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Management Implications from a Stock-Recruit Model for Bighead Carp in Portions of the Illinois and Mississippi Rivers

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Abstract.—The Aquatic Nuisance Species Task Force, Mississippi River Basin Panel on Aquatic Nuisance Species, Mississippi Interstate Cooperative Resource Association, and other entities established goals to control feral populations of bighead carp *Hypophthalmichthys nobilis* in the United States. The Asian Carp Working Group recommended development of stock-recruit models for bighead carp and other Asian carps to assist in management and control of feral populations. We developed a Ricker stock-recruit model, using bighead carp relative abundance data collected in the LaGrange Reach of the Illinois River and Pool 26 of the Mississippi River during 2001–2004, to guide management and control efforts there. The functional relationship that explained the greatest amount of recruitment variation explained 83% of the recruitment (during July through October of the first year of life) variation using stock size and river discharge. Seventy-two percent of recruitment variation was explained by stock size abundance while an additional 11% was explained by the coefficient of variation of discharge in July. Model predictions and empirical data indicated that management efforts to reduce stock size abundance from the optimum of 0.07 adults per unit of standardized fishing effort to 0.02 adults per unit of effort should be the most effective tool to reduce recruitment over the long term. This level of adult abundance (approximately 25% of the mean during 2001–2004) should be the target maximum for bighead carp control efforts in the study areas. Recruitment was inversely correlated with variation in river discharge, so it is possible to combine control of stock size abundance and management of river discharge in an integrated pest management program for bighead carp in the two river reaches.

Introduction

Kolar et al. (2005) concluded that the organism risk potential, based on the probability and consequences of establishment, for bighead carp *Hypophthalmichthys nobilis* in the United States is high and unacceptable. The Mississippi Interstate Cooperative Resource Association and Mississippi River Basin Panel on Aquatic Nuisance Species consider bighead carp among

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the most problematic aquatic invasive species in the Mississippi River basin. Furthermore, the national Aquatic Nuisance Species Task Force considers it a top priority to manage and control bighead carp and other Asian carps in the United States. They then formed the Asian Carp Working Group to develop a national management and control plan for those species. One of the goals of the Management and Control Plan for Black, Grass and Silver Carps in the United States (Conover et al. 2007) is to control feral populations of bighead and other Asian carps in the United States. The working group recommended development of stock-recruit models for each species to scientifically implement control efforts.

The dynamics of most fish populations, and many terrestrial vertebrates, are driven by a combination of recruitment, growth, survival, and immigration and emigration rates. Recruitment is the key factor that most influences abundance of adult populations of many vertebrate species. Stock-recruit models have been developed to help manage recruitment of fish and wildlife populations (e.g., Hoff 2004a, 2004b; Hoff et al. 2004). Protection and enhancement of adult abundance (i.e., stock) is an effective management tool to ensure adequate recruitment (i.e., recruit) and sustain populations for native or other managed species. The basic stock-recruit model uses only adult stock size abundance to predict recruit abundance. If that model accounts for most (e.g., 70–100%) of the variability in recruitment, then that model will be useful to managers. If the basic model does not account for most of the variability, then more complex models can be developed to include additional biotic and abiotic independent variables.

Surprisingly, only one stock-recruit model is known for an invasive fish established in the United States. Hoff (2004b) developed a stock-recruit model for Lake Superior rainbow smelt *Osmerus mordax*. Implications from results of that model could be useful for controlling the species, if management agencies choose to do so. The objective of our study was to develop a stock-recruit model for bighead carp, using data from reaches of the Illinois and Mississippi rivers, and then determine if interpretation of model results provide implications for developing and implementing control plans.

Methods

Fish and Environmental Data Collections

Bighead carp stock and recruit data were collected from catches in gears fished using standardized fishing effort conducted with support of the Long Term Resource Monitoring Program (LTRMP). The LTRMP monitors abundance of many fishes and status of environmental parameters in six areas of the upper Mississippi River system. Five of those areas are within the Mississippi River from Cape Girardeau, Missouri upstream to Lake City, Minnesota, and one of those areas is in the Illinois River near Havana, Illinois (USGS 1999; Figure 1). Fish data were collected in three semi-annual periods (early June through July, early August through mid-September, and mid-September through October) along the La Grange Reach of the Illinois River and Pool 26 on the Mississippi River (Figure 1). Data from only the La Grange Reach of the Illinois River and Pool 26 on the Mississippi River were used in our study because inadequate data on bighead carp abundance were collected in the other four study areas. The standardized effort included electrofishing, fyke nets, mini-fyke nets, and hoop nets following the methods outlined by the LTRMP (Gutreuter et al. 1995). The LTRMP protocol requires a specific amount of effort for these gears and time periods within each study area.

Figure. 1. Locations of Long Term Resource Monitoring Program study areas in the Mississippi and Illinois rivers. Data for two of those areas (Pool 26 of the Mississippi River, La Grange Reach of the Illinois River) were used to develop the stock-recruitment model for bighead carp.

Therefore, relative abundance estimates can be calculated as mean number of individuals captured per time period because the collective grouping of gears have been used in a consistent manner during the years data were collected for our analyses. The aforementioned approach was successfully used during analyses of population dynamics of other fishes in large river systems (Pegg and Pierce 2002; Chick et al. 2006). The final step to parameterize the stock-recruit model required the estimation of abundances of bighead carp adults (stock) and recruits. We used data from the literature to identify stock size (≥470 mm) of bighead carp (Schrank and Guy 2002) while recruits were defined as age-0 fish captured in July–October each year. These data were then applied to the stock-recruit model.

River Discharge Data Collection

Mean daily discharge data (m^3/s) for the month of July were obtained from online data supplied by the U.S. Army Corps of Engineers (2007) for the LaGrange Lock and Dam (Illinois River) and Grafton, Illinois (Mississippi River) to characterize hydrologic conditions in each study area. We used river discharge in the model because we believed that discharge would affect recruitment. Discharge has been identified as a signal for spawning and resultant flooding believed critical in providing nursery areas (Jennings

1988). Furthermore, we used discharge data for July because most spawning is believed to occur at this time in the study reaches. Recruitment was modeled using both mean discharge and coefficient of variation of river discharge.

Recruitment Model

The Ricker (1975) approach was used to model recruitment. That model can be shown in various forms, but one expression is

$$R = S\,e^{a - bS - cX}.$$

The approach models recruit abundance (*R*) as a function of parental stock size abundance (*S*), density-independent mortality (*a*), density-dependent interactions (*bS*), and abiotic and biotic factors such as river discharge (*cX*). The linear form of the model was used to determine the correlations between various dependent variables and recruitment and to calculate the independent variable coefficients. One of the linear forms of that model is

$$\log_e(R/S) = a - bS - cX + 0.$$

The aforementioned approach models the rate of recruitment per spawner, $\log_e(R/S)$, as a function of parental stock size, other abiotic and biotic variables (*X*), and the residual error (0). High collinearity of independent variables typically reduces the accuracy of model predictions. Therefore, models were eliminated from consideration if collinearity existed. Evidence of collinearity was evaluated by (1) viewing the bivariate correlation matrices of independent variables, (2) viewing the coefficient of determination from the multiple regression of each independent variable with the remaining independent variables in the model, and (3) viewing the stability of models (i.e., changes in variable coefficients) after adding each independent variable.

We also implemented a cross-validation approach to assess model validity. Cross-validation compares predictions from the model developed from one portion of a data set to observations from another portion of that data set (Marriott 1991; Hardisty et al. 1995). We used two cross-validation approaches. For simplicity, the term “validation” will be hereafter used instead of the term “cross-validation” to describe that process. In the first approach, we randomly selected two bivariate data points (LaGrange Reach in 2004 and Pool 26 in 2003), and data for those years were not used during model construction. Data for those two points were later used to determine whether the modeled residuals for those points were within the range of residuals for the model construction years (Draper and Smith 1981) and whether recruitment predictions were within the 95% confidence limits of the observed recruitment measurements. In the second validation approach, we constructed eight separate models. Each of those models was constructed after removing one of the eight bivariate data points, and each model was constructed using the remaining data. Each model was used to predict the observed value of recruit abundance. The slope of the linear regression developed from those eight observed and predicted recruit abundances was compared, using analysis of covariance (ANCOVA; Edwards 1985), to the slope (=1.0) of a line constructed that would have occurred if the observed and predicted recruit abundances were identical (i.e., 1:1 relationship of observed and predicted recruit abundance data). An *F*-test was used to determine if the slopes of the two lines differed significantly. The 95% confidence interval of the regression of observed and predicted recruit data were used to determine if the intercept of that line was significantly different from zero. Those two tests were conducted to evaluate all possible models over the entire range of conditions measured. A model or test was significant at $\alpha = 0.05$.

Results

Bighead carp recruitment to the 1–3-month-of-age stage in the LaGrange Reach and Pool 26 varied by a factor of 36 during 2001–2004 while abundance of stock size (≥470 mm) varied by a factor of 51 (Table 1). Recruitment variability was at least one of the factors that caused stock size abundance variability. The abundance of stock-sized (*S*) bighead carp explained 72% (r^2) of the recruit abundance (*R*) variation ($F = 10.23$, df = 5, $P = 0.03$; Figure 2). That functional relationship is

$$R = S\,e^{1.461 - 16.036 \times S}.$$

The modeled functional relation indicated that optimum stock size abundance was about 0.07 adults per unit effort. The model predicted poor recruitment below stock size abundance of about 0.02 adults per unit effort.

The model improved by adding the coefficient of variation of river discharge in July (*D* in m^3/s, Table 1), and that multivariate model explained 83% (R^2) of bighead carp recruitment variation ($F = 13.42$; df = 2,3; $P = 0.03$). That functional relationship is

$$R = S\,e^{5.629 - 18.824S - 0.107D}.$$

The functional relationship of that model showed recruitment decreased as river discharge coefficient of variation increased (Figure 3). The model developed, after randomly selecting two bivariate data points (LaGrange Reach in 2004, and Pool 26 in 2003), predicted recruitment within the 95% confidence limits of the observed recruitment (Table 1). Residuals for those model validation years were within the range of the model construction years (Figure 4).

Several additional analyses were conducted to evaluate the behavior of all stock-recruit models that could be conducted using available data. First, we constructed eight separate stock-recruit models after removing one of the eight bivariate data points. Recruit abundance for the deleted data point was predicted from the model constructed using the remaining data and the observed stock abundance for the missing data point. The slope of the linear regression, developed from those eight observed and predicted recruit abundances, was compared to the regression line that would have resulted if predicted values were identical to the observed ones. ANCOVA results showed that the slopes of the two lines were not significantly different ($F = 0.159$, $P = 0.699$). Also, the intercept of the regression of observed and predicted values was not significantly different from zero. We concluded that all possible models constructed from available data reasonably predicted observed values. The various approaches used to examine models and predictions did not invalidate the model displayed in Figure 3. Therefore, we consider that model validated.

Discussion

Recruit abundance of bighead carp in the LaGrange Reach and Pool 26 was negatively correlated with bighead carp stock-size abundance, and the coefficient for stock-size abundance in the stock-recruit model was significant. Compensatory density-dependent mortality (Hilborn and Walters 1992) affected bighead carp recruitment, so mortality of recruits increased as adult abundance increased above the optimum stock size abundance. That effect must have been due to intraspecific competition. Most (72%) of the variability in recruitment of bighead carp was explained by variation in stock size, so efforts to control populations in the LaGrange Reach and Pool 26 should focus mostly on reducing stock size abundance. The results of this study indicated that stock size abundance should be reduced to less than 0.02 adults per unit of effort to effectively control recruitment. This level of

Table 1. Relative abundance (catch per unit effort [CPUE]) of bighead carp adults (>470 mm), observed and predicted recruit abundances, and coefficient of variation of river discharge, La Grange Reach and Pool 26, 2001–2004.

		Abundance of bighead carp (CPUE)					
Location	Year	Adult abundance	Observed recruitment	Observed 95% confidence interval	Model (2 years randomly selected and deleted during model construction) prediction of recruitment	Model (each year deleted during model construction) prediction of recruitment	Coefficient of variation in river discharge during July (m^3/s)
LaGrange	2001	0.226	0.144	0.070–0.223	0.077	0.0157	22.8
	2002	0.256	0.004	0.000–0.010	0.006	0.0492	42.0
	2003	0.051	0.127	0.000–0.271	0.089	0.0861	38.2
	2004	0.055	0.098	0.043–0.156	0.059	0.0569	42.2
Pool 26	2001	0.005	0.011	0.000–0.024	0.008	0.0073	48.3
	2002	0.043	0.061	0.013–0.112	0.195	0.2464	30.8
	2003	0.019	0.101	0.015–0.195	0.159	0.1656	29.4
	2004	0.011	0.074	0.014–0.137	0.057	0.0500	35.2

$R = S\,e^{\,1.46133\,-\,16.0356\,S}$

$r^2 = 72\%$, df = 5, $F = 10.23$, $P = 0.03$

Where R = recruit catch per unit effort (CPUE) and S = stock CPUE

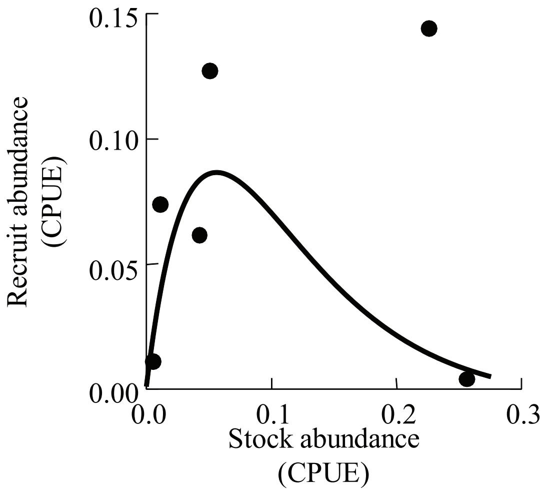

Figure 2. Empirical stock and recruitment data and the stock-recruit model for bighead carp in the LaGrange Reach and Pool 26, 2001–2004. Data for LaGrange Reach in 2004 and Pool 26 in 2003 are not shown and were not used during model construction.

$R = S\,e^{\,5.62869\,-\,18.8237\,S\,-\,0.10746\,D}$

adj. $R^2 = 83\%$, df = 2, 3, $F = 13.42$, $P = 0.03$

Where R = recruit catch per unit effort (CPUE), S = stock CPUE, and D = river discharge coefficient of variation (CV) in July

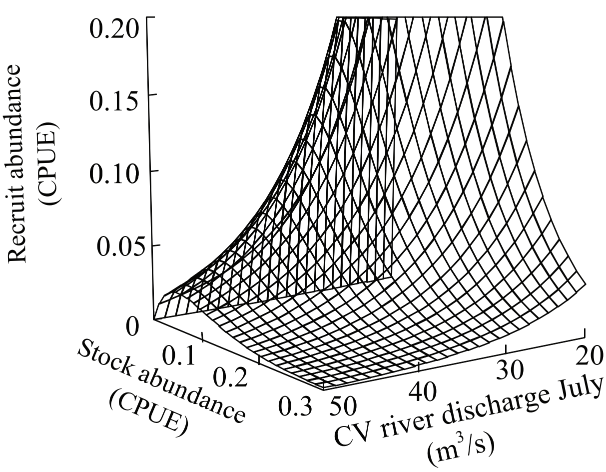

Figure 3. Functional relationship, from the trivariate stock-recruit model for bighead carp, of recruitment to stock size abundance and river discharge coefficient of variation during July. Data for LaGrange Reach in 2004 and Pool 26 in 2003 were not used during model construction.

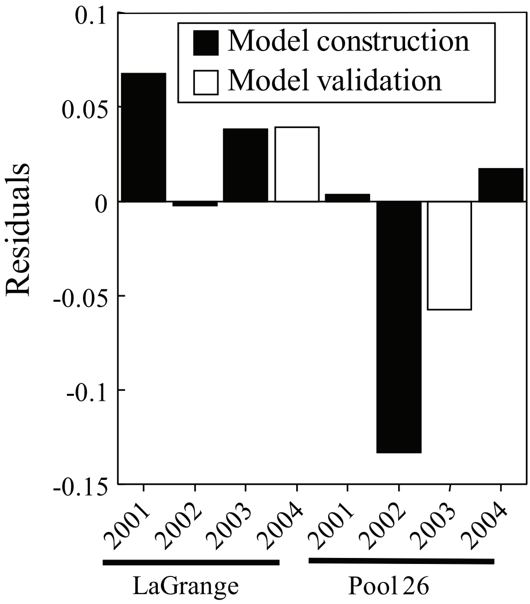

Figure 4. Residuals for bighead carp recruitment from the model developed using stock size abundance and river discharge coefficient of variation during July. Black bars display residual values for model construction data, and open bars display residual values for model validation data.

adult abundance (approximately 25% of the mean during 2001–2004) should be the target maximum for bighead carp control efforts that employ netting or other approaches to reduce adult abundance. Thus, the results of our study clearly show that harvest or other means of suppressing adult abundance is the most effective means of reducing recruitment. Suppressing recruitment over a sustained period will control abundance of bighead carp and minimize its ecological and economic impacts.

Recruitment was inversely correlated with variation in river discharge, which explained 11% of recruitment variation. Therefore, it is possible to combine control of stock-size abundance and management of river discharge in an integrated pest management program for bighead carp in the two river reaches.

Dams constructed in portions of the Illinois and upper Mississippi rivers are intended to enhance navigation but result in a side effect of reducing river discharge variability. Navigation dams in the upper Mississippi and Illinois rivers typically reduce the range of water-level variation over a distance ranging from one-half to two-thirds of the distance upstream to the next dam (Sparks et al. 1998). We interpret our model results to mean that this side effect of dams has been to enhance conditions for bighead carp recruitment by reducing natural variability in river discharge. Potential future modifications to river discharge regimes at dams in the study areas should include consideration of probable effects on bighead carp recruitment. We recommend additional study to develop a more detailed model (i.e., specific timing of discharge variability in relation to specific egg and juvenile life stages) of the relationship between river discharge variability and recruitment.

In the Yangtze River, where the bighead carp is native, spawning activity and larval abundance was highest when river discharge peaked (Duan et al. 2009). Spawning activity and larval production may also be greatest within our study areas during periods of greatest discharge, but peak discharge probably flushes larvae out of those areas. Recruitment to the fingerling stage of larvae flushed out of our study areas occurs downstream of our study areas.

The model displayed in Figure 3 overpredicted Pool 26 recruitment in 2003 by 50%, whereas LaGrange recruitment in 2004 was underpredicted by a factor of 2. Our models were based on only eight data points, so additional study is recommended to collect more data on stock and recruit abundance. Stock-recruit models constructed using additional data should result in more accurate predictions of recruitment.

We recommend that assessing risks of bighead carp establishment, outside the present range, include evaluating whether river discharge variability is at the low or high end of the range measured in our study areas. If river discharge in July (or the probable month of spawning and egg hatching) is at the low end of the range we measured, then our model results are interpreted to mean that risk of establishment is greater because recruitment would tend to be higher than in river reaches where discharge variation was at the high end of the range we measured. Areas with predicted highest levels of recruitment could be those where management efforts most focus on preventing human-assisted introductions of bighead carp.

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