Aquacultural Engineering
March 2009, Volume 40, Issue 3, Pages 113-119
http://dx.doi.org/10.1016/j.aquaeng.2008.12.002

Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment

Emmanuelle Roque d'Orbcastel[a], Jean-Paul Blancheton[a, *], and Joël Aubin[b]

[a] IFREMER, Station d'Aquaculture Expérimentale, Laboratoire de Recherche Piscicole de Méditerranée, Chemin de Maguelone, 34250 Palavas-les-Flots, France
[b] UMR INRA/Agrocampus 1069 SAS Sol Agro et hydrosystème Spatialisation, Equipe FIELDS, 65 rue de Saint Brieuc, CS 84 215, F-35 042 Rennes Cedex, France

*: Corresponding author : Jean-Paul Blancheton, Tel.: +33 4 67130412; fax: +33 4 67130458, email address : Jean.Paul.Blancheton@ifremer.fr

Abstract:

Life Cycle Assessment (LCA) was applied to evaluate the global environmental impact of two scenarios of trout production systems based on the operational information from an operational farm using a flow through system (FTF) and an experimental pilot low head recirculating system (RSF) located on the same site. The main differences between the environmental balances of the two systems were relative to water use, eutrophication potential and energy use. Independently of the system used, feed is the key indicator in determining the environmental balance (notwithstanding eutrophication potential and water dependence) monitored by fish production, chemical products, buildings and energy consumption.

Consequently, when considering the RSF with a lower feed conversion ratio (0.8 versus 1.1 for FTF), the environmental balance of the RSF is more favourable at both global and regional levels, except with regards to energy use. RSF water dependence is 93% lower than the FTF and its eutrophication potential is 26–38% lower due to reduced waste release. On the other hand, at 57,659 MJ per ton of fish produced (16 kWh per kg), the RSF consumes 24–40% more energy than the FTF, especially for aeration and water treatment. Nevertheless, the RSF has significant potential for energy reduction through improvements to airlift and biofilter designs which would reduce RSF energy use to a level similar to that of the FTF (34,869–43,841 MJ per ton of fish produced, corresponding to 10 and 12 kWh respectively). LCA is therefore a powerful tool which can be used on fish farms to define and prioritise the most promising potential improvements to the system.

Keywords: Life Cycle Assessment; Aquaculture; Trout; Recirculation system; Flow through system

1. Introduction

In the light of current social, economic and environmental constraints, aquaculture production systems have to evolve towards more environmentally friendly systems. Given their high level of water dependence, trout production systems are particularly concerned with regards to the global context of diminishing water resources (Varadi, 2000 ; Goldburg *et al*., 2001) and the need to control waste release in recipient ecosystems (EU Water framework directive, 2000/60/EC). In order to reduce the production system footprint both technical and global approaches are required to assess the environmental relevance of the system and to control pollution transfer. Recirculation systems offer the technical possibility of reducing water consumption and waste release by a factor of 100 compared to classic flow through systems (Blancheton, 2000). In recirculation systems, nutrients released are concentrated in a reduced waste water flow rate, which makes waste treatment easier (Pagand, 1999; Blancheton, 2000; Léonard, 2000).

Life Cycle Assessment (LCA), also known as life cycle analysis, is an international standardized method (ISO14040 and 14044 environmental management standards, 2006) designed to evaluate the global impact of a product or a process on the Environment. ‘Life cycle' implies the assessment of all the different phases required for or caused by the product's existence; it includes raw material and energy productions, manufacturing, transport and use. The LCA was recently applied on aquaculture systems by Seppala *et al.* (2001), Papatryphon *et al.* (2004a, b), Aubin *et al.* (2006) and Ayer and Tyedmers (2009). Different categories of environmental impacts were selected to evaluate the effect of the aquaculture production system on the Environment. On a global level, they include global warming potential, primary production and energy use. At the regional level, eutrophication and acidification potential, water dependence and surface use are considered (Aubin *et al*., 2004, 2006; Papatryphon e*t al*., 2004a).

The aim of this study was to compare the LCA of two scenarios of trout production systems, based on different water management methods: (1) a traditional flow through farm (Murgat SAS, France) producing an average of 500 tons of salmonids per year and (2) a hypothetic farm in recirculation (RSF) with the same production capacity. The RSF data were extrapolated from two years of experimental data obtained on a pilot system (7 tons of standing stock) functioning as current Danish model farms (Roque d’Orbcastel, 2008). The Danish concept consists in a semi-closed system for trout ongrowing and comprises a simplified water treatment system with low energy consumption (Roque d’Orbcastel, 2008; Roque d’Orbcastel *et al.,* 2009a).

Results of the two LCA are presented and compared in this paper, with a sensitivity analysis at two different levels: (1) first, at the energy level, with two consumption hypotheses for the FTF: the FTF is fed with well water, either by gravity or pumped (continuously or not), depending on the natural variations of the water table level; and (2) the feed efficiency level, with two feed conversion ratio (FCR) hypotheses based on the current FCR of the farm and the experimental FCR obtained during the experimentation of the recirculation pilot system (Roque d’orbcastel *et al.,* 2009b). These four conditions cover the range of situations met at the farm during the two year period.

2. Materials and method

LCA can be divided into 4 different steps, (1) definition of the goal and scope of the study (including the study system), (2) life cycle inventory (data collection), (3) Life cycle impact assessment (data translation into environmental indicators) and (4) interpretation and analysis of the results). The two systems studied include a production system either in flow through or in recirculation and a waste treatment system. Table 1 summarises the two system characteristics.

2.1. Definition of the two production systems

The LCA analysis were conducted on two farms with the same production capacity: the Murgat farm in FTF and a hypothetical RSF operated for maximizing the productivity while ensuring optimal rearing conditions.

2.1.1. Flow through system farm (FTF)

The first production system (FTF) is the ongrowing unit at the Murgat farm (Fig. 1), producing 478 tons per year of salmonids (2006 data), Brook Trout (*Salvelinus fontinalis*), Brown Trout (*Salmo trutta fario*), Rainbow Trout (*Oncorhynchus mykiss*) and Arctic Char (*Salvelinus alpinus*) in two sectors A and B. The FTF presents an average stocking density of 60 kg m^{-3} which is considered as the optimal condition for operating the farm.

Nine concrete raceways (from 315 m^3 rearing volume each in sector A to 480 m^3 in sector B) are fed with well water partly by gravity, partly by pumping (20 m deep). The global water flow rate of the sector A varies from 600 l s^{-1} to 2000 l s^{-1} (divided between the 3 head tanks), corresponding to a tank renewal rate of 230-760% per hour. The corresponding cumulative feed burden (CFB) (Malone and Beecher, 2000; Colt *et al.*, 2006) of the FTF varies from 52 to 173 m^3 of water kg^{-1} of feed according to the period. The water flow rate of sector B is around 450 l s^{-1} (tank renewal rate of 340% per hour) and the CFB is around 91 m^3 of water kg^{-1} of feed.

The effluent treatment system in use at the farm is comprised of (1) three mechanical filters, one in the pregrowing area and two in the ongrowing area, (2) primary and secondary thickening systems. The outlet of the pregrowing area is filtered through a first drum filter (80µm mesh size) and mixed with well water and outlet water from sector B, to feed sector A. The rearing water from the first three tanks of the sector A (ongrowing facility) is then filtered through a mechanical filter, reoxygenated in a low head oxygenator and reused in the four following tanks. The outlet water from those tanks is filtered with another drum filter before being released into the river (Fig. 1). The waste water from the three filters (backwash water) is passed through three primary thickening systems (around half a cubic meter each). A final thickening system (secondary system) collects the concentrated effluents from the three thickening systems. Sludge is released through an automated valve and stored in tanks before land deposit (as the fish sludge is valorised, it is deduced (as a bonus) from the farm potential impacts). The supernatant from the final thickening system is treated through wetlands built into a raceway divided into 3 sections (each measuring 25 m x 6 m x 0.8 to 1 m).

2.1.2. Recirculation system farm (RSF)

The second system (RSF) corresponds to a hypothetic ongrowing site working in a recirculation system (CFB around 8 m^3 of top-up water kg^{-1} of distributed feed), producing 478 tons of fish per year (equal to the FTF). The RSF hypothetic farm is an extrapolation of the experimental results obtained by Roque d'Orbcastel (2008) on a pilot scale tank (70 m^3 rearing volume, 5-10 tons of fish stock). Experiments were carried out over two years on rainbow trout performance using fish of the same origin and the same inlet water quality and feed composition as for the FTF (control tank). Roque d'Orbcastel *et al.* (2009b) compared growth and welfare in fish reared in recirculating and flow through systems. During a 77 day experiment, fish performance and welfare were compared in the two systems at different stocking densities (from 57 to 98-108 kg m^{-3}). Up to the end of the experiment, the best growth results were observed in the RS (where the stocking density reached 108 kg m^{-3}) and were similar to the farm reference in FTS for an average stocking density of 50 kg m^{-3}. Compared to the RS, a growth retardation was observed in the FTS when the stocking density reached 85 kg m^{-3} which may be attributed to a long term exposure to a high CO_2

concentration (18 mg l^{-1}). The LCA was based on those experimental results, considering an average stocking density of 100 kg m^{-3} for operating the RSF in optimal conditions.
The RSF (Fig. 2) is comprised of 3 independent RS units (80*12*0.7 m^3). Each of them includes 4 rearing units (325 m^3 volume each) and 2 biofilters. A rearing unit is comprised of a rearing area and treatment areas with airlift pumps and particle removal systems (sedimentation cones) (Fig. 3). Units are fed with pumped well water.
The RSF includes a complementary water treatment system comprised of a secondary thickening system (receiving concentrated effluents from sedimentation cones) and 3 constructed wetlands (similar to those of the FTF) for the supernatant treatment. As in FTF, sludge is stored in tanks before being valorised through land deposit.

2.2. Data collection and environmental indicators

The LCA is carried out using data from the farm and data collected during experiments. The environmental contribution for each item of the production system is evaluated from the inputs to the outputs : fish production (FP), feed (F), veterinary products and other chemical products (V), liquid oxygen (O), infrastructure (I), equipment (Eq), and energy sources (E) consumed at the farm (electricity, fuel and gas) (Table 2). The main source of electricity is the French nuclear energy, with 86.6% of contribution (EDF, 2004).
For each item, raw material and energy productions, manufacturing, transport (distances covered) and emissions are evaluated, from manufacture to use. For example, LCA integrates the production of feed ingredients, from the agriculture or fisheries phases.
After collection, the emission and consumption data are aggregated into impact categories on global and regional scales using characterisation factors (Guinee *et al.,* 2004): (1) Global impact indicators (Global Warming Potential, Net Primary Product Use, energy use) and (2) Regional impact indicators (eutrophication potential, acidification potential, water dependence, surface use) (Table 2). The calculation is processed using data fed into SimaPro 6 ® software and CML 2001 data base.
The Global Warming Potential (GWP) assesses the impact of gaseous emissions (CO_2, CH_4, N_2O) on the atmosphere’s capacity of absorbing infrared radiation which contributes to the global greenhouse gas effect. The GWP is calculated with GWP_{100} factors (Houghton *et al.*, 1996).
The Net Primary Product Use (NPPU) refers to the use of NPP as a biotic resource (Papatryphon *et al*., 2004b) ; it measures the trophic level of the rearing system.
The Energy use represents the use of nuclear and fossil energy sources (Pré consultants, 1997) in the system from the input factors to the output factors. The energy consumption for the two systems presented corresponds to the operational energy costs which in turn include pump consumption (for well water, U tube and low head oxygenator, filters, thickening systems, vertical wetland and feeding system), aeration system costs, feed distribution (air compressor) and fish handling costs (elevator, grader), electricity, fuel and gas production costs.
The eutrophication potential (EP) measures the environmental impact of macronutrients such as nitrogen and phosphates (solid and dissolved elements). The EP is calculated with the EP factors described by Guinée *et al.* (2002), Theoretical Oxygen Demand (ThOD) associated with solids released into the ecosystem (Papatryphon *et al.,* 2004b). Waste evaluation was based on the nutritional method described by Papatryphon *et al.* (2005) with results published by Roque d’Orbcastel *et al.* (2008).
The acidification potential (AP) measures the negative impact of acidifying pollutants such as SO_2 (sulphur dioxide), NH_3 (ammonia), NO_2 (nitrite), NO_x (nitrogen oxides) on soil, surface waters and ecosystems. The AP is calculated on the basis of the European average factors described by Huijbregts (1999).
The Water dependence (WD) corresponds to the water quantity flowing into the production system, different from the water consumption of the production system, which is not taken into account in the LCA for the moment.
The surface use (S) corresponds to the ground surface used by the production system.

All the environmental indicators are calculated for the production of 1 ton of fish (Functional unit) (Brentrup *et al.,* 2001).

3. Results

Table 3 presents the LCA 2006 results of the FTF for an annual fish production of 478 tons, with an average feed conversion ratio (FCR) of 1.1 (corresponding to 521 tons of feed distributed per year).

Excepting eutrophication potential and water dependence, feed production and use account for most of the environmental impact of the FTF. This represents 100% of the Net Primary Product Use, 91% of the global warming potential, 87% of the acidification potential and 66% of the energy use. Fish production accounts for 100% of the water dependence and 66% of the eutrophication potential of the farm. 21% of the energy is used for the electricity production and consumption (pumps, water treatment, aeration/oxygenation systems, feed distribution system, fish handling) and 7.5% for oxygen.

Table 4 presents the LCA 2006 results of the RSF, calculated with an FCR of 1.1, similar to the FTF analysis.

When compared to the FTF, the RSF presents the advantages of significantly reducing the eutrophication potential (-26%) and water dependence (-93%). On the other hand, energy use for the RSF is higher than in FTF. Other impacts, mainly explained by the Feed, remain unchanged, because the feed consumption was fixed at the same level as for the FTF (521 tons/ year).

A sensitivity analysis was carried out on the FTF, according to two pumping hypotheses: (1) a Low pumping hypothesis (L-FTF) with make up water pumped one fifth of the time, (2) a High pumping hypothesis (H-FTF) corresponding to high energy consumption, with make up water pumped continuously. The low pumping hypothesis can be considered as the most frequent situation for salmonid French farms, usually fed by gravity from surface waters (river or resurgence classically) (table 3). The high pumping situation is not common but it did represent the operational reality for the FTF during the period studied due to severe drought in this area. The environmental impact of the FTF on the NPPU, water dependence and surface use are unchanged independently of the hypothesis. Differences between hypotheses concern mainly energy use, the GWP and the AP. H-FTF energy use is 8973 MJ per ton of fish produced more than the other hypothesis, mainly due to electricity (+7500 MJ). The GWP of the H-FTF represents 2045 kg CO_2–eq per ton fish produced (30 kg more than the L-FTF) again mainly due to the electricity difference (-25 kg). The AP of the H-FTF is 13.6 kg SO_2-eq per ton fish produced, equally due to the electricity differential.

Another sensitivity analysis can be carried out according to feed conversion ratios (FCR). During 2 years of experiments on rainbow trout (average weights from 100 to 1100 g), a better average for FCR was observed in the recirculation system (0.8) than in the flow through farm (1.1) (Roque d'Orbcastel*.,* 2008). A sensitivity analysis on the FCR was performed to evaluate the LCA of the RSF with an FCR value of 0.8 (Table 5).

As feed explains most of the environmental impacts, the FCR sensitivity analysis confirms that FCR improvement has a positive impact on all the environmental indicators (except water dependence, which is related to fish production): the GWP is reduced by 22%, the NPPU by 24%, Energy use by 9%, Eutrophication potential by 16% and Acidification potential by 21% by comparing the RSF with a FCR of 1.1 and the RSF with a FCR of 0.8.

4. Discussion

The main differences between the environmental global balance of the two systems concern water dependence, energy use and eutrophication potential (Fig. 4). With the current state of the world resources, water and energy are two preoccupations to be considered for sustainable aquaculture practices. The other potential environmental impacts are not linked to the system, but to the feed consumption. The sensitivity analysis showed that 27% of improvement on the FCR (observed in the RS during experiments) reduced other environmental impacts (GWP, NPPU, EP and AP) by 16-27%. As the aim of our study was the two system comparison, we focussed the discussion on the three main system differences: water dependence, energy use and eutrophication potential.

One of the advantages of the recirculation system is to reduce the water dependence: in this study, the water dependence of the RSF is decreased by 93% in comparison to the FTF (Table 6). Moreover, as the stocking density is almost two times higher in the RSF (Roque d'Orbcastel *et al.,* 2009b), space gained on the tanks' footprint is available for waste treatment.

At 57659 MJ per ton of fish produced, the RSF consumes 24 to 40% more energy than the H-FTF and the L-FTF respectively (Table 7). The pumping costs of make up water are divided by 4 to 22 in the RSF (compared to the L-FTF or H-FTF respectively) but more energy is required for aeration (8633 and 1799 MJ per ton of fish produced for the RSF and FTF respectively, corresponding to 2.4 and 0.5 kWh per kg fish). Furthermore, the energy consumed for water treatment is 15 times higher for the RSF (2878 MJ per ton of fish or 0.8 kWh per kg fish) than for the FTF (216 MJ per ton of fish or 0.06 kWh per kg fish).

Energy use calculated by LCA is 1.4-1.8 higher in the RSF (63202 MJ per ton of fish or 16 kWh per kg fish) than in the FTF. However, the RSF energy balance is in the range of existing references for trout production in flow through systems, from 44604 to 97900 MJ per ton of fish (corresponding to 12.4 and 27.2 kWh per kg) (Papatryphon *et al.,* 2004b; Ayer and Tyedmers, 2009). The RSF energy use is 5-6 times lower than in traditional recirculation systems, for turbot (Aubin *et al*., 2006) or artic charr (Ayer and Tyedmers, 2009). Moreover, the RSF presents a significant potential for reductions in energy consumption. Roque d'Orbcastel *et al. (*2009a) proposed ways of improvements through a better system design and management of the airlift (compromise between optimal design for water circulation and for water oxygenation) and of the biofilter (backwash and operation). Such modifications could reduce the energy use of RSF to close to the H-FTF level (43841 MJ per ton of fish or 12.2 kWh per kg fish produced), which could become the most frequent situation in the future if drought conditions persist.

By opposite, opportunities for reducing energy consumption in the FTF are poor; this would imply a reduction of the water treatment and/or aeration/oxygenation system and consequently a potential degradation of the FCR and increased waste emissions. Another solution for reducing energy without a detrimental impact on fish production would be to modify the tank design by changing parallel tanks into series to ensure a sufficient water flow rate in tanks. This would lead to include intermediate water treatments (suspended solid removal and ammonia oxidation systems) in order to ensure a sufficient water quality and to maintain fish performance. Optimal system configuration, from economic (pumping cost minimisation) and environmental point of views, have yet to be defined and studied according to each farming context.

Finally, concerning the eutrophication potential, the RSF is 26-38% lower than FTF, due to differences in waste release (Roque d'Orbcastel, 2008). Differences are 8.1 g of suspended solids per kg feed^{-1}, 5.7 g of total nitrogen per kg feed^{-1} and 0.8 g of total phosphorus per kg feed^{-1} less in RSF than FTF. LCA comparison between trout (Seppala *et al*., 2001 ; Papatryphon *et al*., 2004b), pig (Blonk *et al*., 1997 ; Carlsson-Kanyama, 1998) and poultry farms (Spies *et al.*, 2002) showed that aquaculture presents the most interesting compromise between nutritional (proteinic) value and environmental impact, except with regards to eutrophication potential. Moreover, the EP of a recirculating aquaculture system can be decreased with a high enough CFB. Seppala *et al.* (2001) demonstrated that trout environmental impact was mainly linked to waste emissions. In our study, waste from the production system explains half of the eutrophication potential impact (54-66%), feed being responsible for the remainder.

The eutrophication potential of the RSF (18 kg eq PO_4 per ton of fish produced) and the FTF (28 kg) are lower than those published by Papatryphon *et al.* (2004b) (55-70 kg), in spite of a similar feed conversion ratio and composition. These results may be explained by the high water treatment efficiency, not to mention that the RSF presents a significant potential for improvement, especially with regards to particle removal which decreases phosphorus release and the THOD level associated to solids influence in aquatic ecosystems (Roque d'Orbcastel, 2008).

However, the waste from the production system explains a small part of the global environmental impact; independently of the system, feed is the main factor in the environmental balance. RSF with an FCR of 0.8 shows a better global environmental balance than the FTF, at both global and regional levels, except for energy use. The RSF presents lower eutrophication potential and NPPU, which are two main aspects to be considered according to Guinée *et al.* (2002). The FCR is the key point of the environmental assessment: a 10% FCR variation leads to similar variations on all the potential impact items for the system (Papatryphon *et al*., 2004b). Furthermore, regarding to the feed cost increase, there is also an economical reason for decreasing FCR and getting more production out of less system and water. Between 1993 and 2005, FCR was reduced by 27% on salmonid farms due to improvements made on feed composition, digestibility and distribution management (Breton, 2005). Improving feed efficiency would be possible at the fish level through genetic breeding selection (Kause *et al.,* 2006; Grima *et al., submitted*) and at the feed level through better selection of feed nutrient digestibility that would also probably impact the production cost as feed is the main economic item for salmonid farms. Environmental impact could also be reduced through improved energy management for feed manufacture in relation to raw material selection and transport distances. Given that trawler caught fish present significant fuel consumption levels (from 3600 MJ per ton herring to 97122 MJ per ton fish flatfish, corresponding to 1 kWh and 27 kWh per kg respectively) (Ziegler and Hansson, 2003), the use of raw vegetal products is often presented as a solution. However according to Papatryphon *et al.* (2004b) it requires the same quantity of energy to produce fish oil and meal (for a similar nutritional value) and the eutrophication potential would be higher due to lower digestibility. Fish meal substitution with seafood by-products could save up 3200 MJ per ton fish produced, but it would increase the eutrophication potential (Papatryphon *et al.,* 2004b). A compromise has to be found between feed digestibility (related to waste), manufacturing cost (especially transport distances of raw products), fish performance and flesh quality (economic sustainability of the farm).

Harvested fish not retained at sea (undersized or low value species) are evaluated between 9 and 24% of the commercial catches (FAO, 2005); the by-catch could be used as fish meal for feed. With the current fishing reform the European Commission encourages full utilization of harvested fish ('zero waste approach' applied in Norway, Island and Namibia since 2004) and is planning to support research on the use of wasted fish.

5. Conclusion

After two years of experiments, LCA of the trout recirculation system based on the Danish concept demonstrated a limited environmental impact in comparison with the flow though system and other current recirculation systems. Further experiments are needed to confirm our results especially the better FCR obtained in recirculation system and the highest fish density without decrease of fish performance and welfare.

Whatever the system, feed is responsible for more than half of the environmental impacts (GWP, NPPU, AP and SU). Fish production explains two thirds of the eutrophication potential (feed the third remaining) and the whole water dependence. Energy use due to feed, electricity and oxygen consumption is system-dependent. If the FCR difference between production systems was confirmed at an industrial level, recirculation systems would present

a more favourable global environmental balance than flow through system except with regards to energy use.
According to the specific context of the farm, a compromise has to be found between water dependence, waste emission, energy consumption and productivity in order to orientate the system towards environmentally sustainable production. Combined with sensitivity and economic analyses, LCA could become a valuable management and forward planning tool for salmonid farms. It could contribute to quantifying and prioritising the possible improvements of each item of the system (impact of the addition of a water treatment loop, impact of the oxygenation rate increase on the FCR…) and assessing the cost-benefit of each modification. This environmental approach could be combined with economic and social cost-benefit analyses in order to define the best compromise for sustainable production.

Acknowledgements

We are very grateful to Vincent and Laurent Murgat for welcoming us to their farm and especially to the ongrowing team, Franck Delamare, Thomas Garsi and Ludovic Guillon for their collaboration during experiments and studies. We would like to thank Michaël Corson from the INRA- ENSAR SAS for his help on the Sima-Pro software.

References

Aubin, J., Papatryphon, E., Petit, J., Van der Werf, H.M.G., 2004. Utilisation de l'Analyse du Cycle de Vie pour l'évaluation environnementale des systèmes de production piscicoles. Poster et résumé. Session Développement Durable de l'Aquaculture, Bordeaux Aquaculture 2004, 22 Septembre 2004, Bordeaux.
Aubin, J., Papatryphon, E., Van der Werf, H.M.G., Petit, J., Morvan, Y.M., 2006. Characterisation of the environmental impact of a turbot (*Scophthalmus maximus*) re-circulating production system using Life Cycle Assessment. Aquaculture, 261, 4 : 1259-1268.
Ayer N.W., Tyedmers, P.H., 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture in Canada. Journal of Cleaner Production 17 (2009), 362-373.
Blancheton, J.P., 2000. Developments in recirculation systems for Mediterranean fish species. Aquacultural Engineering, 22: 17-31.
Blonk, H., Lafleur, M. Van Zeijts, H., 1997. Towards an Environmental Infrastructure for the Dutch Food Industry. Exploring the Environmental Information Conversion of Five Food Commodities. Screening LCA on pork. Appendix 4 of the report. IVAM Environmental Research, University of Amsterdam, Amsterdam, The Netherlands. 46 pp.
Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2001. Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. European Journal of Agronomy 14 (2001) 221–233.
Breton, B., 2005. La truite et son élevage. Collection aquaculture pisciculture. Eds TEC et DOC. Lavoisier.
Carlsson-Kanyama, A., 1998. Energy Consumption and Emissions of Greenhouse Cases in the Life-Cycle of Potatoes, Pork Meat, Rice and Yellow Peas. Technical Report n°26. department of Systems Ecology, Stockholm University, Stockholm, Sweden. 67 pp.
Colt, J., Lamoureux, J., Patterson, R., Rogers, G., 2006. Reporting standards for biofilter performance studies. Aquacultural Engineering 34 (2006) 377–388.
EDF, 2004. Rapport annuel EDF 2004.
FAO, 2005. Discards in the world 's marine fisheries. An update. FAO FISHERIES TECHNICAL PAPER 470.

Goldburg, R.J., Elliott, M.S., Naylor, M.A., 2001. Marine Aquaculture in the United States: Environmental Impacts and Policy Options. Pew Oceans Commission, Arlington, VA, 44 pp.
Grima, L., Quillet, E., Boujard, T., Robert-Granié, C., Chatain, B., Mambrini, M., 2008. Genetic variability in feed efficiency in rainbow trout clones and testing of indirect selection criteria. Genet. Sel. Evol., 40(6), 607-624.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment. An Operational Guide to the ISO standards. Kluwer Academic Publishers, Dordrecht, The Netherlands. 692 pp.
Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K., 1996. Climate Change 1995: The Science of Climate Change. Cambridge University Press, Cambridge, United Kingdom.
Huijbregts, M.A.J., 1999. Life-Cycle Impact Assessment of Acidifying and Eutrophying Air Pollutants. Calculation of Characterisation Factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, Amsterdam, The Netherlands.
ISO 14040-14044, 2006. Environmental Management .Life Cycle Assessment Principles and Framework. International Organisation for Standardisation (ISO).
Kause A., Tobin D., Houlihan D.F., Martin S.A.M., Mantysaari E.A., Ritola O., Ruohonen K., 2006. Feed efficiency of rainbow trout can be improved through selection: Different genetic potential on alternative diets, J. Anim. Sci. 84 (2006), 807-817.
Léonard, N. 2000. Recherche et élimination des facteurs inhibiteurs de croissance dans les élevages piscicoles en circuit fermé. Thèse de doctorat de l'université de Montpellier 2. Montpellier, France, 165 p.
Malone, R.F. and Beecher, L.E., 2000. Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems, Aquacultural Engineering 22 (2000) 57–73.
Pagand, P., 1999. Traitement des effluents piscicoles marins par lagunage à haut rendement algal. Thèse de doctorat de l'université de Montpellier 1, Montpellier, France, 220 p.
Papatryphon, E., Petit, J., Van der Werf, H.M.G., 2004a. The development of Life Cycle Assessment for the evaluation of rainbow trout farming in France. Proceedings of the 4th International Conference on: Life Cycle Assessment in the Agri-feed sector. 6-8 October 2003, Horsens, Denmark, 73-80.
Papatryphon, E., Petit, J., Kaushik, S.J., Van Der Werf, H.M.G. 2004b. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). Ambio, 33, 6, 316-323.
Papatryphon, E., Petit J., Hayo, V., Kaushik, S.J., Claver, K., 2005. Nutrient balance modelling as a tool for environmental management in aquaculture: The case of trout farming in France. Journal of Environmental Management, 35: 161-174.
Pré Consultants, 1997. SimaPro 2 method. In: Database Manual. Pré Consultants B.V., Amersfoort, The Netherlands. 65 pp.
Roque d'Orbcastel, E., 2008. Optimisation de deux systèmes de production piscicole : biotransformation des nutriments et gestion des rejets. Thèse de doctorat, INP Toulouse, Université Paul Sabatier -Toulouse III. 144 pp.
Roque d'Orbcastel, E., Blancheton, J.P., Boujard, T., Aubin, J., Moutounet, Y., Przybyla, C., Belaud, A., 2008a. Comparison of two methods for evaluating waste of a flow through trout farm. Aquaculture, 274, 72-79.
Roque d'Orbcastel, E., Blancheton, J.P., Belaud, A., 2009a. Water quality and rainbow trout performance in a Danish Model Farm recirculating system: Comparison with a flow through system. Aquacultural Engineering 40 (2009) 135–143.
Roque d'Orbcastel, E., Person-Le-Ruyet, J., Le Bayon, N., Blancheton, J.P., 2009a. Comparative growth and welfare in rainbow trout reared in re-circulating and flow through rearing systems. Aquacultural Engineering, 40 (2), 79-86.
Seppala, J., Silvenius, F., Gronroos, J., Makinen, T., Silvo, K., Storhammar, E., 2001. Rainbow trout production and the Environment. Finnish Environmental Institure, Helsinki. 164 pp. (In Finnish; abstract, tables and figures in English).

Spies, A., Wegener, M., Chamala, S., Beeton, R., 2002. Estimating Environmental Impact from Poultry Production in Brazil using LCA. Proc. Third Australian Conference on Life Cycle Assessment, Australia. 15-17 July. ALCAS. 1-11.
Varadi, L., 2000. Responsible Management of inland waters for fisheries and aquaculture. In: Creswell, R.L., Flos, R. (Eds.), Perspectives on ResponsibleAquaculture for the New Millennium , World Aquaculture Society, Baton Rouge, LA, USA/The European Aquaculture Society, Oostende, Belgium, 125-141.
Ziegler, F., Hansson, P.A., 2003. Emissions from fuel combustion in Swedish cod fishery. J. Cl. Prod. 11 : 303-314. *In : Ziegler, F., 2006. Environmental Life Cycle Assessment of seafood products from capture fisheries. Thesis. Göteborg university, Faculty of science. 50 pp.*

Figures

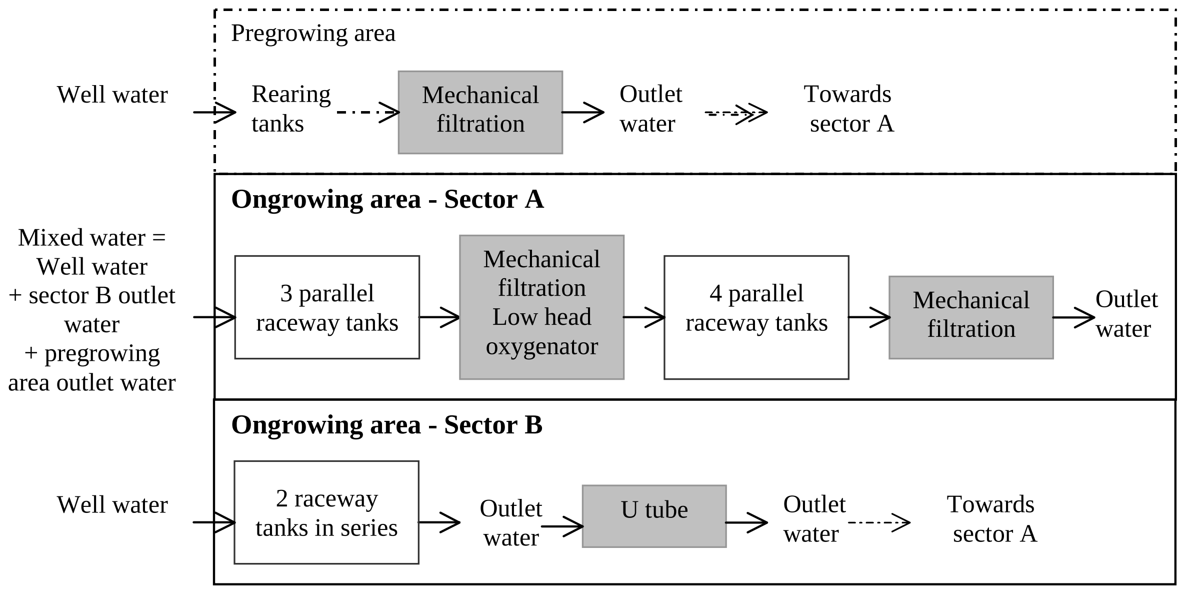

Fig. 1. Diagrame of the FTF scheme comprised of 2 sectors (A and B); the FTF includes an effluent treatment system comprised of mechanical filtration, primary and secondary thickening systems and developed wetlands.

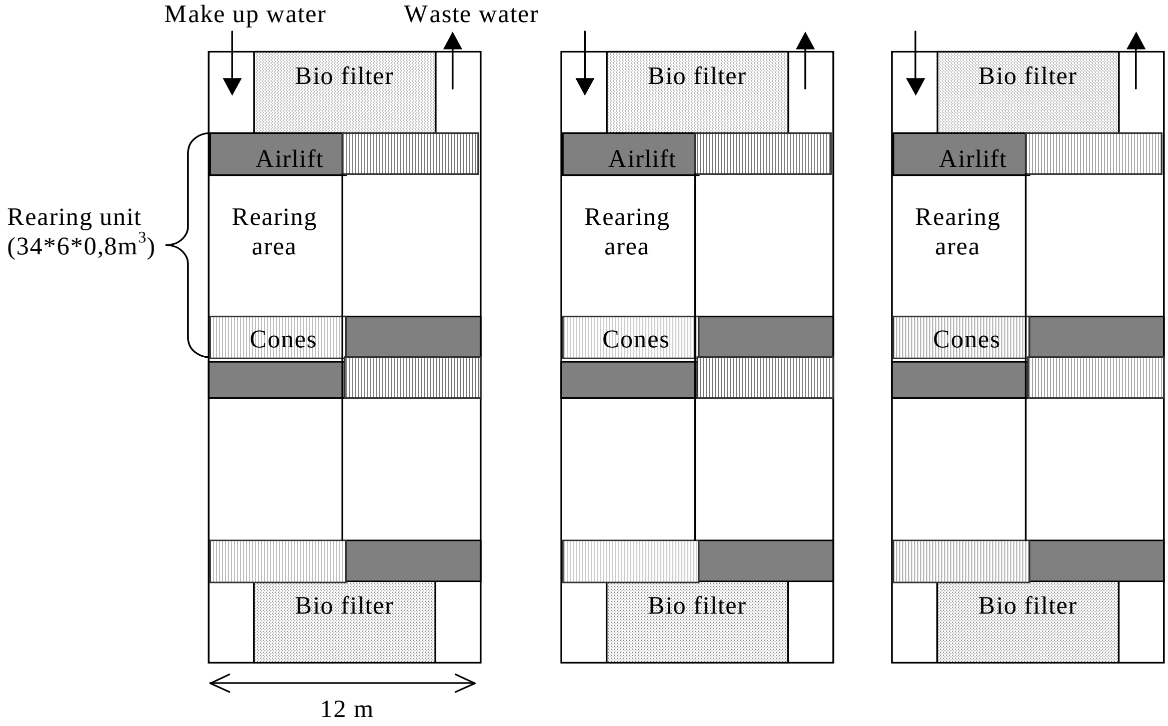

Fig. 2. The RSF, comprised of 3 independent units

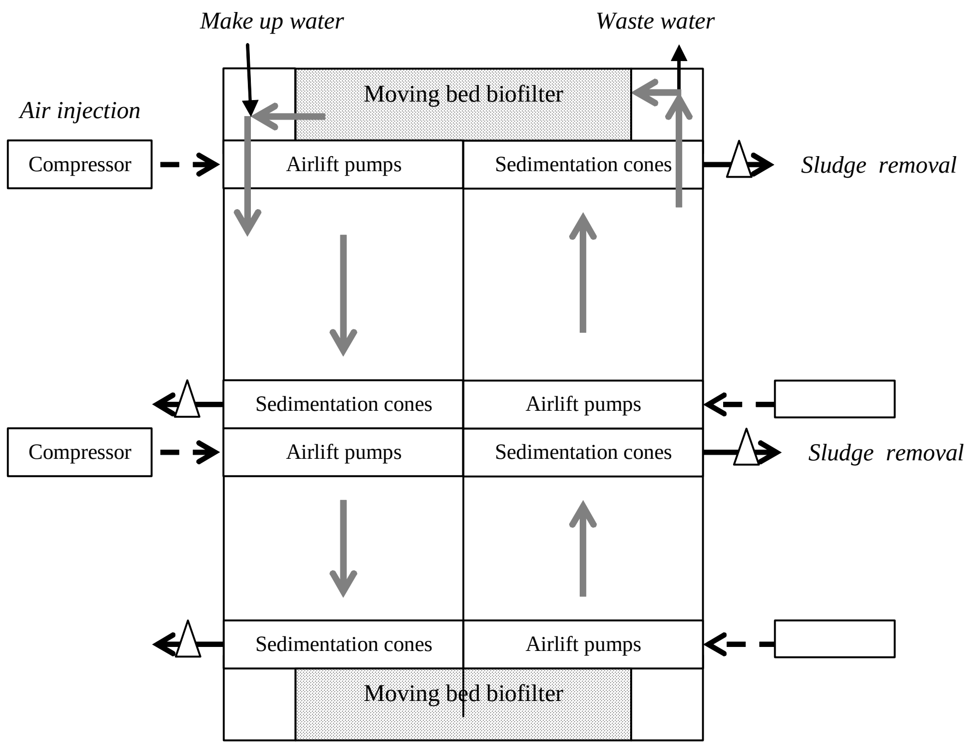

Fig. 3. One unit of the recirculation system; water circulation is represented by arrows.

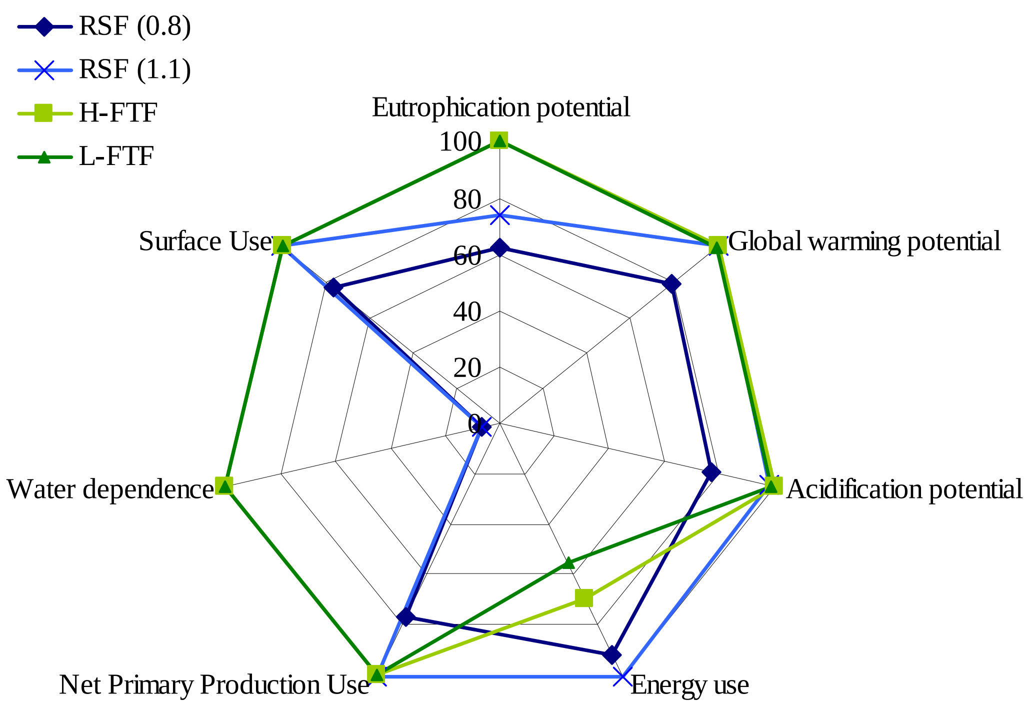

Fig. 4. Comparison of the environmental impact of the FTF (low and high pumping hypotheses, L-FTF and H-FTF respectively) and RSF (FCR of 1.1 and 0.8); environmental impacts are represented in proportion of the largest impact (%).

6. Tables

Table 1. Flow through system farm (FTF) and Recirculation System Farm (RSF) characteristics

	FTF	**RSF**
Water needs (m^3 d^{-1})	From 51840 to 172800	8701
Rearing tanks surface (m^2)	4430	2700
Stocking density (kg m^{-3})	60	100
Average FCR	1.1	0.8
Annual fish production (tons y^{-1})	478	478
Annual distributed feed (tons y^{-1})	521	397
Aeration / oxygenation systems	1 low head oxygenator, 1 U tube, 26 aerators	12 airlift pumps
Water treatment system	3 mechanical filters 3 thickening systems I	6 biofilters (414 m^3) 12 series of sedimentation

	1 final thickening system II 3 constructed wetlands	systems 1 final thickening system II 3 constructed wetlands

Table 2. Environmental impact indicators and production items

Environmental impact indicators	Acronyms	Units
Global Warming Potential	GWP	kg of CO_2 equivalent or CO_2-eq
Net Primary Product Use	NPPU	kg of carbon or kg C
Energy use	Energy	MJ
Eutrophication potential	EP	kg of PO_4 equivalent or PO_4-eq
Acidification potential	AP	kg of SO_2 equivalent or SO_2-eq
Water dependence	WD	m^3
Surface use	SU	m^2

Table 3. Environmental impact of the FTF (Low pumping hypothesis); results are expressed for each production item (in kg, MJ, m^3 or m^2 per ton of fish produced and in %); Fish production (FP), feed (F), veterinary products and other chemical products (V), liquid oxygen (O), infrastructures (I), equipments (Eq), and energy sources (E) consumed at the farm.

	FP	**F**	**V**	**O**	**I**	**Eq**	**E**	**Total**
GWP (kg CO_2-eq) *(%)*	0	1843 *91*	2 *0.5*	40 *2*	21 *1*	9 *0.5*	99 *5*	**2015**
NPPU (kg C) *(%)*	0	27968 *100*	0	0	0	0	0	**27968**
Energy (MJ) *(%)*	0	23159 *66.5*	33	2667 *7.5*	239 *1*	259 *1*	8510 *24*	**34869**
EP (kg PO_4-eq) *(%)*	18.75 *66*	9.5 *34*	0.001	0.04	0.01	0.005	0.11	**28.5**
AP (kg SO_2-eq) *(%)*	0	11.7 *87*	0.02	0.3 *2.5*	0.2 *1.5*	0.3 *2*	0.9 *7*	**13.4**
WD (m^3) *(%)*	98804 *100*	0	0	0	0	0	0	**98804**
SU (m^2) *(%)*	0	2736 *100*	0.2	0	0.02	0.05	0	**2737**

Table 4. Environmental impact of the RSF, with a hypothetic FCR of 1.1; results are expressed in kg, MJ, m^3 or m^2 per ton of fish produced and in % (italic).

	FP	**F**	**V**	**I**	**Eq**	**E**	**Total**

GWP (kg CO_2-eq) *(%)*	0	1853 *91*	2.1	15.5 *1*	38.2 *2*	134 *7*	**2043**
NPPU (kg C) *(%)*	0	28126 *100*	0.02	0	0	0	**28126**
Energy (MJ) *(%)*	0	23289 *37*	33.5	204	1234 *2*	38441 *61*	**63202**
EP (kg PO_4-eq) *(%)*	11.4 *54*	9.6 *45*	0	0.01	0.03 *0.1*	0.04 *0.2*	**21.1**
AP (kg SO_2-eq) *(%)*	0	11.8 *89*	0.02	0.14 *1*	0.39 *3*	0.96 *7*	**13.3**
WD (m^3) *(%)*	6634 *100*	0	0	0	0	0	**6634**
SU (m^2) *(%)*	0	2751.7 *100*	0.2	0	0	0	**2752**

Table 5. Environmental impact of the RSF, with a FCR of 0.8; results are expressed in kg, MJ, m^3 or m^2 per ton of fish produced and in %.

	FP	**F**	**V**	**I**	**Eq**	**E**	**Total**
GWP (kg CO_2-eq) *(%)*	0	1412 *88*	2.1	15.5 *2*	38.2 *2*	134 *8*	**1602**
NPPU (kg C) *(%)*	0	21432 *100*	0.02	0	0	0	**21432**
Energy (MJ) *(%)*	0	17746 *31*	33.5	204	1234 *2*	38441 *67*	**57659**
EP (kg PO_4-eq) *(%)*	10.4 *58*	7 *42*	0	0.01	0.03	0.04	**17.8**
AP (kg SO_2-eq) *(%)*	0	9 *86*	0.02	0.1 *1*	0.4 *4*	0.9 *9*	**10.5**
WD (m^3) *(%)*	6634 *100*	0	0	0	0	0.2	**6634**
SU (m^2) *(%)*	0	2097 *100*	0.2	0.02	0.05	0.05	**2097**

Table 6. Differences in LCA impact categories between the FTF (L-FTF and H-FTF) and the RSF (FCR of 1.1 and 0.8); results are expressed in unit per ton of fish produced and %.

	FCR of 1.1		FCR of 0.8	
	RSF 1.1 - H-FTF	RSF 1.1 - L-FTF	RSF 0.8 - H-FTF	RSF 0.8 - L-FTF
GWP (kg CO_2-eq) *(%)*	-2 *0*	+28 *+1*	-443 *-22*	-413 *-20*
NPPU (kg C) *(%)*	+158 *+1*	+158 *+1*	-6536 *-23*	-6536 *-23*
Energy (MJ) *(%)*	+19361 *+31*	+28334 *+45*	+13818 *+24*	+22791 *+40*
EP (kg PO_4 -eq) *(%)*	-7 *-26*	-7 *-26*	-11 *-38*	-11 *-38*
AP (kg SO_4-eq) *(%)*	0 *-2*	0 *-1*	-3 *-23*	-3 *-21*
WD (m^3) *(%)*	-92170 *-93*	-92170 *-93*	-92170 *-93*	-92170 *-93*
SU (m^2) *(%)*	+15 *+1*	+15 *+1*	-640 *-23*	-640 *-23*

Table 7. Energy efficiency of FTF and RSF for an annual production of 478 tons of fish (with FCR of 1.1)

	RSF	H-FTF	L-FTF
Make up water pumping costs (10^3.MJ)	68	1561	313
Water treatment costs (10^3.MJ)	1446	101	101
Oxygenation / aeration system costs (10^3.MJ)	4133	824	824
Feed distribution and fish handling costs (10^3.MJ)	29	29	29
Fuel + gas costs (10^3.MJ)	450	450	450
Energy efficiency at the farm (MJ. ton fish produced^{-1})	12960	6115	3597
LCA energy use (MJ. ton fish produced^{-1})	63202	43841	34869