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Life cycle assessment of Finnish cultivated rainbow trout

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Rainbow trout is economically the most important cultivated fish in Finland. In this study, new knowledge on the energy consumption, emissions and environmental impacts caused by the production of rainbow trout in Finland was generated. Methodologically the work was based on life cycle assessment (LCA) beginning from the extraction of raw materials and ending with the delivery of gutted fish to the retailers or for further processing. The environmental performances of production methods with different feeds, feed coefficients and technical emission reduction measures were assessed. The environmental impact assessment revealed that atmospheric emissions — originating mainly from the feed raw material production, feed manufacturing and transportation — make only a minor contribution to the total environmental impacts caused by the production of rainbow trout in Finland. Phosphorus and nitrogen emissions from fish farms to waters are the most significant emissions from the point of view of the total environmental impacts. By using new, environmentally friendly feeds with increased feed efficiency it is possible to decrease the nitrogen and phosphorus loads significantly. Technical measures to decrease nutrient emissions to the waters reduce the phosphorus load but have only a minor effect on nitrogen. Energy consumption and the use of renewable energy sources proved to be one of the key indicators for developing more sustainable aquacultural practices in Finland, although the major share of energy consumption associated with the production of rainbow trout takes place outside Finland.

Introduction

In Finland, 97% of fish cultivated for direct consumption in 2003 (12 558 tonnes) was rainbow trout. Around 80% of this was produced in marine farms, mainly in the Åland Islands and Archipelago areas, and 20% in inland waters (Savolainen 2004). Import of Norwegian rainbow trout and Atlantic salmon has been increasing in recent years. The total amount was 7200 tonnes in 1999 and as much as 15 640 tonnes in 2003 (Vihervuori 2000, 2004).

Aquatic eutrophication is considered to be one of the most significant environmental problems associated with fish farming in Finland. This argument is supported by the national environmental programme for fish farming (Tiainen *et al.* 1996), in which it is stated that the main emphasis of the programme is on decreasing nutrient emissions to the waters. Other harmful impacts, such as fish diseases and ecotoxic impacts, have received much less attention.

The emissions and the use of resources during fish cultivation provide only a narrow view of the overall environmental impacts of cultivated fish production, which also requires energy, fish feed, transportation, package materials and pharmaceuticals and other chemicals. All these activities have impacts on the environment. The environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use and disposal can be assessed by a life cycle assessment (LCA) method, which is an internationally standardized tool for assessing the environmental impacts related to products or services (ISO 1997, 1998, 2000). LCAs have been conducted for a number of typical consumer products during the last 15 years. Since the mid-1990s, LCAs for food products have become more common (e.g. Møller and Vold 1995, Weidema *et al*. 1995, Andersson *et al*. 1998, Andersson and Ohlsson 1999, Mattson 1999, Cederberg and Mattsson 2000, Berlin 2002, Høgaas Eide 2002, Ziegler *et al*. 2003).

The aim of this study was to prepare a life cycle assessment of Finnish cultivated rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792). The analysis was made in order to examine the contributions of the different production phases, impacts, emissions and the use of fossil fuels to the total environmental impacts caused by typical rainbow trout production. Furthermore, the environmental impacts of alternative production methods were compared. The main focus was on environmental impacts which could be assessed using quantitative resource use and emission data, but other important impacts relevant to rainbow trout production were also considered.

Materials and methods

Life cycle assessment includes four major phases (ISO 1997): goal and scope definition, inventory analysis, impact assessment and interpretation of the results. In the goal and scope definition the problem and the aims of the study are defined. In this step a functional unit of the work, i.e. the unit for which the results will be presented, is chosen. The system boundary, i.e. the interface between a product system and the environment or other product systems, of the chosen product is also defined. In inventory analysis, data on environmental interventions (emissions, resource extractions and land use) during the life cycle of a product are collected. This requires that the product system is divided into unit processes in order to facilitate data collection. In the inventory analysis there is a need to decide issues that play an important role in the reliability of the assessment, such as acceptability of data sources and calculation rules for assessing environmental interventions. In the case of multi-product systems, environmental interventions are assessed using so-called allocation rules, which should also be determined in the inventory analysis phase. In the life cycle impact assessment (LCIA) the detailed data from inventory analysis are transformed into a more useful format to describe the environmental impacts of emissions and the use of resources within impact categories. LCIA is typically divided into five phases: selection of impact categories, classification, characterisation, normalisation and weighting (*see* e.g. ISO 2000). In the interpretation of the results the conclusions and recommendations are made by combining the results from the inventory analysis and impact assessment.

Products and functional units

The product studied was Finnish cultivated ungutted rainbow trout, and the functional unit was one tonne of ungutted rainbow trout after slaughtering. According to the international standard 14040 (ISO 1997) the functional unit is "quantified performance of a product system for use as a reference unit in a life cycle assessment study". Despite the fact that the functional unit is one tonne of ungutted fish, gutting is included as a unit process in the product system, because gutting takes place at the same time and at the same site as slaughtering.

By using ungutted fish (and not the gutted fish) as the product examined, the allocations, i.e. sharing the environmental interventions between gutted fish, roe and gutting wastes, were avoided, which is in line with the recommendations of the international standards (*see* ISO 1998).

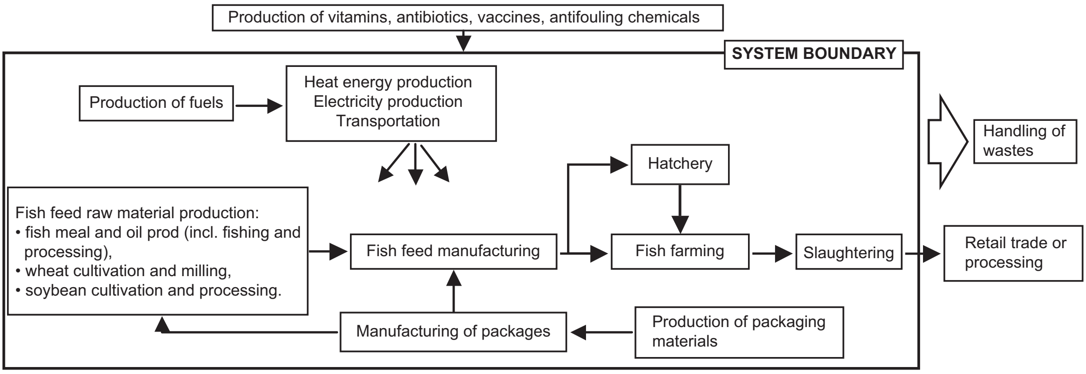

Fig. 1. System boundaries and material and energy flows of the rainbow trout product system.

Product systems, production methods and system boundaries

The production of ungutted rainbow trout beginning from the extraction of raw materials and ending with the delivery of gutted fish to the retailers or to further processing forms the product system of the study (Fig. 1). The product system can be constructed in different ways. In this study, one typical and six alternative rainbow trout product systems (representing the alternative production methods) were studied.

The typical rainbow trout production method was rainbow trout production in net cages mainly in the Archipelago area in Finland with a feed coefficient (FC) of 1.255 (based on the fish farmers' declarations on feed usage). The alternative production methods were:

- FC 0.9 (like the "typical method", but with FC = 0.9, which represents the best observed feed coefficient in Finland in the late 1990s).
- FC 1.53 (like the "typical method", but with FC = 1.53, which represents the statistical average feed coefficient in Finland in 1999 according to the official feed manufacturing and import statistics of the Finnish Food Safety Authority Evira).
- Soy feed (like the "typical method", but with a feed with added soy protein extract. FC in the original study was 0.9 but the results were converted to be comparable with FC = 1.255).
- Closed floating cage (CFC), FC = 1.255.
- Funnel, FC = 1.255.
- Land-based marine farm (LBMF), FC = 1.255.

In the alternative production methods all unit processes except fish farming and — in the case of "soy feed" — feed raw-material production and feed manufacturing were the same as the unit processes of the typical method.

The product system of rainbow trout includes feed and feed raw-material production, hatcheries, the fish farm itself, slaughtering, gutting, transport of raw materials and final products and production of packages, fuels and electricity. The main raw materials of feed are fish meal and oil, wheat meal and soy products. It was not possible or necessary to include all the unit processes of the rainbow trout production in the study because of the lack of data or because of their minor importance in the overall product system. Thus, unit processes such as manufacturing of antifouling materials and pharmaceuticals were excluded. The two following sections describe the unit processes of the different rainbow trout product systems. Detailed inventory data and the data sources concerning the rainbow trout product system are presented in Silvenius and Grönroos (2003).

Typical production method

Juvenile fish production takes place at hatcheries. Most of the fish farming sites are equipped with net cages. The net cages are treated with antifouling material. Nutrient loads from a typical fish farm to water were calculated based on a feed coefficient of 1.255, which was the official feed coefficient in Finland in 1999. This value has remained rather constant during recent years, being 1.239 in 2003 (E. Kaukoranta, Southwest Finland Regional Environment Centre, pers. comm.). The official feed coefficient is based on the feed consumption and fish production reports returned by the fish farmers to the authorities.

The main share of the feed raw materials is imported from abroad, mainly from Denmark. Feed raw materials are transported to the feed factory located in Finland. In the feed factory fish feed is manufactured and packed into sacks. The feed raw materials are (average share in parentheses) fish meal and oil (64.5%), wheat meal (14.1%), soy concentrate (8.3%), vitamins and micronutrients (7.2%), soybean meal (4.2%), and maize meal (1.7%). The average nitrogen and phosphorus contents are 6.8% and 0.91%, respectively.

There is a heat energy requirement in fish meal and oil production. In this study, heat energy was assumed to be produced from coal. Emissions from electricity production were calculated using a Finnish electricity production model (Petäjä and Koskela 2002). The same model was also used for electricity used in unit processes located outside Finland.

Slaughtering (incl. stunning, bleeding and gutting) causes some nutrient emissions to waters and organic wastes. In Finland, solid waste from gutting is mainly used as feed material in fur farms. The amount of solid waste is 17% of the whole mass of the fish (RKTL 1997). For packing materials European average databases were used (APME). Package manufacturing data were collected from separate production plants. Typical packages are feed sacks, made of polyethene and polypropene, for fish feed and polystyrene boxes for transporting the fish. Transport of fish to further processing or use as well as the transport of fish feed, packages and other materials between the unit processes was also taken into account.

Alternative production methods

The main differences between product systems of typical and alternative rainbow trout production systems are in the fish farming phase and in the case of different feeds in the feed production phases. Other unit processes were the same as in the typical method.

Fish farming with different feeds and feed coefficients

Efficiency of the use of fish feed and nutrient contents of feed vary from farm to farm and from feed to feed. Effects of different feed coefficients on the environmental impacts of rainbow trout production were studied using the coefficients of 0.9 and 1.53 in addition to the typical method's average feed coefficient 1.255. Fish farming with feed containing soy protein extract is based on an experimental study carried out in Finland in the late 1990s (Vielma *et al.* 1999). In this study, emissions to waters from fish farming with feed containing soy were compared with emissions from the typical farming method. Raw materials of the soy-based feed were: fish meal 13.3%, fish oil 28.0%, soy protein concentrate 31.5%, soybean meal 12.1%, wheat meal 10.3%, others 4.8%. The phosphorus content of the feed was 0.69% and the nitrogen content 5.46%. In the study as much as over 35% of feed phosphorus was assimilated by the fish. The feed coefficient was 1.1. Because of the comparability of the results with other farming systems, the results of the earlier study were converted to be equivalent to a feed coefficient of 1.255. In practice, however, development of feeds has an effect on both nutrient concentrations and the feed coefficient.

Technically different fish farming methods

In this context, fish farming methods were studied in which the sludge — consisting of feed residuals and fish faeces — was collected in order to decrease nutrient emissions to waters. In these cases the feed coefficients and the nutrient contents of the feeds as well as the amount of nutrients assimilated by fish were assumed to be the same as in the case of the typical rainbow trout production.

Three technically different farming systems were studied. In the funnel system, a funnel is installed underneath the net cage. Farming sludge deposited to the funnel is removed by pumps for an external treatment. Part of the sludge phosphorus can be removed but on the other hand sludge pumping consumes electricity, which in turn increases emissions to the atmosphere. In the closed floating cage system the cages are closed and the water is pumped in. In this system sludge is pumped out and collected. The pumping again increases the electricity consumption, but in this system the main share of the sludge can be removed. In the land-based marine farm system farming takes place in ponds. Water must be pumped into the system, and sludge can be removed. Theoretically, it is possible to purify the water pumped out from the farming system before it enters the sea. Electricity consumption is higher as compared with that in the other systems because water must be pumped from the sea. The study concerning land-based marine farming is based on the theoretical calculations of the Finnish Game and Fisheries Research Institute. In all systems in which sludge is removed, it must also be transported and handled. Transport of sludge was assessed to have only a minor role in the overall product system and was therefore omitted from the study.

Inventory analysis

Inventory analysis was carried out according to the international standard ISO 14041 (ISO 1998). Collected unit process data were fed into the KCL-ECO software (KCL 2003) that was used to calculate the inventory results. Data sources and calculation methods concerning inputs and outputs of unit processes were presented in an earlier paper (Silvenius and Grönroos 2003).

Impact assessment

Impact assessment was performed using the basic phases of life cycle impact assessment (LCIA) represented in the ISO 14042 standard (ISO 2000). Firstly, appropriate impact categories (e.g. climate change and acidification) are selected. Secondly, the inventory data are assigned to the impact categories according to available scientific knowledge on the cause-effect relationships between the environmental interventions and the effects of the impact categories (e.g. CO_2, N_2O, CH_4 to climate change). In the third phase, characterization, values of interventions are changed to impact category indicator results by characterization factors. The fourth phase, normalization, relates the magnitude of the indicator results in the different impact categories to reference values. A reference value is the impact indicator result calculated on the basis of an inventory of a chosen reference system (e.g. all society's activities in a given area and over a specified period of time). Finally, weighting can be conducted in order to aggregate different impact category indicator results into a single number. This requires determining the weights for impact categories.

The impact categories included were: climate change, acidification, ozone formation in the troposphere, aquatic eutrophication, terrestrial eutrophication and depletion of fossil fuels. These impact categories were selected because of their scientifically based characterization factors. Quantitative information on resource use and emissions needed to assess the impacts of these categories was also available. It is important to notice that fossil fuels are assessed on the basis of natural resources, not on the basis of their emission potentials. Emissions from the use of fossil fuels are handled within the other impact categories.

Characterization for climate change corresponds to the same procedures used in national greenhouse gas inventories, i.e. GWP potentials were used as characterization factors, whereas characterization factors for acidification, tropospheric ozone formation and eutrophication were based on the latest scientific knowledge on the impacts of different emissions released in Finland (Table 1). Characterization factors used for the different fossil fuels directly corresponded to the energy contents of each fossil fuel.

The reference values used in normalization (Table 2) are based on the characterization factors and the total emissions and the consumption of fossil fuels in Finland in 2002. The weights of the impact categories (Table 2) represent average weights derived from the earlier LCA studies carried out in the Finnish Environment Institute (Seppälä and Jouttijärvi 1997, Seppälä *et al*. 2000, Grönroos and Seppälä 2000, Tenhunen and Seppälä 2000). The weights in each evaluation work were obtained by asking tens of experts for their opinions about the importance of impact categories from the viewpoint of effect reductions. The elicitation and determination of weights in the studies were conducted according to decision analysis techniques and rules (Seppälä 1999, 2003).

The impact assessment results are presented in two ways. Firstly, characterized and normalized impact category values of different rainbow trout production methods are presented. This shows the impacts of different farming methods within each impact category and makes it possible to compare different farming methods within each impact category. It also shows the importance of rainbow trout production in each impact category in Finland. Secondly, the normalized impact category values were weighted by using the average impact category weights. After this the weighted impact category values were summed up, which gave as a result the total impact values of the alternatives studied. In addition to the average impact category weights, different sets of weights were used in order to reveal the sensitivity of the impact assessment results to the weighting procedure.

The main difference between the LCIA method used in the study and traditional LCIA methods is that our method — at an approximate level — takes into account the impact of the

Table 1. Characterization factors for the emissions to the atmosphere (a) and waters (w) within the impact categories climate change (CC), acidification (AC), aquatic eutrophication (AE), terrestric eutrophication (TE) and tropospheric ozone formation (TO).

Variable	Characterization factor				
	CC (CO_2 eq kg^{-1})	AC (eq kg^{-1})	AE (PO_4 eq kg^{-1})	TE (eq kg^{-1})	TO (1000 m^2 ppm hour kg^{-1})
CO_2(a)	1				
CH_4(a)	23				
N_2O(a)	296				
NH_3(a)		0.535	0.04	10.215	
NO_x(a)		0.186	0.015	1.411	0.35
SO_x(a)		0.463			
NMVOC(a)					0.27
N(w)			0.348*		
P(w)			1.102**		
Source	Ramaswamy *et al.* 2001	Seppälä *et al.* 2006	Seppälä *et al.* 2004	Seppälä *et al.* 2006	Hauschild *et al.* 2004

* Equivalency factor 0.42, transport factor 0.92, effect factor 0.9.

** Equivalency factor 3.06, transport factor 1.0, effect factor 0.36.

Table 2. Normalization values and impact category weights used in the impact assessment.

Impact category	Normalization value	Normalization value unit	Impact category weight
Climate change	81880	million CO_2 eq year^{-1}	0.29
Acidification	94.7	million eq year^{-1}	0.16
Aquatic eutrophication	23.4	million PO_4 eq year^{-1}	0.24
Terrestrial eutrophication	634.0	million eq year^{-1}	0.05
Tropospheric ozone formation	113521	million m^2 ppm hours year^{-1}	0.09
Depletion of fossil fuels	1120324	TJ year^{-1}	0.18

location of the emission source in evaluating the environmental impacts. In the case of rainbow trout production, Finland-specific characterization factors for acidification, tropospheric ozone formation and eutrophication were used because the emissions occur mainly in Finland. In many popular impact assessment methods such as Eco-Indicator 99 (Goedkoop and Spriensma 1999) and EPS (Steen 1999) the location of the emission sources and regional environmental conditions are not taken into account.

In this study, attention was focused on the six impact categories mentioned above. In addition to these, fish farming causes e.g. ecotoxic effects due to the use of antifouling materials and impacts on biodiversity due to the escape of cultivated fishes, fish diseases, discarded yield and over fishing. These impacts are recognized but were not handled systemically because of a lack of suitable data.

Results

The main airborne emissions from rainbow trout production originate from the raw material production and feed manufacturing, and the main waterborne emissions from fish farming (Table 3). Transport also plays an important role in emissions to the atmosphere. The alternative farming methods differ from the typical fish farming method mainly in their emissions to waters (Table 4). If feed with high soy content is used it also affects the emissions from feed production. The total primary energy use (32.6 GJ per 1000 kg of rainbow trout) is mainly caused by feed production. The detailed inventory analysis results can be found in Silvenius and Grönroos (2003).

The normalized impact category indicator results (Table 5) for different rainbow trout product systems show the dominance of the impact category “aquatic eutrophication” as compared with the other impact categories. The values also point to the importance of increasing the feed efficiency. By lowering the feed coefficient all harmful environmental impacts can be decreased at the same time. By using technical measures to prevent nutrient emissions to waters, aquatic eutrophication can be decreased whereas other harmful impacts increase because of the increased use of energy.

The total impact values of the alternative rainbow trout product systems were obtained by using weighting factors and summing up the weighted impact category values. Weighting facilitates identification of the life cycle phases as well as the emission variables that are most harmful from the point of view of the six environmental impact categories. According to the weighted impact assessment results, nitrogen and phosphorus emissions to waters were the most significant emissions causing the impacts, whereas the significance of the airborne emissions was low (Fig. 2). The impacts were linearly dependent on the feed coeffi-

Table 3. Main atmospheric (a) and water (w) emissions (kg t^{-1} of ungutted rainbow trout) and primary energy use (GJ t^{-1} of ungutted rainbow trout) from different production phases of typical rainbow trout production based on the feed coefficient 1.255.

Variable	Feed raw materials	Feed manufacturing	Hatchery	Fish farm	Slaughtering	Packaging	Total
CH_4(a)	1.076	0.023	0.002	0.000	0.004	0.212	1.317
CO_2(a)	421.82	95.03	4.82	8.490	19.50	102.01	651.66
CO(a)	0.427	0.169	0.005	0.062	0.032	0.133	0.827
N_2O(a)	0.529	0.011	0.001	0.000	0.001	0.001	0.542
NH_3(a)	0.384	0.000	0.000	0.000	0.000	0.000	0.384
NO_x(a)	3.648	0.649	0.011	0.140	0.056	0.567	5.075
SO_x(a)	1.071	0.257	0.005	0.004	0.025	0.421	1.783
VOC(a)	3.081	1.816	0.0578	0.029	0.073	1.160	6.214
N(w)	1.624	0.0003	0.636	57.089	0.500	0.0002	59.850
P(w)	0.062	0	0.080	7.296	0.050	0,000	7.488
Energy	23.45	4.04	0.18	0.12	0.44	4.34	32.57

cient, as were the environmental loads in the inventory analysis. Due to the nutrient emissions to waters, fish farming dominates the total impact value (Fig. 3). The most effective way to decrease nutrient emissions and total environmental impacts of fish production is to increase feed efficiency (Fig. 4a). Feed containing soy together with a low feed coefficient would cause rather good impact reduction with relatively low costs. Production methods with different technical solutions mainly affect phosphorus emissions. Low phosphorus reduction with increased emissions to the atmosphere due to the increased use of electricity gives almost the same impact value for the land-based marine farm as the typical production method. The total impact value of land-based marine farming was even higher if the processing of sludge was included in the assessment.

The sensitivity of the impact assessment results to the impact category weights was studied by using the equal impact category weights

Table 4. Main atmospheric (a) and water (w) emissions (kg t^{-1} of ungutted rainbow trout) and primary energy use (GJ t^{-1} of ungutted rainbow trout) from different rainbow trout production systems (FC = feed coefficient).

Variable	Typical (FC 1.255)	FC 0.9	FC 1.53	Soy feed	Funnel	CFC	LBMF
CH_4(a)	1.317	1.014	1.570	0.930	1.359	1.427	2.111
CO_2(a)	651.7	509.6	770.3	601.8	753.7	913.4	2496.1
CO(a)	0.827	0.665	0.962	0.830	0.875	0.902	1.082
N_2O(a)	0.542	0.397	0.663	0.412	0.551	0.567	0.720
NH_3(a)	0.384	0.281	0.471	0.285	0.384	0.384	0.384
NO_x(a)	5.075	3.907	6.052	5.761	5.320	5.606	8.255
SO_x(a)	1.783	1.414	2.093	2.490	1.933	2.173	4.569
VOC(a)	6.214	4.858	7.350	7.359	7.274	8.977	25.96
N(w)	59.85	40.291	83.83	48.08	58.67	58.15	59.51
P(w)	7.488	4.461	10.13	4.836	5.563	2.928	5.077
Energy	32.57	24.73	38.56	27.46	36.70	55.13	109.56

Typical = rainbow trout production in net cages, feed coefficient (FC) 1.255.
FC 0.9 = like “typical”, but FC = 0.9.
FC 1.53 = like “typical”, but FC = 1.53.
Soy feed = like “typical”, but fish feed includes soy meal and soy concentrate, FC = 1.255.
Funnel = funnel system, FC = 1.255.
CFC = closed floating cage, FC = 1.255.
LBMF = land-based marine farm, FC = 1.255.

Table 5. Characterized and normalized impact assessment values for different rainbow trout product systems presented as percentages of Finland’s total emissions for each impact category and for a production volume of 10 000 tonnes of ungutted rainbow trout.

	Typical (FC 1.255)	FC 0.9	FC 1.53	Soy feed	Funnel	CFC	LBM F
Climate change	0.010	0.008	0.012	0.009	0.012	0.014	0.034
Acidification	0.021	0.016	0.045	0.025	0.022	0.024	0.041
Aquatic eutrophication	1.246	0.812	1.733	0.946	1.138	1.006	1.129
Terrestrial eutrophication	0.017	0.013	0.099	0.017	0.018	0.019	0.025
Tropospheric ozone formation	0.030	0.024	0.019	0.035	0.035	0.039	0.087
Depletion of fossil fuels	0.005	0.004	0.006	0.004	0.006	0.007	0.011

Typical = rainbow trout production in net cages, feed coefficient (FC) 1.255.
FC 0.9 = like “typical”, but FC = 0.9.
FC 1.53 = like “typical”, but FC = 1.53.
Soy feed = like “typical”, but fish feed includes soy meal and soy concentrate, FC = 1.255.
Funnel = funnel system, FC = 1.255.
CFC = closed floating cage, FC = 1.255.
LBMF = land-based marine farm, FC = 1.255.

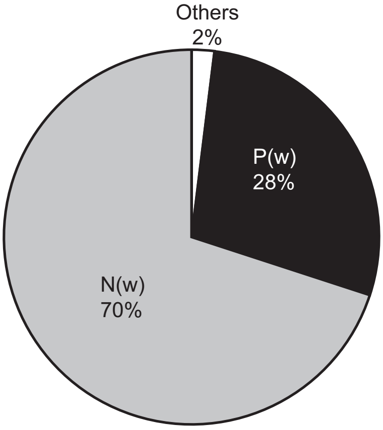

Fig. 2. Contributions of different emissions to the total impact value of typical rainbow trout production in the Finnish Archipelago sea area (N(w) = nitrogen emission to waters, Pw) = phosphorus emission to waters).

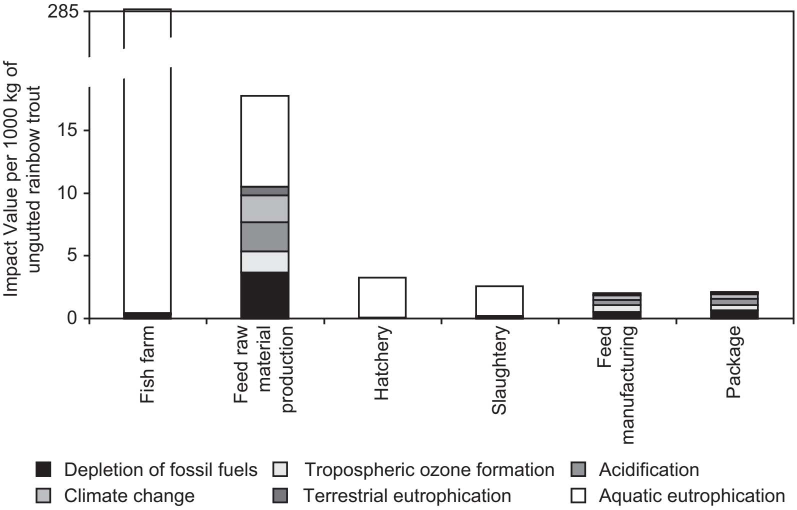

Fig. 3. Contributions of different production phases to the total environmental impact value caused by typical rainbow trout production in the Finnish Archipelago sea area (note the scale of the *y*-axis and the relative importance of the fish farming phase to the total impact value).

and by changing the weight of the impact category "aquatic eutrophication". The results of normalization (Table 5) show that the impact category "aquatic eutrophication" must play a significant role in the aggregated impacts because of the relatively high contribution of aquaculture to eutrophication as compared with that of other impact categories in Finland. The production of rainbow trout causes approximately 1%–2% of the eutrophying emissions in Finland, whereas the contribution of the rainbow trout production to the emissions of the other impact categories and to consumption of fossil fuels is much lower. Use of equal impact category weights (Fig. 4b) leads to a similar outcome as that when the average weights obtained from the expert judgements were used (Fig. 4a). The final results, i.e. the environmental performance of the alternative production systems, will be changed if the weight of the aquatic eutrophication is significantly lower as compared with the other weights than it is in the case of average or equal impact category weights (Fig. 5). In that case the differences in energy use and atmospheric emissions play a more important role in the total impact value, which also affects the environmental performance of the different production alternatives.

Discussion

The comparison of alternative rainbow trout production methods revealed that it is possible to reduce the environmental impacts of fish farming by using new, environmentally friendly feeds.

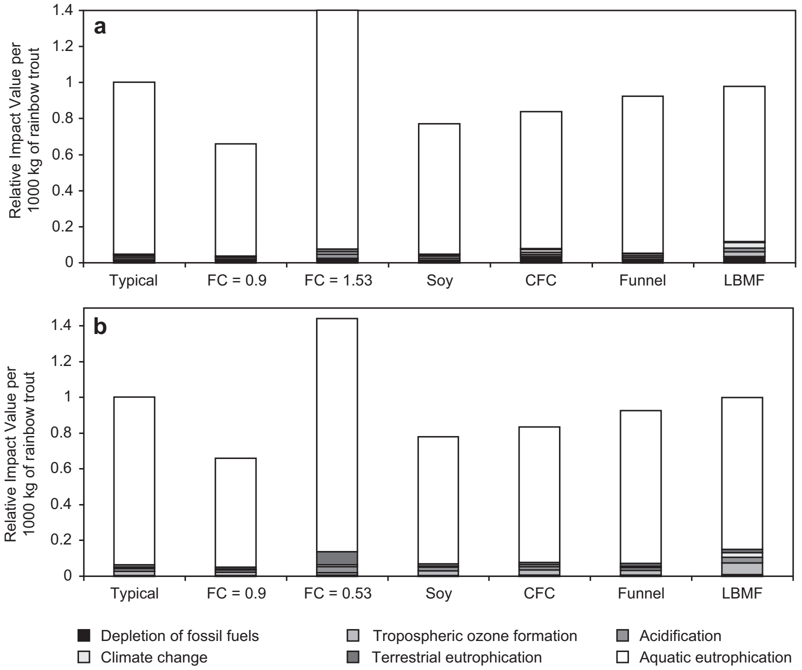

Fig. 4. Relative impact values (typical farming system = 1) of different rainbow trout product systems using (**a**) impact category weights obtained from Finnish experts and (**b**) equal impact category weights (FC = feed coefficient, LBMF = land-based marine farm, CFC = closed floating cage, Soy = soy-based feed).

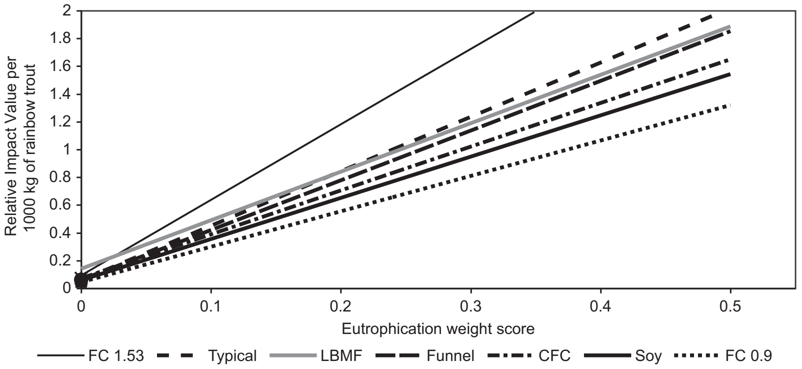

Fig. 5. Effects of changes in the weight score of aquatic eutrophication (0, 0.24 (= default value) and 0.5) on the relative impact values of the different rainbow trout production alternatives (typical production system with default value of aquatic eutrophication weight score = 1). Here, the weight score of aquatic eutrophication is changed while the proportions of weights of the other impact categories remain constant (FC = feed coefficient, LBMF = land-based marine farm, CFC = closed floating cage, Soy = soy-based feed).

Increased feed efficiency reduces emissions to the atmosphere and waters and increases the resource use efficiency. By using a feed containing soy protein or other similar alternative protein sources at the same time as increasing the feed efficiency, it is possible to decrease the nitrogen and phosphorus loads significantly. According to the fish feed industry (E. Norrgård, Raisio Feed Ltd., pers. comm.), the use of soy-based feed means approximately 0.08 € additional cost per kg of rainbow trout produced. This is reasonable compared with the fish farmers' price of 3.02 € per kg of fish in 2003 (without VAT, Nylander 2004), whereas the technical measures to reduce emissions from the fish farms cause higher costs — up to 0.2–0.5 € per kg of fish (Niinimäki *et* *al.* 1991, Tiainen *et al.* 1996, SFT 1998, Wedekind *et al.* 1999). The technical measures reduce phosphorus loading significantly but have only a minor effect on nitrogen. Therefore they are suitable for inland waters only, because phosphorus is the main limiting nutrient in inland waters of Finland.

According to the statistics of the Finnish Environment Institute, fish farming is responsible for 1%–2% of the all eutrophying emissions to Finnish waters. Locally, e.g. in southwestern Finland, the share of fish farming may be much higher. In 2003, the total nutrient loads from fish farming in Finland were evaluated to be 80 tonnes of phosphorus and 644 tonnes of nitrogen, which was 52.6 kg N and 6.6 kg P per tonne of produced fish (E. Kaukoranta, Southwest Finland Regional Environment Centre, pers. comm.). In 2001, the values were 55.6 kg N and 7 kg P per tonne of produced fish (Kaukoranta 2002). Significantly lower nutrient loads have been reached with specific feeds in experimental conditions, for example 36.2 kg N and 4.6 kg P per tonne of produced fish (Vielma *et al.* 1999), or even lower when using the enzyme phytase (Vielma *et al.* 2004). The estimates of nutrient emissions to waters are based on the official statistics based on declarations of fish farmers regarding annual feed use and production volumes, and the average nitrogen and phosphorus contents of the feeds. However, it has been argued that the information obtained from the declarations does not necessarily represent the true feed efficiency. According to the statistics of the Finnish Food Safety Authority (Evira) on feed manufacturing and import, the feed coefficient was 1.53 in 1999. This figure differs from the feed coefficient of 1.255 calculated from the feed use values obtained from the farmers. There are many reasons why the values do not correspond. The statistics based on the fish farmers' declarations do not include exported or stored feeds or feeds used for other purposes. Until the year 2000 the statistics of Evira also included exported feeds or feeds that were stored. Furthermore, not all imported feedstuffs are necessarily included in the statistics (Wideskog 2000).

Electricity production is one source of emissions to the atmosphere. Thus, the electricity production model, which is used to calculate the emissions from electricity generation, may affect the final results. However, the importance of electricity production for the atmospheric emissions is rather small. Fishing, cultivation of the plant raw materials for fish feed and transport mainly affect emissions to air by the direct use of fuels. Thus, the fuel type, fuel use levels, type of machinery and emission factors available have an important effect on the total atmospheric emission levels used in the inventory analysis calculations.

Results from similar studies have not been published. Papatryphon *et al.* (2004) compared different aquaculture feeds — production and use — using LCA methodology. They found that biotic resource use (as net primary production) and eutrophication were the two impact categories of most importance in fish feed production and use. Energy use in fish feed production (21.0 GJ per 1000 kg of feed) was close to the corresponding result of our study (21.9 GJ per 1000 kg of feed). Due to the dry feed ratio used in fish farming the primary energy use originating mainly from fossil fuels is rather high. Papatryphon *et al.* (2004) calculated the characterised impacts for eutrophication, global warming and acidification per 1000 kg of fish feed based on both their and our emission values. Their results are approximately twice as high as our results in the corresponding impact categories. The probable reason for this was in the different emission factors for the use of fuels.

The impact assessment results reveal the importance of decreasing the eutrophying emissions to waters. However, we were not able to include all the important impact categories to the impact assessment method because of the lack of data or suitable methods. In addition to the impact categories used in LCIA, the following impact categories related to rainbow trout production were identified:

- impacts on biological diversity of aquatic ecosystems (fish diseases, over-fishing, discarded yield and impacts of fishing on the sea floor),
- impacts on biological diversity of the associated terrestrial activities (field cultivation in Finland, cultivation of soy),
- ecotoxic impacts on aquatic ecosystems (anti-

fouling agents, pesticides),
- decreased disease resistance due to the use of antibiotics,
- local oxygen depletion of aquatic ecosystems due to the organic load.

Rainbow trout production has indirect impacts on biological diversity, especially via fish feed raw-material production. Overfishing, bycatch and the impacts of fishing on the sea floor are important issues. In addition to fish meal and oil, fish feed used in Finland includes plant raw materials such as soy and corn. Field cultivation causes impacts on biological diversity that are difficult to quantify. Fish escapes and disease outbreaks may also have an impact on natural fish stocks. In Norway, these impacts have been seen as the most serious problems of the fish farming (Directorate for Nature Management 1999).

Ecotoxic effects are caused by e.g. the use of antifouling agents and by the use of pesticides in agriculture during the plant raw material production. The disinfection agents used against parasites may also cause harmful effects. In addition to the ecological effects, the use of chemicals can have unfavourable effects on human health. The use of antibiotics is also an important issue concerning the environmental effects of fish farming. Antibiotic use can lead to antibiotic resistance in fish pathogens and eventually in other microbes. In Finland, the use of antibiotics in fish feeds has decreased rapidly in recent years. In 1999, the use of antibiotics in medicated feeds, as active ingredients, was 382 kg, whereas the total use was only 215 kg in 2003 (Evira 2006a, 2006b). These values do not include the amounts of antibiotics added to the feeds at farms.

The eutrophying effects cause oxygen depletion in waters. Deposited organic waste from the net cages to the bottom of the sea also have the same effect, which in turn may cause other harmful effects such as release of toxic gases from sediments (Wallace 1993). These effects depend on local conditions.

Conclusions

In the Finnish environmental conditions, according to the LCA results, the reduction of nutrient emissions from fish farming is the key factor in developing the ecological sustainability of rainbow trout production. Thus, the administrative measures to control the environmental impacts of fish farming in Finland have been well justified. By using new, environmentally friendly feeds, it is possible to reduce the environmental impacts of cultivated fish production. Increased feed efficiency reduces emissions both to the atmosphere and to waters. It also increases the resource use efficiency. By using feed containing soy protein or other similar alternative protein sources at the same time with increasing the feed efficiency, it is possible to decrease the nitrogen and phosphorus loads significantly. Technical measures can reduce phosphorus loading significantly but have only a minor effect on nitrogen. For this reason, such measures are mainly suitable for inland waters because phosphorus is the main limiting nutrient in inland waters of Finland.

From the point of view of the Finnish environment, other production phases than the fish farming have only a small importance. However, the life cycle assessment revealed that the production of cultivated rainbow trout also causes many other impacts. The use of non-renewable energy sources was determined as another key indicator for developing more sustainable aquacultural practices in Finland, although the major share of energy consumption takes place outside Finland (fishing and fish oil and meat production). Furthermore, the relative importance of the impact categories, which could not be handled in line with eutrophication, energy use or other "traditional" impact categories in the life cycle impact assessment, may be high and must be examined in later studies.

Various needs for further research were identified during this work. The data on many emissions and wastes are incomplete. Although aquatic eutrophication caused by the fish farms was found to be the most important environmental issue in the overall product chain, further development of the database for analysing the other parts of the product system should be taken into account. As indicated above, the assessment should also include other important environmental issues, such as the effects of fishing for production of fish meal on the sea bottom fauna. In this way the fish farming industry could ensure that the raw materials of the feeds used are produced in an ecologically sustainable manner.

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