Environmental impacts of genetic improvement in growth rate and feed conversion in fish farming under density and nitrogen limitation

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ABSTRACT

Many environmental impacts can be attributed to fish farming and there is a need to explore new ways of reducing environmental impacts, such as fish genetic improvement. The environmental consequences of genetic improvement in thermal growth coefficient (TGC) and in feed conversion ratio (FCR) were investigated, therefore, in an African catfish farm in Recirculating Aquaculture System. A Life Cycle Assessment study was conducted and combined with a bioeconomic model of genetic response. Results show that environmental consequences of genetic improvement in TGC and FCR are different among impact categories, depending on their main contributors and on the factor limiting production at farm level. Genetic improvement of FCR always leads to lower environmental impacts while improving TGC decreases environmental impacts only when density was the limiting factor. Those results are important for the future development of selective breeding programs in fish farming taking into account environmental impacts.

Keywords: genetic improvement, life cycle assessment, fish farming, feed conversion ratio, thermal growth coefficient

1. Introduction

Fish farming can have many environmental impacts, such as emission of pollutants (Read and Fernandes, 2003), use of natural resources (Naylor et al., 2000) and eutrophication (Folke et al., 1994). Using life cycle assessment (LCA), feed production and farm operations were shown to be the main stages contributing to environmental impacts of fish farming (Aubin et al., 2006; Pelletier et al., 2009). The environmental impacts of alternative feed compositions or alternative rearing systems were, therefore, investigated. Some studies explored the potential of plant-based diets or organic feed to reduce impacts (Boissy et al., 2011; Papatryphon et al., 2004; Pelletier and Tyedmers, 2007), whereas other studies explored the potential of a recirculating aquaculture system to reduce impacts (Aubin et al., 2009; d'Orbcastel et al., 2009). These studies, however, clarified existing trade-offs between different environmental impacts when changing feed composition or rearing conditions. It appeared difficult, therefore, to decrease all environmental impacts of fish farming. Consequently, there is a need to explore new ways of reducing environmental impacts of fish farming systems.

Genetic improvement, realised through selective breeding programs, is expected to change environmental impacts of livestock production by increasing productivity or improving production efficiency (Wall et al., 2010). The magnitude and the direction of this change in fish farming is, however, not known. Wall et al. (2010) suggested to model emissions at farm level in order to determine the environmental consequences (or environmental values) of a change in traits in order to evaluate the capacity of each trait to decrease environmental impacts. This approach is similar to the framework used to calculate the economic value of economic important traits (Groen, 1988).

We explored, therefore, the capacity of a genetic improvement in thermal growth coefficient (TGC) and in feed conversion ratio (FCR) to decrease environmental impacts of 1 t of African catfish produced in a recirculating aquaculture system (RAS). We chose to investigate TGC and FCR for two reasons. First, fish breeders consider TGC as the main trait to improve in order to increase farm profitability. FCR is also an important trait because the majority of fish reared in intensive systems are carnivorous species, which require high amounts of protein and lipid in their diet, making fish diets expensive. Second, we investigated TGC and FCR because genetic improvement of these two traits is susceptible to affect environmental impacts through higher productivity and better production efficiency. A RAS was studied for three reasons: (1) it is a highly controlled system, which is easy to model, (2) it has a potential as a development model for fish farming because of better waste and water management and (3) the existence of technical limiting factors for production level is well known. In practice, limiting factor can influenced farm management and breeding goals have to be adapted for such limiting factor (Gibson, 1989; Groen, 1989). The factors limiting production are the maximum nitrogen treatment capacity of the bio-filter and the maximum fish density in rearing tanks. Changing TGC and FCR is expected to change the limiting factor and the limiting factor might influence environmental values of both traits.

The capacity of a genetic improvement in TGC and in FCR to decrease environmental impacts was investigated through environmental values calculated using a bioeconomic model combined with a LCA.

2. Methods

2.1. System boundaries

A cradle-to-farm-gate analysis was applied including three stages: feed production, farm operation and waste water treatment (figure 1). The farm studied was a typical commercial Dutch farm producing 500t of African catfish per year in an indoor RAS. Fish processing, hatchery operations as well as sludge agricultural utilization were not taking into account.

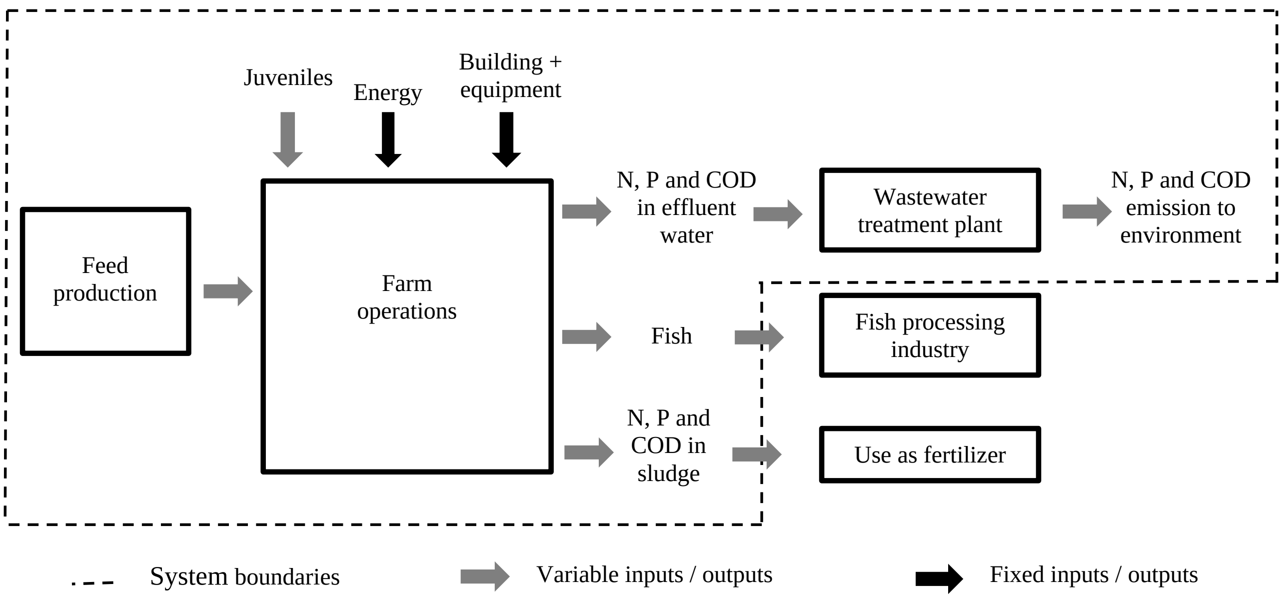

Figure 1. Diagram of the system studied.

2.2. Life Cycle Inventory

Feed production. Crops-derived ingredients were coming from Brazil and France. Fish-derived ingredients were coming from Peruvian fish milling industry and from by-products of Norwegian fish milling industry. In case of a process yielding multiple products, such as soy bean oil and meal, the environmental impact of the process was allocated to the multiple outputs based on their relative economic value (i.e. economic allocation). The transport of feed ingredients to feed manufacture in France was assumed to be by transoceanic ship and by lorry (>32t). The resources required to produce the feed were found in the literature (Pelletier et al., 2009). The transport of pellets from France to the fish farm in Eindhoven were assumed to be by lorry (>32t).

Farm operations. We investigated a farm producing 500t of African catfish per year in an indoor RAS. In this indoor system, water was thermo-regulated around 27 °C through regulating the ambient air. The RAS was composed of four main parts. (1) Rearing tanks growing fish from 13g to 1300g. The maximum density in the tank was 230 kg/m^3, which was one of the limiting factors. (2) A mechanical filter which removed solid waste.

(3) A bio-filter processing nitrification with a nitrification rate of 100%. The nitrification capacity of the bio-filter was limited to 40 kg of dissolved NH_3-N per day, which was the second limiting factor. (4) A denitrification reactor using manure of the fish as C-source with a denitrification rate of 80%.

The amount of equipment used (i.e. pump, tanks), the surface of building needed and the consumption of energy at farm level were considered fixed. The emission of nutrients, the consumption of feed and the production of fish were, however, dependent on growth rate and feed efficiency, which could affect the level of production. In this study, growth rate was expressed through Thermal Growth Coefficient (TGC) (Dumas et al., 2007) and feed conversion was expressed through Feed Conversion Ratio (FCR). A bioeconomic model was developed to calculate annual fish production, annual feed consumption at farm level and annual emissions of nutrients after waste water treatment according to TGC and FCR values. The individual emission of nitrogen (N), phosphorus (P) and chemical oxygen demand (COD) were calculated using a mass-balance approach (Cho and Kaushik, 1990). The proportion of dissolved and solid fractions emitted by the fish was estimated from the digestibility of feed components. Retention capacity of the drum filter, nitrification capacity of the bio-filter and denitrification capacity of the denitrification reactor were used to calculate emission of nutrients in effluent water and in sludge.

Waste water treatment. Effluent water, highly concentrated in nutrients, coming from the fish farm was disposed in a waste water treatment plant. We considered a typical waste water treatment plant running in Europe, including three treatment stages: mechanical treatment, biological treatment, chemical treatment. It also included sludge digestion via fermentation. The treatment capacity of the waste water treatment was used in order to evaluate the amount of nitrogen, COD and phosphorus released into water. 28% of the COD, 75% of the nitrogen and 52% of the phosphorus coming from the farm were, therefore, released into water. Life cycle inventory of water treatment as well as the secondary data were extracted from ecoinvent v2.2 database (Swiss Centre for Life Cycle Inventories, 2010).

2.3. Life cycle impact assessment

The environmental impact of the analysed system was related to a functional unit of 1 t of fish. Four environmental categories were investigated: eutrophication, acidification, climate change and cumulative energy demand (CML2 method and Simapro software) and expressed per t of fish. Land use change, however, was not taking into account. The analysed system was divided in the following sub-systems: (1) feeds consumption, including processing, production of feed ingredients and transportation; (2) N, P and COD emission from biological transformation of the feed at farm level and after waste water treatment; (3) effluent water treatment at wastewater treatment plant; (4) equipment use, including its manufacturing, transport and use; (5) buildings use, including material production and transportation, construction and use; (6) energy consumption (electricity, gasoline, heat gas), including production, transportation and use. Environmental impacts of each of these sub-systems were calculated separately.

Then, the results of these environmental impacts were multiplied by the quantity required at farm level calculated from the bioeconomic model. Feed consumption and nutrients emission are variable at farm level depending on TGC and FCR values. Environmental impacts at farm level of the two sub-systems feed production and nutrients emission are, therefore, variable. In contrary, use of building, use of materials and energy consumption at farm level are considered fixed. Environmental impacts at farm level of those three sub-systems are, therefore, fixed.

Environmental impacts at farm level were divided by annual fish production to expressed environmental impacts per ton of fish. Environmental impacts were calculated for four TGC values corresponding to three generation of selection from the current population mean with a percentage of genetic improvement of 6.8 as calculated by (Sae-Lim et al., 2012). TGC values tested were: 8.33, 8.93, 9.53 and 10.11. For FCR, a wide range of values was tested from current population mean FCR = 0.81, which is a value commonly observed in African catfish farms, to FCR = 0.64.

2.4. Environmental values

The environmental values (ENV) of the four impact categories (eutrophication = E_V, acidification = A_V, climate change = CC_V and cumulative energy demand = CED_V) of a trait t {FCR,TGC} express the environmental impact, in percentage, of a unit change in one trait while keeping the other trait constant. ENV of both traits were calculated in three steps:

1) Calculate environmental impact per ton of fish (i.e. $A_{\mu t}$) using current generation means for trait t (μ_t). The current generation mean (or reference scenario) is 8.33 for TGC and 0.81 for FCR. The TGC of the current population is the result of 119 days required for the fish to grow from 13 to 1300 g with a daily average temperature of 27°C. FCR was set at 0.81 in order to balance cost with revenue when TGC = 8.33.

2) The mean of trait t is increased by Δ_t while keeping the mean of the other traits constant. $\Delta_{TGC} = \mu_{TGC} \times 6.8\%$ and $\Delta_{FCR} = \mu_{FCR} \times -7.6\%$ as calculated by (Sae-Lim et al., 2012). The next generation means are, for instance, TGC = 8.93; FCR = 0.81 and TGC = 8.33; FCR = 0.75. The model was run a second time to calculate environmental impacts.

3) ENV were calculated for trait t as:

$$A\_V_t = \frac{(\mathbf{A}_{\mu t+\Delta t} - \mathbf{A}_{\mu t})}{\mathbf{A}_{\mu t}} \qquad \text{Eq. 1}$$

Environmental values were calculated for 2 situations where the combination of TGC and FCR was: TGC = 8.93; FCR = 0.81 and TGC = 8.93; FCR = 0.69. These two situations were chosen because the limiting factor was different and also because one generation of selection in both trait did not change the limiting factor.

3. Results

Table 1. Percentage of contribution of the different sub-systems to the four impact categories in the reference scenario where TGC = 8.33 and FCR = 0.81.

	Feed production	Nutrients emission	Effluent water treatment	Building use	Material use	Energy use
Acidification	57.5%	0%	0.3%	10.2%	27.3%	4.7%
Eutrophication	33.6%	62.2%	0.2%	0.1%	0.3%	3.1%
Climate change	72.3%	0%	0.8%	1.5%	3.9%	21.4%
Cumulative energy demand	68.7%	0%	0.68%	2%	4.9%	23.6%

Table 1 shows the contribution of each different sub-system to the four impact categories in the reference scenario where TGC = 8.33 and FCR = 0.81. The impact of nutrient emission on acidification is 0% because effluent water are directly directed to effluent water treatment plant, which is responsible of 0.3% of the total acidification. In table 1, we can see that the main contributors to the four impact categories are different. For acidification, climate change and cumulative energy demand the main contributor is feed production (respectively 57.5%, 72.3%, 68.7%). The second contributor to those three impact categories are fixed sub-systems at farm level, building use for acidification (27.3%) and energy use for climate change (21.4%) and for cumulative energy demand (23.6%). In opposite, the two main contributors of eutrophication are nutrients emission (62.2%) and feed production (33.6%).

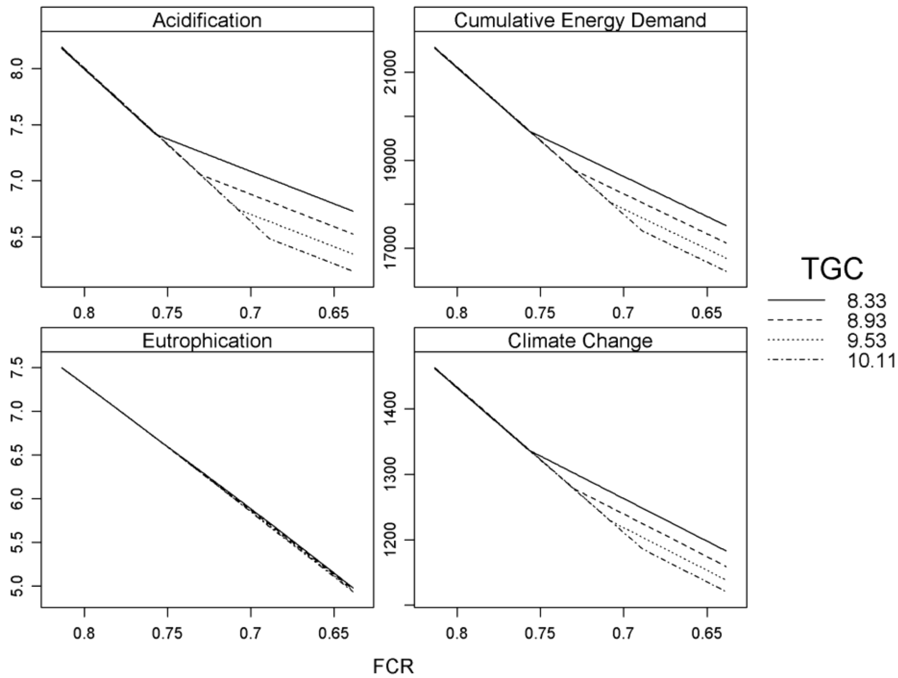

Figure 1. Environmental impacts calculated per t of fish for four impact categories as a function of FCR for four values of TGC.

Figure 1 shows the results of environmental impacts for the four impact categories investigated. First of all, the combination of TGC and FCR defines whether dissolved NH_3-N or density is the limiting factor. Environmental response to genetic improvement in TGC and FCR are different among impact categories according to the factor limiting production. These differences are because TGC and FCR have different effects on production. Two effects are capable of decreasing environmental impacts per unit of fish produced: increasing productivity (annual fish production) and increasing production efficiency (feed consumed per ton of fish). Increasing productivity, while keeping the same production efficiency, dilutes fixed environmental impacts at farm level, such as building use, over more fish produced. Increasing production efficiency, while keeping the same productivity, decreases the amount of feed required to produce one ton of fish and decreases the amount of nutrients emitted per ton of fish which decreases environmental impacts. Depending on the limiting factor, improving TGC or FCR changes either productivity, production efficiency or both.

Dissolved NH_3-N as limiting factor. For instance, when TGC is 8.33 and when FCR decreases from 0.81 to 0.75, the factor limiting production is dissolved NH_3-N. In this situation, improving FCR decreases environmental impacts of the four impact categories while improving TGC does not influence it.

Improving FCR decreases environmental impacts because individual daily excretion of nutrients decreases, which allows to stock more fish per batch to reach dissolved NH_3-N limitation. Consequently, when FCR is improved, both productivity and production efficiency increases, which decreases environmental impacts per ton of fish produced (figure 1).

Additionally, improving TGC does not influence environmental impacts because individual daily excretion of nutrients increases, which constrains to stock fewer fish per batch. This lower number of fish per batch is offset by rearing more batches per year. Consequently, when TGC is improved, productivity and production efficiency remain constant, which keep the environmental impacts at the same level (figure 1).

Density as limiting factor. For instance, when TGC is 8.33 and FCR is lower than 0.75, the factor limiting production is the density of fish in rearing tank. In this situation, the number of fish harvested per batch if fixed.

Improving FCR, therefore, decreases feed consumption per ton of fish and decreases nutrients emission per ton of fish. Consequently, when FCR is improved, only production efficiency increases, which decreases environmental impacts per ton of fish produced but with a lower rate than in dissolved NH_3-N limitation situation (figure 1).

Additionally, improving TGC increases the number of batch harvested per year, which increases annual production of fish. Consequently, when TGC is improved, only productivity increases, which decreases environmental impacts (figure 1).

Different environmental responses to genetic improvement in TGC can, however, be observed when density is the limiting factor. Improving TGC decreases acidification, climate change and cumulative energy demand while the response in eutrophication is smaller. The response to genetic improvement in TGC for eutrophication is smaller because improving TGC increases productivity only, which dilute fixed environmental impacts at farm level, such as use of material, over more fish produced. The contribution of fixed environmental impacts to eutrophication is, however, smaller than the contribution of fixed environmental impacts to acidification, climate change and cumulative energy demand (table 1).

Table 2 gives ENV_{TGC} and ENV_{FCR} of the four impacts categories investigated in both situations, when dissolved NH_3-N is the limiting factor and when density is the limiting factor.

When dissolved NH_3-N is the limiting factor, all ENV_{TGC} are null as TGC do not alter environmental impacts. These results can be explained by the fact that increasing TGC does not influence productivity nor production efficiency. The ENV_{FCR} are, however, negative because when dissolved NH_3-N is the limiting factor, increasing FCR increasing productivity and production efficiency, which decreases environmental impacts.

When density is the limiting factor, ENV_{TGC} have a negative value because increasing TGC increases productivity which dilutes fixed environmental impacts at farm level over more fish produced. E_V_{TGC} is, however, very close to zero because eutrophication is relatively insensitive to fixed environmental impacts at farm level compare to other impacts categories (table 1). The ENV_{FCR} are also negative but CED_V_{FCR}, E_V_{FCR} and A_V_{FCR} are lower when density is the limiting factor than when dissolved NH_3-N is the limiting factor because increasing FCR when density is the limiting factor increases production efficiency only. Moreover, E_V_{FCR} is higher than CED_V_{FCR}, E_V_{FCR} and A_V_{FCR} because the two main contributors of eutrophication are nutrients emission and feed production, which are sensitive to production efficiency.

Table 2. Environmental values of TGC (ENV_{TGC}) and FCR (ENV_{FCR}) of four impacts categories (eutrophication = E_V, acidification = A_V, climate change = CC_V and cumulative energy demand = CED_V) calculated when dissolved NH_3-N is the limiting factor (TGC = 8.93, FCR = 0.81) and when density is the limiting factor (TGC = 8.93, FCR = 0.64).

ENV	Trait	TGC = 8.93 FCR = 0.81 Limiting factor = dissolved NH_3-N	TGC = 8.93 FCR = 0.69 Limiting factor = density
A_V	FCR	-10.3%	-4.3%
	TGC	0%	-2.7%
E_V	FCR	-11.8%	-13.4%
	TGC	0%	-0.3%
CC_V	FCR	-9.3%	-5.5%
	TGC	0%	-1.8%
CED_V	FCR	-9.6%	-5.2%
	TGC	0%	-2.0%

4. Discussion

The results of our simulations show that environmental response to genetic improvement in TGC and FCR is different when density and when NH_3-N are the limiting factors. When NH_3-N is the limiting factor, only genetic improvement in FCR decreases environmental impacts because it increases productivity and production efficiency. On the contrary, when density is the limiting factor both genetic improvement in TGC and FCR decreases environmental impacts because improvement in FCR increases production efficiency and improvement in TGC increases productivity. When density is the limiting factor, however, environmental response to genetic improvement in TGC and FCR are different across impact categories depending on their main contributors. Eutrophication is mainly driven by feed production and nutrients emission, which are influenced by production efficiency. Conversely, other impact categories are mainly driven by feed production and building use or energy use, which are influenced by productivity.

d'Orbcastel et al. (2009) investigated the impact of a RAS producing rainbow trout using two different values of FCR, 1.1 and 0.8. This range corresponds to 27.3% of improvement, or to 3.6 generations of selection when percentage of improvement in FCR is 7.6%. They found, therefore, that decreasing FCR by 7.6% decreased acidification by 5.8%, eutrophication by 4.3%, climate change by 6% and cumulative energy demand by 2.4%. It is, however, difficult to use the results from d'Orbcastel et al. (2009) as a comparison basis for our results because they didn't take into account changes that could occur in farm management when FCR changes. d'Orbcastel et al. (2009) considered that improvement in FCR increased production efficiency but, using dynamic modelling of the relationship between genetic improvement and farm management, our results show that improving FCR can also increase productivity when NH_3-N is the limiting factor. Changes in FCR can also lead to changes in limiting factor.

The results presented here confirm that FCR would be the major trait to include in the breeding goals for decreasing environmental impacts. In fish breeding, however, FCR is a difficult trait to improve as it is difficult to measure individual feed intake. FCR is expected to be correlated to TGC, however, studies diverge on this subject. In rainbow trout, Kause et al. (2006) predicted that selection only for daily gain increases daily gain by 17.6% per generation and simultaneously increases feed efficiency (1/FCR) by 8.4%. In parallel, some other studies in salmonids did not observe any correlation between growth rate and feed efficiency and showed that genetic gain in growth is due to higher feed intake, while feed efficiency remain unchanged (Mambrini et al., 2004; Sanchez et al., 2001).

5. Conclusion

Environmental values could be included in breeding programs in a similar way as economic values and could help fish breeders to design effective breeding programs in terms of environmental consideration by putting more emphasis on the relevant traits, in a specific limiting factor situation. Our results have, therefore, important implications for fish breeders who may need to alter their breeding objectives depending on what is limiting production on the farms of their customers. We show that environmental values of FCR and TGC are dependent on the factor limiting production. Improvement of feed efficiency always improves environmental impacts in any situation. However, selecting for increased growth rate is only relevant in situations where nitrogen emissions are not limiting production. Those results are important for the future development of selective breeding programs in fish farming taking into account environmental objectives.

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