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Are restricted periods of over-stocking of recirculating aquaculture systems advisable? A simulation study

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ABSTRACT

Fish stocking is an important element of aquaculture management. A constant stocking rate is a convenient strategy in intensive aquaculture, being also the best under steady physical and economic conditions. If, however, these conditions vary with time, the best stocking rate may also vary. This problem has been addressed in a previous paper, where water temperature, fish price and/or market demand were allowed to vary sinusoidally over the annual cycle, while a constant upper limit on the water-treatment capacity constrained the process. Considering only situations where feeding is always to satiation, *sinusoidal* stocking rates were shown to perform often significantly better than the best *constant* stocking-rate strategy.

In this paper a further step is taken in that over-stocking (more than hitherto) for certain periods of time is allowed. This leads to restricted feeding at a later time (to avoid overload of the water-treatment system) and to some loss of feeding efficiency. Often, however, the loss in feeding efficiency is more than compensated for by better utilization of the rearing space.

Optimal constant and sinusoidal over-stocking strategies were applied to eight sample combinations of sinusoidal temperature and market conditions. Restricted over-stocking often resulted in a considerable improvement of economic performance over the previous results. The *potential* for increase of yield and profit by over-stocking depends on the amount of under-utilization of the rearing space by the previous solution, namely when only feeding to satiation is allowed. On average (for the system under consideration) out of 10% of under-utilized space when feeding to satiation, 4.4% (almost half) can be recovered by properly applied over-stocking. Expressed in terms of feed processing capability, this 4.4% recovery is equivalent to about 16 kg[feed]/(m^3[tank]y), and to an additional production of about 6.6 kg[fish]/(m^3[tank]y). The gain in profit is of the order of 25 $/(m^3[tank]y) per 10% of previously unutilized capacity.

1. Introduction

1.1. Aquaculture management

Land-based intensive aquaculture is characterised by high investment per unit of rearing volume, as well as by small buffers and tight controls. Good management planning is, therefore, essential. Aquaculture management has been studied at least since the 1970s (Gates and Mueller, 1975) and covers a wide range of systems and situations. Several fish species have been considered, several growing systems have been modelled, and several methods of solution have been applied. A recent review of operational research (OR) methods in aquaculture may be found in Bjørndal et al. (2004), and an earlier one in Cacho (1997). Many of the particular management studies focus on marine cages (Petridis and Rogdakis, 1996; Forsberg, 1996; Forsberg and Guttormsen, 2006; Hernández et al., 2007; Mayer et al., 2008), but other systems, such as (land-based) recirculating aquaculture systems (RAS; Kazmierczak and Caffey, 1995; Halachmi, 2007), or fertilized ponds (Yi, 1999), have also been considered.

A central element of the management model is the fish growth model. It is often represented by a multiplicative function of the form

$$g \equiv \frac{dm}{dt} = g_1\{m\}g_2\{T\}g_3\{f\} \qquad (1)$$

(Hernández et al., 2003), where g is the rate of growth of a single fish (in g[BM]/(fish d)), m is live body mass (BM) of a single fish (in g[BM]/fish), T is water temperature (in K), f is feed ration (in g[feed]/(fish d)) or specific feed ration (in g[feed]/(g[BM]d)), and t

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Notation

Symbols

A	actual supply rate of fish (g[BM]/(m^3[tank]d))
B	unit cost of feed (\$/g[feed])
C	energy ration (kJ/(fish d))
D	costs proportional to production rate excluding feed (\$/g[BM])
d	difference between satiation-feeding and water-treatment capacity (g[feed]/(m^3[tank]d))
e	specific energy content of fish live body (kJ/g[BM])
F	energy excreted as faeces (kJ/(fish d))
f	single fish feed ration (=feed consumption) (g[feed]/(fish d))
G	energy retained (deposited) in the body, growth (kJ/(fish d))
g	growth rate of a single fish (g[BM]/(fish d))
I	gross income (\$/(m^3[tank]d))
J	annual goal (objective) function (\$/(m^3[tank]y))
K	costs proportional to rate of production (\$/g[BM])
M	marketing rate (g[BM]/(m^3[tank]d))
m	live body mass of a single fish (g[BM]/fish)
N	energy in nitrogenous waste (kJ/(fish d))
n	stocking rate (fish/(m^3[tank]d))
P	unit price of marketable fish (\$/g[BM])
p	penalty factor
R	energy dissipated by respiration (kJ/(fish d))
r	relative amplitude
S	production costs proportional to occupied space (rent) (\$/(m^3[tank]d))
T	temperature (K)
t	time (d)
α_n	relative stocking amplitude (S&H)
α_e	energy content coefficient (kJ $\cdot$ fish$^{\beta_e}$/ (g[BM]$^{1+\beta_e}$ d))
α_f	feed intake-rate coefficient (g[feed]/(g[BM]$^{\beta_f}$ fish$^{1-\beta_f}$ d))
α_g	growth-rate coefficient (g[BM]$^{1-\beta_g}$/(fish$^{1-\beta_g}$ d))
α_μ	maintenance-rate coefficient (kJ/(g[BM]$^{\beta_\mu}$ fish$^{1-\beta_\mu}$ d))
β	size exponent
γ	temperature coefficient (1/K)
δ	energy digestibility $\equiv(C-F)/C$
ε	specific energy content of new body mass (kJ/g[BM])
η	energy ratio: growth-respiration/growth $\equiv R_\gamma/G$
ζ	space-utilization factor
θ	specific gross energy content of feed (kJ/g[feed])
κ	feed conversion ratio (FCR) (g[feed]/g[BM])
ν	energy ratio: ammonia/consumed $\equiv N/C$
ρ	energy ratio: growth respiration/maintenance respiration $\equiv R_\gamma/R_\mu$
Φ	feeding rate (g[feed]/(m^3[tank]d))
ϕ	phase shift (time delay) (d)

Subscripts

*	feeding to satiation
0	freezing
1,2,3	single-argument factors of a function
a	amplitude
c	satiation feed ration
e	energy content of fish body
f	feeding
g	growth (in terms of body mass)
i	initial
inc	yield increment
j	index to count cohorts
M	marketing
m	mean
n	stocking rate
P	fish price
sat	feeding to satiation
T	temperature
t	final (termination)
x	maximum (permissible, capacity)
γ	growth (in terms of energy)
μ	maintenance (in terms of energy)

Superscripts

1,2	linear pieces of a function

Acronyms

BM	live body mass of fish
FCR	feed conversion ratio
S&H	Seginer and Halachmi (2008)

is time (in d). Often g_1 has the same units as g, while g_2 and g_3 are dimensionless correction factors. Note that the effect of feed-composition is implicit in the coefficients of Eq. (1). Other factors, such as the effect of fish density (in kg[BM]/m^3[water]), may be added to the model (Heaps, 1995). Other examples of this approach, where the growth process is described by differential equations, and individual cohorts (batches) of fish are considered uniform in size, can be found, for instance, in Corey et al. (1983) and Lupatsch et al. (1998). Stochasticity (Hochman et al., 1990) and fish size distribution (Summerfelt et al., 1993; Gasca-Leyva et al., 2008) may be added to a growth model such as Eq. (1), if required. An alternative deterministic approach is to use Leslie (population) matrices (Forsberg, 1996) to distinguish between age and size of fish.

Two of the arguments (predictors) of the growth function, namely T and f, may be controlled by the grower (operator), but the literature rarely deals with temperature control, presumably because this is not relevant to marine cages and is often not justified for RAS (Seginer and Mozes, 2008). On the other hand, controlling feed ration *is* often considered (Cacho et al., 1991; Arnason, 1992; Heaps, 1993; Mistiaen and Strand, 1999; Hernández et al., 2007), mainly because the cost of feed is a large fraction of the overall rearing costs.

Stocking and harvesting decisions are very important, sometimes more so than the factors which affect directly the growth rate, and as a result are given much attention (Bjørndal, 1988; Arnason, 1992; Forsberg, 1999; Mistiaen and Strand, 1999; Hernández et al., 2007). These decisions are strongly affected by the price system, specifically feed cost, investment cost and the revenue from selling the fish. The latter price may change with time (Forsberg and Guttormsen, 2006), and with size of fish (Gates, 1974; Bjørndal, 1988; Wang and Kellogg, 1988; Hernández et al., 2007). Furthermore, the price dependence on size may be smooth, as in the examples already given, or piecewise continuous, as in Gates and Mueller (1975) and Mistiaen and Strand (1999). Harvesting may be in batch mode or graded (Forsberg, 1999), the latter requiring the sorting of fish. Finally, there may be