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

Introduction

Breeding programs can improve the profitability and efficiency of commercial fish farms by selecting the best fish for a particular production system (Gjedrem et al., (2012)). Although genetic improvement programs can lead to high economic benefits (Ponzoni et al., (2007); Ponzoni et al., (2008)), economic values of breeding goals traits of most fish species are still lacking. Additionally, breeding programs are expected to change environmental impacts of fish farming. The magnitude and the direction of this change is, however, not known. In the dairy sector, genetic improvement of milk yield per cow has decreased CH_4 emission (Bell et al., (2011)). Wall et al. (2009) 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 et al., (1988)). Therefore, a bioeconomic model combined with Life Cycle Assessment was developed in order to calculate economic and environmental values of Thermal Growth Coefficient (TGC) and Feed Conversion Ratio (FCR) of African catfish reared in a Recirculating Aquaculture System (RAS). In RAS, there are two factors limiting production. Both of these limitations affect both traits differently. Therefore, economic and environmental values of TGC and FCR were calculated in a situation where emission of dissolved N-NH_3 was the limiting factor and in a situation where density of fish in rearing tanks was the limiting factor.

Materials and Methods

Farm design. We modeled, using R software (R Development Core Team, (2008)), a typical commercial Dutch farm producing 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/m^3, 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-NH_3 per day, which is the second limiting factor. (4) A denitrification reactor.

Fish growth. We calculated daily weight (W_n) and daily weight gain (DWG_n) using Thermal Growth Coefficient (TGC) (Dumas et al. (2007)). W_n was then used to fit daily FCR (FCR_{Wn}) using a power function : $\mathrm{FCR_{Wn}} = 0.38 \times \mathrm{W_n^{0.106}}$. Individual daily feed distributed (DFD_n) was calculated with DWG_n and FCR_{Wn}, 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_fish_0, depends on the emission of dissolved N-NH_3 of all batches j reared at Maximum Standing Stock ($N\_dissolved_{MSS}$) and cannot exceed 40 kg/day (maximum N-NH_3 load):

$$\mathrm{Nb\_fish_0} = \frac{\mathrm{maximum\ \ N\_NH3\ \ load}}{\sum_{i=1}^{j}\left(\mathrm{N_{dissolved_{MSS}}}\right) \times (1 - \mathrm{M_{Wn}})\mathrm{i}}$$

M_{Wn} is the cumulative mortality in batch i at fish weight Wn: $\mathrm{M_{Wn}} = 0.0001 \times (\mathrm{W_n}) + 0.0113$. We used Nb_fish_0 and M_{Wn} 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: $\mathrm{Nb\_batch_{year}} = 9.22 \times \mathrm{TGC}$. We used $\mathrm{Nb\_batch_{year}}$

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:

$$\mathrm{profit\_kg} = \frac{\text{annual profit per farm}}{\text{annual fish production}}$$

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 values of the four impact categories (eutroV, acidV, ccV and edV 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 ($\mathrm{profit\_kg}_{\mu t}$) and environmental impact per ton of fish (i.e. $\mathrm{acid}_{\mu t}$) using current population means for trait t (μ_t). 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 Δ_t while keeping the mean of the other traits constant. $\Delta_{TGC} = \mu_{TGC} \times 6.8\%$ and $\Delta_{FCR} = \mu_{FCR} \times -7.6\%$. 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:

$$\mathrm{EV}_t = \mathrm{profit\_kg}_{\mu t+\Delta t} - \mathrm{profit\_kg}_{\mu t}$$

$$\mathrm{acid\ V}_t = \frac{(\mathrm{acid}_{\mu t+\Delta t} - \mathrm{acid}_{\mu t})}{\mathrm{acid}_{\mu t}}$$

EV and enV were calculated for two situations: when dissolved N-NH_3 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-NH_3 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-NH_3 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 1: Effect of limiting factors on economic values (€/kg of fish produced) and environmental values (% of change) of FCR and TGC.

	Trait	N-NH_3 limitation	Density limitation
EV	FCR	0.11	0.07
	TGC	0	0.02
acidV	FCR	-10.3	-4.6
	TGC	0	-2.6
eutroV	FCR	-11.7	-11.3
	TGC	0	-0.2
ccV	FCR	-9.3	-5.7
	TGC	0	-1.7
edV	FCR	-9.6	-5.4
	TGC	0	-1.9

EV_{FCR} is 0.11 €/kg fish produced (table 3) because lower FCR decreases total feed distributed per fish, which decreases individual daily N-NH_3 emission. Hence, the number of fish stocked and the annual production of fish can be increased in order to reach limitation on dissolved N-NH_3 (table 1). In this situation, fish/feed ratio increases, which reduces eutroV_{FCR}, acidV_{FCR}, ccV_{FCR} and edV_{FCR} 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_{FCR} 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,

$eutroV_{FCR}$, $acidV_{FCR}$, ccV_{FCR} and edV_{FCR} are all negative (table 3).

Table 2: Effect of different values of TGC and FCR on annual production parameters when production is only limited by N-NH_3 dissolved at MSS.

TGC	FCR	Limiting factor = dissolved N-NH_3 at MSS (40 kg)			
		Feed intake, kg/fish	Fish harvest per batch	Batches per year	fish/feed ratio, ton/ton
8.33	0.81	1.057	7729	52	522/424 = 1.23
8.33	0.75	0.977	8973	52	606/455 = 1.33
8.93	0.81	1.058	7183	56	520/423 = 1.23

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-NH_3 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.

TGC	FCR	Limiting factor = density at harvest (230 kg/m^3)			
		Feed intake, kg/fish	Fish harvest per batch	Batches per year	fish/feed ratio, ton/ton
8.33	0.81	0.813	8846	52	597/486 = 1.23
8.33	0.75	0.752	8846	52	597/449 = 1.33
8.93	0.81	0.813	8846	56	640/521 = 1.23

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-NH_3 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-NH_3 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-NH_3 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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