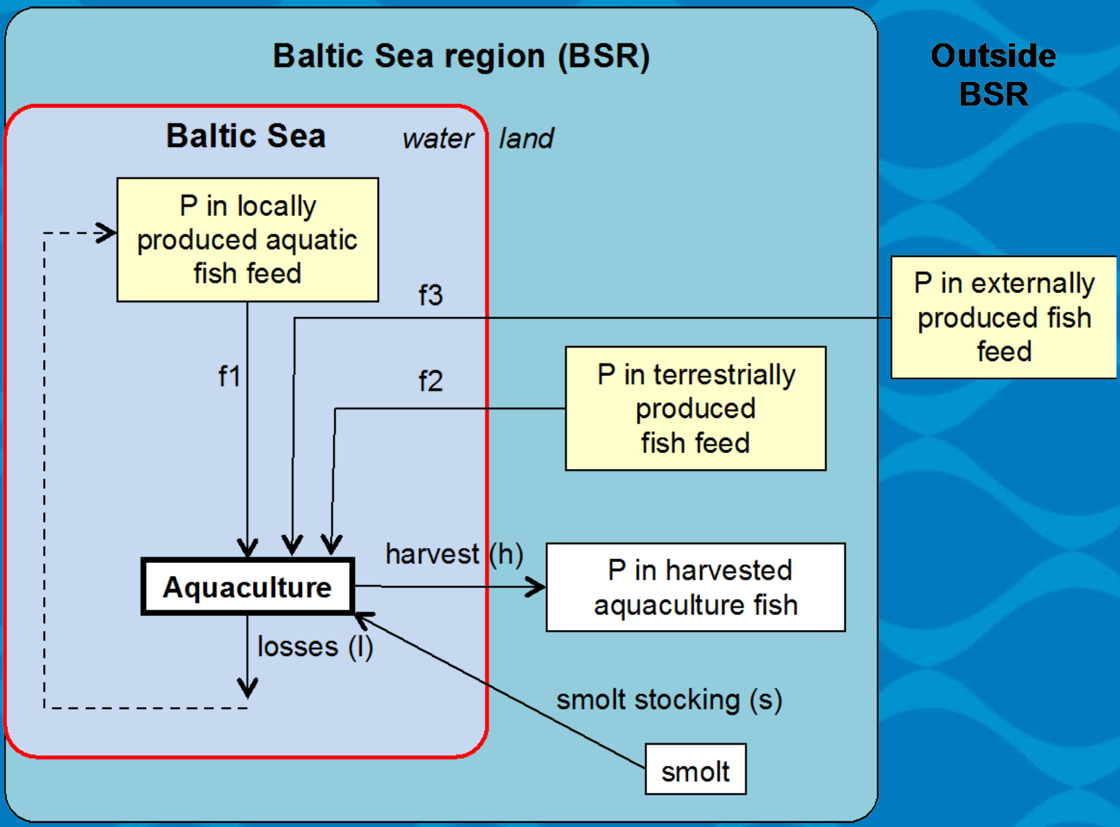

Modeling the effects of locally sourced fish feed ingredients on net phosphorus loading to the Baltic Sea

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Modeling the effects of locally sourced fish feed ingredients on net phosphorus loading to the Baltic Sea

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Description

Authors Tobias Vrede, Teresa Lindholm, Martyn Futter and Hampus Markensten		
Title Modeling the effects of locally sourced fish feed ingredients on net phosphorus loading to the Baltic Sea		
Year 2014	**Pages** 18	**ISBN** 978-952-303-084-8
Abstract Phosphorus and nitrogen release from open cage fish farms is an environmental problem that may result in eutrophication. This concern needs to be addressed if aquaculture is to expand in the Baltic Sea area. All of the nutrients released from the fish farm come from the feed used in fish production. Currently, the vast majority of the nutrients are imported to the Baltic Sea in the form of raw ingredients used in feeds. In order to achieve a more sustainable industry, from the eutrophication point of view, it is thus important to develop more environmentally sound feeds. In order to reduce the import of nutrients, and to close nutrient cycles within the sea, the inclusion of Baltic Sea sourced ingredients in fish feeds could be a solution. Here we present a simple steady state model of phosphorus (P) fluxes in aquaculture in the Baltic Sea. By replacing half of the fishmeal used in the feed with Baltic Sea sourced fishmeal the net P loading can be reduced by 65% if the fish production remains constant, or alternatively, the fish production could be more than doubled while still meeting a target of a 20% P loading reduction. A zero net P load to the Baltic Sea can be achieved if a wider variety of raw ingredients sourced from the Baltic Sea are included. We also present other scenarios to illustrate the gains of using an increased amount of Baltic Sea sourced nutrients in fish feeds. Due to the probable increase in price for fish feeds if more local ingredients are used, incentives that favor an increased utilization of Baltic Sea sourced nutrients need to be put in place. Increased nutrient recirculation, potentially even a closed nutrient loop within the industry, would improve many aspects of the sustainability of fish farming, as well as show the dedication of Baltic Sea aquaculture to act in an environmentally responsible manner while developing to fulfil the increased demand for local high quality fish. In conclusion, the model presented here gives results that are relevant and of great value for strategic management purposes, and form a basis for discussions and decision making. The model output is qualitatively sound and gives a good understanding of potential net P loading in different scenarios, although the exact numbers should be interpreted with great care.		
Keywords Nutrient model, Baltic Sea aquaculture, closing the nutrient loop, phosphorus, rainbow trout		
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Additional information		

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1. Introduction

Fish is an important food resource and the sector shows fast growth worldwide where a growing percentage of the food fish demand is being met by aquaculture (FAO, 2013). In the Baltic Sea the demand for food fish is currently mainly being met by import of fish, but could potentially also be met by an increased aquaculture production in the region. While Sweden and Denmark have increased their aquaculture production, the production in Finland and Estonia has remained at a constant level. Aquaculture is an industry that is often located in rural areas where other jobs are not readily available. It is thus important from a social and economic sustainability point of view to secure the status of aquaculture in the Baltic Sea region. Further, strengthening Baltic Sea aquaculture will also contribute to improved local food security and ensure high quality food products for consumers.

Aquaculture production in Finland has decreased and stagnated since the 1990s. Even though the production methods have developed, fish farming is still conducted in smaller scattered production units at traditional localities (Ministry of Agriculture and Forestry, 2009). Strict environmental legislation and quality demands have weakened the industry's ability to compete with foreign imports. Out of fish for food 83% was produced in sea areas, mainly farming of salmonids in open cages (Game and Fisheries Research Institute, 2013). The majority of open cage aquaculture is conducted on the Åland Islands, comprising 42% of Finland's total production. The south west archipelago accounts for 28% of the production and 13% is produced elsewhere. Out of a total production of 13 000 tons 17% was produced inland (Game and fisheries research, 2013).

Swedish aquaculture is also conducted mainly in open cages, the most common species being rainbow trout, but also other salmonids and eel are farmed. Rainbow trout is farmed at a yearly rate of 10.499 tons (Jordbruksverket, 2012), comprising 84% of the total fresh weight harvest. 24% of the rainbow trout was farmed at sea. The total aquaculture production in Sweden was 12.447 tons, 35% of this in coastal or archipelagic areas (Jordbruksverket, 2012).

Denmark, similar to Sweden and Finland, mainly produces rainbow trout. Total annual production is 31 000 tons in freshwater and 9 000 tons in the sea (Jokumsen & Svendsen, 2009). An increasing number of the Danish freshwater farms are being rebuilt as partly recirculatory farms, so called model farms, due to stricter environmental legislation.

Estonia produced a total of 371 tonnes of farmed fish in 2007, out of which 66% was rainbow trout (Statistics Estonia, 2013). Aquaculture production is small in Estonia compared to other Baltic Sea countries, and the fish is mainly sold on the domestic market.

The biggest environmental concern of aquaculture in the Baltic Sea is nutrient release from open cage fish farms. This has been the cause of many legal actions to limit pollution from the aquaculture industry. Phosphorus (P) and nitrogen (N) are of special concern, as these nutrients cause eutrophication. The local effects of open cage fish farming can be significant if the farm is placed in an unsuitable location and the combined nutrient load from diffuse and point sources increases to above the critical load of the ecosystem. However, despite contributing considerably to local eutrophication at certain locations of the Baltic Sea, the nutrient release from the aquaculture industry as a whole remains small in comparison with other sources. In 2006, fish farms in the Baltic Sea released 102,5 tons of P and 795 tons of N, comprising only 0,4% and 0.1% of the total waterborne P and N load to the Baltic Sea (Table 1).

Table 1. Loading of P and N to the Baltic Sea by country in 2006. Total: total nutrient load from monitored rivers, unmonitored areas and direct point sources; Fish farms: nutrient load from fish farms in the Baltic Sea (data from HELCOM, 2011)

	Total		Fish farms	
Country	**P (t year^{-1})**	**N (t year^{-1})**	**P (t year^{-1})**	**N (t year^{-1})**
Denmark	1 520	53 000	55	417
Estonia	790	20 400	2	15
Finland	3 490	79 000	36	280
Germany	490	16 900		
Latvia	2 800	59 500		
Lithuania	1 240	28 000	<<1	<1
Poland	10 240	152 600		
Russia	4 070	107 600		
Sweden	3 730	121 000	11	83
Total	**28 370**	**638 000**	**103**	**795**

All of the nutrients that are released from open cage fish farms originate from fish feed. As the raw ingredients used in the fish feed are for the most part imported, there is a constant loading of nutrients to the sea that is larger than the removal of nutrients by means of harvesting the farmed fish. The current practice of open cage fish farming thus contributes to eutrophication of the Baltic Sea. Since reducing eutrophication is of vital importance for improving the ecological status, innovative ways of reducing the nutrient loading from aquaculture are needed. One way to achieve such a reduction of the nutrient load would be to close the nutrient cycles. A conceptually important aspect of this approach is that there is a distinction between gross and net nutrient load. While the gross load is the sum of all nutrients that are released to the surrounding ecosystem, the net load is the loading to the system after considering that nutrients may also be reused by harvesting of resources for feed production in the surrounding ecosystem and that nutrients are removed from the Baltic Sea by harvesting of farmed fish.

On the Åland Islands aquaculture comprises 62% of the local anthropogenic P loading (ÅSUB, 2012), even though this is only 0,9% of the total Finnish P loading on the Baltic Sea (HELCOM, 2011). Because aquaculture contributes significantly to the local nutrient load, compared to other industries on the Åland Islands, fish farming is subject to a negative public opinion and strict environmental regulation. Despite efforts in moving aquaculture further out to locations with more rapid water exchange, and a considerable reduction in nutrient release has been achieved due to better feeds and feeding techniques, the industry has not been given any leeway for increased production. The waters in the outer Åland Islands archipelago, however, often have an ideal high water exchange rate and thus a large number of localities suitable for open cage fish farming. Because of this, the outer Åland Islands archipelago comprises one of the most suitable areas for open cage fish farming in the Baltic Sea. Considering aquaculture's high share of the local pollution, the potential for increased aquaculture and the significant importance of the industry for the economic and social sustainability of smaller archipelago communities, Åland Island fish farming is an ideal case study for modeling the gains of using fish feed originating from the Baltic Sea.

In this report, we present a mass balance model that is used for calculating the net nutrient load from open cage fish farms using a range of scenarios with different sources of fish feed (from within and outside the Baltic Sea and the Baltic Sea region). The objective is to estimate the current net nutrient load and to investigate under which circumstances aquaculture does not contribute to a net nutrient load to the ecosystem. We use the Åland region as a first case study area, but we also extend the calculations to the entire Baltic Sea region.

2. A model of aquaculture P fluxes in the Baltic Sea Region

The model presented here is a simplistic steady state mass balance model of nutrient fluxes in which major fluxes related to aquaculture are accounted for from a Baltic Sea point of view (Figure 1). The model uses P as the currency, i.e. all stocks and fluxes are expressed in terms of P. The rationale for this is that biogeochemical cycles of P and N are to a large extent coupled, but there is an increasing degree of complexity in modelling N fluxes, since there are additional pathways for N (N fixation, denitrification, etc). The P load from fish farms in the Åland region also contributes a very large fraction of

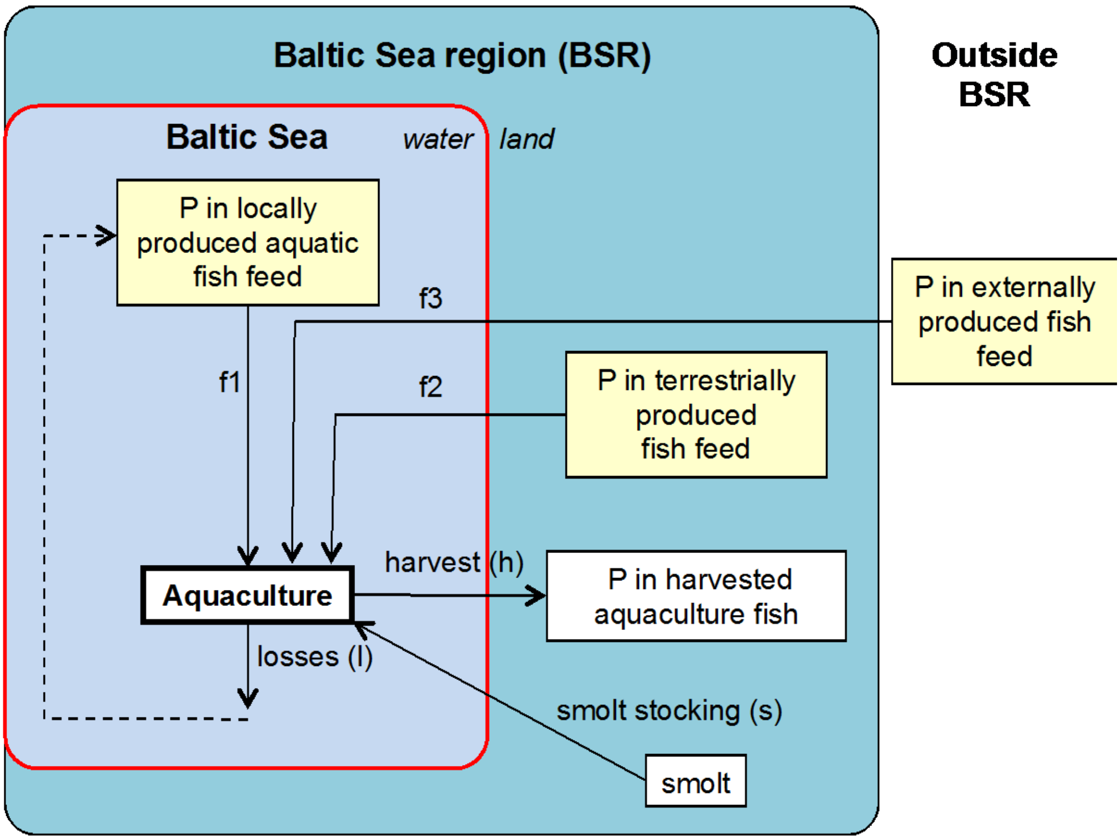

Figure 1. General graphic outline of the P mass balance model of aquaculture in the Baltic Sea region. Boxes denote standing stocks of P, and arrows denote fluxes of P. The red line shows the system boundary for which we calculate the net P load.

the total P load in that region, which is larger than the relative contribution of N from fish farms. However, the model can be extended to include other elements than P.

The major output of the model is the net P load from fish farms, which we define as the sum of the P load from fish feed from terrestrial and external sources and from stocked smolt (f2 + f3 + s) minus the harvesting of P from the aquaculture (h). In addition to these P fluxes there is also a flux of P to aquaculture from fish feed resources within the Baltic Sea (f1) and gross P losses from the fish farms (l). The model was set up as static Microsoft Excel work sheets, and the Excel solver function was used for optimizing the feed blend with respect to minimizing the net P release, while still conforming to constraints on feed composition (see below).

2.1. Model assumptions, parameter values and limitations

The turnover of nutrients in the Baltic Sea ecosystem is a very complex question and the ecosystem is affected by many anthropogenic disturbances such as fisheries, climate change, eutrophication from aquaculture, other point sources and diffuse sources, etc. While the overall management of the Baltic Sea ecosystem is outside the scope of the current report, we acknowledge that there are major ongoing efforts that aim for a more holistic understanding of the ecosystem and the nutrient turnover within it. For example, the Nest model was developed by the research program MARE and is now maintained and refined by the Baltic Nest Institute (an international research alliance between the Stockholm University Baltic Sea Centre, the Swedish Agency for Marine and Water Management, the University of Aarhus and the Finnish Environment Institute). Nest is a decision support system aimed at facilitating adaptive management of environmental concern in the Baltic Sea and with much emphasis on eutrophication (Wulff et al. 2013). While such an approach is useful for understanding the broad picture, it is of limited use for studying nutrient cycling in relation to aquaculture. We also argue that there is a great heuristic value in keeping a model simple, particularly at an early stage of model development. Using a simplistic approach facilitates the understanding of the model, and the model can readily be made more complex if it is considered necessary or desirable. Hence, we make the following assumptions:

- It is a steady state model, i.e. states and fluxes are assumed to be constant over time. This is admittedly a simplification since both animal physiology and nutrient turn over is temperature dependent, and there are changes in the standing stock of fish in the cages. However, a temporally explicit model would be substantially more complex and more difficult to parameterize.
- We assume that the nutrients released from the open cage farms are bioavailable for organisms in the Baltic Sea food web (mainly phytoplankton uptake) and that there is no net accumulation of nutrients in the sediments. While much of the released nutrients probably are immediately available for algal uptake, some nutrients are deposited on surface sediments. Depending on local conditions such as oxygen status, sediment resuspension and microbial activity, these nutrients may be remineralized and released to the water column. Hence, whether or not these nutrients are bioavailable is also a matter of the time frame that is considered. Here, we make the most conservative possible assumption, i.e. that all nutrients are bioavailable. This could partly be justified by the fact that large bottom areas in the Baltic Sea are anoxic and retain P very inefficiently. Because of this assumption, modeled net P loadings can

be considered as potential maximum loading under each scenario, and any inclusion of sediment nutrient accumulation would make the loading smaller.

- We assume that the total amount of nutrients released from fish farming does not change the nutrient concentrations, standing stocks or productivity of the Baltic Sea ecosystem. This assumption can be justified from the point of view that aquaculture represents a tiny fraction of the total nutrient turnover in the ecosystem. On the other hand, harvesting of fish or mussels from the Baltic Sea for inclusion in the fish feed has a potential for altering the ecosystem structure. Here, we assume that the use of biomass from the ecosystem remains at the same level as today.
- As the model organism we selected Rainbow trout, *Oncorhynchus mykiss*. The rationale for this is that it is the most commonly cultured fish species in the Baltic Sea, and realistic parameter values for the model are well known, thus reducing uncertainties. We assumed a constant P content of rainbow trout, 4 g P per kg fresh weight rainbow trout, and a constant P uptake efficiency, 55% (i.e. 55% of the P in the food will be incorporated into fish biomass, the rest being released). This can be justified by the fact that the feed blend is optimized or nearly optimized in terms of feed P content (which we allowed to vary between 6.85 and 8.0 g per kg fish feed fresh weight, 6.85 g/kg being the P content of the feed in the null scenario, that is considered a minimum level).
- The fish feed composition was also constrained in terms of minimum amounts of classes of biochemical compounds in the feed: 360 g protein, 330 g fat and 140 g carbohydrates per kg fish feed fresh weight.
- The maximum allowed fishmeal content was constrained to 200 g per kg fish feed fresh weight. This constraint comes mainly from economical considerations from the feed industry, and due to increasing price of fishmeal; this inclusion might drop even further in the future.
- The vitamin content (2%) and fish oil content (17.5%) was kept constant across feed blends.
- We also assumed that the amount of P imported by smolt stocking is negligible in comparison with the P load that comes from the feed.
- In order to calculate the total net P load, we estimated the current aquaculture fish production in the Baltic Sea, using the estimates cited above, to totally 24 000 tonnes per year. This production was then multiplied with the weight-specific net P load.

The model presented here is based on a hypothetical feed recipe which is altered when examining different scenarios. This differs from the approach used by Abrahamsson et al. (2014) where calculations were based directly on data received from the Government of Åland. Such detailed data is difficult to obtain for all Baltic Sea aquaculture as many countries have not gathered precise data on the nutrient release from fish farming. The same P content in harvested fish and P content in fishmeal is assumed in Abrahamsson et al. (2014) and the model presented here. Both models count P from marine Baltic Sea ingredients as a net removal of P. The model presented in Abrahamsson et al. (2014) is more conservative as it only counts part of the P removed through harvested fish as a P load reduction originating from Baltic Sea fish meal and thus being an improvement from regular feeds. The model presented here counts all P removed by harvesting as a direct net removal. However, for the total net load to the Baltic Sea it is not relevant whether the P in the harvested fish originates from Baltic Sea fishmeal or from other fishmeal, the harvest still contributes to lowering the P load from aquaculture to the sea.

Table 2. Protein, fat, carbohydrate and phosphorus (P) content of various components of the fish feed ingredients used in the model simulations.

Feed component	Protein (g/kg)	Fat (g/kg)	Carbohydrate (g/kg)	P (g/kg)
Fishmeal, non-Baltic Sea	700	100	0	20
Fishmeal, from the Baltic Sea	650	99	0	20
Mussel meal, from the Baltic Sea	648	108	0	10
Soy protein	600	20	166	6.8
Field bean	300	15	565	6
Rapeseed protein	691	36	7	11.6
Yeast	463	17	376	10
Wheat flour	129	17	693	3.7
Rapeseed oil	0	980	0	0
Fish oil	0	980	0	0
Vitamin mix	0	0	0	0

2.2. Model scenarios

Seven different scenarios were simulated with the model described above, using feed ingredients differing in their protein, fat, carbohydrate and P content (Table 2) and with different amounts of marine raw ingredients from the Baltic Sea (Table 3).

In the null scenario (scenario 0), which is intended to resemble current practise, the feed is composed of fishmeal of non-Baltic Sea origin, soy protein, rapeseed oil, wheat flour, fish oil and vitamins. The proportions are similar to commercially used feed blends (Table 3). In this scenario, all the P in the feed is assumed to originate from outside the Baltic Sea. Using this feed blend, we also explore the consequences for the net nutrient load of a 50% increase of aquaculture (scenario 0b).

In scenario 1, the net P release is set to 0, i.e. there is a zero net nutrient load. In this scenario, we allowed the solver function in Excel to include Baltic Sea fishmeal in addition to the feed components used in scenario 0 (Table 3). It should be noted that in this scenario, and other potential solutions that result in a net zero nutrient load, the amount of produced fish has no impact at all on the total nutrient load. In addition, the feed blend contains 45% P of Baltic Sea origin, which is a consequence of the assumption that the P incorporation efficiency is 55%. Because the selected feed blend in scenario 1 contained more fish from the Baltic Sea than is currently economically feasible, we included another option (scenario 2) in which the feed was allowed to contain only up to 10% Baltic Sea fish. The resulting feed blend was also used in scenario 2b to estimate the potential fish production given that the net P load should decrease with 20% compared to scenario 0. The rationale for this calculation is that this is a target for nutrient loading reduction that is under political consideration in the Åland region at present.

In scenario 3, the constraints were the same as in scenario 2, except that also mussels and field beans were allowed, but the total mussel and fishmeal content was still limited to max 20%. The reason to include field beans was that there was no possible solution that contained mussels that met all

Table 3. Overview of the different modeling scenarios, with resulting feed compositions, P contents and the proportion of the feed P that comes from the Baltic Sea.

Scenario:	**0**	**0b**	**1**	**2**	**2b**	**3**	**4**	**5**	**6**
Fish feed component (% by weight)	Current practise	As scenario 0, but 50% pro-duction increase	BS fish included, zero net P load	As scenario 1, but max 10% BS fish in the feed	Feed as in scenario 2, total P load reduced as suggested by political targets	As scenario 2, but mussels and field beans allowed, max 10%BS fish	As scenario 3, but yeast and rapeseed protein allowed	As scenario 0, but inland aquaculture	As scenario 2, but inland aquaculture
Fishmeal, non-BS	20.0	20.0	4.6	10.0	10.0	9.2		20.0	10.0
Fishmeal, from BS			15.4	10.0	10.0	10.0	10.0		10.0
Musselmeal, from BS						0.8	10.0		
Soy protein	35.6	35.6	35.5	35.5	35.5	34.4	15.7	35.6	35.5
Field bean						4.9			
Rapeseed protein							8.2		
Yeast							15.4		
Wheat flour	11.7	11.7	11.7	11.8	11.8	8.0	8.0	11.7	11.8
Rapeseed oil	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Fish oil	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
Vitamin mix	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Feed P content (g/kg)	6.85	6.85	6.85	6.85	6.85	6.85	6.85	6.85	6.85
% of P with BS origin	0	0	45	29	29	30	44	0	29

constraints without including beans. In scenario 4, we also included other more experimental fish feed sources such as yeast and rapeseed protein.

Finally, in scenarios 5 and 6, we estimated the net nutrient load to the Baltic Sea if aquaculture operations were located in freshwaters instead of within the Baltic Sea, but with the same amount of fish produced as today. This was done both with the same feed blends as in the null scenario (scenario 5), and with the feed blend from scenario 2 (scenario 6) (Table 3). The retention varies among catchments, generally with lower retention in areas close to the sea and higher in sub-catchments further away from the sea (Figure 2). Since most of the aquaculture in freshwater takes place in large lakes, and because there is a potential for increased aquaculture in northern Swedish hydropower reservoirs, both of which have a high retention, we assume that the retention will be high in lakes where the aquaculture potentially could expand. Hence, we assume a mean retention of 50% in freshwaters, i.e. 50% of the local net P load will reach the Baltic Sea. This assumption is probably a conservative one.

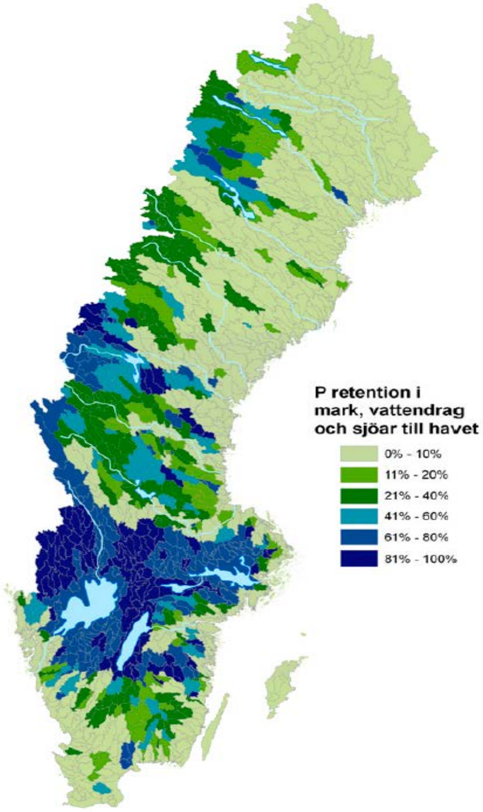

Figure 2. P retention to the sea in soil, running waters and lakes (%) in Sweden (from Brandt, Ejhed & Rapp 2008, Fig 14). Retention rates were calculated on a daily basis, including a runoff component simulating nutrient transport from one subcatchment to the next until it reaches the sea.

3. Results

3.1. Current practise feed composition – Scenarios 0 & 0b

In scenario 0, the estimated P load is 79 and 18 tonnes year^{-1} to the Baltic Sea and the Åland region, respectively (Table 4, Figure 3). Keeping this feed blend, the loading will be proportional to the amount of cultured fish. Hence, in scenario 0b, a 50% increase in aquaculture also result in a 50% increase in P loading.

3.2. Baltic Sea fishmeal in the feed – Scenarios 1, 2 & 2b

One possible solution to achieve a zero net P load (scenario 1) is to increase the amount of fishmeal of Baltic Sea origin from 0 to 156 g/kg feed and decrease the non-Baltic Sea fishmeal correspondingly (Table 3). The resulting total net P load is 0 ton year^{-1} (Table 4, Figure 3), and it does not scale with the amount of fish produced.

Using an increased amount of Baltic Sea sourced fishmeal in the fish feed is currently the most viable alternative for reducing nutrient import to the Baltic Sea. However, the feed industry has estimated that Baltic Sea fishmeal could currently not exceed half of the fishmeal in the feed (O. Lerche, Raisioagro, pers. comm. 2013). The resulting P load from a feed containing approximately 100 g/kg feed of fishmeal from the Baltic Sea and outside the Baltic Sea region would not be able to yield a net zero P load, but a 65% decrease compared to the null scenario (scenario 2, Table 4, Figure 3). This feed blend would allow a total fish production that is more than twice as high as in the null scenario, at

Table 4. Modelled net P load from open cage rainbow trout aquaculture in the Baltic Sea and the Åland region. *: the P load does not vary with fish production.

Scenario:	**0**	**0b**	**1**	**2**	**2b**	**3**	**4**	**5**	**6**
	current practise	As scenario 0, but 50% production increase	BS fish included, zero net P load	As scenario 1, but max 10% BS fish in the feed	Feed as in scenario 2, total P load reduced as suggested by political targets	As scenario 2, but mussels and field beans allowed, max 10%BS fish	As scenario 3, but yeast and rapeseed protein allowed	As scenario 0, but inland aquaculture	As scenario 2, but inland aquaculture
Specific net P load (gP/kg feed)	3.08	3.08	0	1.08	1.08	1.00	0.08	1.58	1.08
Rainbow trout production, Baltic Sea (ton year^{-1})	24 000	36 000	*	24 000	55 000	24 000	24 000	24 000	24 000
Total net P load, Baltic Sea (ton P/year)	79	118	0	28	63	26	2	39	14
Rainbow trout production, Åland region (ton year^{-1})	5 500	8 300	*	5 500	13 000	5 500	5 500		
Total net P load, Åland region (ton P/year)	18	27	0	6.3	14	5.9	0.5		
Change in total net P load, Baltic Sea (∆%)	0	+50	–100	–65	–20	–67	–97	–50	–82

the same time as the political goal of a 20% decrease in P loading can be achieved (scenario 2b, Table 4, Figure 3).

3.3. Alternative regional ingredients – Scenarios 3 and 4

Inclusion of mussel meal (scenario 3), while keeping the constraints of maximum 20% fish- and mussel meal, protein content and P content, would only allow a minor contribution of mussel meal and the total P load is only marginally less than in scenario 2 (Table 4, Figure 3). In scenario 4, the inclusion of other protein- and P-rich feed sources such as rapeseed protein and yeast makes it possible to find a solution that is very close to the zero net nutrient load, yielding a net P load that is only 3% of the load in the null scenario (Table 4, Figure 3).

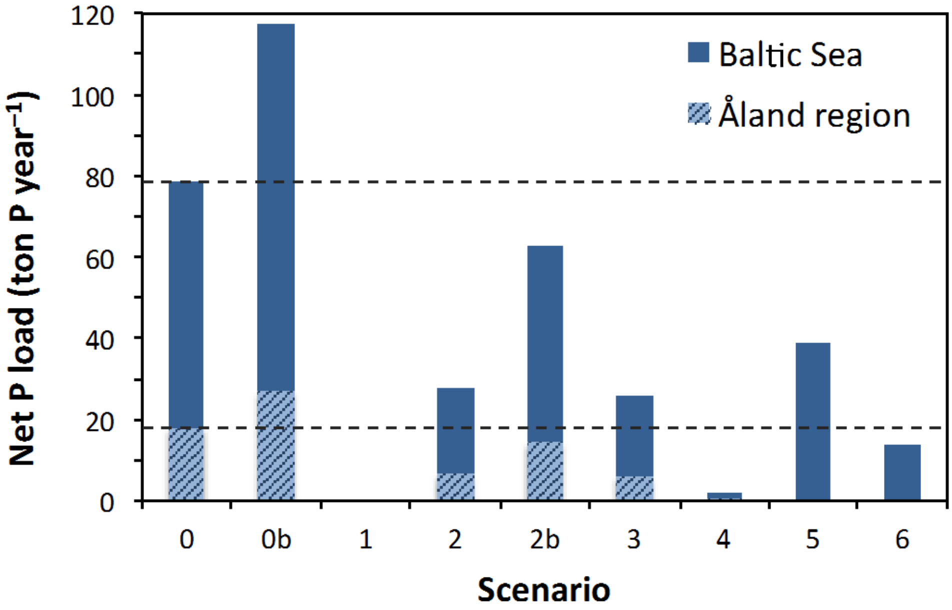

Figure 3. Total net P load to the Baltic Sea and the Åland region under different scenarios (see Table 3). The calculations build on the assumptions of 55% P incorporation efficiency, a total production of 24 000 ton year^{-1} (all scenarios except 0b: 36 000 ton year^{-1}, and 2b: 55 000 ton year^{-1}) and 50% nutrient retention in inland water ecosystems (scenario 5, 6). Dashed lines indicate net P load in the null scenario in the Åland region and the Baltic Sea region, respectively.

3.4. Aquaculture in freshwater – Scenarios 5 & 6

If the aquaculture production in the Baltic Sea is moved to inland waters in Northern Sweden (and assuming a constant fish production and a 50% retention in the catchments), the net P load will decrease by 50% compared with the null scenario if the same feed is used (scenario 5), and by 82% if the feed composition is the same as in scenario 2 (scenario 6) (Table 4, Figure 3).

4. Discussion

The results of the model simulations clearly illustrate that, from a regional phosphorus budget point of view, current practise results is a small but significant contribution to the eutrophication of the Baltic Sea. A further expansion of open cage aquaculture using current practise would increase the negative impact of the industry. In other words, current technology is not sustainable.

However, the model results also show that it is possible to develop aquaculture further within the Baltic Sea at the same time as the net P load to the Baltic Sea ecosystem decreases. In fact, there are feed blends that would result in a net zero nutrient load, or even a negative net nutrient load. This would, however, require a significant use of fish harvested from the Baltic Sea (sprat and herring) and/or novel and unconventional feed sources (e.g. blue mussels farmed in the Baltic Sea) that are still in an experimental stage of development. A major problem, though, is that these feed sources might be more expensive compared to currently used feed. Introducing novel ingredients, or increasing the inclusion of Baltic Sea sourced fish meal, would thus require that proper incentives are introduced, allowing farmers to see the gain in potential increased costs caused by a more environmentally friendly feed. Detailed discussion about the regulatory requirements of Baltic Sea aquaculture and other aspects to implementing a Baltic Sea fish feed can be found in the Aquabest report series (Abrahamsson et al 2013, Granholm & Leskinen 2013, Granholm 2014, Leskinen et al 2013, Paavola et al 2012).

In the Åland region, there is currently a discussion on whether or not part of the gain from including recycled feed sources could be used for increased production. Such a target would imply that when all measures that are taken to improve nutrient recirculation, the final gain in increased production volumes can be estimated. Scenario 2b thus describes how, on the Åland Islands, gains from using a realistic recirculation feed based on currently available fishmeal from the Baltic Sea would result in a 20% reduction of the net nutrient load and a production that is approximately two times higher than at present. In order for farmers to adapt a recirculating feed, which will most likely be more expensive than conventional feed, clear incentives that allow increased production need to be in place. Especially on the Åland Islands, where production volumes have stagnated, farmers are seeking new alternatives that could open the door for development. The results from the modelling suggest that a possible area of improvement in that direction would be to facilitate and decrease costs for including fish feed that is based on recirculated nutrients.

It would also be in principle possible to achieve a further improved sustainability and even a net zero P load if 45% of the feed P content originates from the Baltic Sea ecosystem. This would require that unconventional feed sources are used. The only currently available ingredient, apart from Baltic Sea fish meal, that directly reduces net nutrient loading is mussel meal. Baltic blue mussels (*Mytilus trossulus* or *Mytilus edulis*) feed by filtrating phytoplankton and thus remove nutrients and increase visibility in waters. Mussel meal is a high quality replacement for fishmeal, but contains less P. It could potentially be included in feeds, but current farming quantities are too low and production too expensive for it to be included on a commercial level today. Increases in fishmeal prices may make mussel meal a viable alternative in the future. Other alternative regional ingredients include field beans, rapeseed protein and yeast protein produced on waste biomass. Vegetable ingredients grown in the catchment area do not directly reduce nutrient inflow to the Baltic Sea, but can have positive effects on the regional economy and reduce dependency on foreign imported goods. Yeast produced on waste biomass also contributes to recirculating nutrients from waste into better use in feed. These Baltic Sea region sourced ingredients all contain much protein and P, thus they can aid with meeting the constraints on feed protein and P content without any use of fishmeal from outside the Baltic Sea. This would also contribute to a more sustainable use of fisheries resources on a global level.

Another avenue of decreasing the nutrient load on the Baltic Sea would be to locate fish farms in inland waters in areas with high retention. In particular if the feed that is used originates from the Baltic Sea (scenario 6), a major reduction in the industry's nutrient load to the Baltic Sea can be achieved. However, locating the fish farms in inland waters may have severe negative local effects if the localisation and dimensioning of the farms are not carefully considered and the environmental impact need to be properly monitored (Markensten, Fölster, Vrede and Djodjic 2012; Andersson 2012).

While the null scenario underestimates the nutrient loading from aquaculture compared to HELCOM numbers by approximately 28%, the latter also contain nutrient loading from inland water ecosystems, which contributes to the mismatch. The difference between our model and the HELCOM loading could potentially also be explained by uncertainties in the model. For example, if the realized P incorporation efficiency is lower than the 55% we assumed, the estimated loading would increase. On the other hand, our assumption that there is no permanent net nutrient sequestration in the sediments would result in an overestimation of the amount of P that become bioavailable and thus contribute to eutrophication. The mesocosm study by Gyllenhammar, Håkanson and Lehtinen (2008) came to the conclusion that the system reached the zero load threshold value for aquaculture when the feed included more than 11% Baltic herring. This result suggests that a lower amount of P from the Baltic Sea is needed to break even in the P balance than our model simulations suggest. Potential explanations are that sedimentation and subsequent permanent burial of nutrients plays a role, or that the P incorporation efficiency we used is too low. As a result, the actual break-even point for zero net nutrient loading may be even lower than the 45% of the feed P content sourced from the Baltic Sea as in our model.

The model can be developed in order to make it more realistic and quantitatively accurate. Major improvements would be 1) to include considerations of the cost of the feed, 2) to model P incorporation efficiency and growth efficiency as a function of feed composition, 3) to model sediment nutrient burial, and 4) to include nitrogen in the model. Furthermore, a sensitivity analysis of the model in relation to the uncertainties in the model parameters would be very useful to identify other areas of improvement and research needs.

We also acknowledge that our results are only reflecting one of several important environmental issues relevant to aquaculture. For example, the model does not account for local eutrophication effects that can be significant if proper location planning and dimensioning is not applied. However, fish farms on the Åland Islands have been moved out to off shore positions where the good water renewal rate is high and local effects are negligible. In other parts of the Baltic Sea we assumed that proper location planning is conducted and followed in order to minimize risks. Another important aspect, both from the human health and economic points of view, are environmental toxins such as persistent organic pollutants (e.g. dioxins, PCBs and perfluoroalkyl acids) and algal toxins. When including feed originating from the Baltic Sea, it would be of great importance to keep the feed content of these compounds to a minimum.

Although the model is very simple, we argue that it gives results that are relevant and of great value for strategic management purposes, and form a basis for discussions and decision making. The model output is qualitatively sound and gives a good understanding of potential net P loading in different scenarios, although the exact numbers should be interpreted with great care.

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