Applications of POND© as a Tool for Analysis and Planning

Interim Work Plan, DAST Studies 1 and 2

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Introduction

POND© provides a useful framework for synthesizing knowledge about pond aquaculture and presenting it in a form that can be used for decision support (Bolte et al., 1995). In a previous PD/A CRSP report (Nath et al., 1996), modifications made to the software since the first release (Version 2.0) were presented. The applications of such modifications for pond aquaculture planning and management are the focus of this report. Additionally, the results of ongoing model verifications and sensitivity analyses are presented.

POND© Applications

Assessment of Water Requirements

Development of pond water budgets is important from the perspectives of estimating water requirements for ponds that rely on rainfall events and runoff as primary water sources (Boyd, 1982) and for flow-through pond facilities (which mainly use levee ponds). Water budget analysis may also be useful in comparing the value of available water for different agricultural crops as suggested by Green and Boyd (1995) and may have implications for examining the environmental effects of pond water discharge due to either intended water release or overflow.

Although various research efforts have focused on developing water budgets for different pond aquaculture systems, the general methodology used in these studies has not been presented in the form of a model that can be easily adapted to new locations as a general purpose tool for forecasting water budgets over long-term periods. Such a model that includes various sources and sinks (Figure 1) has been developed and implemented in POND©.

The model has been validated for ponds located at the Asian Institute of Technology (AIT), Thailand, and at El Carao, Honduras, which are respectively located in humid and dry tropical regions. Simulation results indicate that precipitation accounted for 69.8% of the total water gains for AIT and 43.2% for El Carao. Similarly, regulated inflow provides 27% of the gains for AIT and 52.8% for El Carao. Runoff gains were minimal at both locations, presumably a result of small watershed areas. Evaporation accounted for 54.9% and 40.1% of the overall water loss predicted for the AIT and El Carao locations while seepage accounted for the remaining loss. The difference between actual and predicted amounts of regulated water inflow for the AIT pond was only 20.3 m^3 over a simulation period lasting five months. For El Carao, predicted water requirements were 141.3 m^3 lower than the amounts actually added, apparently due to poor estimates of evaporative water loss, which averaged 0.32 cm d^{-1} compared to pan evaporative measurements of 0.43 cm d^{-1}. In contrast, the predicted evaporative water loss for the AIT pond (0.47 cm d^{-1}) was very comparable to the pan evaporation estimate of (0.45 cm d^{-1}) for this site.

More complete weather datasets for AIT (which included measurements, such as cloud cover and relative humidity, that are not routinely reported in the CRSP Central Database, but were retrieved from an international weather station in the vicinity of the ponds) compared to El Carao appear to explain the higher accuracy in evaporative water loss estimates for the former site. If such comprehensive weather datasets are available for different locations, the water budget model shows considerable potential for the estimation of water requirements during the planning and operational phases of individual aquaculture facilities. For instance, the model can

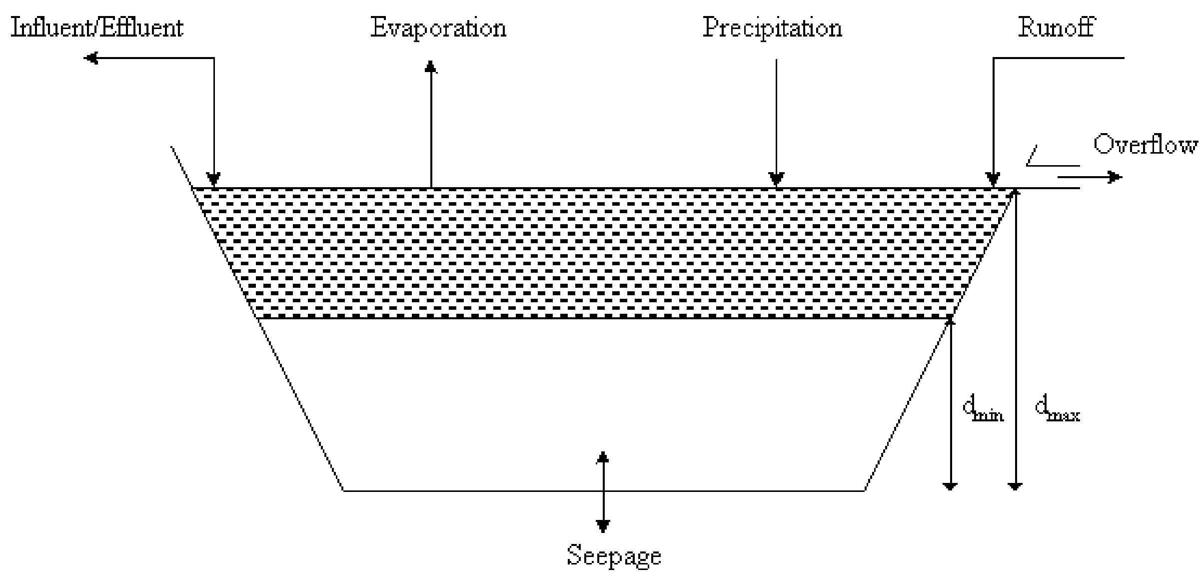

Figure 1. Schematic diagram showing the types of water sources and sinks that can be considered in the POND© water budget model, d_{min} and d_{max} respectively refer to the minimum desired and maximum possible pond water depth.

be used for pond aquaculture farms in the United States (e.g., for catfish, baitfish, and striped bass), particularly because more complete weather datasets are likely to be available for areas in the country where such farms are likely to be located.

The model can also be applied to regional-scale analysis of pond aquaculture water requirements and can be used as a tool to compare the benefits of water use for aquaculture relative to other agricultural practices. Analysis of water budgets for AIT and El Carao also suggests that the PD/A CRSP weather data collection protocols should be expanded to include measurements of cloud cover and relative humidity. If such measurements are available, it may not be necessary to routinely collect pan evaporation data, because the POND© water budget model can be used to estimate daily water losses. Further, the additional weather data are likely to be beneficial to researchers from the University of California at Davis who are involved in the validation of stochastic models of stratified pond systems over long-term periods.

Assessment of Fertilizer Requirements

Previous verification of the PONDCLASS fertilization guidelines was fairly successful in the Philippines (Hopkins et al., 1994) and Thailand (Hopkins and Knud-Hansen, submitted) in that the amount of fertilizer required to produce one unit of fish production was typically lower compared to control treatments or prevailing practices. Similar results were obtained in Thailand as part of the Global Experiment undertaken during the Seventh Work Plan of the PD/A CRSP (Szyper and Hopkins, 1995).

However, fish growth in Honduran ponds that were managed using PONDCLASS guidelines (Teichert-Coddington and Ramos, 1995) appeared to be limited by the build-up of ammonia nitrogen (NH_3-N). Reasons for high NH_3-N concentrations at this location are unclear, but they may in part be due to the use of a maximum net primary productivity (NPP_{max}) value of 4 g C m^3 d^{-1} that appears to be high—at least in terms of consistent primary productivity—for this location and which may have resulted in excessive N loading. In contrast, Szyper and Hopkins (1995) typically set NPP_{max} to 3 g C m^{-3} d^{-1} in the PONDCLASS software while estimating weekly fertilizer needs at the Thailand site where primary productivity is usually higher than at the Honduras site. Additionally, the effects of high NH_3-N concentrations on fish growth at the latter site were presumably amplified because of relatively high pH values in the range of 8 to 10 (Teichert-Coddington and Ramos, 1995). At these pH values, the fraction of NH_3-N that exists in the toxic, unionized form would be quite high (Emerson et al., 1975). Finally, the poor results obtained with PONDCLASS at Honduras may also have been due to inadequate consideration of nutrient cycling within the

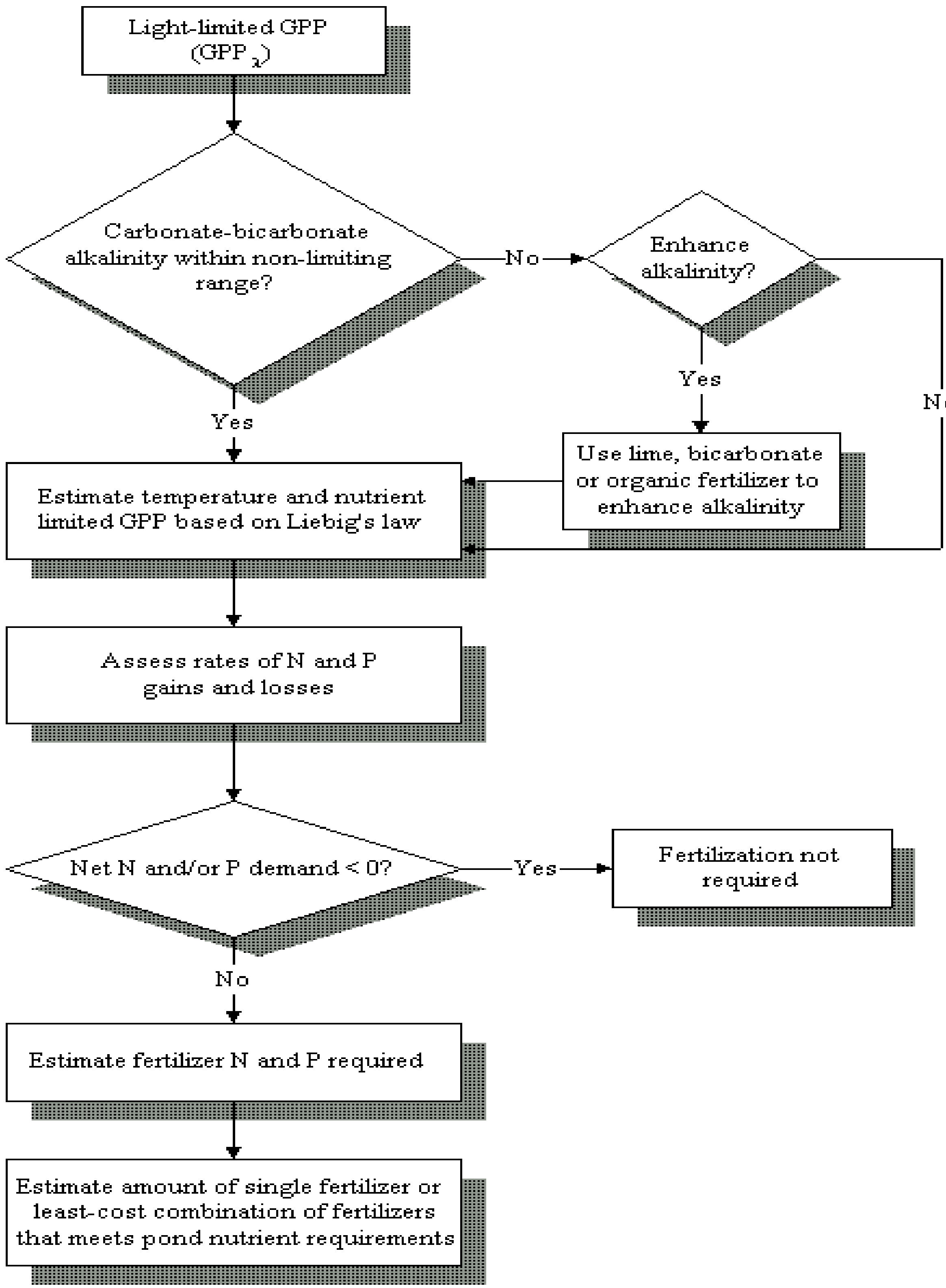

Figure 2. A summary of the POND© fertilization model that can be used to assess nutrient requirements of ponds, and estimate associated fertilizer needs over short-term simulation periods (one to two weeks).

software. Water quality data for the PONDCLASS experiment in the Philippines (Hopkins et al., 1994) also indicate frequent occurrence of high total ammonia concentrations.

Examination of PD/A CRSP data for PONDCLASS-treated ponds thus suggests that the guidelines developed by Lannan (1993) may recommend unexpectedly high fertilizer application rates even though ambient nutrient concentrations may already be in excess of amounts needed for rapid algal growth. This appears to be primarily due to inadequate consideration of algal growth potential and nutrient cycling processes in ponds. These limitations of PONDCLASS have been addressed in a fertilization model that has been implemented in POND©.

The model assumes that a maximum level of gross primary productivity (GPP_l), limited only by light availability, is possible for any pond. The effects of nutrient concentrations on algal growth rate are assessed using Michaelis-Menten kinetics, whereas a skewed normal function is used to describe temperature effects. Liebig's minimum factor rule is used to approximate the combined effect of temperature and nutrient levels on algal growth, which when applied to GPP_l provides an estimate of the realized GPP for a given pond. The carbonate-bicarbonate alkalinity of pond water is assumed to be the main source of inorganic carbon. Simplified mass balance equations are developed to account for processes that affect nitrogen and phosphorus concentrations. The primary sink for these nutrients is assumed to be algal uptake, whereas algal respiration and fertilizer addition are the main sources. An additional term that accounts for miscellaneous processes (fish uptake, sediment exchange, etc.) by the use of first-order kinetics, and which may be either a nutrient source or sink, is also considered. For nitrogen, available data suggest that there is a net overall gain of this nutrient via the above processes, whereas phosphorus is generally lost from the pond water to the underlying sediments. The steps involved in evaluating nutrient requirements and generating fertilizer application rates by the use of the POND© fertilization model are summarized in Figure 2.

Model verification was undertaken by comparing fertilizer application data obtained from PONDCLASS-treated ponds in El Carao (Honduras), AIT (Thailand), and the Freshwater Aquaculture Center (FAC, Philippines) to those generated by the fertilization model. This comparative analysis indicates that the fertilization model generates nutrient application rates that are in general more conservative than those recommended by PONDCLASS for ponds where ambient nutrient concentrations are already fairly high (Table 1). However, recommendations obtained from both approaches are comparable when ponds require high dosages of nitrogen and/or phosphorus to ensure rapid algal productivity rates (Table 1). Model verification results are consistent with previous work (e.g., Knud-Hansen and Guttman, submitted; Hopkins and Knud-Hansen, submitted) in that responsive fertilization strategies (i.e., strategies that take into account ambient pond water conditions during evaluations of pond nutrient needs) are likely to be superior in terms of cost and fertilizer use efficiency compared to the more traditional fixed input strategies. Further, because nutrient concentrations in pond water vary substantially over time, it is highly unlikely that fixed application rates of nitrogen, phosphorus and/or carbon fertilizers, which are expected to be economically optimal, can be determined for the entire duration of a culture cycle. The term "economically optimal," within the context of this study, is used to indicate fertilizer application rates which result in the highest economic efficiency measured in terms of fertilizer costs required to produce one unit of fish. The term does not address alternate uses of the fertilizers in terrestial crop production. Arguments in support of responsive management strategies are further strengthened by the fact that, in addition to the variability of nutrient concentrations in a given pond with time, there is also variability among ponds at a given site, as well as among geographical locations as a result of differences in pond water, soil, and climatic characteristics.

During a visit to baitfish farms in the Southern United States (in the vicinity of Pine Bluff, Arkansas) by one of the OSU-DAST researchers, a frequent problem mentioned by extension agents and farmers alike was the lack of appropriate fertilization guidelines for the different source water and soil types in the region. Most of the fertilizer application rates recommended by extension agents are based on experimental data generated at locations with very different water and soil characteristics. These rates have apparently not produced acceptable results at new locations. Because the POND© fertilization model takes into account climatic, water, and soil characteristics in generating fertilization rates, it

Table 1. Weekly fertilizer recommendations generated by PONDCLASS at El Carao, AIT, and FAC compared to those obtained from the model developed in this study (indicated in parentheses). PONDCLASS fertilizer application rates and water quality data were extracted from the PD/A CRSP Central Data Base. Mean GPP predicted by the use of the POND© fertilization model is also shown.

Date[a]	Mean GPP ($g C m^{-3} d^{-1}$)	Ambient Nutrient Concentrations ($g m^{-3}$)			Nutrient Requirements ($g m^{-3} wk^{-1}$)[d]			Weekly Fertilizer Recommendations ($kg ha^{-1} wk^{-1}$)	
		DIN	*DIP*[b]	*DIC*[c]	*N*	*P*	*CM*[e]	*Urea*	*Other*[f]
El Carao									
May 25	3.50	0.04	1.50	11.0	2.21 (15.75)	0	230 (0)	(35.0)	0 (0)
June 29	4.33	1.97	0.95	23.4	0.07 (0.53)	0	230 (0)	(1.1)	0 (0)
Aug 10	3.98	0.31	0.49	15.7	2.22 (15.82)	0.07 (0.52)	206 (0)	(34.2)	0 (0)
Sept 18	4.26	0.89	0.25	21.3	(12.43)	0.25 (1.75)	240 (0)	61.7 (24.0)	0 (7.7)
AIT									
Jan 24	6.38	0.06	0	34.8	4.04 (29.74)	0.68 (4.99)	437.7 (582.7)	56.9 (51.6)	0 (0)
Feb 04	4.87	0.31	0	35.4	(20.58)	0.52 (3.81)	242.5 (210.2)	38.0 (40.4)	0 (0)
Feb 11	6.20	0.92	0	27.3	2.98 (21.98)	0.66 (4.85)	242.5 (266.7)	47.6 (42.1)	14.1 (0)
Apr 08	6.10	1.13	0.02	24.4	(19.64)	0.63 (4.85)	242.5 (266.7)	47.6 (42.1)	14.1 (0)
FAC									
Jan 15	5.58	0.66	0.45	43.6	(21.90)	0.24 (1.82)		72.0 (41.2)	14.8 (21.1)
Jan 29	5.61	2.41	0.79	47.4	(3.07)	0.06 (0.42)		46.0 (4.9)	0 (5.3)
Feb 12	5.14	0.19	0.15	22.0	(23.67)	0.40 (3.15)		(39.8)	(36.0)
Feb 26	5.42	2.52	0.93	32.0	0	0		44.0 (0)	0 (0)

[a] Dates of fertilizer application. PONDCLASS experiments were conducted in 1993 at El Carao and FAC and at AIT in 1994.
[b] Zero DIP values in the PD/A CRSP Central Database for AIT presumably indicate negligible concentrations of soluble ortho-phosphate.
[c] Calculated from pH, alkalinity and water temperature data.
[d] Weekly nutrient requirements predicted by the use of POND©. Data in parentheses are requirements expressed in $kg ha^{-1} wk^{-1}$.
[e] CM = chicken manure on a wet weight or as-is basis. This fertilizer was used only at El Carao and AIT.
[f] Refers to other synthetic fertilizers that were used principally for P supplementation. These included DAP (diammonium phosphate) at El Carao, TSP (triple superphosphate) at AIT, and a 16-20-0 mix at FAC.

should have widespread applications for baitfish farms located in the Southern United States.

As with any computer-assisted management tool, users of the POND© fertilization guidelines should observe certain precautions when the software is used. For instance, although the effects of nutrient cycling are considered in the fertilization model, fairly high application rates of N can still be suggested, particularly for locations where algal productivity is likely to be high (e.g., results for AIT in Table 1). If urea is chosen to meet this demand and its use is prolonged, fairly high pH values and total ammonia levels may occur simultaneously in ponds. Because the toxicity of unionized ammonia varies among fish and crustacean species (Colt and Armstrong, 1981), tables such as those provided by Emerson et al. (1975; see also Boyd, 1990) should be used to determine the proportion of total NH_3-N that exists in the unionized form for the ambient water pH and temperature. If the potential exists for growth-limiting concentrations of unionized NH_3-N for the cultured fish species, then alternate N sources should be used or fertilization with synthetic nitrogenous fertilizers should be suspended for a few days so that NH_3-N concentrations can drop to levels that are safe for fish.

As a general rule, available data suggest that fertilization with synthetic nitrogen sources should be deferred if total ammonia levels exceed about 1.0 mg l^{-1} and water pH values are routinely higher than about 8.0. During periods when local weather conditions (e.g., prolonged cloudy days) result in decreased light, nitrogen fertilization rates should be adjusted downward. Overcast weather conditions are likely to impede phytoplankton growth—plankton blooms may crash because of reduced nitrogen uptake—and lead to the accumulation of ammonia-N in the pond.

Despite the encouraging results obtained with the fertilization model, field verification of its recommendations should be undertaken in the form of pond experiments designed to enable estimation of various parameters used in the fertilization model. In particular, it would be beneficial to develop nutrient budgets for locations with diverse pond water and soil conditions and to estimate the rates of nutrient fluxes. This is particularly important for nitrogen because very little is known about the fate of this nutrient in aquaculture ponds. For phosphorus, there is much evidence to suggest that it may in fact be returned to the water column at relatively high rates once equilibrium has been established between the pond water and the underlying sediments after long periods of heavy phosphorus fertilization (e.g., Eren et al., 1977; Boyd, 1995; Shreshtha and Lin, 1996). Under such conditions, there will actually be a gain of phosphorus via miscellaneous processes, with an associated rate constant that is likely to vary depending on the soil type and its phosphorus adsorption capacity. Experiments should also be conducted at different locations to examine ranges of nutrient addition, to develop associated GPP-nutrient relationships, and to evaluate economic consequences of forcing ponds to be nutrient limited. For instance, it may be advisable to reduce nitrogen loading rates in order to minimize the possibility of unionized ammonia accumulation. Further, it may also be useful to vary N:P ratios in ponds either for cost concerns or to manage the composition of algal species in ponds.

Assessment of Feed Requirements

In this section, we discuss the applications of the POND© bioenergetics (BE) model to 1) assess fish growth and feed requirements in fertilized and unfertilized ponds and 2) examine the effects of feed quality on these requirements. All the simulation runs were performed using the Level 1 modeling option in POND©.

Supplemental Feeding in Fertilized Ponds

Two key elements of any supplemental feeding strategy for pond aquaculture systems include: (i) initiation of feed addition, and (ii) quantity of feed to be added. For species such as tilapia and carp that efficiently use natural food resources in fertilized ponds, the arguments of Hepher (1978) and several CRSP researchers (e.g., Teichert-Coddington et al., 1990; Green, 1992) strongly suggest that supplemental feed addition is not required until the critical standing crop or fish biomass (CFB) for a pond is reached.

Although it is necessary to specify the CFB for a pond prior to a simulation run, the BE model can be used to determine when feed addition should commence at various locations. This is because the model accounts for differences in fish growth rates caused by variations in environmental conditions among geographical regions. Consequently, the time period required to reach CFB (as predicted by the model) also varies from region to region, and can be used to determine when supplemental feeding should be initiated.

With regard to the amount of feed required, available feeding tables for fish such as tilapia and carp suggest that feeding rates (on a %BW basis) in ponds should decline with increasing fish weight. Although this is certainly true for situations where the artificial feed is the primary source of nutrition (because the relative food requirement of fish decreases as they grow), it is not clear whether such feeding rates are appropriate for ponds where fish continue to derive a portion of their nutritional requirements from natural food resources. Further, although authors such as Hepher (1988) indicate that supplemental feeding rates developed for a given set of conditions should be adjusted according to local conditions (primarily ambient water temperatures), it is difficult to predict how the adjustments should be made. It is also important to note that both the time period required to reach CFB and the amount of feed to be added to a pond are also functions of fish stocking density (SD). These issues can be addressed in a heuristic, if not practical, manner by the BE model.

Effects of temperature: Consider, for instance, the problem of estimating supplemental feed requirements for Nile tilapia culture at three sites with altitudes of 0, 500 and 1000 m above maximum sea level (MSL), respectively. For convenience, it is assumed that all the sites are located at the same latitude and longitude as El Carao. Ponds at these sites are expected to show decreasing water temperatures with increasing elevation; therefore, fish growth rates and appetite levels are also likely to decline with elevation. Model experimental conditions were assumed to be identical to those reported by Teichert-Coddington et al. (1991).

Two sets of simulations were conducted to predict fish growth at the three sites using the weather model in POND© to provide inputs for generating water temperature profiles. For the first set of simulations, a fixed feeding rate (FFR) of 3% BW d^{-1} was provided after the first month of culture. For the second set, the fish were allowed satiation feeding rates (SFR). CFBs at MSL, 500 m, and 1000 m were assumed to be 0.20, 0.15, and 0.10 kg m^{-3}. The value of 0.15 kg m^{-3} assumed for the 500 m site was similar to that estimated for the El Carao ponds. A higher value was assumed for the site located at MSL, which was consistent with previous estimates from heavily fertilized ponds at a warmwater site in Thailand (Bolte et al., 1995). The lower value assumed for the 1000 m site reflects the likelihood of slower rates of natural food production in cooler waters.

Mean predicted water temperatures (°C) at MSL, 500 m, and 1000 m were 29.6, 26.8, and 24.1, respectively. Final predicted fish weights at these elevations for both the FFR and SFR simulations were 431.7, 340.4, and 144.2 g, respectively. Total feed requirements for the FFR simulations at MSL, 500 m, and 1000 m were 7410, 6579 and 3773 kg ha^{-1}, respectively. Corresponding food conversion ratios (FCR) were 2.15, 2.52, and 4.01, respectively. For the SFR simulations, feed requirements at the three elevations were 1913, 1742, and 455 kg ha^{-1}, respectively. Similarly, FCRs were 0.55, 0.67, and 0.48.

Results of the FFR simulations suggest that this practice is likely to be economically inefficient, presumably because it does not take into account the proportion of natural food in the diet of pond fish, and changes in fish appetite caused by increasing size and varying temperature conditions. Apart from economic considerations, wasted feed also contributes to poor water quality in ponds, which can depress fish growth, and may have adverse effects on the surrounding environment if water is routinely discharged from the pond facility. On the other hand, feeding curves predicted for the SFR simulations (Figure 3) take into consideration factors affecting fish appetite as well as contributions to the diet from endogenous food resources. These curves also provide some indication as to when feeding should commence at the different elevations (Figure 3). In a similar manner, the BE model should also be of use in generating supplemental feeding guidelines for locations that show seasonal differences in water temperature and photoperiod.

<u>Effects of stocking density</u>: In the BE model, SD does not directly impact growth rates. Rather, stocking density affects the biomass of fish in a pond, which in turn is used to estimate the parameter f_n (0-1). This parameter reflects the proportion of fish appetite satisfied by natural food in the pond. Thus, for a given CFB, ponds stocked at higher densities may be expected to reach this biomass earlier, and require larger amounts of feed thereafter if a certain satiation feeding level is to be maintained. These concepts are illustrated for Nile tilapia in the model experiments below.

Fish were assumed to be cultured over a 150-d growout period at El Carao. The CFB was set at 0.15 kg m^3. The treatments were as follows: (i) SD of 1 fish m^{-2}, no feed (SD1-NF), (ii) SD of 1 fish m^{-2}, fish fed to full satiation after the CFB is reached (SD1-F), (iii) SD of 2 fish m^{-2}, no feed (SD2-NF), and (iv) SD of 2 fish m^{-2}, fish fed to full satiation after the CFB is reached (SD2-F). The non-fed treatments were included in this analysis to compare the effects of SD and supplemental feeding on f_n as predicted by the BE model. For all the treatments, the initial stocking weight was set to 30 g, and a 90% survival rate was assumed. Pond water temperature for use in the BE model was predicted using input data from the weather generator in POND©.

Final predicted fish weights for the SD1-NF, SD1-F, SD2-NF, and SD2-F treatments were 224.0, 294.6, 147.2, and 294.6 g, respectively. These results are within the ranges for similarly treated ponds at the El Carao research station (Green et al., 1994). Of more interest, however, are profiles for the natural food index (which corresponds to f_n expressed on a percentage basis) obtained from the CFB-based function (Figure 4). As expected, these curves indicate that increasing fish biomass causes a rapid decrease in natural food availability for all treatments. However, within each of the SD treatments, this trend is more pronounced for the fed ponds. Further, supplemental feed should perhaps be added earlier in ponds stocked at higher densities (compare points A and B in Figure 4) because the CFB will be reached earlier. These

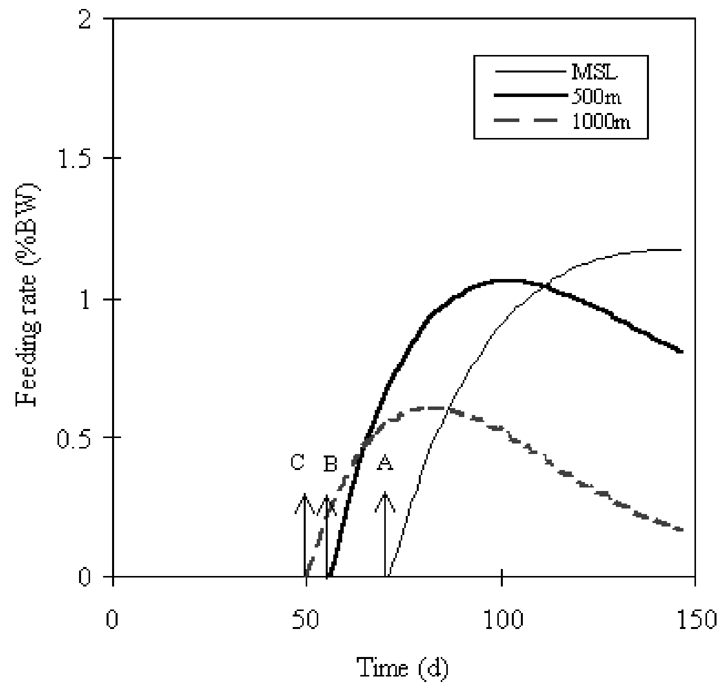

Figure 3. Feeding curves generated by the BE model for Nile tilapia that are assumed to use both natural and supplemental food resources in ponds located at three different elevations (MSL, 500 m and 1000 m). Points A, B, and C in the curves indicate when supplemental feeding should commence.

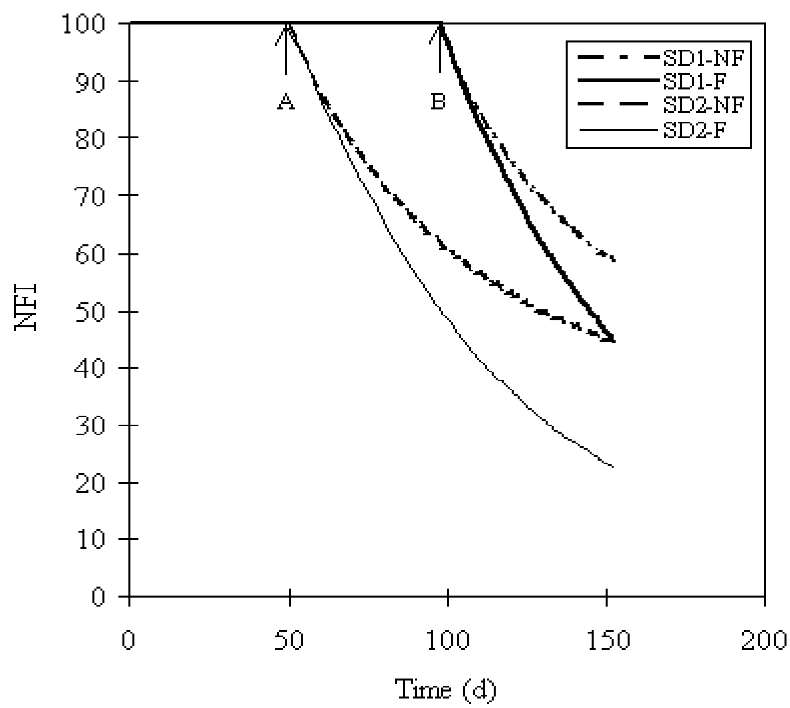

Figure 4. Natural food index (NFI) profiles for ponds stocked at 1 and 2 fish m^{-2} which either did not receive feed (NF) or were fed (F). Points A and B in these profiles appear to indicate when supplemental feeding should commence in ponds stocked at 1 and 2 fish m^{-2} respectively.

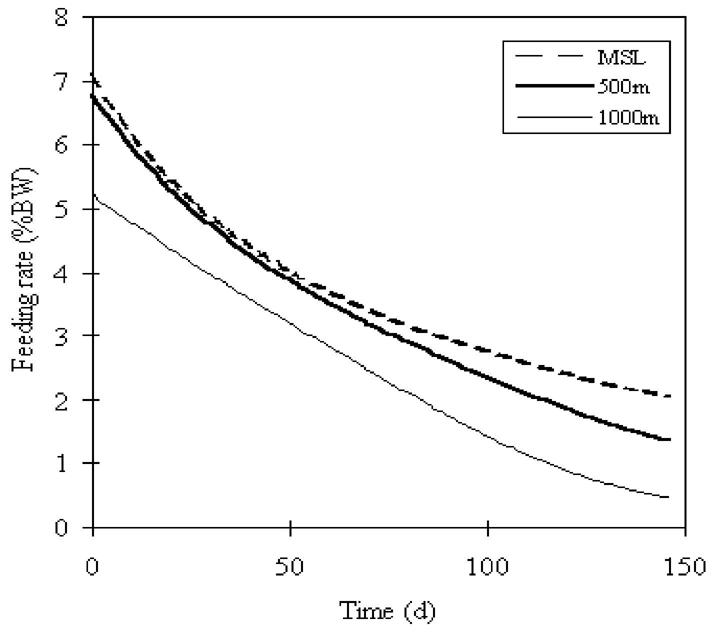

Figure 5. Feeding curves generated by the BE model for Nile tilapia that receive only artificial feed in ponds located at three different elevations (MSL, 500 m and 1000 m).

concepts have previously been described by Hepher (1978) but not illustrated in a quantitative manner. Another advantage of the BE model, of course, is that it can be used to generate such natural food index profiles for other culture conditions (e.g., different species, temperature conditions, and/or management strategies).

Feed requirements predicted by the BE model for the SD1-F and SD2-F treatments were 1118.8 and 5051.6 kg ha^{-1}, respectively. Although gross yields for the SD2-F treatment were about twice as high as those for the SD1-F treatment, local feed costs will determine whether use of the higher SD is economically superior. These types of comparative analyses will be of considerable use to aquaculture planners and managers.

It is important to note that the conclusions reached in the above discussion are valid only for conditions in which feed is added after the CFB is reached, and where natural food is preferred over supplemental feed. It is possible that profiles of the natural food index different from those indicated in Figure 4 may be obtained when the fish species shows a marked preference for supplemental feed over natural food resources.

Supplemental Feeding in Unfertilized Ponds

Simulations were conducted with the BE model to examine feeding rates at MSL, 500 m, and 1000 m elevations in ponds that were not fertilized. Model assumptions were identical to those made for the comparison of fish growth in fertilized ponds at these elevations (as previously discussed), with the exception that Nile tilapia were fed to satiation from the beginning of the experiment, and the contribution of natural food resources to the diet of fish was assumed to be zero.

The BE model generated somewhat different feeding curves for the MSL, 500 m, and 1000 m sites (Figure 5). Over time, feeding rates decreased from 7.1 to 2.1% BW d^{-1} for the MSL site, from 6.6 to 1.4% BW d^{-1} for the 500 m site, and from 1.5 to 0.6% BW d^{-1} for the 1000 m site. Predicted feeding rates for the MSL and 500 m sites were within the ranges given by Hepher (1988) and Lim (1989) for tilapia. The feeding tables provided by these authors only account for differences in fish size, whereas the BE model in its simplest form generates feeding curves (Figure 5) that reflect the effects of size as well as ambient water temperature and photoperiod on appetite. Curves similar to those for Nile tilapia can be generated by applying the BE model to other species for which model parameters have been estimated. These species include channel catfish (*Ictalurus punctatus*), tambaquí (*Colossoma macropomum*), pacu (*Piaractus mesopotamicus*), and common carp (*Cyprinus carpio*). Depending on the economics of feeding and marketing, the BE model can also be used to generate different feeding curves by adjusting the target feeding level. Such curves will likely be useful for making decisions regarding the intensity of the fish culture operation.

As noted earlier, predicted fish weights obtained by use of the BE model for fed ponds (i.e., $f_n = 0$) are independent of SD. In reality, growth rates of fish stocked at high densities may be depressed due to accumulation of metabolites in the pond water or because of behavioral changes. Such behavioral changes in fish cannot be easily addressed by the use of simulation models. However, it may be possible to address the effects of water quality variables (e.g., low DO or high unionized ammonia) by linking the BE model either to time-series data for these variables or to suitable models that describe the dynamics of such variables in aquaculture ponds. Researchers in Mississippi are interested in developing and validating such models for channel catfish ponds, and collaborative opportunities will be pursued with them in the future. Until such refinements are made, stocking densities consistent with typical practices for the selected species should be used when fish growth in fed ponds is simulated with the BE model.

Feed Quality

All the simulation experiments previously described assumed that the feed quality parameter q was equal to one. To examine the effects of this parameter on fish growth and feed requirements, model experiments were conducted assuming culture conditions as described for the feed-only treatment in an experimental study conducted at El Carao (Green, 1992). Additionally, the following treatments were assumed: (i) a high quality feed (HQF; $q = 1$) expected to correspond to the pelleted ration used by Green (1992), and (ii) a low quality feed (LQF; $q = 0.8$).

For the HQF treatment, predicted fish weights and feed requirements were 266.7 g and 9612 kg ha^{-1}, respectively. Corresponding experimental results reported by Green (1992) were 262.3 g and 8971 kg ha^{-1}. Although predicted and observed fish weights were very similar, the predicted feed quantities were somewhat higher than the reported values perhaps due to differences between the fish biomass calculated from the BE model during the simulation run compared to the biomass estimated by Green (1992) on the basis of routine samplings. For the LQF treatment, predicted fish weights and feed requirements were 140.0 g and 6691 kg ha^{-1}, respectively.

These results indicate that the use of a lower value for q will lead to depressed fish growth rates, as might be expected with feeds of lower quality. If results from actual experimental trials using different feed types are available, the appropriate value of q to be used in the BE model could be determined by calibration. Such values can then be used in comparative analyses to gauge the economic benefits of using feeds of various qualities in pond aquaculture.

Model Verifications

Analysis of Fish-plankton Relationships

Past PD/A CRSP research has predominantly emphasized fertilization practices, although a few studies on supplementary feeding, stocking, and polyculture practices have been conducted. The development of guidelines to better manage fertilizer, feed, and stocking/harvest practices can be enhanced through an increased understanding of pond ecology via tools such as systems models. Such models provide a mechanism for rigid definition of relationships among system components and enable hypothesis testing in a manner analogous to physical experiments.

A variety of time-series data (e.g., size- and/or type-classified phytoplankton and zooplankton biomasses) are required to parameterize and validate systems models in POND©. Unfortunately, such data are typically not collected during CRSP experiments. Further, data that we collected from non-CRSP researchers lacked both data types and desired resolution. Nonetheless, we conducted a set of numerical experiments to verify whether some of the more complex POND© models generated results that are consistent with observations that have been made for actual ponds.

As previously documented (Nath et al., 1995), models in POND© are organized on the basis of increasing complexity into three hierarchical levels (Levels 1, 2, and 3). The Level 2 models in POND© were used in this study to explore the relationship between Nile tilapia and its natural food resources in ponds. These resources were assumed to comprise two phytoplankton pools (pool A and B), and one pool each of zooplankton and bacteria. Changes in the former three resources were described by differential equations that account for a variety of losses and gains, whereas bacterial concentrations were assumed to be constant. Fish consumption of these resources was described by the resource substitution function (Tilman, 1982; see also Bolte et al., 1995). Phytoplankton pool A was assumed to be preferred over pool B. Three SDs of Nile tilapia (1, 2, and 3 fish m^{-2}) were used in the simulation experiments.

Final predicted fish weights were 191.9, 136.1, and 106.8 g for ponds stocked at 1, 2 and 3 fish m^{-2}. Weights predicted for the lowest SD compared favorably with observed harvest weights of 189.7 g (Diana et al., 1990); at the other two densities, predicted weights exceeded observed weights by about 20 g. Although zooplankton biomass was similar for all three treatments, the biomass of the two phytoplankton pools differed substantially among the treatments (Figures 6-8). At the lowest SD, phytoplankton pool A increased slightly at the beginning of the simulation and then began to decline after about 40 d (Figure 6). Phytoplankton pool B, however, increased over time. At the intermediate SD, the decline in pool A was more rapid, and pool B after an initial increase remained more or less constant (Figure 7). Finally, at the highest SD, the biomass of pool A dropped sharply before reaching steady-state conditions (Figure 8). At this SD, pool B increased slightly at the beginning of the simulation, and then began to decline gradually. These results were presumably due to increased grazing pressure in simulated ponds with a high fish biomass, and also because the overall phytoplankton biomass was divided into two pools for which tilapia were assumed to have different preferences. The predicted changes in overall phytoplankton biomass obtained by the use of Level 2 models in POND© are consistent with the observations of Colman and Edwards (1987) for Nile tilapia stocked at different densities in tanks treated with septage. Further refinements of the more complex POND© models are planned during the next phase of OSU-DAST activities. These refinements should be of use in examining inter-relationships among natural and supplemental

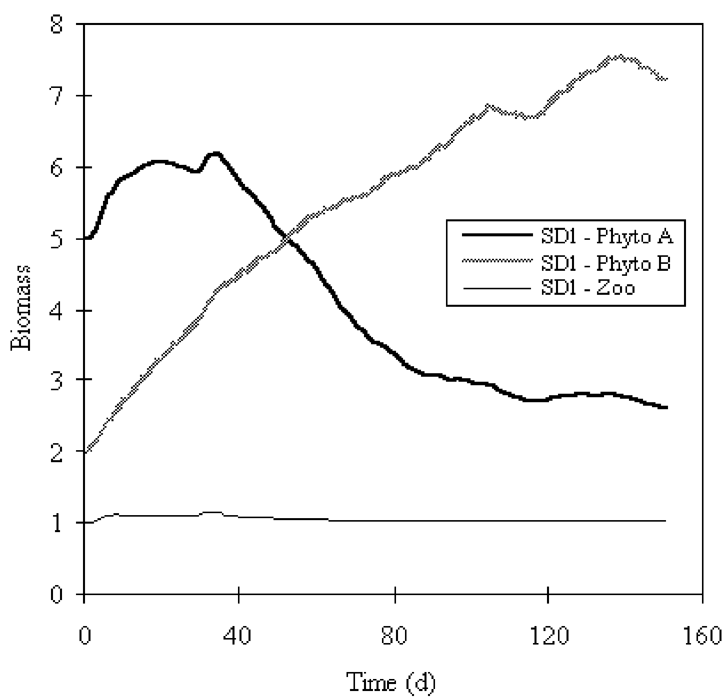

Figure 6. Biomass of the two pools of phytoplankton (in g C m^{-3}) and that of zooplankton (g m^{-1}) predicted by Level 2 models in Nile tilapia ponds stocked at 1 fish m^{-2}.

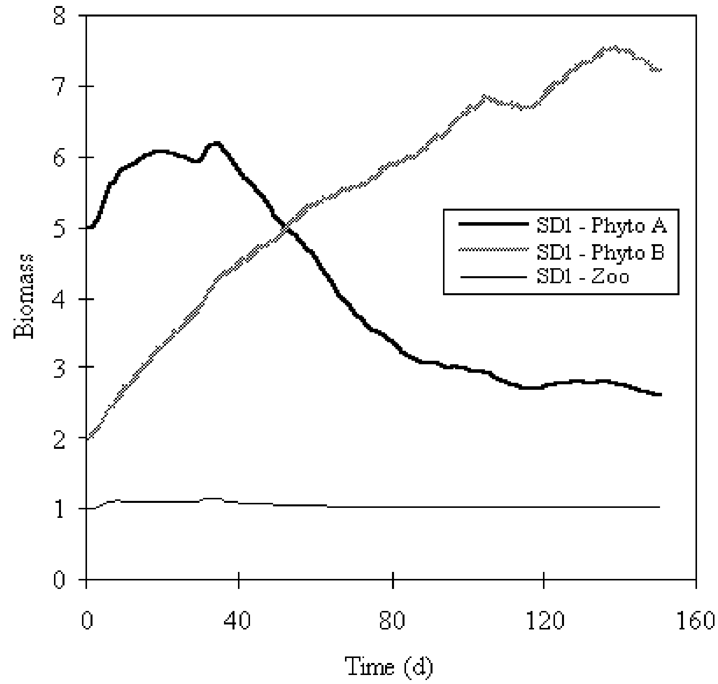

Figure 7. Biomass of the two pools of phytoplankton (in g C m^{-3}) and that of zooplankton (g m^{-1}) predicted by Level 2 models in Nile tilapia ponds stocked at 2 fish m^{-2}.

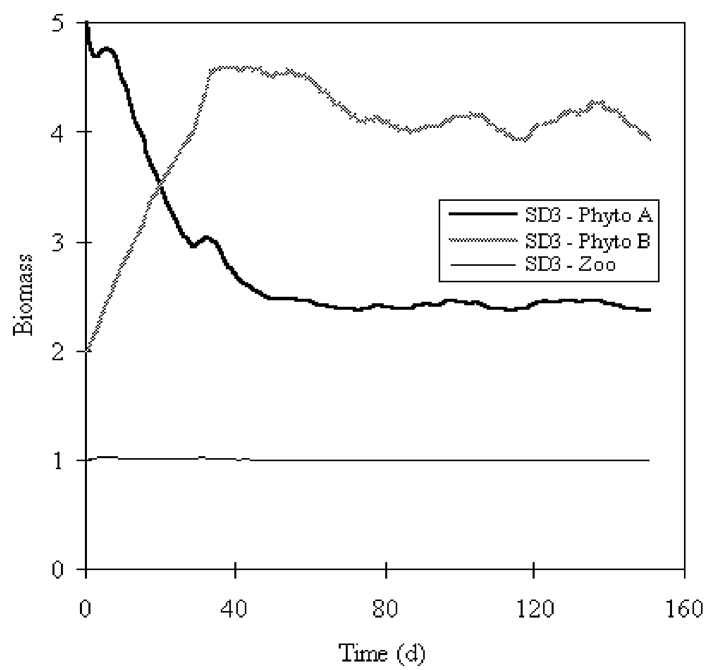

Figure 8. Biomass of the two pools of phytoplankton (in g C m^{-3}) and that of zooplankton (g m^{-1}) predicted by Level 2 models in Nile tilapia ponds stocked at 3 fish m^{-2}.

food resources and among fish species feeding from different trophic niches in polyculture ponds.

Sensitivity Analyses

It is often desirable to know model sensitivity to input data. Such sensitivity analyses are useful to assess and modify data collection protocols and often lead to improvements in model structure and predictive capabilities. Results of sensitivity analyses conducted for the water temperature and fish bioenergetics models in POND© are discussed below.

Water Temperature Model

The POND© water temperature model was subjected to a generalized sensitivity analysis with regard to input weather data, particularly because water temperature profiles are sensitive to these variables. This analysis was accomplished for both daily and diurnal simulations by a ± 10% adjustment in the values of the recorded weather data. Simulation results from these multiple runs were compared to model output (referred to as the base runs) generated by the use of the original weather dataset. Sensitivity analysis was performed for two CRSP sites (Bang Sai and AIT), where more or less complete weather records were available.

For all the sensitivity analysis scenarios described above, absolute changes in model output were summarized in terms of the average shift in water temperature with respect to the change in each of the input (I) weather variables (i.e., DT/DI). Dimensions of the weather variables were chosen to enable easy interpretation of the results. Thus, instead of expressing DT for a 10% change in air temperature, sensitivity analysis results were summarized in terms of DT for a one degree change in air temperature. Finally, in order to rank the weather variables on the basis of the magnitude of their

Table 2. Relative (RS) and absolute (AS) sensitivities of water temperature model output to a ± 10% change in the values of input weather variables for daily and diurnal simulations. The units for AS with regard to air temperature (T_a), relative humidity (R_h), short-wave solar radiation (f_{sn}), cloud cover (C_c) and wind speed (u_2) respectively are: °C/°C, °C/%, °C/MJ m^{-2} d^{-1}, °C/tenth, and °C/m s^{-1}. Negative values indicate that water temperature decreases with an increase in the value of the weather variable.

Simulation Type	Bang Sai		AIT	
	RS	*AS*	*RS*	*AS*
DAILY				
T_a	0.959	0.942	0.788	0.855
R_h	0.210	0.080	0.204	0.084
f_{sn}	0.091	0.308	0.149	0.295
C_c	0.045	0.244	0.063	0.268
u_2	-0.038	-0.701	-0.053	-1.324
DIURNAL				
T_a	0.379	0.391	0.677	0.618
R_h	0.085	0.036	0.157	0.061
f_{sn}	0.083	0.173	0.115	0.264
C_c	-0.021	-0.634	-0.036	-1.340
u_2	0.004	0.050	0.024	0.142

effects on model output, relative sensitivities (RS) were also calculated as follows:

$$RS = \frac{\left(\frac{\Delta T}{T_{mw}}\right)}{\left(\frac{\Delta I}{I_m}\right)} \qquad (1)$$

where,
T_{mw} = mean water temperature (°C) for the base run; and
I_m = mean value of the weather variable in the original dataset.

Water temperatures generated from daily simulations were most sensitive to mean air temperature, followed by relative humidity, short-wave solar radiation, cloud cover, and wind speed (Table 2). This ranking of model sensitivity towards the weather variables for daily simulations was identical at both Bang Sai and AIT, although there were some differences in the magnitude of the sensitivities between the two sites (Table 2). For diurnal simulations at both sites, the ranking of model sensitivity was similar, with the exception that the sensitivity of wind speed was marginally higher than that of cloud cover (Table 2). Further, sensitivity of model output towards all the input weather variables was lower in the diurnal simulations compared to seasonal long daily simulations. Direct comparison of these two sets of simulations is, however, not strictly valid because the daily runs ignored diurnal trends and were conducted for several months, whereas the diurnal simulations lasted only 24 h.

The generally high sensitivity of model predictions to air temperature is not surprising because both seasonal and diurnal profiles of water and air temperatures in shallow static ponds are closely correlated. However, the comparatively low sensitivity of model response to changes in the short-wave solar radiation (f_{sn}) is somewhat surprising because this variable fluctuates substantially from day to day according to atmospheric conditions (Henderson-Sellers, 1984). Moreover, previously developed pond water temperature models (e.g., Fritz et al., 1980; Krant et al., 1982; Losordo, 1988) are apparently quite sensitive to f_{sn}.

Results of the sensitivity analysis in this study, however, indirectly suggest that both daily mean as well as diurnal water temperatures are closely related to evaporative heat flux, which is predominantly a function of ambient air temperature, relative humidity, and wind speed. As with assessment of pond water budgets, sensitivity analysis results suggest that weather data collection protocols for aquaculture facilities such as those established by the PD/A CRSP should include routine measurements of relative humidity in addition to variables that are already measured. It may also be useful to measure daily cloud cover if more accurate predictions of water temperature are desired.

Fish Bioenergetics Model

The bioenergetics model in POND© was subjected to a generalized sensitivity analysis with regard to the 10 model parameters (M) listed in Table 3. Sensitivity analysis was conducted only for Nile tilapia at the El Carao research station. Other model experimental conditions were as described in Teichert-Coddington et al. (1991). Sensitivity analysis was accomplished by a ± 10% adjustment in the values of the model parameters for tilapia (Table 3). Simulation results from these multiple runs were compared to model output (referred to as the base runs) generated by the use of the original parameter set.

For all the sensitivity analysis scenarios, absolute sensitivity (AS) was summarized in terms of the mean change in fish weight over the simulation period of about five months with respect to the change in each of the model parameters (i.e., DW/DM). Further, in order to rank the sensitivity of the model parameters on the basis of the magnitude of their effects on fish weights, relative sensitivities (RS) were also calculated as follows:

$$RS = \frac{\left(\frac{\Delta W}{W_m}\right)}{\left(\frac{\Delta M}{M_i}\right)} \qquad (2)$$

where,
W_m = mean fish weight (g) for the base run; and
M_i = base value of the i^{th} parameter (from Table 3).

Results of the sensitivity analysis indicate that the model is extremely sensitive to the anabolism exponent parameter (m), followed by optimum temperature scaler (T_{opt}), food consumption

Table 3. Base values of bioenergetic parameters for Nile tilapia together with relative (RS) and absolute (AS) sensitivities of tilapia weight to a ± 10% change in the values of parameters for this species as predicted by the fish growth model. Parameters are ranked according to the magnitude of the relative sensitivities. Negative values indicate that fish weight decreases with an increase in the parameter value.

Bioenergetic Parameter	Base Value	RS	AS
Anabolism Exponent (m)	0.6277	5.3461	87.5213
Optimum Temperature Scaler (T_{opt})	32.4	-1.9374	31.7167
Food Consumption Coefficient (h)	0.4768	1.6916	27.6932
Catabolism Exponent (n)	0.8373	-1.6696	-27.3342
Efficiency of Assimilation (b)	0.7108	1.6617	27.2034
Minimum Temperature Scaler (T_{min})	18.7	-0.8272	13.5413
Minimum Catabolism Coefficient (k_{min})	0.0104	-0.4292	-7.0258
Temperature Parameter (s)	0.0288	-0.1080	-1.7674
Feeding Catabolism Coefficient (a)	0.0559	-0.0992	-1.6247
Maximum Temperature Scaler (T_{max})	39.7	0	0

coefficient (*h*), catabolism exponent (*n*), efficiency of assimilation (*b*), and minimum temperature scaler (T_{min}) (Table 3). It is therefore important that these parameters be estimated as accurately as possible via a combination of field experimentation (e.g., frequent sampling or estimation of food consumed) and appropriate use of POND© parameter estimation package (Bolte and Nath, 1996). The model is, however, only marginally sensitive to the other parameters (Table 3). Further, there was no response to the changes in maximum temperature scaler (T_{max}) because the effects of this parameter occur only when ambient water temperatures exceed T_{opt}, a situation that was not encountered at El Carao. Thus, the effects of parameter changes on model output are in part a function of site characteristics. For El Carao, model output was marginally sensitive to T_{min}, but the situation will likely be reversed if $T_{opt} \leq T \leq T_{max}$.

Although the BE model is substantially different from the model developed by Liu and Chang (1992) due to the higher number of variables considered, there are some similarities in the two models because they are extensions of Ursin's (1967) work. Comparison of the results of the sensitivity analyses for parameters that are common to the two models is therefore of interest. Thus, Liu and Chang (1992) reported that model output was extremely sensitive to the parameter *n*, with an RS of 8.80 (i.e., about five times as sensitive as the BE model's response to a change in the same parameter). It is not clear whether this is due to the additional parameters that are included in the catabolic component of the BE model or related to the different parameter values in the two models. On the other hand, the sensitivities of both models to the parameters *m*, *h*, and *b* are fairly comparable.

Anticipated Benefits

Model verification results presented in this report demonstrate the wide range of planning and management applications (i.e., assessment of water, fertilizer, and feed requirements) that can be addressed using the relatively simple models in POND©. Ongoing validation of the more complex models in the software has generated information on patterns of natural food consumption that is likely to be useful in further understanding fish-plankton relationships. The results obtained from both model verification exercises and sensitivity analyses should be useful in enhancing PD/A CRSP data collection protocols and designing experiments to further examine model assumptions and improve parameter estimates.

Future Directions

Although further development of POND© will involve continued model refinement, it is expected that the bulk of our efforts will focus on model verifications and applications of the software for different pond aquaculture systems. We also plan on promoting efforts for field experimentation designed to test the POND© models both within the PD/A CRSP and among other collaborators.

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