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Optimum harvest time in aquaculture: an application of economic principles to a Nile tilapia, *Oreochromis niloticus* (L.), growth model

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Abstract. A simple method is presented for determining the optimum time to harvest fish and the effect of fertilization type on optimum harvest time for aquaculture. Optimum harvest time was similar for either maximizing fish yield or maximizing profit of fish harvested (price of fish times fish yield minus fish production cost), because the daily change in fish production cost was low for the low-input Nile tilapia, *Oreochromis niloticus* (L.), production system in Thailand. At a harvest time of 150 days for an organic fertilization treatment compared to an inorganic fertilization treatment fish yield increased from 1·505 t/ha to 2·295 t/ha, and profit of fish harvested increased from 15657·1 baht/ha (US$ 590·8/ha) to 25127·5 baht/ha (US$ 948·2/ha). For the organic treatment, optimum harvest time occurred at 191 days, with a fish yield of 2·328 t/ha and a profit of 25520·5 baht/ha (US$ 963·0/ha), compared to the inorganic treatment where optimum harvest time occurred at 105 days with a fish yield of 1·536 t/ha and a profit of 16035·4 baht/ha (US$ 605·1/ha).

Introduction

Total yield of fish stocked in a pond increases to a maximum and then begins to decrease as a result of continual low mortality and a decrease in growth rate with age (Ricker 1979). The biologically optimum harvest time can be defined as the time when fish yield (fish number times fish weight) is at a maximum value. The fish weight at this maximum directly reflects stocking density and fish weight stocked; however, this optimum harvest time does not consider the economics of fish production. The economically optimum harvest time occurs when profit of fish yield sold at market (price of fish times fish yield minus fish production cost) is at a maximum value. This point occurs where marginal revenue (value of selling an additional unit of product) is equal to marginal cost (cost of producing an additional unit of product). This economic optimum harvest time is more useful for determining optimum time to harvest fish and it can be calculated when price and cost data are available. Both optimum harvest times can be estimated using an equation for fish yield which can be developed by coupling an equation for growth with an equation for mortality.

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In this study an equation for fish production derived from simple equations for growth and mortality, and data for cost and price are applied to determine optimal harvest time of *Oreochromis niloticus* (L.) in an experimental pond in Thailand.

Methods

Model development

Many different equations have been applied to describe fish growth (Ricker 1979; Moreau 1987). Von Bertalanffy's equation was chosen for this study because it is the most widely used model and fish growth is easily interpreted in terms of biologically meaningful parameters of a growth coefficient and asymptotic size. The initial value solution of von Bertalanffy's equation for growth in length is (Beverton & Holt 1957)

$$L_t = L_{inf}[1 - \exp(-Kt)] + L_o \mathrm{esp}(-Kt) \tag{1}$$

where L_o is initial length. The initial value solution for growth in weight can be derived from the power relation between fish weight and length assuming the length exponent is 3·0 (Springborn 1991)

$$W_t = [a^{1/3} L_t]^3 \tag{2}$$

Substituting the initial value solution for growth in length (equation 1) into equation 2 gives

$$W_t = \{a^{1/3} L_{inf}[1 - \exp(-Kt)] + a^{1/3} L_o \exp(-Kt)\}^3,$$

but from equation 2

$$W_{inf} = a^{1/3} L_{inf}$$

$$W_t = \{W_{inf}{}^{1/3}[1 - \exp(-Kt)] + W_o{}^{1/3} \exp(-Kt)\}^3 \tag{3}$$

where W_o is initial weight.

Fish yield at time t is

$$Y_t = W_t N_t \tag{4}$$

where W_t is fish weight and N_t is number of fish at time t which is (Ricker 1975)

$$N_t = N_o \exp(-Zt) \tag{5}$$

where N_o is number of fish stocked and Z is the instantaneous mortality coefficient.

Net economic rent (profit) at time t is

$$R_t = PY_t - C_t \tag{6}$$

where P is price per unit of fish and C_t is fish production cost at time t. Fish production cost at time t is (Engle & Skladany 1991)

$$C_t = C_0 + C_1 t + C_2 \text{(at time of harvest)} \tag{7}$$

where C_0 is start-up cost which includes fingerling cost and pond lime cost, C_1 is cost during the treatment, which includes manure cost, cost of labour gathering and applying manure and fixed cost of depreciation and interest on investment capital, and C_2 is cost occurring only at the time of harvest which includes cost of labour at harvest, cost of transportation to market and interest on operating cost (Table 1). Interest on operating cost is charged to the total

Table 1. Itemized fish production costs for experiments conducted in Thailand based on stocking 10000 fish/ha (US$1.00 = 26·50 baht)

Item	Cost
Start-up cost (C_0)	
Fingerling cost (baht/ha)	646·10
Pond lime and preparation cost (baht/ha)	300·00
Daily cost during the experiment (C_1)	
Manure cost (baht/ha/day)	14·29
Cost of manuring labour (baht/ha*day)	5·16
Fixed cost (baht/ha/day)	27·39
Cost at time of harvest (C_2)	
Cost of harvest labour (baht/ha)	4·58
Transportation cost (baht/ha)	40·00
Interest on operating cost (baht/ha)[a]	1397·00
Fish production cost at time t is	
$C_t = 946{\cdot}10 + 46{\cdot}84/\text{time} + 1441{\cdot}58$ (harvest only)	

[a]This interest is charged to the total amount of operating cost incurred throughout the production cycle, but paid at the time of harvest as a farmer who had borrowed operating capital for the production season would need to pay interest after harvesting fish.
Source: Engle & Skladany (1991).

amount of operating cost incurred throughout the production cycle, but paid at the time of harvest just as a farmer who had borrowed operating capital for the production season would need to pay interest on this loan after harvesting and selling fish.

The biologically optimum time to harvest fish t_β occurs when fish yield Y_t is at a maximum value and rate of growth in fish yield dY/dt equals zero. Time t_β can be derived by substituting equations 3 and 5 into equation 4, taking the derivative of equation 4 with respect to time t and setting the result to zero; this gives

$$t_\beta = (-1/K)\text{Log}_e\{(ZW_{inf}^{1/3})/(3K + Z)(W_{inf}^{1/3} - W_o^{1/3})\}$$

Similarly, the economically optimum time to harvest fish t_ϵ occurs when net economic rent R_t is at a maximum value and rate of change in net economic rent dR/dt equals zero. Time t_ϵ can be derived by substituting equations 3 and 5 into equation 4, substituting equations 4 and 7 into equation 6, taking the derivative of equation 6 with respect to time t and setting the result to zero. A simpler approach to estimate this optimum harvest time is to take the derivative of equation 6 as

$$dR/dt = PdY/dt - C_1$$

and remember that the objective is to find that value of time t_ϵ for which

$$dR/dt(t_\epsilon) = 0$$

or written differently the objective is to find that value of time t_ϵ for which

$$dY/dt(t_\epsilon) = C_1/P.$$

An equation for t_ϵ cannot be found in closed form. Simulated estimates of dY/dt were used to estimate the economically optimum harvest time t_ϵ.

Economic theory indicates that, all else being equal, the economically optimum harvest time will occur at a yield less than the maximum possible yield. At some point below that of maximum yield, costs generally begin to increase faster than additional revenues such that the point of maximum profitability is generally at a point less than that of maximum yield.

Parameter estimates for growth in weight were obtained from the initial value of solution (equation 3) using a non-linear fitting procedure, the multivariate secant or false position method, on SAS (Statistical Analysis System 1985). Many IBM-compatible software packages are available which feature non-linear fitting methods. Residual plots and mean square error were used to evaluate the fit of the initial value solution to growth data.

The resulting parameter estimates for growth in weight were used to estimate daily values of fish yield Y_t, fish production cost C_t, and net economic rent R_t for a 150-day treatment period.

Pond experimental design

The above model was applied to calculate biologically and economically optimum harvest times for two experiments conducted in the wet season of 1984 in Ayutthaya, Thailand (Collaborative Research Support Program 1983, 1984). Experiment 1 received organic fertilization of cow and chicken manure (assayed at 2·8, 4·5 and 3·1% (N-P-K)) at 500 kg/(ha/wk) and experiment 2 received inorganic fertilization (30 kg urea/ha/wk) and 100 kg triple superphosphate/(ha/wk)) applied with the total concentration of P and N equivalent to that in experiment 1. Both experiments consisted of four ponds (0·022 ha each) stocked with 32-g all male (hand sexed) Nile tilapia, *Oreochromis niloticus* (L.), at a rate of 10 000 fish/ha.

Inputs of organic and inorganic fertilizers to ponds can lead to changes in primary producers and water quality. Comparisons were made between ponds with organic and inorganic treatments. The results indicated that the responses of primary producers as indicated by primary productivity and chlorophyll *a* concentration in ponds with either organic or inorganic treatment change with time and that neither treatment led to a higher level of primary productivity and chlorophyll *a* concentration over time during the culture period.

Water quality as indicated by dissolved oxygen (DO) concentration showed that the mid-day dissolved oxygen concentrations were higher with inorganic treatments than with organic treatments. This difference in DO was largest from 2–4 pm about 5–7 ppm, but the DO concentrations under both treatments levelled off to about 5 ppm in the pre-dawn hours. The degree of diurnal changes in dissolved oxygen is related to the addition of nutrients, particularly inorganic nutrients such as phosphate and nitrogen (Chang & Ouyang 1988). The vertical difference in DO concentrations is larger in the ponds with inorganic treatments than those with organic treatments. Dissolved oxygen stratification is in general at its maximum between 2 and 4 pm and can exceed 10 ppm for some warmwater ponds (Chang & Ouyang

1988). The vertical DO difference becomes less noticeable after midnight in ponds with either type of treatment as vertical mixing of surface and bottom water takes place (Chang 1989). The dissolved oxygen concentrations in pre-dawn hours is a critical point in warmwater fish culture and can have major impact on fish yield. Since the dissolved oxygen concentrations in pre-dawn hours were similar in ponds with either treatment, differences in fish yield attributable to DO differences are small.

Results and discussion

For both experiments, von Bertalanffy's equation gave a good fit to observed growth in weight (Fig. 1, Table 2). Residual plots for growth in weight were heteroscedastic for both experiments.

Optimum time to harvest fish can be calculated biologically in terms of time to maximize fish yield, or economically in terms of time to maximize profit of fish yield sold at market (price of fish times fish yield minus fish production cost). Fish yield is at a biological maximum at time t_β and profit of fish yield sold at market is at an economic maximum at time t_ϵ. Optimum time t_β is based on maximizing fish yield without considering profit of raising fish. Optimum time t_ϵ includes profit of raising fish and is therefore more useful to the fish farmer. The profit of fish yield sold at market increases to an economic maximum at time t_ϵ and then decreases. Profit is the difference between market value of fish yield (price of fish times fish

Table 2. Parameter estimates of growth, survival, optimum harvest time, fish yield, fish production cost and net economic (profit) for fish in the organic and inorganic fertilization experiments in Thailand (US$1.00 = 26·50 baht)

Statistic	Organic fertilization	Inorganic
W_o	32·5	31·8
W_{inf} (g)	268·8	171·8
K (per year)	7·59	14·18
S(%)	0·9136	0·8795
Z	0·21986	0·31241
t_β (days)	191	105
t_ϵ (days)	191	105
End of treatment (days)	150	150
B (t/ha)	2·295	1·505
C (baht/ha)	2406·9	2406·9
R (baht/ha)	25127·5	15657·1
Optimum time t_ϵ (days)	191	105
B (t/ha)	2·328	1·536
C (baht/ha)	2412·2	2401·2
R (baht/ha)	25520·5	16035·4

t_β — biologically optimum harvest time.
t_ϵ — economically optimum harvest time.
B — fish yield at harvest (equation 4).
C — fish production cost (equation 7).
R profit or net economic rent (equation 6).

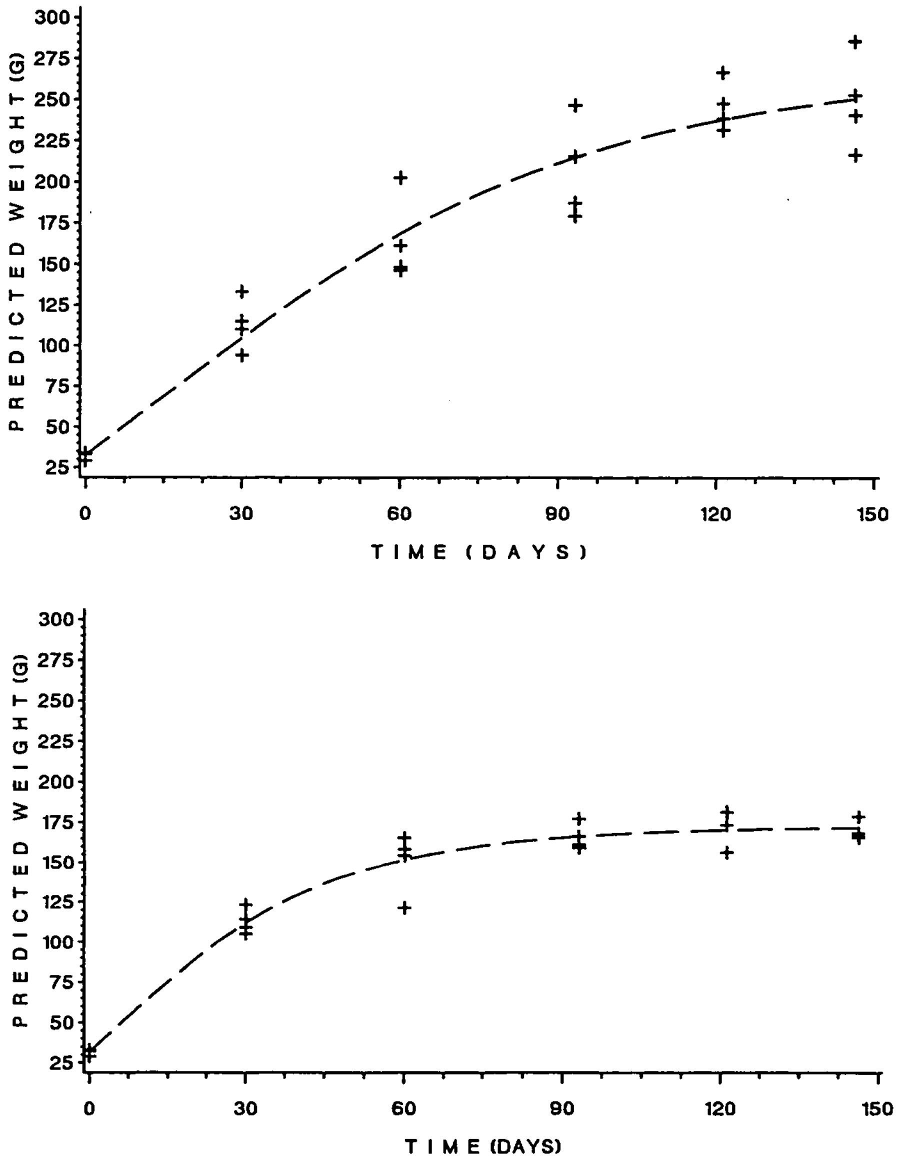

Figure 1. The initial value solution for growth in weight (equation 3) for fish in the organic fertilization experiment (top figure) and inorganic fertilization experiment (bottom figure).

yield) and fish production costs. If price of fish is constant, market value of fish yield at harvest will increase to an asymptote as the length of the experiment increases because fish growth is asymptotic. Fish production costs will increase during the growth cycle. For culture of *O. niloticus* in Thailand, start-up cost is 946·1 baht/ha, daily cost is 46·84 baht/day/ha, and harvest cost is 1441·58 baht/ha (Table 1). The cost at harvest is 1·5 times the start-up cost. The largest cost item is interest on operating cost at 1397·0 baht/ha and the largest daily cost is fixed cost at 27·39 baht/(ha/day). Fish harvest time will be delayed one day if marginal

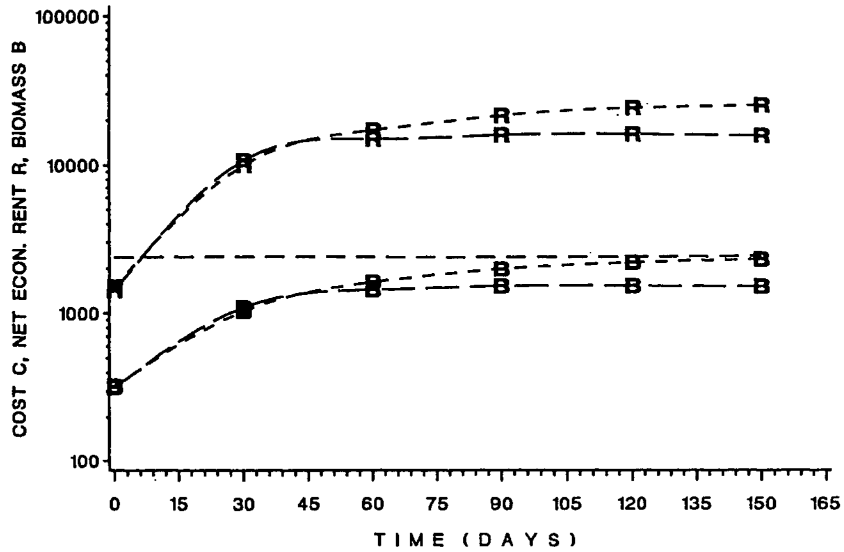

Figure 2. Daily estimates of fish biomass (B, kg/hectare) fish production cost (horizontal reference line, baht/hectare), and net economic rent (R, baht/hectare) for the organic fertilization (short dashes) and the inorganic fertilization (long dashes) experiments.

revenue (change in market value of fish yield for that day) exceeds marginal cost (change in fish production cost for that day).

Fertilization type had a direct effect on fish growth and optimum time to harvest fish. At a harvest time of 150 days the effect of the organic treatment compared to the inorganic treatment was to increase fish yield from 1·505 t/ha to 2·295 t/ha and to increase the theoretical asymptotic weight from 171·8 g and 268·8 g (Table 2). The effect of fertilization type on the growth coefficient is more difficult to interpret because this parameter is not a growth rate but a coefficient representing a rate of increase to an asymptotic weight. For the organic treatment, optimum harvest time was 191 days, profit was 25 520·5 baht/ha and fish yield was 2·328 t/ha. For the inorganic treatment optimum harvest time was 105 days, profit was 16035·4 baht/ha, and fish yield was 1·536 t/ha (Table 2, Figs 1 and 2). Profit for the organic treatment could have been increased 393 baht/ha if harvest time was delayed from the 150 days used in this experiment to the economically optimum harvest time of 191 days. Profit for the inorganic treatment was reduced by 378·3 baht/ha because fish were harvested at 150 days instead of harvesting at the economically optimum harvest time of 105 days. At the economically optimum harvest time t_ϵ, the effect of the organic treatment compared to the inorganic treatment was to increase profit of fish yield 9485·1 baht/ha and to increase fish yield 0·790 t/ha (Table 2). This shows a clear relation between fertilization type and profit of fish yield at harvest, which strongly motivates the fish farmer not only to determine the optimum time to harvest fish but also to choose the best fertilization type.

For each experiment, the optimum time to harvest fish was similar based on either t_β or t_ϵ. Theoretically, we do not expect both indexes to be the same. Estimates of t_β and t_ϵ were similar in this study because the difference C_1t between rate of change in net economic rent dR/dt and rate of change in fish biomass dY/dt was very low (see below). Or interpreted differently, fish production cost on a daily basis C_t was minimal in this study. The relation between dR/dt and dY/dt can be seen by substituting equation 7 into equation 6 and taking the derivative dR/dt

$$dR/dt = PdY/dt - C_t t$$

The difference between rate of change in net economic rent dR/dt and rate of change in fish biomass dY/dt will be negligible in this study because daily fish production cost is only 46·84 baht/ha/day. Therefore the time t_B for maximum value of fish yield will be very similar to the time t_ϵ for maximum value of net economic rent.

A recommendation to extend the duration of the experiment and harvest fish at the economically optimum harvest time should include, in the case of *O. niloticus,* the reproductive strategy of this species as well as practical management practices. It is clear that the method presented above for an economic evaluation of fish production is important for aquaculture, but whether or not the recommended harvest time is realistic must be considered. This analysis assumes that fish growth and mortality during the first 150 days of the organic treatment can be used to accurately predict fish growth and mortality over an additional 41 days to the economically optimum harvest time. *O. niloticus* are prolific mouth brooders and fish harvested from both experiments at 150 days were sexually mature (J. S. Diana, University of Michigan School of Natural Resources, personal communication). This natural reproduction in fish ponds over an extended time period results in a few large adult fish and a large population of small offspring. Once the carrying capacity of a pond is reached fish will not continue to grow. In these experiments *O. niloticus* were hand sexed before stocking, which significantly delays but does not eliminate this problem. Delaying harvest time for *O. niloticus* would be economically attractive for the organic treatment, but number and size of both adult and offspring should be monitored.

Extending the production season to 191 days would make it impossible to produce two crops/year of tilapia. Due to seasonal fluctuations in rain, temperature and light intensity, the actual production season for tilapia in Thailand is limited to about 300–350 days. Additional cost would be incurred if in fact a second crop of tilapia had to be foregone to extend the production season to 191 days. However, most tilapia farmers utilize a partial harvest/re-stocking production system. Thus, these results indicate that planning to harvest more intensively after 191 days is more profitable even though smaller amounts may still be harvested before and after the 191-day peak.

This simple method of evaluating optimum harvest time in aquaculture will help the fish farmer maximize profit of fish yield at harvest and quantify the effect of fertilization on optimum time to harvest fish. The economic optimum was similar to maximum yield in this study because the data were from low-input fish production systems. However, this technique should prove especially valuable for fish production at higher levels of input utilization and operating cost. By varying prices and cost according to market conditions, this type of model and analysis can be used to adjust projected harvest dates to changing market conditions during the production cycle. This would enable the grower to be flexible and responsive to changing prices and economic conditions while harvesting at economically optimum moments. In the case of *O. niloticus* this final recommendation for optimum time to harvest fish must also consider the reproductive strategy of this species.

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