seafood but recently aquaculture, which includes both freshwater and ocean-based mariculture, has overtaken wild caught fisheries in seafood-based protein production.[8] An important player in these trends is Atlantic Salmon (*Salmo salar*), whose farmed production has recently overtaken total wild production of the major salmon species, statistics that continue to diverge.[8] In terms of revenue produced by mariculture, Atlantic Salmon is the highest valued fish species.[8] A top carnivore, salmon are initially bred and reared in land-based freshwater facilities but the majority of growth occurs in the coastal ocean pens. Salmon grow very rapidly to large sizes thereby requiring large amounts of protein-rich food. Rapid expansion of salmon farming has generated great demand for salmon feeds, which now represent the highest cost in salmon production and comprise the majority of the environmental impacts of salmon farming.[9,10] As such, developing low cost, environmentally less-impactful feeds is one of the biggest obstacles to aquaculture sustainability.

Globally, the aquaculture industry used ~40 million tonnes of feed in 2012, an amount that has grown at an average annual rate of 10.3% per year since 2000 and is expected to reach over 65 million tonnes by 2020[11]. For carnivorous species such as salmon, fish-based feed ingredients (i.e., fishmeal and fish oil) enhance growth rate mainly by providing essential amino acids and lipids[11]. Through innovations, the conversion rate of 4 kg of fish-based ingredients in feeds to 1kg of salmon biomass has decreased to <1:1, due mainly to the emergence and use of alternative, mostly plant-based ingredients. The alternatives have been developed primarily because of the rising cost of fishmeal and oil, as well as a growing concern about overfishing vulnerable wild fish stocks.[12,13] In response, fish nutritionists and health scientists have produced an impressive array of alternative salmon feed ingredients to replace fish-based inputs while maintaining rapid growth and survivorship rates in salmon.[12,14]

Replacements for fish-based ingredients are usually plant based, with soy inputs making up most heavily used substitutes.[15] Soy has high protein and lipid content and other important essential nutrients, which make them great substitutes for nutritious fishmeal and oil ingredients. As a result, soy is now found in almost all aquaculture feeds.[15–19] Impacts on wild fisheries and overall costs associated with predominantly fish-based feeds have declined by integrating soybean and other crops (e.g., wheat, corn, rapeseed) but other environmental costs have apparently increased. Recent studies indicate that intensified crop production, and soy in particular, has increased land conversion and use in farming.[20–22] Saponins in soybean meal can cause enteritis in salmon which leads to slower growth,[23–27] a limitation that can be overcome by condensing the soy product further into soy protein concentrate. Condensing soy, however, requires a greater total input of soy per unit of salmon, which in turn requires additional land use, energy, fossil phosphorous inputs and other limited resources.[28,29] Finally, and perhaps most importantly for human welfare, using soy and other products as alternatives in salmon feed reduces their availability for direct human consumption, particularly for the least food-secure people living in less developed countries which depend primarily on crop-based foods.[6,7] Use of these important protein-rich crops to produce high value products such as salmon diverts these important and accessible resources away from those who most need them. Further exacerbating the issue, feeding crops to livestock is inefficient energetically because energy conversion rates between trophic levels is low.[30] To address these inefficiencies and inequalities, the livestock feed industry is working to develop feeds that minimize human-food ingredients, with the intended outcomes being increased supply of human-food resources and reduced environmental impacts.[11,31–33]

Emerging single cell proteins (SCP) make up a diverse group of promising feed ingredients.[33] SCPs, which include methanotrophic bacteria, *Methylococcus capsulatus (Bath)*, and a common yeast, *Saccharomyces cerevisiae*, are fast growing, protein-rich organisms that are produced at relatively low cost in closed, controlled environments. SCP-derived nutrients are naturally high in protein but can also be manipulated to meet different nutritional requirements, including salmon diets.[34] Methanotrophic bacteria oxidize methane into carbon dioxide, which would generate climate change benefits if the methane was to be otherwise released into the environment.[35] Salmon fed *M. capsulatus* diets resulted in increased growth compared to salmon fed soy-based diets. Bacteria-inclusive feeds may also produce healthier fish through bioactive components that enhance gut health in Atlantic salmon.[36,37] For centuries, *S. cerevisiae* yeast have been used for centuries for human consumption in foods like beer and bread and were traditionally grown on simple sugar media. In order to conserve resources yeast producers, particularly those producing yeast for animal feeds, have used byproducts from other industrial processes to feed the yeast cells, such as wheat grains from biofuels production.[33] These low resource methods are being further improved upon by sourcing more non-human food inputs, such as algae and lumber byproducts, to feed cell propagation.[38] Whether the replacement of human-food ingredients with SCP ingredients in salmon feeds could decrease the overall environmental impacts of salmon farming has yet to be determined.

High environmental impacts of feeds in aquaculture production are well documented[9,10,39] and further studies indicate that fish-based ingredients in salmon feeds have higher impacts than soy-based feeds.[14,39] Still, nutritionists and fish farmers understand the importance of fish ingredients in feeds for carnivorous fish,[14,39] therefore, salmon feeds today minimize fish inclusion while maintaining nutritious diets. With fish ingredients at a minimum, focus has turned to increasing sustainability of feeds through other highly demanded ingredients, particularly soy.[28] Here we test whether the replacement of soy-based ingredients in salmon feed with protein-rich bacteria and yeast can further reduce the environmental impacts of Atlantic salmon production. The use of life cycle assessments to measure the environmental impacts of seafood products is becoming more common, and provides a way to compare disparate production methods (fishing versus aquaculture, different feeds, etc.) side-by-side[40]. We use attributional life cycle assessment (ALCA) to compare the impacts of soy protein concentrate against bacteria meal and yeast protein concentrate directly, then also compare feeds in which soy ingredients are replaced with either bacteria- or yeast-based ingredients. Environmental performance was assessed based on seven resource use and emissions metrics. Results are intended to inform feed producers, salmon industry, researchers, consumers and consumer awareness campaigns of the tradeoffs between current and emerging feeds and feed inputs. There are many different ways to assess environmental impacts from food production; while the use of LCA is growing in popularity, it is important to remember that LCA does not measure all environmental impacts equally well and should be complemented with other types of assessments.

Methods

ISO-compliant ALCA was used to assess the environmental impacts of replacing soy ingredients with novel single cell protein (SCP) meals, focusing on resource use and emissions to the natural environment.[41,42] We first compared these ingredients directly by assessing the impacts of soy protein concentrate compared to bacteria meal and yeast protein concentrate. Bacteria meal is produced through fermentation and drying of methanotrophic bacteria. The bacteria are fed fossil methane as a growth medium and also require additional chemical inputs for the initial fermentation step. Cells are then harvested from the fermenter, condensed and heat dried into a meal. For yeast protein concentrate, yeast cells are fed a wheat byproduct from biofuels production. The wheat byproduct requires enzyme treatment to make a viable growth medium for the yeast cells. These cells are similarly harvested, condensed and dried into a concentrated meal. These meals were compared on an equal protein basis: 660g of protein, which is the protein content of 1kg of soy protein concentrate. Two feed analyses were also conducted. One assessed how total feed impacts change when soy protein concentrate is replaced by the SCP meals on an equal protein basis, with all other ingredients held constant (Feeds Analysis 1, FA1).

FA1 allows for comparison of the different protein meals in a whole feed context without conflating the meal impact differences with impact changes due to varying the non-target ingredients. In the second analysis, soy protein concentrate is replaced by the SCP meals on an equal mass basis and non-target ingredients were adjusted to meet the nutrient requirements of salmon, they were formulated to have equal protein and lipid levels (Feeds Analysis 2, FA2). FA2 is believed to be a more realistic scenario in commercial feed formulations. All products were assessed from cradle-to-factory-gate at the industrial scale. System boundaries for the three analyses are defined in Figure 1. In each analysis, each of the three treatments were assessed based on the following seven midpoint impact categories: climate change impacts, acidification, aquatic eutrophication (freshwater and marine separately), land occupation, water consumption, and primary production requirement (Table S1).

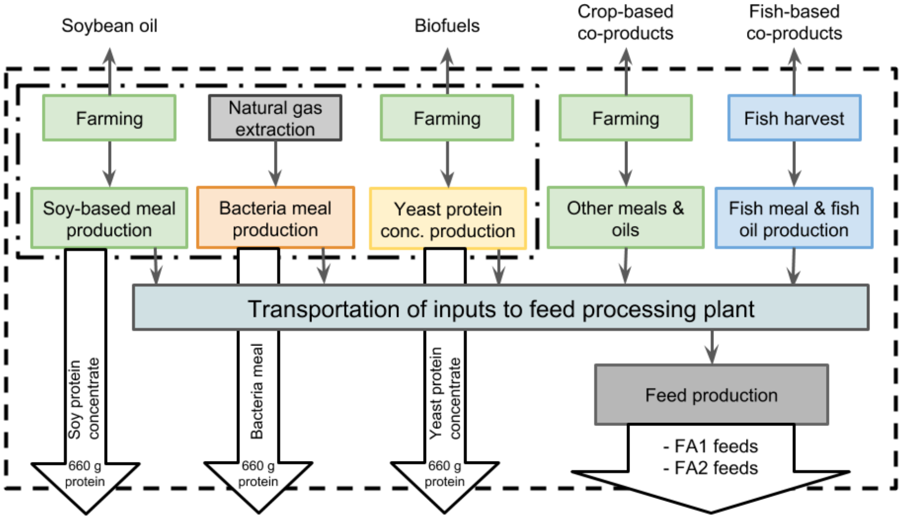

Figure 1: System boundary. *These analyses assess the processes of novel single cell protein meals and salmon feeds production from cradle to factory gate. Boundaries for the meals*

analysis are represented by the dot-dashed line, and each of the FA1 (380g of protein equivalent) and FA2 feeds (1 kg of feed) by the black dashed line.

ReCiPe[43,44] methods (v.1.11) were used to calculate environmental impact indicators for all impact categories except land occupation and primary production requirements (PPR) (Table S1). Climate change impacts quantify all emitted greenhouse gases converted to kilograms of CO_2-equivalent.[44] We excluded biogenic carbon from this analysis since any uptake of carbon in crop material will quickly be digested and respired through consumption of the food items by salmon and human consumers in a relatively short timespan so no true sequestration is achieved.[45] Acidification impacts measure the emissions of acidifying compounds from the process (SO_x, NO_x, NH_3). Aquatic eutrophication (freshwater and marine) impacts were considered separately since each system is limited by different nutrients (kilograms of phosphorous and nitrogen, respectively). Land occupation measures the total area of land occupation (m^2) per portion of a year (a) from agriculture, urban and transformation activities.[43] Freshwater consumption was measured in meters cubed of water removed from the local watershed.[44] For simplicity of analysis and interpretation the land occupation and water consumption indicators used here are accounting metrics and lack characterization factor calculations. PPR is quickly becoming an important impact indicator in food and aquaculture LCAs with developments still emerging[40] (Table S1). The calculations used here employed the methods of Cashion et al. (2016), which uses Pauly and Christiansen's (1995) equation for primary production requirement with updated trophic level and trophic efficiency data[8,30,46,47]. PPR was calculated for each feed ingredient and weighted sums were used to assess the total PPR for each feed. Impacts from fish-based ingredients were calculated using species specific data for transfer efficiencies[47] and trophic level[8] while standard values were used for carbon content[30] and inclusion in fishmeal and fish oil for all input fish species. PPR values for plant-based ingredients were sourced from the literature[9] and weighted based on their inclusion in each feed.

These three analyses compare how impacts will change with replacement of soy ingredients with novel SCP meals. The meal analysis compares soy protein concentrate, bacteria meal and yeast protein concentrate at equal protein levels (660g protein). Since the meals have different protein concentrations, the masses of meals differ for this analysis: 1kg soy protein concentrate, 0.94kg bacteria meal, 1.07 kg yeast protein concentrate. The FA1 analysis is based on a standard industrial salmon feed use in Norway which uses 25% soy ingredients. These ingredients are directly replaced with one each of bacteria meal and yeast protein concentrate at masses that maintain equal protein levels for the entire feed (Table 1). The FA2 analysis similarly replaces the soy ingredients with the novel feeds, while also maintaining consistent lipid levels by varying the other ingredients in the feed. Total feed masses as well as inclusion of fish ingredients, fishmeal and fish oil, were held constant in the FA2 feeds (Table 1). Full product inventories are documented in the supporting information file: “customProcessesLCI.xlsx” for review and reuse.[48]

Since the feed commodities market fluctuates widely, and therefore commercial feed compositions as well, the standard feed used in this study was formulated based on the relative amounts of feed ingredients imported by the Norwegian fish feed industry in 2016[49] and balanced to meet the nutritional needs of salmon. This feed includes fishmeal and soy protein concentrate as the main protein ingredients. Mineral and vitamin mixes were included at a consistent rate in all feeds but comprised only 2% of the total feeds so were excluded from this analysis. Globally, Norway is the largest producer of farmed salmon, so we assumed production of all three feeds occurs in Oslo, Norway and transportation[50] of feed ingredients to Norway were based on the sourcing and imports data from the Norwegian government.[49]

		FA1		FA2	
	Standard	Bacteria	Yeast	Bacteria	Yeast
Meals					
Soy protein concentrate	220.0	0.0	0.0	0.0	0.0
Bacteria meal	0.0	227.1	0.0	250.0	0.0
Yeast protein concentrate	0.0	0.0	257.3	0.0	250.0
Soybean meal	30.0	0.0	0.0	0.0	0.0
Non-target ingredients					
Wheat starch	90.0	90.0	90.0	122.6	92.8
Wheat gluten	90.0	90.0	90.0	55.6	86.2
Corn gluten	20.0	20.0	20.0	19.5	23.1
Sunflower meal	40.0	40.0	40.0	51.7	49.6
Fava/field beans	40.0	40.0	40.0	48.5	47.8
Rapeseed oil	180.0	180.0	180.0	162.2	160.5
Fishmeal	160.0	160.0	160.0	160.0	160.0
Fish oil	110.0	110.0	110.0	110.0	110.0
Mineral & vitamin mix	20.0	20.0	20.0	20.0	20.0
Nutrients					
Protein	381.3	381.3	381.3	381.3	381.3
Lipid	314.5	331.4	317.8	314.5	314.5
Starch	83.2	82.6	82.6	109.6	90.0

Table 1: Formulations for each feed analyzed. *Values are in grams, FA1 feeds may not sum to 1kg. Mineral and vitamin mix was excluded from analysis.*

Data for our analyses were gathered from a variety of sources. Feed formulations were designed with the goal of achieving nutritional balance between the feeds. Through close collaborations with industry we understand that feed formulations change often and quickly, so we use Norwegian imports data combined with nutritional requirements to guide the formulation of the standard feed and design the novel feeds to match this nutritionally (Table 1). Data for the novel meals were more difficult to acquire. Bacteria meal data were obtained directly from a company producing bacteria meal at an industrial scale. Yeast protein concentrate production data were sourced from Tallentire et al. 2018. Data for input ingredients to these feeds were mainly sourced from the Gabi and Ecoinvent databases.[51,52] Additional data were gathered from the scientific literature (Table S2).

Economic-based allocation was used for the many inputs that are co-produced in this analysis. Price allocation was employed for all input ingredients since production and use of input resources is driven by the more valuable product. Also, no common nutritional allocation (calories, protein content, etc.) exists for the co-produced pairs. A sensitivity analysis of allocation choice compared results from economic versus mass allocations. To test sensitivity of results to our assumption that production occurs in Norway, we also model production of the FA1 in high salmon producing (farming) and geographically disparate locations: Chile and British Colombia, Canada. Data for these analyses used imports data from each country to determine the sources of feed ingredients and calculate transportation distances from the source locations.[50,53,54]

Life cycle assessments come with large uncertainty in data and methods, but unfortunately uncertainty for this analysis was hindered by lack of actual uncertainty measures and use of uniform distributions would not add to the results.

Results & Discussion

Based on the data used here, the novel meals are able to decrease environmental impacts of protein meals and feeds compared to human food, soy-based ingredients and feeds. These benefits are realized at varying degrees due to trade-offs between environmental performance and nutritional quality of the SCP meals (Figure 2). For all of the impact indicators tested, yeast protein concentrate had much lower impacts than soy protein concentrate. Bacteria meal was also able to decrease impacts for most indicators compared to soy protein concentrate with two exceptions: climate change impacts and freshwater consumption, for which bacteria meal and soy protein concentrate had similar impacts. Low impacts of the yeast protein concentrate give the yeast-based feed lower overall impacts in the FA1 feed compared to the standard feed. The bacteria-based feed showed similar impacts to soy protein concentrate for five of the seven indicators and lower impacts in the remaining two, with impacts matching the yeast-based feed. Despite yeast protein concentrate having lower environmental impacts at the protein level, higher protein and lipid levels in the bacteria meal result in equal impacts in five of the seven indicators from their respective FA2. Low climate change and water consumption impacts of the yeast feed relative to the other two feeds make it the overall lowest impact feed for the FA2 analysis (Figures 2C and 3). Sensitivity analyses of the geographic location and allocation methods show that these assumptions only modestly affect the results and did not change the overall findings.

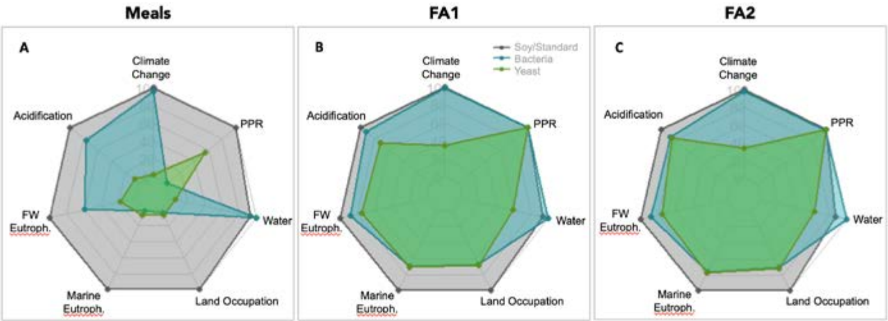

Figure 2: Radar charts comparing the three (soy-based (gray), bacteria-based (blue), yeast-based (green)) meals (A) and feeds (B, C) based on seven impact indicators. *Axes for each of the impact indicators: (from the top counter clockwise) climate change, acidification, freshwater eutrophication, marine eutrophication, land occupation, water consumption, primary production requirement (PPR). Results are scaled to the highest value for each indicator.*

Meals

For all seven environmental indicators assessed, soy protein concentrate had or was among the highest impacts of the three meals. Yeast protein concentrate showed the lowest impacts for all indicators except primary production requirements (PPR), and had the lowest impacts overall. Both SCP meals performed better than soy protein concentrate in five of the seven impact indicators tested. Of these five, yeast and bacteria both had considerably lower impacts than soy protein concentrate in marine eutrophication and land, with bacteria meal showing intermediate freshwater eutrophication impacts; between the yeast and soy protein concentrates. These impact indicators are associated with farming, which is necessary for soy production. While yeast protein concentrate also uses crop-based inputs, allocation with valuable biofuels, makes these impacts low for the yeast product. PPR impacts for yeast protein concentrate (0.582 kg C) are therefore intermediate between bacteria meal, which does not depend on primary production at all (0.00 kg C), and soy protein concentrate (1.06 kg C). While soy protein concentrate impacts are also allocated with soybean oil co-production, soy protein concentrate receives a higher percent of the impacts than yeast protein concentrate. In a similar trend as we saw with the freshwater eutrophication impacts, bacteria meal and yeast protein concentrate both had lower acidification impacts than soy protein concentrate, yeast protein concentrate causing significantly lower impacts, and bacteria meal only marginally lower. Many of the differences in relative impacts are likely due to the low allocation of yeast impacts in the biofuels production (both economically and mass-based). Climate change impacts and water consumption were remarkably similar for bacteria meal and soy protein concentrate production. Bacteria meal produces 8.26 kg CO_2 eq. per 660 grams of protein and soy protein concentrate produces 8.55 kg CO_2 eq. High climate change impacts in bacteria meal production are expected, given the use of methane to feed the bacteria and carbon dioxide release from the cells during the fermentation phase. Comparable climate change impacts in soy protein concentrate production are caused, in large part, by land use changes for soy farming (64%). Water consumption was also similar for bacteria meal (1.03×10^{-1} m^3) and soy protein concentrate (9.56×10^{-2} m^3), with bacteria meal requiring slightly more water to produce 660g of protein. Yeast protein concentrate, in contrast, had considerably lower climate change and water consumption impacts (0.21 kg CO_2 eq. and 5.90×10^{-3} m^3). Fermentation of the methanotrophic bacteria requires aqueous chemical inputs, which increase the water requirements for this process (particularly calcium chloride (41%) and ammonia (35%)), despite attempts by the producer to recycle water internally. Higher acidification in bacteria meals is likely the result of greenhouse gas emissions from the fermentation process as well, although, they are below the acidifying emissions of soy protein concentrate production.

Requirements for cell growth are already being addressed by the feeds industry, although innovations are still in development. Yeast protein concentrate producers are learning to extract lignocellulose from non-human food sources such as lumber by-products to be used as a growing medium for yeast cells and also testing yeast growth on sugars from fast-growing macroalgae. Similarly, labs that produce methanotrophic bacteria are investigating ways to efficiently sequester methane from existing sources, to create a net reduction of greenhouse gases during this fermentation phase. These innovations could help further decrease the environmental impacts of these SCP inputs. Since these meals would likely not be used in isolation, the impacts may change when these meals are incorporated into compound salmon feeds.

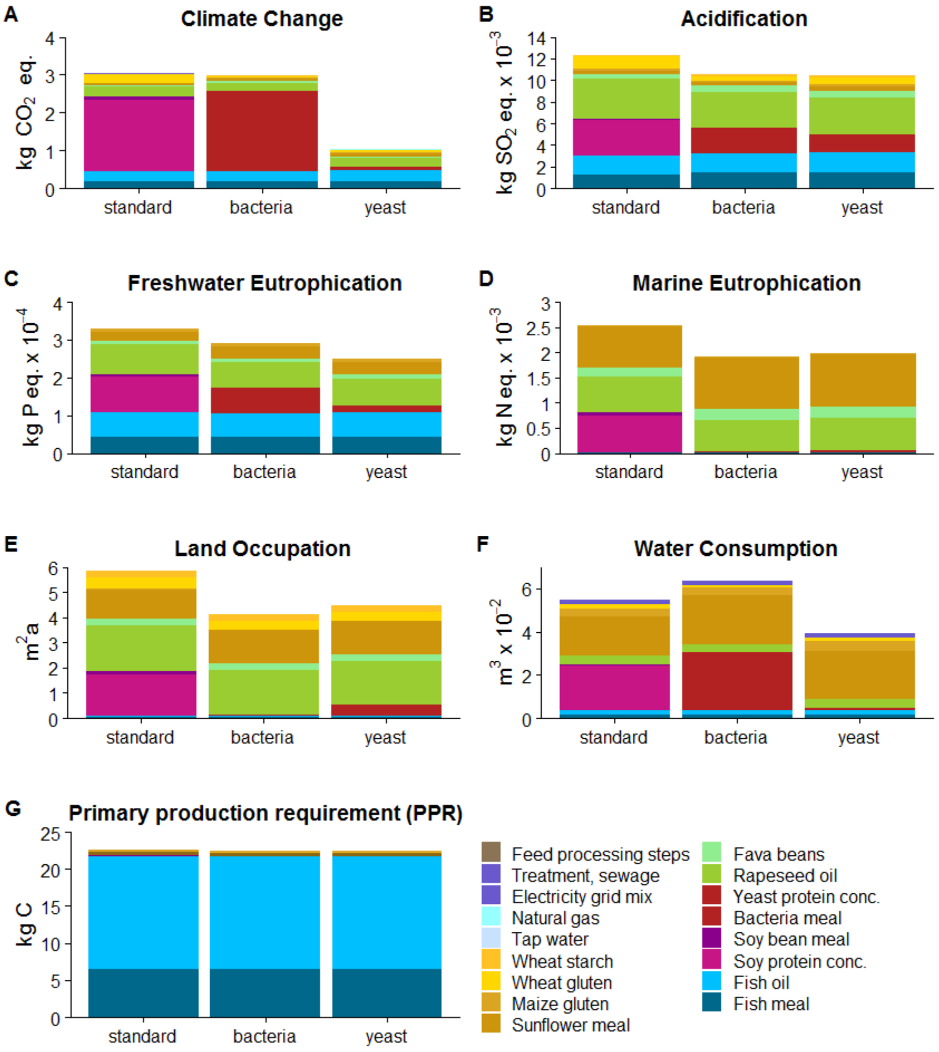

Figure 3: Results of environmental indicators for the FA2 feeds. Single cell protein feeds were formulated to match the standard feed for protein and lipid content, fish inclusion, and total feed mass. *(A) Climate change impacts, (B) acidification potential, (C) freshwater eutrophication, (D)*

marine eutrophication, (E) land occupation, (F) freshwater consumption, (G) primary production requirement.

Feeds Analysis 1 (FA1)

Benefits of the novel SCP salmon feeds are significantly muted in the FA1 feed results since the impacts of the target meals are low compared to impacts from the other feed ingredients. Since Feed Analysis 1 holds all other ingredients constant and allows the meals to vary to meet consistent protein levels, it is predictable that the soy-based standard feed would maintain the highest impacts, as we saw in the meals analysis. Differences in target meal inclusion in the FA1 feeds were insufficient to alter which treatments had the lowest and highest impacts. In fact, many of the same trends described for the meals analysis are maintained, with the notable exception that PPR impacts are so dampened by the high (and equal) fishmeal and fish oil inclusion in the FA1 feeds, that differences in PPR impacts between treatments are lost (standard: 22.62 kg C, bacteria: 22.54 kg C, yeast: 22.55 kg C). Relatively low impacts of yeast protein concentrate production lead to overall lower impacts in the yeast feeds, despite lower protein content in this meal. Particularly for climate change impacts bacteria (3.25 kg CO_2 eq.) and standard (3.23 kg CO_2 eq.) feeds remain about equal, and the yeast feed (1.05 kg CO_2 eq.) results in much lower impacts. The other five impact indicators track similarly to the meals results, again, with muted impacts relative benefits of the SCP feeds (Figure 2B). Yeast again, has the lowest impacts for acidification, freshwater eutrophication, and water consumption.

In contrast to the meals results, bacteria had only two indicators that are considerably lower than the standard feed, the remaining five are about equal to the standard feed. The bacteria feed did show slightly lower acidification (1.28×10^{-2} kg SO_2 eq.) and freshwater eutrophication (2.91×10^{-4} kg P eq.) compared to the standard feed (1.34×10^{-2} kg SO_2 eq., 3.31×10^{-4} kg P eq.), but the relative benefits of the SCP ingredient for these metrics were diminished when included in the FA2 feed. Marine eutrophication and land occupation impacts for bacteria (1.78 x 10^{-3} kg N eq., 1.90 m^2a) and yeast (1.97 x 10^{-3} kg N eq., 1.85 m^2a) FA1 feeds were about equal to each other and lower than the standard feed (2.55 x 10^{-3} kg N eq., 2.68 m^2a), although less significantly than in the meals analysis.

When feeds are compared on an equal protein basis, the yeast feed results in the lowest environmental impacts overall, with lower impacts than the standard feed for all indicators and lower impacts than the bacteria feed for four indicators and similar results for three. The bacteria-based feed also improves environmental performance compared to the standard feed for marine eutrophication and land occupation, and shows similar results for the remaining five indicators. Since this feeds analysis uses an equal base of non-target ingredients the results closely mirror the results of the meals analysis, but show that when incorporated into a whole feed, the impacts of non-target feed ingredients reduce the differences in impact. The FA1 results highlight that impacts from the non-target ingredients are large compared to those of the target meals, leading to relatively similar impacts across treatment feeds.

Feeds Analysis 2 (FA2)

To learn more about how the non-target feeds might impact the environmental impacts of salmon feeds with the SCP meals, FA2 substitutes the meals on an equal mass basis and then varies the other ingredients to produce feeds with equivalent protein and lipid concentrations. In FA2, the impacts of the novel SCP feeds became even more similar to each other, with about equal impacts for four of the seven indicators, and maintained similar or lower impacts compared to the standard feed for all indicators except water consumption, for which the bacteria feed exceeded the standard feed (Figure 2C). Impacts from the FA2 SCP feeds converged for acidification and marine eutrophication impacts. Bi-directional shifts in acidification impacts led to about equal impacts for the SCP feeds, with the FA2 bacteria feed (1.06 x 10^{-3} kg SO_2 eq.) causing lower impacts than its FA1 counterpart and the FA2 yeast feed (1.04 x 10^{-3} kg SO_2 eq.) causing higher impacts than in FA1. Both feeds had lower acidification impacts than the standard feed. Both novel SCP-based feeds saw increases in marine eutrophication impacts compared to the FA1 feeds. Increases were greater for the bacteria-based FA2 feed (1.93 x10^{-3} kg N eq.), which led to equal impacts (yeast: 1.98 x10^{-3} kg N eq.) between the novel feeds. Water consumption was also marginally higher for both SCP feed than in the previous analysis, increasing the disparity between the standard and bacteria feed. It should be noted, that in the FA2 analysis, bacteria meal (which has relatively high water consumption impacts) inclusion was higher than in FA1, whereas yeast protein concentrate inclusion was decreased compared to FA1 (Table1). Climate change impacts, PPR, freshwater eutrophication and land occupation did not change compared to FA1 for any of the treatments.

Compared to the FA1 feeds, the FA2 feeds held the mass of target meals constant which resulted in higher bacteria meal and lower yeast protein concentrate inclusion than the FA1 feed compositions. Overall, the FA2 yeast feed remains the lowest impact feed due to significantly lower impacts for the climate change and water consumption indicators. Based on these data, these novel SCP meals are both strong alternatives to soy protein concentrate in salmon feeds and improvements in these technologies could help make them even more beneficial.

Sensitivity analyses

Our analysis required a number of assumptions. We assumed that each of the feeds were produced in Norway, which is the largest producer of farmed salmon,[7] and therefore accounted for transportation from source locations to Oslo, Norway. Fish oil and fishmeal species compositions were based on weighted combinations of species caught in each source country. Importantly, yeast was produced domestically in Norway, whereas both soy protein concentrate and bacteria meal were produced in the Americas and therefore required much further shipping. Bacteria meal was produced in the United States in this study since this is the location of a plant set to open this year. Ingredient sourcing was based on recent Norwegian imports data for feed production. To test the sensitivity of our results to the feed production location, we also modeled the same FA1 feeds produced in Chile and British Columbia, Canada. Results from this sensitivity analysis show that this model is not sensitive to the location of production (Figure S1). Allocation was based on price for all co-produced ingredients. A second sensitivity analysis tested the impacts of our allocation method by comparing results from an economically allocated model to mass allocated results. While results varied slightly between the methods, relative results between the treatments were consistent, suggesting our model is robust with regard to allocation methods (Figure S2).

Future work

Future studies should incorporate ongoing developments in bacteria and yeast meals production to assess whether these changes can further reduce the environmental footprint of SCP feeds. Bacteria cells could potentially be grown using diverted methane rather than newly extracted natural gas, but realized efficiencies and proof of concept have not yet been tested. Similarly, work continues developing industry byproducts for yeast production rather than human-food wheat inputs,[55] which could further decrease land use and primary production requirements as well as outputs from farming. This analysis stops at the feed factory gate due to lack of information on the effects of these novel feeds on salmon growth and waste production. Following a series of robust feeding trials, a more inclusive study from cradle to grave would provide a more complete picture of the impacts of these feeds.

The presented life cycle assessment suggests that replacing soy protein concentrate with bacteria meal or yeast protein concentrate in salmon feeds has the potential to decrease the environmental impacts of salmon farming in addition to easing stress on human-food resources. Tallentire et al. 2018 suggest that the climate change impacts of bacteria meal could be even lower than was estimated here. These SCP meals are still being developed with a focus on improving efficiency and reducing impacts of these novel ingredients, particularly through feeding cells byproducts from other industries. Additional single celled proteins such as microalgae could prove environmentally beneficial or supplement these benefits as well.[56,57] Many of these SCPs are still in the developmental stages but feed companies are rapidly developing industrial scale production lines for these feed ingredients. Developments such as these are essential for moving aquaculture towards the food security solution our planet needs.

Supporting information:

The supporting information files include a word document and two data files. The word document includes a description of the impact indicators used in these analyses as well as a table with the indicator definitions and descriptions and results of the sensitivity analyses: Table S1: Impact categories with definitions, units and data sources; Figure S1: production location sensitivity analysis results; Figure S2: Allocation sensitivity analysis results. Data file “customProcessesLCI.xlsx” includes a complete description of the product inventories use to generate the study results, to facilitate independent review and reuse.[48] Product impacts and data for figures 2 and 3 are included in the data file, “lciaResults.xlsx”

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