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A Yield Model for Walking Catfish Production in Aquaculture Systems

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ABSTRACT

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A yield model for *Clarias* culture was produced using a combination of laboratory data for *Clarias lazera* and field data on *Clarias batrachus* culture in Thailand. The model was used for simulations to fulfil three distinct objectives: (1) to consolidate knowledge of fish physiology and aquaculture practices for *Clarias* into a model which can be validated; (2) to determine sensitivity of predictions to variation in model parameters; and (3) to predict yield of *Clarias* ponds under different stocking density, size at stocking, and type of containment. The accuracy of this model was tested with an independent data set of 32 grow-out periods. The model was relatively poor at predicting yield when the measured feeding rate was input ($r^2 = 0.022$), but reasonably good at predicting yield if maximum feeding rate was input ($r^2 = 0.52$). This may reflect poor data collection of feeding rate in the ponds. Sensitivity analyses indicated that changes in parameters related to maximum consumption showed high importance in predicting yield, while changes in metabolic parameters had low importance. A doubling of feeding rate increased yield 548% in earthen ponds and 465% in concrete tanks. Density stocked was of secondary importance in increasing simulated yield, while size at stocking was relatively unimportant. The maximum consumption rate of different food types (pellets, trash fish) was also extremely important in determining simulated yield.

INTRODUCTION

The walking catfishes, *Clarias batrachus* and *C. macrocephalus*, are very popular species for aquaculture in Southeast Asia and East Africa (Bardach et al., 1972). This popularity stems from several characteristics of the fish, which include the ability to tolerate anoxia, wide-ranging food habits, and extremely high yields. Yields up to 97 000 kg ha^{-1} yr^{-1}, reported by Bardach et al. (1972), were the highest for standing water systems and among the highest for any culture technique. The unique combination of biological characteristics leads

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to very high production with relatively unsophisticated pond management. *Clarias* culture is economically important in Thailand, with annual yields near 20 000 metric tons (FAO, 1983). Common culture techniques in Thailand include stocking fish in earthen ponds using pellets or trash fish as food, and use of concrete recirculating tanks with pellets (Diana et al., 1985). Average growth and mortality are much better in concrete tanks (5% body weight per day and 0.12%/d) than in earthen ponds (3% bw/d and 0.89%/d) (Tarnchalanukit et al., 1983; Diana et al., 1985). Variations in survival between ponds or tanks are believed to be due to differences in water quality (Tarnchalanukit et al., 1983). If this is true then earthen pond culture could also produce higher yields by improving water quality through better pond management.

We currently are unable to estimate the proximal factors causing differences in yield between the two culture techniques. The purpose of this paper is to develop a yield model for *Clarias* culture, utilizing basic energetic data to predict individual growth, and water quality data to estimate mortality. There are three distinct objectives to this work. The first is to consolidated our knowledge of fish physiology and aquaculture practices for *Clarias* into a model which can be validated; the second is to determine the sensitivity of the model to variations in the model parameters, and the third is to predict yield of *Clarias* ponds under different stocking density, size at stocking, and type of containment.

MODEL DESCRIPTION AND DEVELOPMENT

Energetics submodel

Information on *Clarias* energetics is rather limited. The best information comes from the various studies of Hogendoorn (1980, 1983; Hogendoorn et al., 1981, 1983) on *C. lazera*, and we have used these data in our energetics submodel. Specific parameters and equations for the *Clarias* energetics submodel follow the forms utilized by Kitchell et al. (1977) and are referenced to the balanced energy equation (Webb, 1978):

$$Q_G = Q_R - (Q_M + Q_F + Q_N + Q_{SDA}) \qquad (1)$$

where all variables are in kcal/day and Q_G = growth rate, Q_R = daily ration consumed, Q_M = routine metabolic rate, Q_F = fecal loss, Q_N = nitrogen excretion costs, Q_{SDA} = apparent specific dynamic action.

For walking catfish, we have estimated respiration as routine metabolic rate (Q_M) since the respirometers commonly used allow movement of the fish between an air surface and the water, and therefore swimming speed is uncontrolled (see Hogendoorn et al., 1981). We assume that routine activity in the respirometer and nature are similar. In addition, we assume no reproduction occurs in culture. Thus the model may be inaccurate once fish reach a size at which they mature and spawn, which is about 150 g for *Clarias*.

Routine metabolism (Q_M) was calculated as:

$$Q_M = 0.18W^{0.78} \tag{2}$$

(Hogendoorn, 1983) where Q_M = kcal/day and W = wet body weight (g). Maximum daily ration ($Q_R$max) was considered:

$$Q_R \max = 0.23W^{0.78} \tag{3}$$

(Tarnchalanukit et al., 1983), where $Q_R$max = maximum kcal/day consumed (for pelleted feed). This set an upper limit for ration, and daily ration consumed (Q_R, an input variable) was compared to this to determine actual daily ration. Q_R was reduced to $Q_R$max when $Q_R > Q_R$max.

Excretion (Q_N) and fecal loss (Q_F) were considered functions of Q_R (0.03 and 0.26, respectively) (Hogendoorn, 1983). Specific dynamic action (Q_{SDA}) was calculated as (Hogendoorn, 1983):

$$Q_{SDA} = (0.24W^{-0.26})Q_R \tag{4}$$

Initial fish biomass and feeding rate were input to the model, which then subtracted energy use ($Q_M + Q_F + Q_N + Q_{SDA}$) from daily ration ($Q_R$) to determine daily growth (Q_G). Growth was added to initial weight to calculate final weight each day. The time step for this submodel was 1 day.

The most difficult feature in the submodel was evaluating maximum consumption ($Q_R$max) for fish under different diets. As pellets or trash fish (common *Clarias* feeds) vary in quality, maximum consumption also varies. For example, satiation of *Clarias* with pellets measured by Hogendoorn (1983) and Tarnchalanukit et al. (1983) differed considerably for two types of pellet. Both probably differ from maximum consumption of trash fish. We used the data of Tarnchalanukit et al. (1983) for maximum consumption of pellets commonly used in Thailand (2.4 kcal/g) and then made two extrapolations for trash fish (assumed to be 1 kcal/g wet weight). Models run with maximum trash fish consumption equalling pellets in calories would yield identical values to runs with pellets. We also evaluated the range of production possible with trash fish feed by using maximum consumption in weight.

An additional assumption was that all delivered feed was consumed when feed application rate was less than maximum consumption. Although some food may not be eaten, there are no available data to define the relationship between food type, feed application rate, and percentage of applied food actually consumed. This assumption causes estimates of actual feed application rate to be low for a given growth rate, or will result in overestimates of growth rate.

Temperature normally influences energetics considerably (Brett and Groves, 1979). Data from Hogendoorn (1980, 1983) were for a temperature of 27°C.

Normal culture temperatures for *Clarias* vary in Thailand from 25 to 32°C. Therefore, we were forced to assume no temperature effects on the energetic model within the range of temperatures specified above.

Water quality submodel

Water quality, as indicated by dissolved oxygen, was modeled by comparing oxygen consumption of fish to oxygen addition. Total daily oxygen consumption (QO_2) per fish was calculated from Q_M (kcal/day) using an oxycalorific equivalent of 3.22 kcal/mg O_2 consumed (Brafield and Solomon, 1972). Total oxygen consumption by *Clarias* includes use of dissolved and gaseous oxygen, and the importance of each breathing method varies with pO_2 of the water. Our model used data from Jordan (1976) to determine the percentage of total respiration derived from consumption of dissolved oxygen. Oxygen addition could occur by primary production or diffusion into earthen ponds. Total daily oxygen consumption from water was calculated by multiplying QO_2 by the percent respiration from the water, then by the total number of fish (n, an input value). Oxygen addition and use by plankton and benthos were modeled using Romaire and Boyd's (1979) relationships for channel catfish ponds (with secchi disk depth assumed to be 50 cm). Once ponds became anoxic, we assumed no additional primary production.

Oxygen dynamics in recirculating tanks was modeled assuming that all addition was due to circulation of new water at air saturation, and all consumption was due to fish respiration as before. Primary production in tank waters, BOD of recirculating water, and diel oxygen cycles in supply water reservoirs were ignored. These simplifying assumptions were necessary since there were no data on those parameters for *Clarias* culture systems.

Water quality deterioration, as indicated by low dissolved oxygen, was used to estimate mortality rate for *Clarias* in earthen and concrete ponds. In earthen ponds at dissolved oxygen levels greater than 1 mg/l, daily mortality was considered constant at 0.89% per day (Tarnchalanukit et al., 1983). For DO less than 1 mg/l, mortality (% per day) was calculated as -0.8037 DO $+ 1.6915$. Comparable values used for concrete ponds were 0.11% per day when DO exceeded 1, and 0.915% per day when DO was less than 1. Values calculated for both of these culture systems are similar to average empirical values (Diana et al., 1985). Mortality rate was then multiplied by initial number of fish to calculate final number of fish each day.

Overall model

The overall model simply integrated the two submodels. Input parameters were daily ration, stocking density, culture duration (days, D) and individual weight at stocking. The energetics submodel was run to calculate daily individual growth. The water quality model was run to calculate dissolved oxygen content and mortality rate. The total number of surviving fish (n) was then calculated and used to estimate total biomass ($n \times W$). All input values except ration were updated to new levels for the following day, and the calculations repeated for D days.

MODEL VALIDATION

Accuracy analysis

Accuracy of the model's predictions was tested with an independent data set collected by Kasetsart University, from earthen ponds in Thailand. These data were for 32 grow-out periods, with culture conditions varying from 32 to 167 days, with 12.5–156 g initial fish weights, and stocking densities of 65 000–211 000 fish/ha. Feed application rates, estimated by farmers during the first and last week of the grow-out, varied from 0.3× to 1× satiation ration. These overall culture conditions were much more variable than typical Thai grow-outs (Diana et al., 1985), and represent rigorous test conditions of simulation performance. The only output data available were observed yield of each pond, and these were compared to predicted yields.

The relationship between actual and predicted yields was extremely variable (Fig. 1). The mean percentage error (|actual − predicted| × 100/actual yield) was 35.8%, and there was a bias, though not significant, toward underestima-

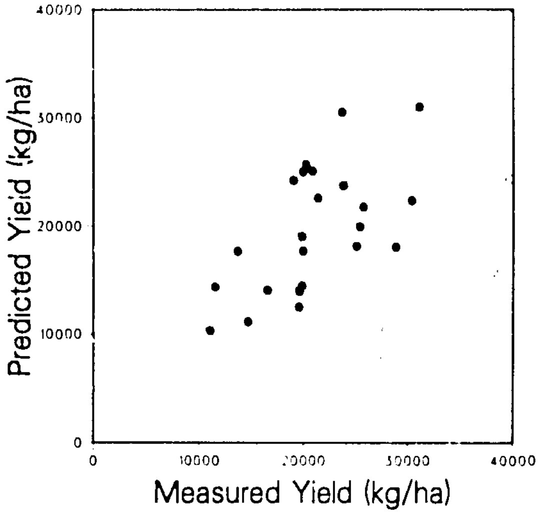

Fig. 1. Relationship between predicted and measured yields for *Clarias* in earthen ponds. The line for a perfect relationship is dotted. The regression is $y = 0.15x + 13103$ ($r^2 = 0.022$). Open circles signify the eight outliers mentioned in the text.

tion of actual yield (mean difference = −20.9% ± 37.3%). Measured yields were generally underestimated at high yields, while the predicted and measured yields agreed well at low yields.

Yields for eight of the 32 ponds were largely underestimated. Regression of feed application rate and initial weight on the deviation between measured and predicted yields explained 76% of the variance in yield deviation. Pond area, duration of culture, percent mortality, and measured yield were not significant explanatory variables. Outliers all were at low reported feeding rates (0.51 ± 0.13 $Q_{\rm R}$max, mean ± SD), which normally would not occur in commercial culture where the goal is to grow fish quickly (overall average feeding rate was 0.77 ± 0.23 $Q_{\rm R}$max). It is likely that the measured rations (which were reported only for the first and last weeks of culture) did not accurately reflect actual rations fed throughout the culture period.

Sensitivity analyses

Simulations were also done to estimate the sensitivity of results to variations in model parameters. Routine metabolic rate ($Q_{\rm M}$), apparent specific dynamic action ($Q_{\rm SDA}$), assimilation efficiency ($Q_{\rm F}$), nitrogen excretion ($Q_{\rm N}$), and maximum food consumption ($Q_{\rm R}$max) were varied by ± 10% of the parameter values. Variations in growth, yield, and the time (in weeks) when the oxygen in ponds first dropped below 1 mg/l were measured to assess sensitivity. Vari-

TABLE 1

Model sensitivity to changes of ± 10% for parameters listed. Analyses were done for standard runs with 4-g fish, fed ad libitum, at 500 000/ha (earthen) or 5000/15 m^3 (concrete), and run for 90 (concrete) or 120 (earthen) days

Parameters	% Change			
	Yield (kg/ha (or tank))	Final weight (g)	Mortality rate (%)	DO depletion
Earthen ponds				
$Q_{\rm M}$	5.6	4.0	0.7	4.5
$Q_{\rm SDA}$	4.6	4.1	0.2	4.5
$Q_{\rm F}+Q_{\rm N}$	9.3	13.2	1.8	9.1
$Q_{\rm R}$max	20.0	28.4	7.2	40.9
Concrete ponds				
$Q_{\rm M}$	5.4	3.7	4.5	16.7
$Q_{\rm SDA}$	6.3	4.3	5.7	16.7
$Q_{\rm F}+Q_{\rm N}$	12.6	12.5	2.1	25.0
$Q_{\rm R}$max	22.8	26.3	8.7	16.7

ations were measured as percentage changes (|final – initial result| × 100/initial result), and averages of ± 10% variations were reported.

The model was not particularly sensitive to metabolic components, but was very sensitive to maximum consumption (Table 1). A 10% change in $Q_R$max gave a 20–33% change in yield, 26–28% change in growth, and 7–8% change in mortality rate. Routine metabolic rate and specific dynamic action affected yield much less, while egestion and excretion rates had intermediate effects. These and earlier analyses indicate that feeding and feed utilization are very important in modeling yield of *Clarias*.

MODEL EXPERIMENTATION

Techniques

Simulations of actual culture systems are complex due to the relationship between feeding, growth, and control of ration. Small fish can eat a very large ration (on a percent body weight basis) relative to larger fish (Brett and Groves, 1979). Holding ration at a fixed percent body weight underestimates feeding potential. Keeping ration at a fixed weight results in either overfeeding at small size or underfeeding at large size. We chose to control ration by using ad-libitum and 1/2 ad-libitum rations for all analyses, as this more likely represents feed application patterns used by culturists.

Comparative simulations were done on fish in earthen ponds for 120 days, at densities of 250 000, 500 000, 1 000 000, and 2 000 000 per ha, for fish stocked at 0.5, 1.0, 2.0, 4.0, and 8.0 g, to examine differences between various pond management options. Simulations for earthen pond culture were run with both trash fish and pelleted feed. Concrete tank simulations were similar to those for earthen ponds, except only pellets were used, culture duration was 90 days, and stocking densities were 2500, 5000 or 10 000 fish per 15-m^2 tank. Input values were set to mimic normal culture operations (Srisuwantach et al., 1981; Colman et al., 1982; Tarnchalanukit et al., 1983; Diana et al., 1985). Output values evaluated were fish growth, mortality, gross yield, and time (in weeks) before oxygen content of the water became less than 1 mg/l.

Earthen pond simulations

Yield in earthen ponds varied considerably in relation to the input parameters of initial stocking size, feeding rate, and stocking density (Table 2). Using a standard grow-out duration of 120 days, and assuming two harvests per year, predicted gross yields varied from near zero to 344 584 kg ha^{-1} yr^{-1}.

Changes in input variables altered yield substantially. The most important factor was feeding rate; yield was on average 549% ± 19% greater (x ± SD for 20 paired simulations) when fed ad-libitum than when fed 1/2 ad-libitum ra-

TABLE 2

Simulation results for earthen ponds, with a 120-day grow-out period and pelleted feed

Density (*n*/ha)	Stocking weight (g)	Final weight (g)	Total biomass (kg/ha)	% Mortality	1st week DO < 1
One half ad-libitum ration					
250 000	0.5	19	1655	65.7	—
	1	27	2308	65.7	—
	2	37	3214	65.7	—
	4	53	4526	65.7	—
	8	76	6492	65.7	—
500 000	0.5	19	3310	65.7	—
	1	27	4616	65.7	—
	2	37	6429	65.7	—
	4	53	9052	65.7	—
	8	76	12 985	65.7	—
1 000 000	0.5	19	6620	65.7	—
	1	27	9234	65.7	—
	2	37	12 857	65.7	—
	4	53	18 104	65.7	—
	8	76	25 969	65.7	—
2 000 000	0.5	19	13 240	65.7	—
	1	27	18 465	65.7	—
	2	37	25 697	65.7	17
	4	53	33 244	68.5	8
	8	76	33 771	77.6	1
Ad-libitum ration					
250 000	0.5	195	16 732	65.7	—
	1	230	19 733	65.7	—
	2	274	23 509	65.7	—
	4	332	28 443	65.7	—
	8	409	35 103	65.7	—
500 000	0.5	195	33 459	65.7	17
	1	230	39 045	66.0	15
	2	274	45 246	66.9	13
	4	332	52 249	68.4	11
	8	409	58 741	71.3	8
1 000 000	0.5	195	55 786	71.4	9
	1	230	62 922	72.6	8
	2	274	71 346	73.9	6
	4	332	81 573	75.4	4
	8	409	94 267	76.9	2
2 000 000	0.5	195	96 732	75.2	5
	1	230	109 383	76.2	4
	2	274	124 878	77.2	2
	4	332	139 683	78.9	2
	8	409	172 293	78.9	2

TABLE 3

Comparison of yield for *Clarias* when maximum consumption of trash fish is equivalent to pellets in energy or in weight. Percent difference = 100 × ($Y_{\mathrm{Energy}} - Y_{\mathrm{Weight}}$) / Y_{Weight}

Density (*n*/ha)	Initial size (g)	Yield (kg/ha) Energy equivalence	Yield (kg/ha) Weight equivalence	% difference
250 000	0.5	16 732	766	2084
	1	19 733	1183	1568
	2	25 509	1792	1323
	4	28 443	2714	948
	8	35 102	4155	745
500 000	0.5	33 459	1533	2083
	1	39 045	2366	1550
	2	45 246	3583	1163
	4	52 249	5427	863
	8	58 741	8310	607
1 000 000	0.5	55 786	3066	1720
	1	62 922	4732	1230
	2	71 346	7166	896
	4	81 573	10 855	651
	8	94 267	16 620	467
2 000 000	0.5	96 732	6132	1477
	1	109 389	9468	1055
	2	124 878	14 333	771
	4	139 683	21 709	543
	8	172 293	30 713	461

tions. Stocking density was next in importance, although at most a doubling in density could double yield. Due to density-dependent mortality, a doubling in density resulted in an 84% ± 19% increase in yield. Size at stocking was least important in increasing yield; a doubling of size only increased yield 29% ± 13%.

Oxygen reached levels below 1 mg/l in less than half of the simulations for earthen ponds. Oxygen usage was increased mainly by changes in feeding rate, followed by stocking density, then size at stocking.

Feeding with trash fish in earthen pond culture altered yield largely, depending on maximum feeding levels used. If feeding was assumed to be controlled by weight eaten, then use of trash fish declined yield by 91% (Table 3). Obviously, maximum food intake as related to food type is an extremely important factor in management of pond culture.

Recirculating pond simulations

Simulations for recirculating ponds showed trends somewhat similar to those for earthen ponds (Table 4). Doubling feeding rate resulted in an average

TABLE 4

Simulation results for concrete tanks, with a 90-day grow-out period and pelleted feed

Density (n/ha)	Stocking weight (g)	Final weight (g)	Total biomass (kg/tank)	% Mortality	1st week DO < 1
One half ad-libitum ration					
2500	0.5	9.8	22.3	9.5	—
	1	14.6	33.1	9.5	—
	2	21.6	48.9	9.5	—
	4	32.1	72.7	9.5	—
	8	48.6	110.0	9.5	—
5000	0.5	9.8	44.6	9.5	—
	1	14.6	66.3	9.5	—
	2	21.6	97.8	9.5	—
	4	32.1	145.5	9.5	—
	8	48.6	204.9	15.7	11
10 000	0.5	9.8	89.2	9.5	—
	1	14.6	131.0	10.5	13
	2	21.6	176.9	18.1	10
	4	32.1	240.5	25.2	6
	8	48.6	327.8	32.5	3
Ad-libitum ration					
2500	0.5	85.9	193.5	9.9	12
	1	106.0	238.4	10.0	11
	2	132.2	296.9	10.1	10
	4	167.5	375.3	10.3	9
	8	216.7	485.4	10.4	7
5000	0.5	85.9	343.1	20.1	8
	1	106.0	409.6	22.7	7
	2	132.2	494.5	25.2	6
	4	167.5	615.5	26.5	6
	8	216.7	765.0	29.4	3
10 000	0.5	85.9	616.1	28.3	5
	1	106.0	740.6	30.1	4
	2	132.2	893.2	32.4	3
	4	167.5	1086.9	35.1	3
	8	216.7	1363.6	37.0	1

465% ± 145% increase in yield. Doubling fish density increased yield 81% ± 14%, while increasing size at stocking increased yield 34% ± 19%.

Surprisingly, recirculating tanks reached low oxygen levels in 67% of the simulations, indicating lower simulated water quality in these systems than in earthen ponds. Again, the sensitivity of oxygen concentration was similar to that of yield, with feed application rate, density, and size having decreasing importance.

GENERAL DISCUSSION

The most pertinent outcome of the model is that factors increasing food consumption have the most significance to increasing production. Overfeeding may improve growth, but also results in food decay and decreased water quality, including increased bacterial levels (Colman et al., 1982). These factors were not included in our model. Nevertheless, factors affecting rate of food consumption as well as assimilation efficiency, are very important in predicting growth and yield. There remains a very large deficiency in our knowledge of feeding rates, conversion efficiencies, and nutritional requirements for *Clarias* and many other cultured tropical fishes (Colt, 1985; Yamada, 1985).

Two biological factors probably had a major effect on variability in actual vs. predicted yields: (1) outbreak of disease in natural systems, and (2) changes in *Clarias* growth after maturation. Disease outbreaks would result in very low or variable survival and drastically affect pond culture practices (Panayotou et al., 1982). Our simulation results indicate intermediate survival in all ponds, and thus underestimate changes in yield for any culture combination due to disease. However, the occurrence and extent of disease outbreaks and mortality cannot currently be predicted (Brock, 1985). Our modeling also assumes that *Clarias* growth continues at a constant rate throughout adulthood, while in reality growth probably declines in mature fish due to energy use for gonad growth, although this decline in growth is not well documented for *Clarias* (Hogendoorn et al., 1983).

As in any mathematical model, simplifying assumptions had to be made. Probably the most unrealistic feature of the model is its determinism. All fish are predicted to grow at the same rate, and no probabilistic processes, such as disease or weather variations, were included. Thus, model yields were always identical under any given combination of variables. Pond yields vary tremendously under similar management practices in nature, and reasons for this variability are unclear (Lannan et al., 1985). Errors in yield estimation in the present study could be related to natural variations in mortality rate, due to management practices. Fig. 1 indicates that the largest excursions from predicted yields occurred at high standing crops, where natural systems are most stressed and sporadic mortalities due to poor water quality most likely. Under these conditions, yields measured were often much greater than those predicted, apparently in the absence of large mortalities. While accounting for mortality variations might improve agreement between measured yield and predicted yield, it would not improve the ability to forecast average yield.

Estimation of oxygen consumption and production is another area of major concern in the model. Romaire and Boyd's (1979) models for conditions in channel catfish ponds may have limited applicability to conditions in *Clarias* ponds. Knowledge of primary and secondary production for Thai aquaculture systems is also limited, so we cannot improve on Romaire and Boyd's model at present. This is particularly true for anoxic ponds. Since so few fish species grow well in anoxic conditions, little is known of biological processes in these systems. However, available data indicate a cessation in photosynthesis once ponds become anoxic (National Inland Fisheries Institute, 1981).

Our results have done little to clarify differences between concrete tank and earthen pond culture of *Clarias*. Tarnchalanukit et al. (1983) indicate that the improved water quality in recirculating tanks allows greater growth and survival of *Clarias*. Water quality indicated by our predicted DO levels was no better in concrete tanks than in earthen ponds. Improved yield may result from better feeding practices possible in tank culture, where applied feed is probably consumed more efficiently, and better estimation of fish size and density in tanks also allows more precise feeding.

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