Closing a Loop: Substance Flow Analysis of Nitrogen and Phosphorus in the Rainbow Trout Production and Domestic Consumption System in Finland

Eero Asmala, Laura Saikku

Received: 26 January 2009 / Revised: 10 August 2009 / Accepted: 22 August 2009 / Published online: 13 May 2010

Abstract Ongoing eutrophication is changing the Baltic Sea ecosystem. Aquaculture causes relatively small-scale nutrient emissions, but local environmental impact may be considerable. We used substance flow analysis (SFA) to identify and quantify the most significant flows and stocks of nitrogen (N) and phosphorus (P) related to rainbow trout aquaculture in Finland. In 2004–2007, the input of nutrients to the system in the form of fish feed was 829 t N year⁻¹ and 115 t P year⁻¹. Around one-fifth of these nutrients ended up as food for human consumption. Of the primary input, 70% ended up in the Baltic Sea, directly from aquaculture and indirectly through waste management. The nutrient cycle could be closed partially by using local fish instead of imported fish in rainbow trout feed, thus reducing the net load of N and P to a fraction.

Keywords Baltic Sea · Eutrophication · Aquaculture · Industrial ecology · Finland

INTRODUCTION

The Baltic Sea today faces a wide variety of environmental risks. These include environmental toxins, invasive species, and oil transport; yet, the most widespread, concrete, and severe of all problems is eutrophication (Elmgren 2001; Rönnerberg and Bonsdorff 2004). Eutrophication is by definition the increase in primary production in the ecosystem caused by excess nutrients, essentially nitrogen (N) and phosphorus (P). Eutrophication hits the semienclosed Baltic Sea hard, since the nutrient emissions are huge and continuously increasing (Nausch et al. 1999), water exchange with the Atlantic Ocean is restricted, and the Baltic Sea itself is relatively small (e.g., Liljebladh and Stigebrandt 1996). The impacts of nutrient emissions are

not uniform. A minimum factor alternates in the Baltic Sea; in general, N limits primary production in the outer sea regions and P in the coastal areas (Moisander et al. 2003). In addition, so-called thresholds exist, making the responses of primary producers to nutrient addition nonlinear, meaning that, e.g., small changes in nutrient quantities might lead to major consequences in ecosystems (Tamminen and Andersen 2007). Therefore, the specific effects of quantitative nutrient reductions are hard to predict.

Tackling eutrophication with conventional end-of-pipe technologies in, e.g., agriculture is seldom cost-efficient (HELCOM 2007a). Instead eutrophication should be approached with problem-oriented interdisciplinary research, as discussed by Tapio and Willamo (2008). During 2001–2006, total nutrient emissions to the Baltic Sea were ca. 840,000 t N year⁻¹ and 30,000 t P year⁻¹ (HELCOM 2009). Roughly half of the nutrient emissions to the Baltic Sea originate from agriculture and the rest from municipal wastewaters, atmospheric deposition, and other sources (HELCOM 2005). In recent years, a wide array of both national and international policy actions have occurred in the Baltic Sea countries. For instance, the Baltic Sea Action Plan incorporates goals for the mitigation of nutrient load: 18% reduction in N and 42% reduction in P emissions from the average annual level of 1997–2003 by the year 2016 (HELCOM 2007b). The treaty was ratified by the members of the Helsinki Commission.¹

Aquaculture is responsible for <0.5% of total nutrient emissions to the Baltic Sea. This share is a few percent in Finland, but the local environmental impact through

¹ The Helsinki Commission (HELCOM) works to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental cooperation between Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia, and Sweden.

eutrophication may be considerable in areas of intense aquaculture (Karttunen and Vielma 1993; Helminen et al. 1998). Local disputes in SW Finland between fish farmers and the general public escalated in the 1990s to a nationwide discussion of aquaculture's nutrient emissions (Peuhkuri 2002). Aquaculture in the Baltic Sea produced 11,300 t of rainbow trout [*Oncorhynchus mykiss* (Walbaum)] for human consumption in Finland in 2007, covering 22% of all fish for human consumption (Finnish Game and Fisheries Research Institute 2008a). Nearly all fish production in the Baltic Sea is rainbow trout (Finnish Environmental Institute 2008). Finnish rainbow trout are cultivated in net-pens, from which uneaten food and fish excreta come immediately in contact with the surrounding body of water (Silvenius 2000).

Net nutrient discharges per fish production unit have decreased during 1980–2007, totaling 50 and 80% for N and P, respectively (Finnish Environmental Institute 2008). Virtually all N and P entering the Finnish aquaculture system in the form of feed originate from outside the Baltic Sea basin (P. Jessen, Biomar A/S, Aarhus, Denmark, pers. comm. 18 October 2007; E. Norrgård, Raisio Feed Ltd, Raisio, Finland, pers. comm. 3 October 2007). Thus, even the most efficient use of feed results in net input of nutrients to the Baltic Sea. By using local fish for feed, nutrients that already exist in the Baltic ecosystem could be partly recirculated (Ruohonen and Mäkinen 1991). Gyllenhammar et al. (2008) showed that nutrient emissions from aquaculture could be reduced significantly by replacing the imported fish feed with feed originating from waters surrounding the production site. Baltic herring (*Clupea harengus membras* L.) from the Baltic Sea were used as feed for rainbow trout from the 1970s to the 1990s, but the high contents of dioxin and polychlorinated biphenyl (PCB) compounds in herring ended the practice (Setälä et al. 2007). Feeding fresh Baltic herring to rainbow trout also resulted in higher direct P emissions than feeding with dry pellets (Ruohonen 1994; Ruohonen et al. 1998).

In this study, we applied a system-scale perspective to identify and quantify the most significant flows and stocks of N and P related to rainbow trout farming in Finland during 2004–2007 by examining the production and consumption system. More precisely, we asked:

1. What are the amounts of N and P in the flows and stocks of the rainbow trout production and consumption system in Finland?
2. What are the N and P emissions to the Baltic Sea from the system?
3. How closed is the system and how much could the net nutrient load to the Baltic Sea be reduced by substituting foreign fish in rainbow trout feed with local fish?

MATERIALS AND METHODS

Substance Flow Analysis

We approached the system-scale nutrient balance with the perspective of industrial ecology (e.g., Frosch and Gallopoulos 1989; van der Voet 2001). One central idea is to close the flows of materials and energy between the biosphere and anthroposphere, and also within the latter (Ayres 1989). We used substance flow analysis (SFA), which enables quantification of the stocks and flows of selected substances, thus making it possible to locate leakages and other problematic phases of a defined system (van der Voet 2001; Brunner and Rechberger 2004). SFA is based on the law of mass conservation, which states that the mass of a closed system will remain constant, regardless of the processes acting inside the system (e.g., van der Voet 1995). SFA has been used to study nutrient flows in several studies (Sokka et al. 2004; Antikainen et al. 2005; Chen et al. 2008).

System Definition

Flows of N and P in the rainbow trout production and consumption system were identified and quantified for the period 2004–2007 (Fig. 1). Only aquaculture in the Baltic Sea was considered. The inputs of N and P to the aquaculture unit were presumed to originate from fish feed only, thus atmospheric deposition of N was not considered. We determined the flows of N and P from feed usage in aquaculture to the Baltic Sea basin. The Baltic Sea basin was considered to be a stock of nutrients, from which nutrients do not return to the cycle where the feed originates. Export of rainbow trout and parings directed to fur production were also considered as stocks. We assumed that there is no accumulation of nutrients in the aquaculture unit, thus the nutrients in fish feed are transferred either to fish tissue as incremental growth or directed straight to the surrounding body of water.

Data Sources and Quantification Methods

Information on annual fish production and nutrient emissions from fish farms were obtained from the Finnish Environment Institute (2008). The average annual production of rainbow trout for the study period amounted 10,769 t. The statistics of domestic consumption and foreign trade of cultivated rainbow trout was from the Finnish Game and Fisheries Research Institute (2008c). The average nutrient content of fish feed used in rainbow trout cultivation in Finland was gathered from manufacturers' product information data (Raisio Feed Ltd 2007; Biomar A/S 2007). Feed use averaged 12,409 t year⁻¹, containing

Fig. 1 System model of the rainbow trout production and consumption system in Finland with flows and stocks of N and P depicted

on average 6.68% N and 0.93% P. The concentrations of N and P in different components of rainbow trout are presented in Table 1. Domestic consumption of fish fillets and whole fish was taken from Vihervuori and Ahvonen (1997).

When processed for human consumption, whole rainbow trout are usually cleaned at fish farms. The cleaning process produces liquid waste, which is directed to a communal sewer system, and solid waste, of which 80% is used at fur farms as feed (Silvenius 2000; Vielma et al. 2000). The remaining solid waste from fish processing is

Table 1 N and P contents in different portions of rainbow trout

	N (%)	P (%)	Portion
Whole fish ^{a,b,c}	2.66	0.33	1
Fillet ^{a,c}	2.69	0.26	0.57
Blood ^a	2.50	0.15	0.05
Roe ^{a,c}	3.33	0.08	0.03
Parings (incl. head and spine) ^a	2.58	0.49	0.35

Source: ^a Karttunen and Vielma (1993)

^b Vielma et al. (2000)

^c Fineli (2008)

managed at municipal waste treatment plants. From domestic consumption, 95% of the N and 98% of the P originating from rainbow trout flow to waste management (Antikainen et al. 2005). The remainder is accumulated as stock in the human population. Of the flows to waste management, 85% of the N and 80% of the P are directed to wastewater management and the remainder to solid waste management. From wastewater treatment, 62% of the N and 17% of the P are released to the water system, in this case to the Baltic Sea. In the wastewater treatment process, 17% of the N is released to the atmosphere (Sokka et al. 2004). The remaining nutrients are deposited as sludge, used mainly in landscaping (Santala et al. 2006). A small portion of the solid waste from wastewater treatment is directed to landfills, which also receive the solid waste from consumption.

To study the effects of closing the nutrient loop partially, we developed a scenario in which fish meal manufactured from local fish replaces the foreign fish meal now used in rainbow trout feed. Currently, rainbow trout feed contains 30% fish meal, while other components include fish oil and soy protein (E. Norrgård, Raisio Feed Ltd, pers. comm. 3 October 2007). The scenario is based on the use

of fish meal made of Baltic herring, which contains 11% N and 2% P (Ruohonen et al. 1998). Currently, all of the fish meal in feeds used in Finland is manufactured from imported fish, mostly Atlantic herring (*C. harengus harengus*, L.) (P. Jessen, Biomar A/S, pers. comm. 18 October 2007; E. Norrgård, Raisio Feed Ltd, pers. comm. 3 October 2007). The system remains otherwise unchanged, since the feed properties remain virtually identical.

Uncertainty Analysis

The uncertainty of the data is taken into account, using a method developed by Hedbrant and Sörme (2001), and further refined by Danius (2002) and Antikainen et al. (2005). With the method, it is possible to determine the intervals within which the uncertain value is very likely to be, i.e., a 95% probability will be achieved. The uncertainty intervals are presented in Table 2. We calculated the uncertainty range for the flows of N and P by dividing and multiplying the annual average flow with the uncertainty factor of Hedbrant and Sörme (2001). Since the flows contain data from different sources, the factors are multiplied, e.g., if the reported amount of incremental rainbow trout growth is 1000 t */1.33 and the N content for whole fish is 2.66% */1.33, the amount of N in the incremental growth is 26.6 t. The uncertainty for this flow is calculated as follows:

$$1 + \left[(1.33 - 1)^2 + (1.33 - 1)^2 \right]^{0.5} = 1.47$$

Therefore, the amount of N in the incremental growth is very likely between 18.1 and 39.1 t.

RESULTS

Flows and Stocks of N and P

The annual flows and stocks of N and P in the rainbow trout production and consumption system are illustrated in

Fig. 2a, b. Fish feed in marine aquaculture in Finland contained annually an average of approx. 829 t N and 115 t P in the period 2004–2007 (Table 3). Of the nutrient content in feed, 34% of the N and 31% of the P were transformed into rainbow trout incremental growth. Conversely, 66% of the N and 69% of the P in feed flowed directly to the surrounding body of water as uneaten food and fish excreta. The flows from aquaculture to human consumption were 170 t N year⁻¹ and 21 t P year⁻¹, equaling 21 and 18% from the initial feed input, respectively. Fish parings were directed to fur production and amounted to an average of 63 t N year⁻¹ and 18 t P year⁻¹, thus being a stock of 8% of the initial N and 13% of the P. The stock in Finnish human population was 9 t N and 1 t P, annually. The waste management system was a stock of 104 t N and 22 t P and emitted 24 t of gaseous N into the atmosphere. Eventually, the waste management system emitted an amount relative to 5% of the N and 1% of the P of the initial input of fish feed to the Baltic Sea.

Local Fish as Feed Component—Effects on Nutrient Flows

The fish meal in the rainbow trout feed contributed an average annual input of 410 t N and 74 t P in 2004–2007. In principle, local fish could substitute for Atlantic herring as the source of fish meal in feed, equal to the corresponding nutrient emissions. This would have led to reduction of net nutrient flows to the Baltic Sea, by 75% for N and 93% for P (Fig. 3).

DISCUSSION

Current Stocks and Flows of N and P

The input of nutrients to the rainbow trout aquaculture system in the form of fish feed was 829 t N year⁻¹ and 115 t P year⁻¹ for 2004–2007. Of this amount,

Table 2 Uncertainty intervals with sources of information and examples (based on Hedbrant and Sörme 2001; Danius 2002; Antikainen et al. 2005)

Level	Source of information	Example
0 (interval */1)	Official statistics	Population
1 (interval */1.1)	Official statistics on local, regional and national levels	Foreign trade
	Values in general (from literature)	N and P contents in feed
	Information from facilities subjected to permit requirement	Amount of N and P in treated wastewater
2 (interval */1.33)	Official statistics on regional and national levels	Food consumption
	Values in general for content (from literature or on request)	N and P contents in fish
3 (interval */1.5)	Monitored data	Amount of wastewater directed to the Baltic Sea
4 (interval */2)	Values in general for flows (from literature)	Solid and liquid waste of consumption

Fig. 2 **a** Average annual flows of N in the rainbow trout production and consumption system in Finland 2004–2007 (t). **b** Average annual flows of P in the rainbow trout production and consumption system in Finland 2004–2007 (t)

548 t N year⁻¹ and 80 t P year⁻¹ ended up in the Baltic Sea directly from the aquaculture unit. Of the nutrients in the feed, 21% of the N and 18% of the P ended up in

human consumption. Of the primary input, ultimately 70% of the N and P ended up in the Baltic Sea directly from aquaculture and also through the waste management

Table 3 Average annual flows of N and P in the rainbow trout production and consumption system in Finland with uncertainty intervals

Flow	Uncertainty intervals (t year ⁻¹)					
	N _{min}	N _{average}	N _{max}	P _{min}	P _{average}	P _{max}
Fish feeding	726	829	946	101	115	131
Incremental growth	195	286	420	24	36	52
Feed and excrement emissions to water	475	542	619	70	80	91
Liquid waste of fish preparation	10	13	18	1	1	1
Solid waste of fish preparation	17	16	31	3	3	6
Domestic fish trade	126	170	228	16	21	28
Fish parings to fur production	45	63	191	9	12	36
Export	12	16	22	1	2	3
Liquid waste of consumption	68	137	275	8	16	33
Solid waste of consumption	12	24	48	2	4	8
Emissions to atmosphere	22	26	29	0	0	0
Emissions to the Baltic Sea	62	93	141	2	3	4
Solid waste from wastewater management	16	32	63	7	14	29
Scenario with local fish in feed	373	410	451	67	74	81

See text for details on calculating the intervals

Fig. 3 Net rainbow trout aquaculture nutrient load to the Baltic Sea with different fish meal origins (average flows 2004–2007)

system. This emphasises the importance of controlling the nutrient flows in early stages of the rainbow trout production and consumption system.

Similar studies are scarce, but Antikainen et al. (2005) studied the food production system in Finland, in which the flows of all fish production in 1995–1999 were the same order of magnitude as in our study, namely, 370 t N and 50 t P. The magnitude of fish production in relation to the total food sector is minimal. Approximately 180,000 t N from fertilizers flowed annually to the agricultural soil and

some 51,000 t N flowed from the agricultural production system to the food and fodder processing industry in plant and animal products (Antikainen et al. 2005). The atmospheric N flow from agricultural production included 29,000 t N in NH₃ emissions and 8,200 t N in N₂O emissions. Leaching from agriculture was 32,500 t N and 2,400 t P.

Today aquacultural production in Finland is sixfold higher than that in 1980, and the related gross N emissions are roughly twofold higher and P emissions similar, following a peak in gross nutrient discharges in the early 1990s (Finnish Environmental Institute 2008). Future fish consumption may further increase (e.g., Delgado et al. 2002; Halweil 2008). Fish is seen as a healthy food (e.g., Sidhu 2003; Rembold et al. 2004; Mozaffarian and Rimm 2006), and salmon production has fewer environmental and ethical problems in production than beef or pork (Seppälä et al. 2001). Since the world's fisheries are depleting, aquaculture is producing increasingly larger portions of the fish consumed (FAO 2007). In Finland, aquacultural production with its nutrient emissions may further increase. However, the imports of Atlantic salmon (*Salmo salar* L.) have increasingly fulfilled the demand for salmonids (Finnish Game and Fisheries Research Institute 2008b). Norwegian Atlantic salmon imports have increased manifold, competing with rainbow trout in the market with similar features such as taste and nutritional values (Seppälä et al. 2001). Even though the amount of exported rainbow trout has increased recently, totaling 1,356 t in 2007, the amount is exceeded multifold by import of rainbow trout, mainly from Sweden (Finnish Game and Fisheries Research Institute 2008b).

Closing the Loop and Decreasing the Flows

One of the main elements in industrial ecology is technical change and eco-efficiency (Lifset and Graedel 2002). In rainbow trout aquaculture, current practices with feed coefficients of around 1.2 and feed formulas with optimal nutrient contents leave little room for increased efficiency. Furthermore, removal of all the floating and descending particles is technically and economically extremely challenging (Seppälä et al. 2001). The greatest technological opportunities for reducing emissions from rainbow trout cultivation are in feed processing, feed delivery techniques, and physiological features of cultivated fish.

One central idea in industrial ecology in general is the objective of closing flows of materials and energy between the biosphere and anthroposphere, and also within the latter (Ayres 1989). The nutrient loop of rainbow trout production and consumption in Finland would be closed partially if the N and P in feed fish would originate from the same water system as where the nutrient load ends up. However, the amount of fish needed to compensate for Atlantic herring is large. Considering the average yearly rainbow trout production during the study period, the fish meal used (3,723 t) equals a catch of about 20,000 t of fish. This would have amounted to approx. 16% of the total Finnish commercial catch in 2007 (Finnish Game and Fisheries Research Institute 2008d).

Currently used rainbow trout feeds containing herring and anchovies (Engraulidae) are highly optimized for fast rainbow trout growth. Using Baltic herring for fish meal manufacturing would not change the feed qualities, since it is almost identical in its properties to currently used herring and anchovies. The drawback is that Baltic herring contains high levels of envirottoxins, namely dioxin and PCB compounds (Isosaari et al. 2002). However, fish meal factories with dioxin-removal capabilities are operating in Denmark. From merely technological point of view, up to 20% of fish other than Baltic herring could be used in feed without changing the feed formulas (O. Lerche, Raisio Feed Ltd, pers. comm. 27 November 2007). Pekcan-Hekim and Horppila (2008) introduced a net-loading system, in which fish farmers compensate for the nutrient emissions of aquaculture by extracting fish biomass from the nearby waters of aquacultural production sites. This biomass would consist of so-called trash fish, e.g., roaches (genus *Rutilus Rafinesque*).

The cost of using local fish as feed components is difficult to determine, since production systems do not exist in Finland. However, an increase in feed price can be expected, one estimate being +15% (O. Lerche, Rehuraisio Ltd, pers. comm. 27 Nov 2007). Increased feed prices would follow the polluter pays principle, as the producers

would be obliged to compensate for the negative environmental impacts of aquaculture.

Fish meal in fish feed could also be substituted with plant-derived matter, e.g., soybean and peas (Vielma et al. 2000; Carter and Hauler 2000), assuming that changes in price, protein ratio, and potential nutrient effluents are not overly negative (Hardy and Tacon 2002). Fish oil could also be replaced with vegetable oils (Bell et al. 2001). Using food from the lower level of the food chain is more efficient than that of higher levels, such as fish. Even though the overall global nutrient flows may decrease by using plant-derived matter instead of imported fish, there is no difference concerning the impact on the Baltic Sea; the loop remains open.

Uncertainties

The limitations of SFA must be kept in mind when interpreting the results. SFA only deals with a single material and the problems related to this material (Udo de Haes et al. 1997). Other material, energy, and monetary flows are not considered. Also, it must be noted that data are collected here according to political boundaries of Finland. However, ecosystem boundaries rarely match the political boundaries of a country (Mayer 2007), and particularly Baltic Sea ecosystems are highly connected through hydrologic circulation patterns. Since SFA alone is rarely sufficient in dealing with complex problems, it often needs to be complemented by other methods, such as life cycle analysis (LCA) and economic modeling (Bouman et al. 2000). Indeed, some life cycle assessments of rainbow trout aquaculture in Finland have been previously conducted (Seppälä et al. 2001; Grönroos et al. 2006).

Annual variation in flows causes uncertainty; we used the annual averages of 2004–2007 to avoid extreme bias in the results. Relatively high levels of uncertainty apply to nutrient emissions to the Baltic Sea from waste management, because these emissions vary depending on the other factors in the flow chain, such as domestic consumption and liquid wastes of consumption (Table 3). Foreign trade and food consumption are based on official statistics of Finland. Uncertainties in these data can be assumed to be relatively low. Nutrient content in feed and nutrients in treated wastewater also originate from monitoring data with high accuracy.

There are some data-related uncertainties not shown in the uncertainty analysis conducted in this study. Wideskog (2000) showed that fish farmers tend to report their use of feed as smaller than the actual use to meet the environmental legislation, amounting to approximately 20% smaller numbers in 1997–1998. This results in a

discrepancy in nutrient load statistics, because they are based solely on feed use data. However, in recent years the introduction of an online reporting system has made the process less prone to human error and misuse. The wastewater treatment efficiency data used in our study may be underestimated, since the development of treatment procedures has dramatically increased N removal capacities in recent years. For instance, the treatment plant managing the wastewaters of Helsinki Metropolitan Area is obliged to remove 70% of the N in wastewaters (The Western Finland Environmental Permit Authority 2004).

In defining the system, we estimated that all domestic consumption occurs in such municipalities that direct their wastewaters to the Baltic Sea. This may lead to overestimation of the nutrient flows to the Baltic Sea, since some rainbow trout are consumed inland. It is also difficult to determine how large a portion eventually ends up as food for human consumption, since food-preparing practices and dietary preferences vary widely. The effects of foreign trade in terms of import of rainbow trout and other salmonids were not quantified, since the focus was on domestic production. Imports are continuously increasing, as discussed in depth in Saikku and Asmala (2010).

CONCLUDING REMARKS

The rainbow trout production and consumption system in Finland has improved since the 1980s, but is still open and inefficient in the perspective of industrial ecology. During 2004–2007, approximately one-fifth of the primary nutrient input in feed ended up as food for human consumption. Ultimately, 70% of the N and P in feed ended up in the Baltic Sea, directly from aquaculture and also through waste management. The nutrient cycle could become more closed if local fish were used in rainbow trout feed instead of imported fish. Our study showed that the net nutrient load for N could be reduced to one-fourth and for P almost entirely. Finland has committed to reducing nutrient load by 1200 t for N and 150 t for P (HELCOM 2007b). Our results show that by replacing foreign fish meal in rainbow trout feed, Finland's nutrient reduction quota could be fulfilled by one-third for N and by half for P. Or, in turn, reduced net emissions per unit of rainbow trout produced could allow increases in production within the nutrient limits set in environmental permits. This could in turn compensate for the growing imports of salmon, which are currently outsourcing some of the nutrient emissions.

Acknowledgments This study was funded by the Serlachius Foundation, and the project IFEE (Indicator Framework for Eco-Efficiency, Grant 117822) funded by the Academy of Finland. We are grateful to Pekka Kauppi for comments on this article.

REFERENCES

- Antikainen, R., R. Lemola, J. Nousiainen, L. Sokka, M. Esala, P. Huhtanen, and S. Rekolainen. 2005. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. *Agriculture, Ecosystems & Environment* 107: 287–305.
- Ayres, R. 1989. Industrial metabolism and global change. *International Social Science Journal* 41: 363–373.
- Bell, J., J. McEvoy, D. Tocher, F. McGhee, P. Campbell, and J. Sargent. 2001. Replacement of fish oil with rapeseed oil in diets of Atlantic salmon (*Salmo salar*) affects tissue lipid compositions and hepatocyte fatty acid metabolism. *Journal of Nutrition* 131: 1535–1543.
- Biomar A/S. 2007. Rainbow trout feed information. <http://www.biomar.fi/2foder/Fodertype/Orred.aspx>. Accessed 26 Nov 2007.
- Bouman, M., R. Heijungs, E. van der Voet, J.C.J.M. van den Bergh, and G. Huppes. 2000. Material flows and economic models: An analytical comparison of SFA, LCA and partial equilibrium models. *Ecological Economics* 32: 195–216.
- Brunner, P., and H. Rechberger. 2004. *Practical handbook of material flow analysis*. Boca Raton: CRC Press.
- Carter, C., and R. Hauler. 2000. Fish meal replacement by plant meals in extruded feeds for Atlantic salmon, *Salmo salar* L. *Aquaculture* 185: 299–311.
- Chen, M., J. Chen, and F. Sun. 2008. Agricultural phosphorus flow and its environmental impacts in China. *Science of the Total Environment* 405: 140–152.
- Danius, L. 2002. Data uncertainties in material flow analysis. Local case study and literature survey. Licentiate thesis at Kungliga Tekniska högskolan, Chemical and Engineering and Technology.
- Delgado, C., M. Rosegrant, N. Wada, S. Meijer, and M. Ahmed. 2002. Fish as food: Projections to 2020 under different scenarios. MTID Discussion Papers 52, International Food Policy Research Institute (IFPRI).
- Elmgren, R. 2001. Understanding human impact on the Baltic ecosystem: Changing views in recent decades. *Ambio* 30: 222–231.
- FAO. 2007. *The state of world fisheries and aquaculture 2006*. FAO.
- Fineli. 2008. National Public Health Institute, Nutrition Unit. Finnish Food Composition Database. Release 9. <http://www.ktl.fi/fineli/>
- Finnish Environmental Institute. 2008. *Aquaculture nutrient load statistics 1989–2007*. Helsinki, Finland: The Finnish Environmental Institute, VAHTI-Database.
- Finnish Game and Fisheries Research Institute. 2008a. *Aquaculture 2007*. Helsinki, Finland: Finnish Game and Fisheries Research Institute.
- Finnish Game and Fisheries Research Institute. 2008b. *Foreign trade in Fish 2007*. Game and Fisheries. Statistics nr. 2, 2008. Helsinki, Finland: Finnish Game and Fisheries Research Institute.
- Finnish Game and Fisheries Research Institute. 2008c. *Fish consumption 1999–2007*. http://www.rktl.fi/english/statistics/economy_and_the_fish_consumption/. Accessed 28 Jan 2008.
- Finnish Game and Fisheries Research Institute. 2008d. *Commercial Marine Fishery 2007*. Game and Fisheries. Statistics, nr. 3, 2008. Helsinki, Finland: Finnish Game and Fisheries Research Institute.
- Frosch, R., and N. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* 189: 152.
- Grönroos, J., J. Seppälä, F. Silvenius, and T. ja Mäkinen. 2006. Life cycle assessment of Finnish cultivated rainbow trout. *Boreal Environmental Research* 11: 401–414.
- Gyllenhammar, A., L. Håkanson, and K.-J. Lehtinen. 2008. A mesocosm fish farming experiment and its implications for

- reducing nutrient load on a regional scale. *Aquacultural Engineering* 38: 117–126.
- Halweil, B. 2008. *Farming fish for the future*. Washington, DC: Worldwatch Institute.
- Hardy, R., and A. Tacon. 2002. Fish meal: Historical uses, production trends and future outlook for sustainable supplies. In *Responsible marine aquaculture*, ed. R.R. Stickney, 311–324. Wallingford, UK: CAB International.
- Hedbrant, J., and L. Sörme. 2001. Data vagueness and uncertainties in urban heavy-metal data collection. *Water, Air, and Soil pollution* 1: 43–53.
- HELCOM. 2005. Nutrient pollution to the Baltic Sea in 2000. *Baltic Sea Environment Proceedings No. 100*.
- HELCOM. 2007a. Activities 2006. *Baltic Sea Environment Proceedings No. 112*.
- HELCOM. 2007b. The Baltic Sea action plan.
- HELCOM. 2009. Eutrophication in the Baltic Sea—an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. *Baltic Sea Environment Proceedings No. 115B*.
- Helminen, H., E. Juntura, J. Koponen, P. Laihonon, and H. Ylinen. 1998. Assessing of long-distance background nutrient loading to the Archipelago Sea, northern Baltic, with a hydrodynamic model. *Environmental Modelling Software* 13: 511–518.
- Isosaari, P., T. Vartiainen, A. Hallikainen, and K. Ruohonen. 2002. Feeding trial on rainbow trout: comparison of dry fish feed and Baltic herring as a source of PCDD/Fs and PCBs. *Chemosphere* 48: 795–804.
- Karttunen, E., and J. Vielma. 1993. Kalankasvatus ja ympäristö. Suomen Kalankasvattajaliitto Ry (in Finnish).
- Lifset, R., and T. Graedel. 2002. Industrial ecology: Goals and definitions, Chapter 2. In *Handbook of industrial ecology*, ed. R.U. Ayres, and L. Ayres. Cheltenham: Edward Elgar Publishers.
- Liljebladh, B., and A. Stigebrandt. 1996. Observations of the deepwater flow into the Baltic. *Journal of Geophysical Research* 101: 8895–8911.
- Mayer, A.L. 2007. Strengths and weaknesses of common sustainability indices for multidimensional systems. *Environment International* 34: 277–291.
- Moisander, P., T. Steppe, N. Hall, J. Kuparinen, and H. Paerl. 2003. Variability in nitrogen and phosphorus limitation for Baltic Sea phytoplankton during nitrogen-fixing cyanobacterial blooms. *Marine Ecology Progress Series* 262: 81–95.
- Mozaffarian, D., and E. Rimm. 2006. Fish intake, contaminants, and human health: evaluating the risks and the benefits. *Journal of the American Medical Association* 296: 1885–1899.
- Nausch, G., D. Nehring, and G. Aertebjerg. 1999. Anthropogenic nutrient load of the Baltic Sea. *Limnologia* 29: 233–241.
- Pekcan-Hekim, Z. and J. Horppila. 2008. Net loading system for fish farming: trash fish reduction and internal loading. *Riista- ja kalatalous—Tutkimuksia* 1/2008.
- Peuhkuri, T. 2002. Knowledge and interpretation in environmental conflict: Fish farming and eutrophication in the Archipelago Sea, SW Finland. *Landscape Urban Plan* 61: 157–168.
- Raisio Feed Ltd. 2007. Kirjolehrehujen tuotetiedot 2007. http://www.raisiogroup.com/modules/sgeditor/sgeditor_download.aspx?P=147&VID=default&SID=528353643017012&S=1&action=handle_download_link&dfpath=andfname=biw8jg0vde5.pdf&C=55125. Accessed 26 Nov 2007 (in Finnish).
- Rembold, C., R. Hites, J. Foran, D. Carpenter, M. Hamilton, B. Knuth, and S. Schwager. 2004. The health benefits of eating salmon. *Science* 305: 475.
- Rönnerberg, C., and E. Bonsdorff. 2004. Baltic Sea eutrophication: Area-specific ecological consequences. *Hydrobiologia* 514: 227–241.
- Ruohonen, K. 1994. *Gastrointestinal responses of rainbow trout (Oncorhynchus mykiss Walbaum) to dry pellet and low-fat herring diets: Consequences for growth, feed utilisation and nutrient load into the water*. Bangor: University of Wales. ISBN 951-8914-96-6.
- Ruohonen, K., and T. Mäkinen. 1991. Potential ways to diminish the environmental impact of mariculture in the Baltic Sea. *Finnish Fisheries Research FNFRAK* 12: 91–100.
- Ruohonen, K., J. Vielma, and D. Grove. 1998. Comparison of nutrient losses into the water from rainbow trout culture based on fresh Baltic herring, moist and dry diets. *Aquaculture International* 6: 441–450.
- Saikk, L. and E. Asmala. 2010. Eutrophication in the Baltic Sea: The role of salmonid aquaculture, consumption, and international trade. *Journal of Industrial Ecology* 14. doi:10.1111/j.1530-9290.2010.00221.x.
- Santala, E., L. Etelämäki, and O. Santala. 2006. Yhdyskuntien jätevesien puhdistus. *Suomen Ympäristökeskuksen raportteja* 13 (in Finnish).
- Seppälä, J., F. Silvenius, J. Grönroos, T. Mäkinen, K. Silvo, and E. Storhammar. 2001. Kirjolehen tuotanto ja ympäristö. *Suomen ympäristö* 529 (in Finnish).
- Setälä, J., J. Vielma, J. Koskela, A. Honkanen, K. Saarni, T. Jokelainen, M. Suvanto, and M. Kankainen. 2007. Ahvenanmaan kestävän kalankasvatuksen kehittämisvaihtoehtoja. *Kala- ja riistaraportteja* 412 (in Finnish).
- Sidhu, K. 2003. Health benefits and potential risks related to consumption of fish or fish oil. *Regulatory Toxicology and Pharmacology* 38: 336–344.
- Silvenius, F. 2000. Kalankasvatus ja ympäristö. Kalankasvatuksen prosessikuvaus. *Kala ja riistaraportteja* 198 (in Finnish).
- Sokka, L., R. Antikainen, and P. Kauppi. 2004. Flows of nitrogen and phosphorus in municipal waste: A substance flow analysis in Finland. *Progress in Industrial Ecology* 1: 165–186.
- Tamminen, T., and T. Andersen. 2007. Seasonal phytoplankton nutrient limitation patterns as revealed by bioassays over Baltic Sea gradients of salinity and eutrophication. *Marine Ecology Progress Series* 340: 121–138.
- Tapio, P., and R. Willamo. 2008. Developing interdisciplinary environmental frameworks. *Ambio* 37: 125–133.
- The Western Finland Environmental Permit Authority. 2004. Länsi-Suomen ympäristölupavirasto, decision 56/2004/1 Dno. LSY-2003-Y-38. <http://www.ymparisto.fi/download.asp?contentid=80451>.
- Udo de Haes, H.A., E. van der Voet, and R. Kleijn. 1997. Substance flow analysis (SFA), an analytical tool for integrated chain management. In *Regional and national material flow accounting: From paradigm to practice of sustainability*, ed. S. Bringezu, M. Fischer-Kowalski, R. Kleijn, V. Palm, 32–42. *Proceedings of the ConAccount Workshop*, 21–23 January 1997. Leiden, The Netherlands: Wuppertal Institute for Climate, Environment and Energy.
- van der Voet, E. 1995. Substance flows through the economy and environment of a region. *Environmental Science and Pollution Research International* 2: 89–96.
- van der Voet, E. 2001. SFA methodology, Luku 9. In *Handbook of industrial ecology*, ed. R.U. Ayres and L. Ayres. Cheltenham: Edward Elgar Publishers.
- Vielma, J., T. Mäkinen, and J. Koskela. 2000. Influence of dietary soy and phytase levels on performance and body composition of large rainbow trout (*Oncorhynchus mykiss*) and algal availability of phosphorus load. *Aquaculture* 183: 349–362.
- Vihervuori, A. and A. Ahvonen. 1997. Miten kalankulutusta arvioidaan. Kalavirrat. *SVT. Ympäristö* 1997:13, 34–38 (in Finnish).

Wideskog, M. 2000. Kalankasvatuksen kuormitusilastoinnin luotettavuus vuosina 1997–1998. Lounais-Suomen ympäristökeskuksen moniste 3/2000 (in Finnish).

AUTHOR BIOGRAPHIES

Eero Asmala (✉) is a Ph.D. student in environmental science and policy at the University of Helsinki. He has a Master of Science degree in environmental sciences. His field of interest is the eutrophication phenomenon in the Baltic Sea and industrial ecology, especially industrial metabolism. His recent research focuses on applying industrial ecology to eutrophication mitigation.

Address: Environmental Sciences, Faculty of Biological and Environmental Sciences, University of Helsinki, P.O. Box 27, Viikki, E-Building, FI-00014 Helsinki, Finland.
e-mail: eero.asmala@helsinki.fi

Laura Saikku is a Ph.D. student in environmental science and policy at the University of Helsinki. She holds a Master's degree in agriculture and forestry. Her research interests are in the field of industrial ecology, including nutrient flows of the human economy as well as the linkages between environmental problems and the population, economy, consumption and production. Her recent research focuses on aquaculture in Finland, but also European climate policy and the challenge of meeting emissions reduction targets.

Address: Environmental Sciences, Faculty of Biological and Environmental Sciences, University of Helsinki, P.O. Box 27, Viikki, E-Building, FI-00014 Helsinki, Finland.
e-mail: laura.saikku@helsinki.fi