Economic and Environmental Impacts of Improving Growth Rate and Feed Efficiency in Fish Farming Depend on Nitrogen and Density Limitation

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ABSTRACT: The aim of fish breeding is to increase profit by producing faster growing fish with lower feed intake. However, little is known about the economic and environmental impacts of selective breeding programs for fish. We modelled a fish farm producing African catfish in a Recirculating Aquaculture System (RAS) to calculate economic values of growth rate and feed efficiency with production limited by fish density in rearing tanks and fish nitrogen emission. We also calculated “environmental values” with Life Cycle Assessment. The economic and environmental values of growth rate and feed efficiency depended on the limiting factor. When nitrogen was the limiting factor, economic and environmental values of growth rate were zero. But, on the other hand, feed efficiency always had positive economic and environmental values. Therefore, fish breeders may need to adapt their breeding objectives according to the limiting factor.

Keywords: Economic values; Environmental impacts; Fish farming

Farm design. We modeled, using R software (R Development Core Team, (2008)), a typical commercial Dutch fish farming 500t of African catfish per year in an indoor RAS. The RAS is composed of four main parts. (1) rearing tanks growing fish from 13g to 1300g. The maximum density in the tank is 230 kg/m³ which is one of the limiting factors. (2) A mechanical filter, which removes solid waste. (3) A bio-filter processing nitrification. The nitrification capacity of the bio-filter is limited to 40 kg of dissolved N-NH₃ per day, which is the second limiting factor. (4) A denitrification reactor.

Fish growth. We calculated daily weight (Wn) and daily weight gain (DWGₙ) using Thermal Growth Coefficient (TGC) (Dumas et al. (2007)). Wn was then used to fit daily FCR (FCRₙ) using a power function: FCRₙ = 0.38 × Wₙ⁻⁰.¹⁰⁶. Individual daily feed distributed (DFDₙ) was calculated with DWGₙ and FCRₙ, assuming 1% of feed wasted (not consumed by the fish).

Waste emission. The quantity of nitrogen, phosphorus and Chemical Oxygen Demand (COD) emitted per fish 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.

Batch model. A batch is defined as a group of fish of the same age stocked in the same tank. The number of fish stocked per batch, Nb_fishb, depends on the emission of dissolved N-NH₃ of all batches j reared at Maximum Standing Stock (N_dissolvedMSS) and cannot exceed 40 kg/day (maximum N-NH₃ load):

\[
Nb\_fishb = \frac{\text{maximum N-NH}_3 \text{ load}}{\sum_{i=1}^{j} (N\_dissolvedMSS)} \times (1 - M_{Wn})
\]

Mw is the cumulative mortality in batch i at fish weight Wn: M_{Wn} = 0.0001 \times (W_{n}) + 0.0113. We used Nb_fishb and Mw to calculate fish production, feed consumption and nutrient emissions at batch level.

Farm model. The number of batches that can be harvested per year depends on the time interval between batches and can be expressed as:

\[
N_{b\_batchyear} = 9.22 \times TGC.
\]

We used Nb_batchyear
to calculate annual fish production, feed consumption and nutrient emissions. The average FCR over the year was calculated as the total feed distributed per year divided by the total fish produced per year.

**Profit function.** Annual profit per farm = (annual fish production × harvest weight × fish price) − (annual feed consumption × feed price) − (annual number of juveniles stocked × juvenile price) − (annual pollution unit × cost of pollution unit) − fixed cost

Profit per kg of fish produced is given by:

\[
\text{profit}_k\text{g} = \frac{\text{annual profit per farm}}{\text{annual fish production}}
\]

**Environmental impact.** A cradle-to-farm-gate Life Cycle Inventory was conducted, including three stages: feed production, farm operation and waste water treatment. The environmental contribution of the inputs and the outputs for each stage was evaluated. Annual fish production, feed consumption and nutrient emissions are variable inputs and outputs that depend on FCR and TGC. They were calculated from the bioeconomic model. Calculation of four impact categories, eutrophication (eutro), acidification (acid), climate change (cc) and energy demand (ed) per ton of fish produced were conducted using the CML2 method and SimaPro® 6.0 software. The results for impact categories were combined with results of the bioeconomic model, using R software.

**Economic (EV) and environmental values (enV).** The economic value (EV in €/kg of fish produced) and environmental impact (enV in % of change) of a trait t (FCR,TGC) express the impact of a unit change in one trait while keeping the other trait constant. EV and ENV of both traits were calculated in three steps:

1) Calculate profit per kg of fish (profit_kg) and environmental impact per ton of fish (i.e. acid,µt) using current population means for trait t (µt). The current population mean is 8.33 for TGC and 0.81 for FCR. We set FCR at 0.81 in order to balance cost with revenue when TGC = 8.33.

2) The mean of trait t was increased by Δt while keeping the mean of the other traits constant: A TGC = µTGC × 6.8% and A FCR = µFCR × -7.6%. 6.8% and -7.6% represent the percentage of improvement per generation in TGC and FCR as calculated by Sae-Lim et al. (2012). The next generation mean is 8.93 for TGC and 0.75 for FCR. The model was then run a second time to calculate profit and environmental impacts.

3) EV and enV were calculated for trait t as:

\[
\text{EV}_t = \frac{\text{profit}_k\text{g}}{\mu_t + \Delta t} - \text{profit}_k\text{g}_{\mu_t}
\]

\[
\text{enV}_t = \frac{(\text{acid}_{\mu_t + \Delta t} - \text{acid}_{\mu_t})}{\text{acid}_{\mu_t}}
\]

EV and enV were calculated for two situations: when dissolved N-NH3 was the limiting factor and when density was the limiting factor.

**Results**

Feed production contributed more than 60% to acidification, climate change and cumulative energy demand, while nutrients (N and P) released contributed more than 60% to eutrophication. Therefore, levels of acidification, climate change and energy demand were sensitive to the ratio fish produced over feed consumed (fish/feed) and to the amount of fish produced. The level of eutrophication was, however, sensitive to fish/feed ratio only.

**EV and enV when dissolved N-NH3 is the limiting factor.** EV TGC is 0 €/kg of fish produced (table 3) because faster growing fish have higher daily weight gain, which increases daily N-NH3 emission per fish. Therefore, less fish can be managed at MSS, which decreases fish harvested per batch. This decrease in density is offset by rearing more batches per year. Therefore, annual fish production, fish/feed ratio, and profit do not change with increasing TGC values (table 1). Additionally, since fish production and fish/feed ratio do not change, eutroV TGC, acidV TGC, ccV TGC and edV TGC are zero (table 3).

<table>
<thead>
<tr>
<th>Trait</th>
<th>N-NH3 limitation</th>
<th>Density limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td>FCR 0.11</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>TGC 0</td>
<td>0.02</td>
</tr>
<tr>
<td>acidV</td>
<td>FCR -10.3</td>
<td>-4.6</td>
</tr>
<tr>
<td></td>
<td>TGC 0</td>
<td>-2.6</td>
</tr>
<tr>
<td>eutroV</td>
<td>FCR -11.7</td>
<td>-11.3</td>
</tr>
<tr>
<td></td>
<td>TGC 0</td>
<td>-0.2</td>
</tr>
<tr>
<td>ccV</td>
<td>FCR -9.3</td>
<td>-5.7</td>
</tr>
<tr>
<td></td>
<td>TGC 0</td>
<td>-1.7</td>
</tr>
<tr>
<td>edV</td>
<td>FCR -9.6</td>
<td>-5.4</td>
</tr>
<tr>
<td></td>
<td>TGC 0</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

EV TGC is 0.11 €/kg fish produced (table 3) because lower FCR decreases total feed distributed per fish, which decreases individual daily N-NH3 emission. Hence, the number of fish stocked and the annual production of fish can be increased in order to reach limitation on dissolved N-NH3 (table 1). In this situation, fish/feed ratio increases, which reduces acidV TGC, ccV TGC and edV TGC by around 10% (table 3).

**EV and enV when density is the limiting factor.** EV TGC is 0.02 €/kg of fish (table 3) because even when the number of fish harvested per batch is constant, the number of batches per year increases, increasing annual fish production (table 2). Producing more fish causes slightly negative acidV TGC, ccV TGC and edV TGC (table 3). TGC, however, has no effect on eutroV TGC because the fish/feed ratio is constant and the amount of nutrient released per ton of fish do not change.

EV TGC is 0.07 €/kg fish produced (table 3) because less feed is required for the same annual fish production (table 2). Consequently, fish/feed ratio and profit increases with decreasing FCR. Additionally,
economic and environmental impacts of improving growth rate (TGC) and feed efficiency (FCR) of African catfish reared in RAS. Results show that TGC and FCR have different economic values and environmental impacts when either dissolved N-NH₃ or density limits production. These differences are because TGC and FCR have different effects on production. Two effects are capable of increasing profit while decreasing environmental impacts per unit of fish produced: increasing productivity (fish production) and increasing production efficiency (fish/feed ratio).

**Table 2: Effect of different values of TGC and FCR on annual production parameters when production is only limited by N-NH₃ dissolved at MSS.**

<table>
<thead>
<tr>
<th>TGC</th>
<th>FCR</th>
<th>Feed intake, kg/fish</th>
<th>Fish harvest per batch</th>
<th>Batches per year</th>
<th>Fish/feed ratio, ton/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.33</td>
<td>0.81</td>
<td>1.057</td>
<td>7729</td>
<td>52</td>
<td>522/424</td>
</tr>
<tr>
<td>8.33</td>
<td>0.75</td>
<td>0.977</td>
<td>8973</td>
<td>52</td>
<td>606/455</td>
</tr>
<tr>
<td>8.93</td>
<td>0.81</td>
<td>1.058</td>
<td>7183</td>
<td>56</td>
<td>520/423</td>
</tr>
</tbody>
</table>

**Discussion**

The objective of this study was to evaluate the economic and environmental impacts of improving growth rate (TGC) and feed efficiency (FCR) of African catfish reared in RAS. Results show that TGC and FCR have different economic values and environmental impacts when either dissolved N-NH₃ or density limits production. These differences are because TGC and FCR have different effects on production. Two effects are capable of increasing profit while decreasing environmental impacts per unit of fish produced: increasing productivity (fish production) and increasing production efficiency (fish/feed ratio).

**Table 3: Effect of different values of TGC and FCR on annual production parameters when production is only limited by density at harvest.**

<table>
<thead>
<tr>
<th>TGC</th>
<th>FCR</th>
<th>Feed intake, kg/fish</th>
<th>Fish harvest per batch</th>
<th>Batches per year</th>
<th>Fish/feed ratio, ton/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.33</td>
<td>0.81</td>
<td>0.813</td>
<td>8846</td>
<td>52</td>
<td>597/486</td>
</tr>
<tr>
<td>8.33</td>
<td>0.75</td>
<td>0.752</td>
<td>8846</td>
<td>52</td>
<td>597/449</td>
</tr>
<tr>
<td>8.93</td>
<td>0.81</td>
<td>0.813</td>
<td>8846</td>
<td>56</td>
<td>640/521</td>
</tr>
</tbody>
</table>

When density limits production, TGC increases productivity, which increases profit and dilutes environmental impacts due to fixed inputs, such as use of energy at farm level, over more fish produced. Here, increasing TGC will have a positive economic value and a negative environmental value, except for eutrophication, which depends on nutrients released. When density limits production, FCR increases production efficiency, which decreases feed cost and environmental impacts per ton of fish produced. This has an impact on both profit and environmental impacts because feed production contributes more than 60% to the farm cost and to acidification, climate change and energy demand. Therefore, when density limits production, farmers should put emphasis on both TGC and FCR.

When dissolved N-NH₃ limits production, TGC had no impact on either profit or the environment. This is because higher TGC does not change productivity or production efficiency. When dissolved N-NH₃ limits production, improving FCR increases both productivity and production efficiency, which decreases feed cost and environmental impacts per ton of fish produced but also increases annual fish production. Therefore, when dissolved N-NH₃ limits production, farmers should put more emphasis on FCR because improving production efficiency by decreasing FCR is the only way to increase profit and decrease environmental impacts.

**Conclusions**

Our results have important implications for fish breeders who may need to alter their breeding objectives depending on what is limiting production on fish farms of their customers. We show that economic and environmental values of FCR and TGC are dependent on the factor limiting production. Improvement of feed efficiency always improves farm profit and 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 impacts.

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**Literature cited**


