Applications of Heat Balance and Fish Growth Models for Continental-Scale Assessment of Aquaculture Potential in Latin America

Interim Work Plan, DAST Study 3

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Introduction

Strategic assessments of pond aquaculture potential require estimates of fish yields that are possible at different geographical locations. In a previous study that assessed the potential for warmwater aquaculture in Africa (Kapetsky, 1994), fish yields (expressed as the number of crops per year or crops/y) were estimated on the basis of temperature thresholds established for the model species (Nile tilapia, *Oreochromis niloticus*). However, this approach is not readily extended to other species of potential interest. Moreover, the approach does not directly consider the effects of seasonal water temperature variation on fish growth and food consumption rates, nor does it account for the effects of other factors (e.g., feeding levels, photoperiod, and fish size) on these rates. Bolte et al. (1995) have developed a fish growth model that accounts for the effects of temperature, photoperiod, size, and feeding level on fish weight. Techniques have also been developed to parameterize this model for different fish species (Bolte and Nath, 1996).

Water temperature is an important input variable required for assessment of fish yields. Kapetsky (1994) estimated the mean monthly water temperature for African ponds on the basis of a linear regression relationship between this variable and the mean monthly daytime air temperature. An alternative approach of predicting water temperature involves the use of heat balance models (e.g., Fritz et al., 1980). Such models account for the effects of geographical variations in air temperature, and in other weather characteristics (i.e., solar radiation, cloud cover, wind speed, and relative humidity) on pond water temperature. Nath (1996) developed and validated a heat balance model for use in pond aquaculture. The heat balance and growth models cited above have been packaged in the decision support system POND© (Bolte et al., 1995; Nath et al., 1995), which runs under the Microsoft Windows operating system.

This report focuses on the adaptation and application of these two models to estimate fish yields for four species across continental Latin America, as part of an FAO effort to assess pond aquaculture potential in the inland regions of Latin America. This report focuses primarily on the output generated by the fish growth model. Integration of these results with the rest of the GIS procedures, and a complete discussion of the potential for aquaculture in Latin America are presented elsewhere (Kapetsky and Nath, in prep.).

The fish species chosen for analysis were Nile tilapia (*O. niloticus*), tambaquí (*Colossoma macropomum*), pacu (*Piaractus mesopotamicus*), and common carp (*Cyprinus carpio*). Of these species, Nile tilapia culture is increasing in the warmer waters of Latin America because Nile tilapia are easy to culture, have rapid growth rates, and can tolerate a wide range of water quality conditions. Currently, carp is not widely cultured in Latin America; however, this species tolerates a wide range of temperatures and has a high potential for culture. The characids (tambaquí and pacu) are commercially cultured in several countries (e.g., Brazil, Colombia, and Venezuela) and are good candidates for pond aquaculture (Saint-Paul, 1989; Lovshin, 1995). Tambaquí generally perform well in warm waters (exceeding approximately 20˚C), whereas pacu tolerate colder temperatures.

Methods

FAO's general framework for the continental-scale assessment of pond aquaculture potential in Latin America involves the use of a geographical information system (GIS), for which data were taken from direct sources or were generated by the use of one or more models. The GIS software used for the overall analysis at FAO is ARC/INFO, which runs under the UNIX operating environment. In order to predict water temperature and fish yields, it was necessary to modify the POND© heat balance and fish growth models so that the output information could be displayed within ARC/INFO. This was accomplished by implementing the two models as 'free-standing' applications (i.e., independent of the POND© software). Further minor modifications to the models and simulation settings are described below.

Water Temperature Modeling

The water temperature model is fully documented elsewhere (Nath, 1996). Validation of this model has been completed for different geographical locations using daily weather and site-specific input data recorded in the PD/A CRSP Central Database (Nath, 1996).

However, daily weather data required for the water temperature model are not easily available or accessible for large geographical regions such as Latin America. Moreover, manipulating and storing daily weather data for such a large grid are non-trivial tasks. Even if capabilities for such operations existed, it is unlikely that their use would result in significant advantages to strategic planning applications, such as continental-scale analysis of aquaculture potential.

The alternative approach taken in this study was to procure gridded data sets of the monthly values of air temperatures required for the water temperature model developed by the FAO Agrometeorology Group. Unfortunately, due to problems encountered by this group during interpolations of recorded weather data, gridded data sets of the other weather variables required as input to the water temperature datasets were not available. Air temperature data were interpolated to obtain daily values for use in the water temperature model; other input variables were predicted by the use of a simple weather generator described by Nath (1996). The analysis assumed that all the simulated ponds have a

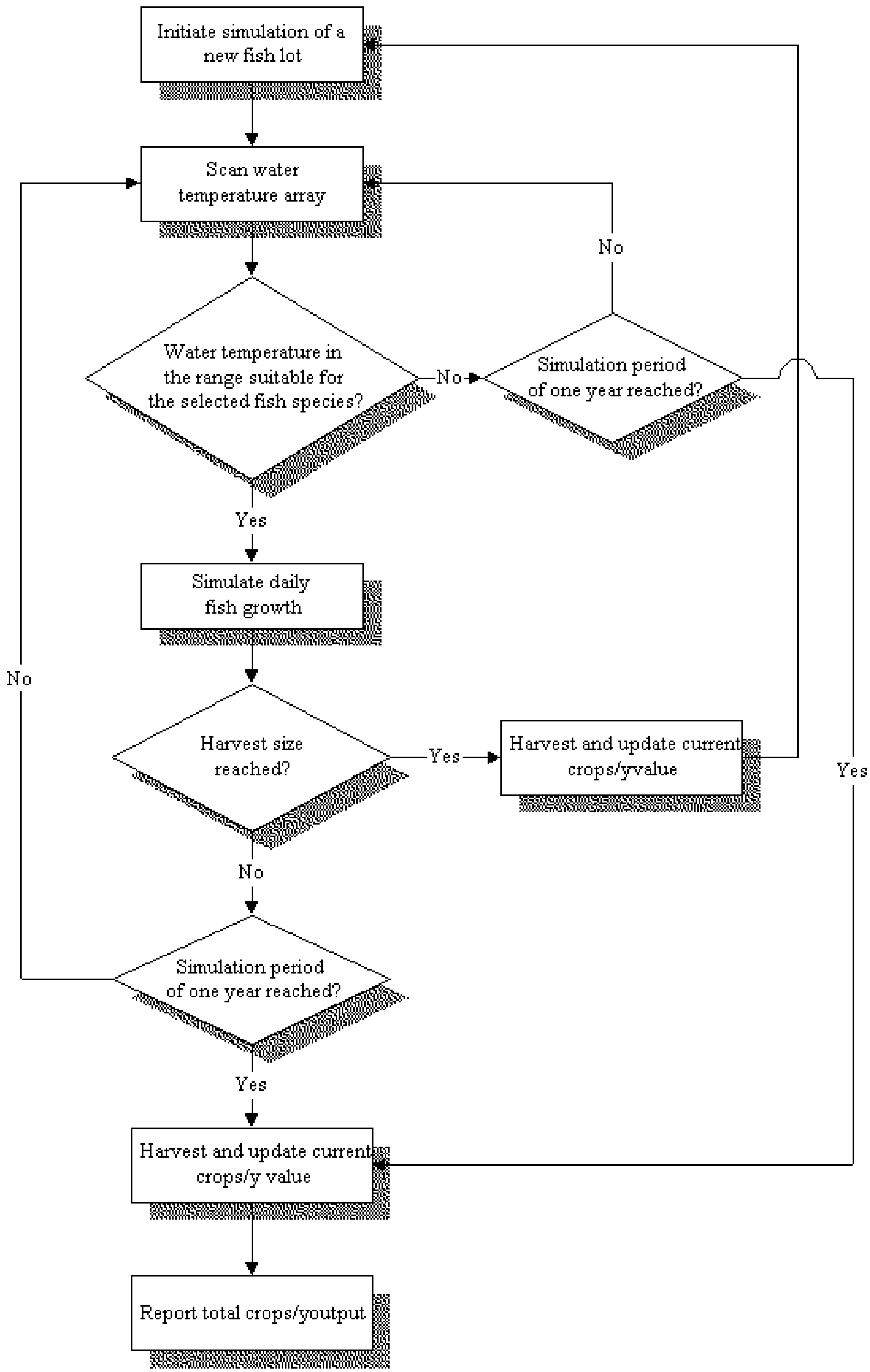

Figure 1. Flow diagram depicting the procedure used to calculate crops/y output using the simulation model of fish growth.

Table 1. Stocking densities and harvest sizes (small and large) assumed within each of the commercial farming scenarios for tilapia, tambaquí, pacu, and carp. Expected gross and net yields (after accounting for mortality) of a hypothetical output of one crop/y are also shown.

Species	Stocking Density (fish m^{-2})	Harvest Size (g)	Gross Yield (kg ha^{-1} yr^{-1})	Net Yield (kg ha^{-1} yr^{-1})
Tilapia	3	300	7200	5700
	1.5	600	7200	6450
Tambaquí	1.5	600	7200	6450
	0.9	1000	7200	6750
Pacu	1.5	600	7200	6450
	0.9	1000	7200	6750
Carp	1.25	600	6000	4750
	0.5	1500	6000	5500

constant pond area of 2000 m^2 and a depth 1.2 m. Consequently, pond volume was assumed to be constant (i.e., 2400 m^3).

One-year simulations were conducted for each cell within the grid for Latin America using a one-day time step, and the resulting daily water temperature values were averaged for each month. The latter set of values was then used to generate maps of monthly mean water temperature. To test water temperature conditions < 0˚C, a condition was inserted during map creation to plot the mean monthly air temperature. Previously the model had been tested adequately only under water temperature conditions > 0˚C.

Fish Growth Modeling

An existing fish growth model (Bolte et al., 1995; see also Nath, 1996) was modified for use in this study. The model was parameterized for all four species according to Bolte and Nath (1996), and one-year simulations were conducted across the entire Latin American grid. Daily water temperatures required for the growth model were obtained by linear interpolation of monthly means predicted by the water temperature model discussed above.

It was necessary to make minor modifications to the growth model in order to generate crops/y output. For example, it is difficult to specify exact stocking and harvest times for simulation runs that are relevant to a large geographical region because the time period required to reach the desired harvest size varies among locations. Further, depending on temperature preferences of different species, fish culture may be possible only during a certain period in the year. This is difficult to predict *a priori*; therefore, it was assumed that a fish lot (population) would be stocked when water temperatures were favorable. Favorable water temperature was arbitrarily defined as a 15-day period when temperatures are within the range necessary for the growth of a particular fish species. The desired harvest weight for each species was also specified before a simulation run commenced.

During the simulations, the fish population was "harvested" if any of the following conditions were encountered:

- The specified harvest weight (implying a full crop) was reached before completion of one year;
- The simulation duration of one year was reached without registration of one or more crops; or
- Water temperatures were unfavorable for growth.

In the first case, if water temperatures continued to be suitable for the selected fish species, it was assumed that an additional fish lot would be stocked and harvested according to the above conditions. In the second and third cases, the crops/y output was expressed as a decimal fraction of the current fish weight relative to the harvest weight (i.e., a partial crop was reported). The simulation procedure is summarized in Figure 1.

Commercial Farming

In order to explore a range of commercial aquaculture possibilities by the use of the growth model, simulations were conducted for all four fish species assuming two different feeding levels and

Table 2. Stocking sizes, densities, and harvest sizes (small and large) assumed within each of the small-scale farming scenarios for tilapia and carp. Expected gross and net yields (after accounting for mortality) for a hypothetical output of one crop/y are also shown.

Species	Stocking Density (fish m^{-2})	Stocking Size (g)	Harvest Size (g)	Gross Yield (kg ha^{-1} yr^{-1})	Net Yield (kg ha^{-1} yr^{-1})
Tilapia	2	25	150	2400	1900
Carp	1	50	350	2800	2300

two harvest weights. Natural food availability was assumed to be negligible. Feed application rates required for 50% and 75% satiation were assumed to represent commercial aquaculture operations with low and high feeding rates, respectively. The primary effect of higher feeding rates, according to the model, increases fish growth and thus allows target size to be reached earlier. The advantage of using percent satiation feeding levels instead of feeding rates on a percent body weight basis is that the former approach takes into account variations in the factors affecting fish appetite during calculation of feed requirements. Within each of the percent satiation feeding levels, two harvest weights (small and large) were also established in consideration of market preferences for each of the fish species.

The stocking weight for tilapia, tambaquí, and pacu was assumed to be 50 g for all the scenarios; carp were stocked at 100 g. A survival rate of 80% was assumed for all the simulation runs. Additional parameters assumed for commercial farming are indicated in Table 1.

To achieve the overall objectives of the GIS study and for easy interpretation of the results, it was necessary to aggregate crops/y outputs from the simulation runs into four classes. However, specification of rigid classes that pre-judge the value of the output without accompanying production cost and marketing data would not be appropriate. Furthermore, differences in model output were expected depending on the particular species, harvest size, and feeding levels. To avoid these problems, output for each simulation scenario was divided into equal quarters of the range of crops/y. They are designated as 1st quarter, (highest crop/y), 2nd quarter, (2nd highest crop/y), etc.

Small-scale Farming

It is difficult to precisely define small-scale, subsistence-level aquaculture operations because of the wide variety of materials used as inputs to these systems and the variation of fish sizes that are harvested. In general, however, such systems are characterized by low intensity management and smaller sizes of fish at harvest. Analysis of the potential for small-scale farming was limited to tilapia and carp. These two species effectively utilize natural food resources in ponds, whereas tambaquí and pacu perform well primarily in ponds that receive artificial feed of relatively high quality.

Natural food availability was modeled as a function of fish biomass (Bolte et al., 1995). This approach requires definition of the critical standing crop (kg ha^{-1}) or critical fish biomass (CFB) (kg m^{-3}). For tilapia ponds that are not heavily fertilized or fed, a CFB of about 0.075 kg m^{-3} (equivalent to a fish biomass of 750 kg ha^{-1}) appears to be reasonable (Bolte et al., 1995). This value was also assumed for carp ponds in this study.

Parameters assumed for the simulation of both species under small-scale farming conditions are indicated in Table 2. These simulations assumed a survival rate of 80%.

Model output as crops/y for tilapia and carp under small-scale simulation conditions was also divided into equal quarters (as described in the section on commercial farming above).

Results

Yield in terms of crops/y was the key output of the growth model for the four different fish species. This output is presented first from a continental viewpoint and then from a country viewpoint. The continental results are expressed in terms of the total surface area. For simplicity, crops/y results were separated into quarter parts of the ranges that have been attained with each feeding rate-harvest weight combination. Only a brief overview of the results is presented here because complete documentation including maps of crops/y output for individual species is available elsewhere (Kapetsky and Nath, in prep.).

Continental Level

Relatively large areas of Latin America were shown to be suitable for the commercial farming of the four species considered in this study. For example, areas in which first (i.e., highest) quarter crops/y were attainable ranged from a high of 73% in Latin America for carp to a low of about 34% for Nile tilapia; however, one result for Nile tilapia was only 9%. Results for individual species ranged from 66 to 73% for carp, 55 to 66% for tambaquí, 48 to 60% for pacu, and 9 to 43% for Nile tilapia.

Areas corresponding to second and third quarter crops/y were relatively small. Thus, significantly, most of the area suitable for farming these four species seems capable of producing relatively high numbers of crops/y in each feeding rate-harvest weight combination.

Within individual species results, there was relatively little difference among the first quarter surface areas that resulted from different feeding rate-harvest size combinations. Rather, it was the numbers of crops/y that varied markedly when the different regimes were simulated. As would be expected, it was the combination of low feeding rate and high harvest weight that produced the least crops/y. In general, among the four species, feeding at the high rate (75%) and harvesting at the low weight provided the best results in terms of relatively large surface areas and the highest number of crops/y.

Feeding at 75% and harvesting at the high weight produced the second best combination of high crops/y along with large surface areas. The same pattern applied to Nile tilapia; however, for carp slightly higher crops/y were attained with 50% feeding and the low harvest size.

A somewhat surprising result generated by the fish growth model showed that the number of crops/y of pacu tended to exceed that of tambaquí in regions where water temperatures were relatively warm. This was unexpected because water temperatures appeared to be more favorable for the latter species.

For small-scale farming, the results varied considerably between the two species considered. For a relatively small area of Latin America (34%), Nile tilapia harvested at 150 g can yield 1.3 to 1.7 crops/y and an additional 13% of the surface area can produce 0.9 to 1.3 crops/y. In contrast, 70% of the continent can produce 1.4 to 1.8 crops/y of carp harvested at 350 g and an additional 12% of the area can produce 0.9 to 1.4 crops/y.

Country Level
Commercial Farming

In this section we present the spatial distribution of species potential from a country by country viewpoint in the form of histograms that indicate the relative surface area applicable to each country. Within each species, the spatial patterns are similar for each feeding rate-harvest weight combination; therefore, only one histogram per species is presented herein.

Tambaquí

First quarter crops/y for this species were possible in Southern Mexico, in nearly all of the Central American countries, throughout the northern countries of South America, and over much of Brazil and parts of Peru, Bolivia, and Paraguay (Figure 2). North Central Mexico, Uruguay, Chile, and all but northern Argentina were disadvantaged.

Pacu

The spatial pattern for pacu was similar to that of tambaquí but more restricted. First quarter crops/y areas were less, and second quarter crops/y areas were larger (Figure 3).

Nile tilapia

The spatial distribution for commercial culture opportunities of Nile tilapia was markedly more restricted than for the other species; however, the same group of Central American and north and northwest South American countries maintained first quarter crops/y potential. Much of the relatively high yield potential was lost in the marginal countries (Figure 4).

Carp

As would be expected for a species with a relatively wide temperature range for growth, the spatial distribution for carp culture was greater compared to the other species (Figure 5). For example, first and second quarter crops/y ranges

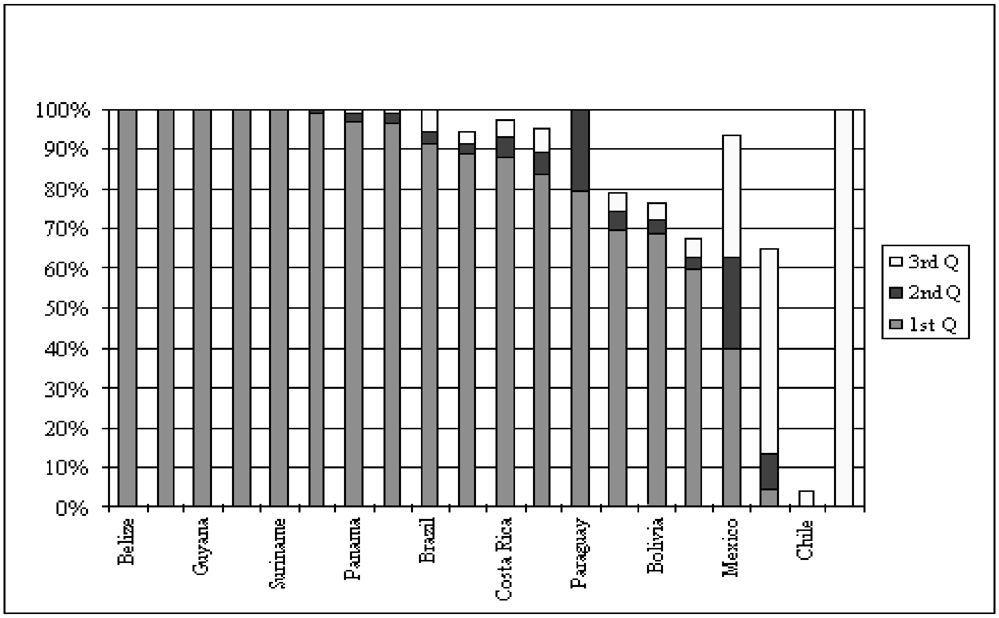

Figure 2. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of tambaquí fed to 75% satiation and harvested at 600 g.

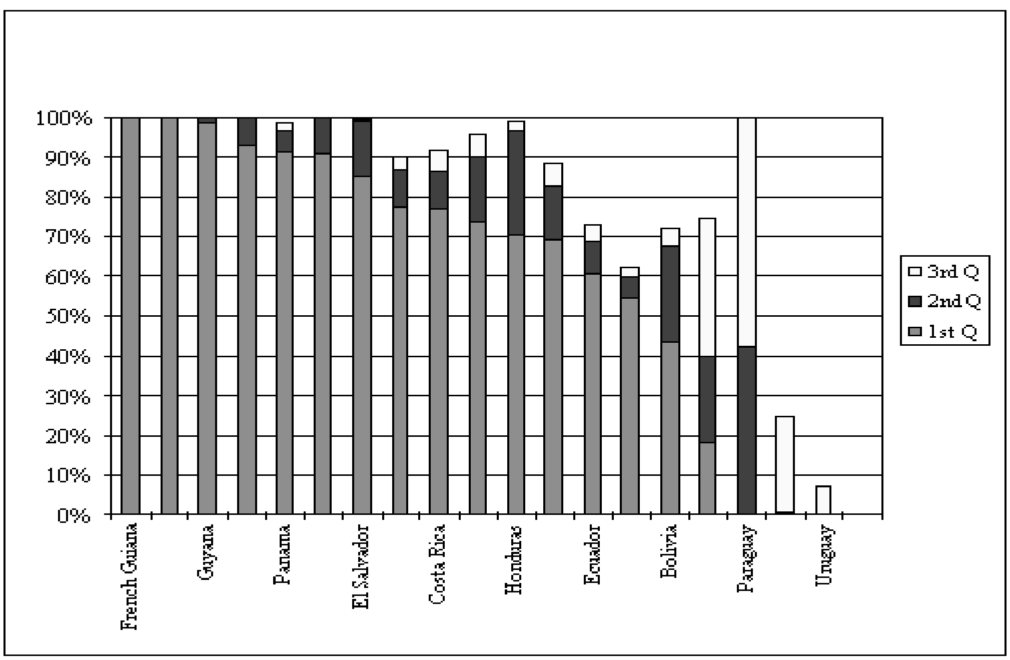

Figure 3. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of pacu fed to 75% satiation and harvested at 600 g.

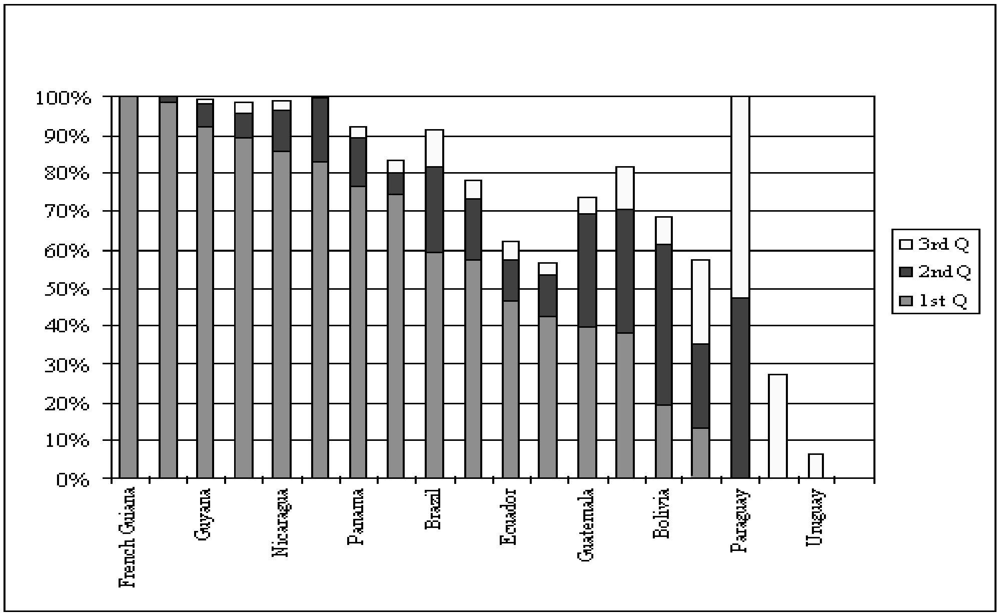

Figure 4. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of Nile tilapia fed to 75% satiation and harvested at 300 g.

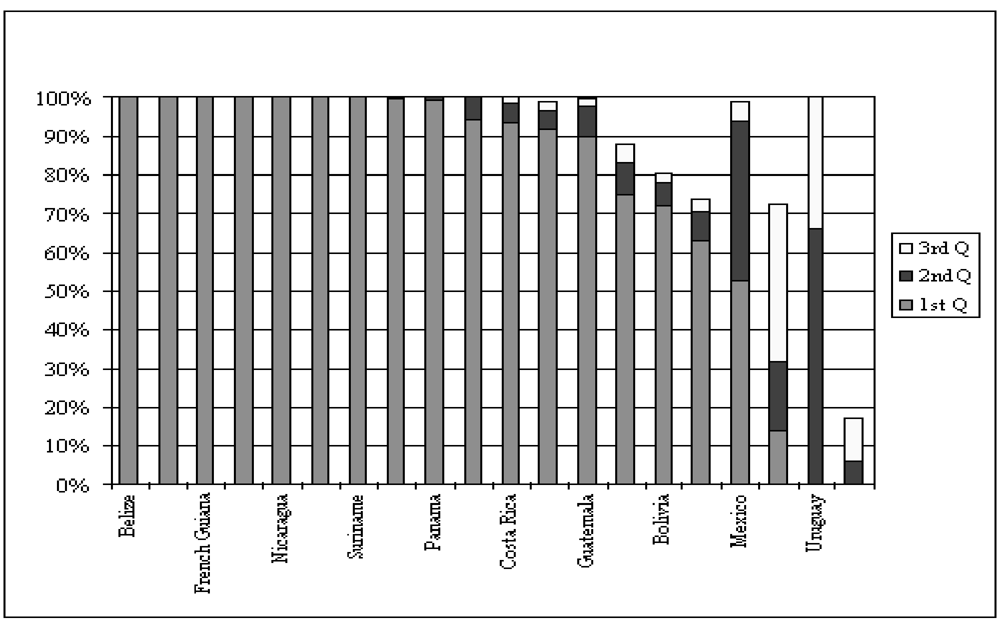

Figure 5. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of common carp fed to 75% satiation and harvested at 600 g.

could be realized over much of Mexico and in Northern Argentina, whereas only small areas of these regions were suitable for the other three species.

Country Level
Small Scale Farming

Carp and Nile tilapia contrasted greatly in the spatial distribution of their small-scale culture potential. Nile tilapia was suited for small-scale farming in the same countries as carp, and first and second quarter crops/y ranges were similar to those of the carp; however, tilapia potential extended over a smaller area (Figures 6 and 7). Nevertheless, first quarter crops/y (1.3 to 1.7) could be obtained in 50% or more of 11 countries. Only Uruguay and Chile offered no possibilities for yields in the first and second quarter ranges. Opportunities for small-scale farming of carp were extensive. First quarter yields ranging from 1.4 to 1.8 crops/y could be attained from more than 50% of the areas of all but three of the countries, and only Chile was quite disadvantaged.

Discussion and Conclusions

This study is the first attempt to integrate a fish growth model within a continental-scale GIS to predict the number of fish crops possible per year. The results suggest that such integration is a useful mechanism to address the effects of various factors (primarily water temperature and feeding rates) on fish yields and to estimate the production potential at various levels of culture intensity. The approach may also be applicable to the analysis of pond aquaculture potential at different geographical scales (e.g., for single countries, or states/districts within individual countries). Moreover, the parameterization of the fish growth model developed by Bolte et al. (1995) for various species proved to be very beneficial.

As indicated previously, crops/y output obtained for tambaquí and pacu were somewhat unexpected for the warmer waters of Latin America, because the former species generally grows more rapidly in waters ranging from 25 to 35°C (e.g., Saint-Paul and Werder, 1980; Saint-Paul, 1989). Although some experiments (e.g., Miyasaka and Castagnolli, 1992) have shown that pacu may grow better than tambaquí in mean water temperatures ranging from 27 to 30°C, we suspect that the crops/y results obtained for these species may in part be due to the lack of sufficient growout data to better parameterize the growth model for tambaquí (see also Nath, 1996). The higher crops/y output registered from Central Brazil southward for pacu compared with tambaquí is perhaps not surprising because pacu appear to better tolerate colder temperatures than tambaquí (Saint-Paul, 1989).

In general, the results were quite positive for the development of inland fish farming in Latin America because large areas of the continent were shown to be suitable for the farming of a variety of species. The numbers of crops per year could be maximized through a combination of relatively high feeding rates and harvest at moderate weights.

It should be noted, however, that not all of the potential aquaculture areas identified for one or more of the species used in this study will be available for aquaculture development. In addition to growth potential, some of the areas may not be appropriate because of a variety of other factors (water requirements, urban market potential, potential for farm gate sales, availability of agricultural by-products as feed/fertilizer input, and engineering and terrain suitability for pond construction) necessary to determine site suitability for pond aquaculture. The fish growth model predictions obtained in this study were combined with analyses of these additional factors within GIS to identify areas of Latin America that are either very suitable, suitable, marginally suitable, or unsuitable for aquaculture development. Further, regions unavailable for inland fish farming development were identified by incorporating constraints such as protected areas, large inland water bodies, and urban centers. Complete details of these analyses are given in Kapetsky and Nath (in prep.).

Finally, additional improvements such as use of stochastic weather data to investigate the best and worst climate situations, as well as the average situation for the production of fish, may be useful in future assessments of aquaculture potential for large geographic areas. Such analysis could include inter-annual temperature variations as they affect growth and associated yields. It may also be useful to extend the range of species considered to include cold-water candidates and to examine the potential for other fish production systems including polyculture, recirculation systems, and flow-through facilities.

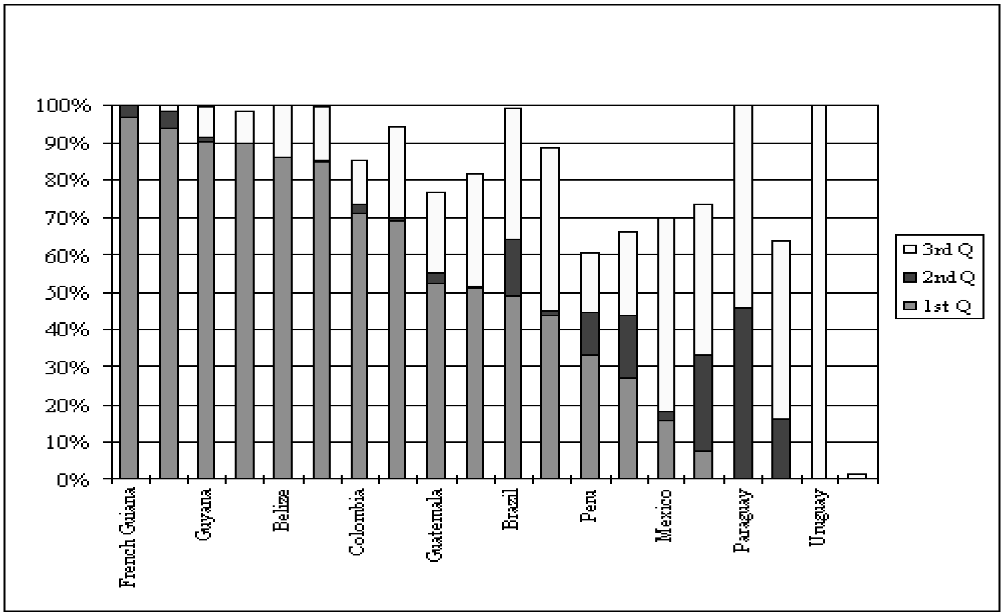

Figure 6. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of Nile tilapia under small-scale farming conditions.

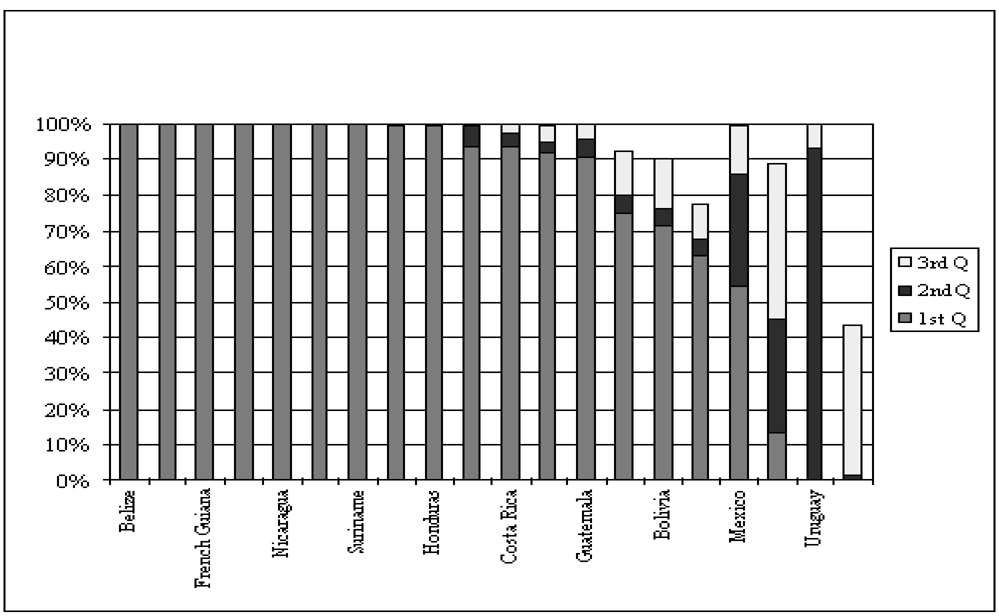

Figure 7. Relative area (%) of continental Latin American countries capable of producing first, second, and third quarter crops/y of common carp under small-scale farming conditions.

Anticipated Benefits

This study has demonstrated that the integration of water temperature and fish growth models is a useful mechanism for generating yield estimates of different fish species at a continental scale. The approach will also be useful for analyses of aquaculture potential at different geographical scales (e.g., within specific countries, or states/districts within individual countries). Fish yield estimates obtained in this study demonstrate the high potential for pond aquaculture in the inland regions of Latin America. In addition, these estimates were combined with other important factors relevant to fish farming suitability within a GIS. The ensuing outputs of this study are expected to be very useful in strategic planning for aquaculture development at national levels, and as a tool to guide technical assistance activities by international organizations.

Acknowledgments

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