Regression Analysis of the Relationships Among Life-stage Abundances of Brown Shrimp (*Penaeus aztecus*) and Environmental Variables in Southern Louisiana, USA

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ABSTRACT

Brown shrimp (*Penaeus aztecus* Ives) landings in the Gulf of Mexico display substantial interannual variability. We used regression techniques to analyze relationships among 27 years of postlarval, juvenile, and adult abundance estimates and a suite of environmental variables. Environmental variables included water temperature, salinity, turbidity, river flow rate, acres of suitable habitat, and precipitation. We used a combination of manual and stepwise model building procedures to develop annual models with offshore catch, late-juvenile, early-juvenile, and postlarval abundances as dependent variables. Environmental variables and preceding life history stages were exploratory variables. Commercial catch was described by late-juvenile abundance, water temperature, previous commercial catch, and river flow. The biological variables in the model explained 55% of the variability in offshore catch, whereas the environmental variables explained 24% of the variability. Environmental variables explained variation between each life history stage and were the only significant predictors of postlarval and juvenile abundance. The lack of biological links among early life history stages may result from environmentally-driven, density-independent relationships or biologically-driven, nonlinear relationships. We are designing an individual-based simulation model of shrimp to further explore the relationships among their early life history stages. Both the regression and simulation models are ongoing efforts. We hope the combination of statistical and individual-based simulation modeling will provide further insight into the factors that affect variability in brown shrimp recruitment.

KEY WORDS: Penaeid, brown shrimp, annual recruitment

INTRODUCTION

Like many penaeid fisheries, brown shrimp (*Penaeus aztecus* Ives, *Farfantepenaeus aztecus* Ives) landings in the Gulf of Mexico display substantial interannual variability. Because most of the shrimp caught in the Gulf fishery are less than one year old (Caillouet and Koi 1981), brown shrimp have an essentially annual life cycle. Adults spawn offshore, larvae move toward the coast, juveniles grow within the estuaries, and adults move away from the shallow coastal zone and enter the offshore fishery. The short life cycle and intense fishing pressure should make brown shrimp one of the easiest fisheries to forecast (Matthews et al. 1994).

With the world-wide commercial importance of penaeids, there are many models which attempt to predict shrimp abundance. Although the details of these models vary geographically and by species, they exhibit several common features. Commercial catch is related to several environmental variables including temperature (Barrett and Gillespie 1973, Barrett and Ralph 1977, Hettler 1992), rainfall (Staples 1985, Staples et al. 1995), intertidal vegetation (Turner 1977), and water level in the marsh (Zimmerman and Minello 1984). Many studies that examine biological variables use juvenile abundance to predict subsequent catch (Berry and Baxter 1969, Caillouet and Baxter 1973, Barrett and Gillespie 1973). Some models use postlarval abundance to forecast catch (Delauncy et al. 1994, Matthews 1995). Fewer studies (Vance et al 1998) look for links among the earlier life history stages.

Our objective in this paper is to use regression analysis to better understand the sources of interannual variation in Louisiana's brown shrimp recruitment. Recruitment in this paper is defined as the abundance of shrimp that reach the next life stage. We are interested in the prediction of annual catch and in what regression analysis reveals about penaeid ecology. We used 28 years (1970 – 1997) of biological and environmental data related to brown shrimp recruitment in order to examine the linear relationships among successive life history stages and environmental variables.

METHODS

We assembled a dataset that included annual values of brown shrimp abundance estimates by life stage and monthly or annual values of a suite of environmental variables. The four life stages examined were postlarval (number of shrimp/m^3), early juvenile (number of shrimp/10 minute trawl with six foot net), late juvenile (number of shrimp/10 minute trawl with sixteen foot net), and adult (pounds of offshore catch). Environmental variables examined water temperature, salinity, turbidity, river flow rate, precipitation, and acres of habitat > 10 ‰. Because shrimp may be affected by the environment at critical periods in the spring, annual monthly averages (for February through July) were calculated for salinity, temperature, turbidity, precipitation, and river flow. We dropped February salinity and turbidity because we had incomplete data at the beginning of the season.

The Louisiana Department of Wildlife and Fisheries (LDWF) provided postlarval and juvenile abundance estimates. A detailed description of the data collection procedures can be found in Marine Fisheries Division Field Procedures Manual (LDWF 1996). Table 1 summaries the LDWF sampling protocol for each life stage. In general, LDWF sampled weekly when the brown shrimp densities were known to be historically high. Postlarval data were collected from four major tidal passes in Barataria Bay, which functions as an index for brown shrimp recruitment. We calculated postlarval densities based on tow catch and flow meter readings. Estimates of juvenile abundance in Louisiana were obtained from six and sixteen foot otter-trawl surveys. Because of sample location and mesh size, the six foot trawl selected for smaller shrimp than the sixteen foot trawl. Hence, we used the six foot trawl data to estimate early-juvenile abundance and the sixteen foot trawl data to estimate late-juvenile abundance. The mean total length of the early juveniles was 65 mm, and the mean total length of the late juveniles was 75 mm.

Table 1. LDWF sampling protocol used to monitor the brown shrimp fishery in southern Louisiana.

Stage	Gear	Mesh Size	Sampling Location
Postlarvae	0.5 m plankton net	500 micron	Tidal passes
Early juvenile	6' trawl	3/8 inch	Shallow marshes
Late juvenile	16' trawl	3/4 inch	Bays, sounds, or lakes

We estimated adult abundance by using commercial catch data (in pounds) provided by the National Marine Fisheries Service. We also converted the annual pounds of commercial catch to annual numbers of shrimp caught. The use of numbers reduces effects of differential growth of individual shrimp during the juvenile stage when they are in the estuaries. Very similar results were obtained with numbers and pounds. We used total annual offshore heads-off catch as a dependent variable because offshore catch accounted for over 50% of the total annual recorded catch, and offshore catch was well correlated with total catch ($R^2 = 0.84$).

The LDWF provided two sets of environmental data. The first set of data was acquired in conjunction with the biological sampling of the postlarvae and juvenile abundances, and it included surface and bottom water temperature, surface and bottom salinity, and turbidity. The second set of environmental data was collected independently of the biological sampling, and included an annual estimate of the total number of acres with a salinity greater than 10 ‰, mean monthly precipitation in southern Louisiana (Source: NOAA Climatological Data), and mean monthly Mississippi River (at Tarbert Landing, Miss) and Atchafalaya River (at Simmesport, LA) flow rates (Source: US Corps of Engineers, New Orleans District). Examples of water temperature and river flow variables are shown in Figure 1a.

We did not discriminate between surface and bottom measurements of the environmental variables because the water column in areas of data collection were generally shallow and well-mixed. In cases where the LDWF sampled salinity and temperature at the top and bottom of the water column, we deleted outliers and used simple linear regression models to compare the surface and bottom values for each life history stage (postlarval, early juvenile, and late juvenile). The salinity near the bottom explained > 90% of the variation in surface salinity, and the bottom temperature explained > 97% of the variation in surface temperature. Because brown shrimp are primarily benthic, we used the bottom values of temperature and salinity. If bottom values were not available, we substituted surface values.

We used regression analysis to explore the relationships among life history stages and environmental variables. Specifically, we created regression models to describe the interannual variation in total annual pounds of offshore catch, mean annual late-juvenile abundance, mean annual early-juvenile abundance, and mean annual postlarval abundance. In order to describe each life history stage, we used the entire suite of environmental variables plus all preceding life history stage abundances. Because commercial catch may be an indicator of spawning potential, we used last year's catch (in pounds and numbers) as possible indicators of this year's abundances.

We used a combination of manual and stepwise (automated) regression to build our models. Automated stepwise model building presented potential problems due to the loss of data because of missing values. When multiple regressions were performed using SAS stepwise regression (SAS Institute 1989), the data were limited to years that had a value for all exploratory variables. Thus, initial regressions were run on few data points ($n < 10$) and had inappropriately large correlation coefficients ($R^2 > 0.95$). We therefore used a manual model-building procedure to identify a reduced set of exploratory variables, which were then used in the stepwise procedure. First the dependent variable was correlated to each exploratory variable. A simple linear regression was run using the dependent variable and the exploratory variable with the highest single correlation. The residuals from this regression were then correlated with all of the remaining exploratory variables. A second model was built using the residuals as the dependent values and the exploratory variable with the highest correlation as the new predictor variable. We repeated this procedure until no additional predictor variables were significantly correlated to the residual from the preceding model.

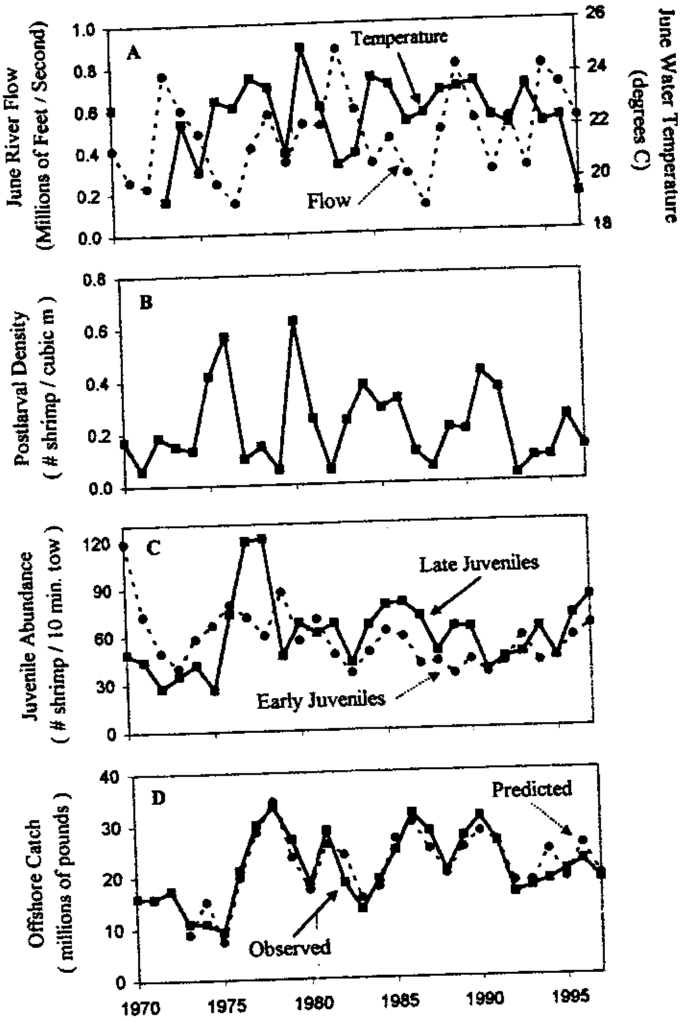

Figure 1. Annual values of selected environmental variables and brown shrimp life stage abundances. **1a.** June estuarine water temperature (°C) and June Atchafalaya and Mississippi River flow rates (10^4 cubic feet/second). **1b.** Postlarval Abundance (# of shrimp/m^3) **1c.** Early and Late-juvenile abundance (# of shrimp/10 minute trawl) **1d.** Offshore commercial catch (in millions of pounds).

We then preformed an automated stepwise multiple regression using the variables that were selected with the manual procedure. The stepwise process allowed the removal of predictor variables in later models. All variables that were not significant at the 0.10 level were removed one at a time from the regression equation. Removing variables changed the regression relationship because it allowed more years to be included in the analysis. We used the resulting regression equation to predict catch for each year in the study period. We report the final models which were identified by the combination of manual and stepwise model building. In an attempt to explore the contribution of environmental and biological variables, the model predicting commercial catch was subsetted into two reduced models. The first reduced model contained only biological variables, and the second reduced model contained the environmental variables.

RESULTS

Commercial catch of brown shrimp in Louisiana was described by late-juvenile abundance, April water temperature, total estimated number of shrimp caught in Louisiana in the previous year, and June Mississippi and Atchafalaya River flow (Table 2, Figure 1d). The reduced biological model explained 55% of the variability in offshore catch, whereas the reduced environmental model explained 24% of the variability in catch.

The early life history stages were correlated with environmental variables but not with preceding life-stage abundances. Late juvenile abundance was correlated with salinity variables and with May water temperature (Table 2). All of the salinity variables, except March salinity, suggested that abundance of late juveniles was higher under saltier conditions. Early juvenile abundance was correlated with turbidity, river flow, precipitation, and salinity (Table 2). Post larval abundance was correlated with temperature in the tidal passes, salinity, precipitation, and river flow (Table 2).

DISCUSSION

Environmental variables helped explain the variation between each life history stage and were the only significant predictors of the postlarval and juvenile abundances. In general, environmental conditions in the later months (May and June) were correlated more closely with the later life stages (late-juveniles and adults) and earlier months (February and March) were correlated more closely with the earlier life stages (postlarvae and early-juveniles). Although there were exceptions, higher shrimp abundance was generally associated with higher salinity and warmer water temperature.

Table 2. Final regression models from the analysis of brown shrimp life stage abundances and environmental variables. Final models are those determined from the combination of the manual and stepwise model building procedure.

Dependent Variable	Predictor Variables (Positive or Negative Relationship)	n	R^2	P
Commercial Catch	Full Model: + Late juvenile abundance + April estuarine water temperature + Number of shrimp caught last year + June river flow	25	0.85	$p < 0.0001$
	Reduced Biological Model: + Late juvenile abundance + Number of Shrimp caught last year	27	0.55	$p < 0.0001$
	Reduced Environmental Model: + April estuarine water temperature + June river flow	26	0.24	$p < 0.0454$
Late Juveniles	+ March estuarine salinity + June estuarine salinity - Annual precipitation (in SE LA) + May estuarine water temperature + May precipitation (in SE LA) - March salinity (in lower estuary)	21	0.87	$p < 0.0001$
Early Juveniles	- June estuarine turbidity - February river flow - Annual precipitation (in SE LA) - March salinity (in lower estuary)	23	0.66	$p < 0.0005$
Postlarvae	+ February temperature (in passes) - May temperature (in passes) + March salinity (in lower estuary) - February precipitation (in SE LA) + April river flow	20	0.77	$p < 0.0004$

As is the case with most regression analysis, correlation does not necessarily mean causation. Variables selected by the regression procedure may represent a controlling mechanism or may simply be correlated with a controlling mechanism. For example, June turbidity was selected as a significant predictor of early juvenile abundance. Turbidity might directly affect juvenile abundance by affecting predator prey relationships (Minello et al. 1987). Alternatively, turbidity may simply be correlated with a controlling mechanism, such as wind-driven events that affect postlarval transport and salinity regimes. The lagged catch variable is a second example of an uncertain controlling mechanism. Whereas last year's catch may reflect this year's spawning potential, it may also be a reflection of trends in expended effort and gear efficiency.

Caution in the interpretation of the final regression models is appropriate due to the multicollinearity among predictor variables. Collinearity can arise from covariance among related variables (e.g. salinity and precipitation) and from using several monthly values of a single environmental variable (e.g. April temperature and May temperature). Because each iteration of the selection procedure chose only one variable for inclusion, several well-correlated variables were not included in the prediction equation. For example, the selection procedure included late juvenile abundance (r = 0.62) but did not include annual mean turbidity (r = 0.56). Correlated environmental variables might help explain the inclusion of suspicious variables. For example, May temperature predicted postlarval abundance even though the postlarval abundance peak is in March and April.

Whereas environmental variables were significant predictors at all life history stages, the biological link among abundances at successive life history stages was only detected between the late-juvenile and adult abundance. Failure to document the biological links among the early life history stages could be explained in several ways. One explanation is that we have inappropriate or insufficient data to detect relationships in abundance. The juvenile abundance estimates may be inappropriate because trawl data can be qualitative rather than quantitative measures of abundance (Rozas and Minello 1997). The postlarval data stage is especially susceptible to insufficient sampling due to the difficulties in capturing pulses of immigrants. Nevertheless, we presume that because the LDWF sampling protocol captured the pattern in the late-juvenile to adult abundance, it could also capture an abundance pattern in the early to late-juvenile stage.

Assuming we have appropriate and sufficient data to detect relationships among successive life stages, the lack of biological links among early life history stages may result from environmentally-driven, density-independent relationships and density-dependent, nonlinear relationships. To explore these possibilities, we are designing an individual based model to simulate early life history stages. The simulation model begins at post-larval immigration into the estuaries and tracks individual shrimp in a spatial grid of land and water cells until the shrimp emigrate back to coastal waters. Habitat-dependent growth and mortality are recorded at each tidal cycle. Initial simulations indicate the important, but complex, role of edge habitat in affecting shrimp survival within the estuary.

Both the regression and simulation models are ongoing efforts that are still being refined. We plan to expand the regression model by adding variables associated with estuarine water levels, acres of vegetated habitat, shrimping effort, and timing of the inshore fishing season. Using a biological year (Klima et al. 1982) rather than a calendar year might also strengthen the regression relationships. After we expand the regression model, we will examine regression diagnostics and then use the same regression procedures to examine inshore shrimp catch. The pounds caught inshore and offshore are not well correlated ($r^2 = 0.22$) and may be related to a different suite of variables. We are also considering alternative analytical methods to regression, such as neural network analysis and general additive models, to explore any relationships among the early life stages. We hope the combination of statistical and individual-based simulation modeling will provide further insight into the factors that affect variability in brown shrimp recruitment.

ACKNOWEDGEMENTS

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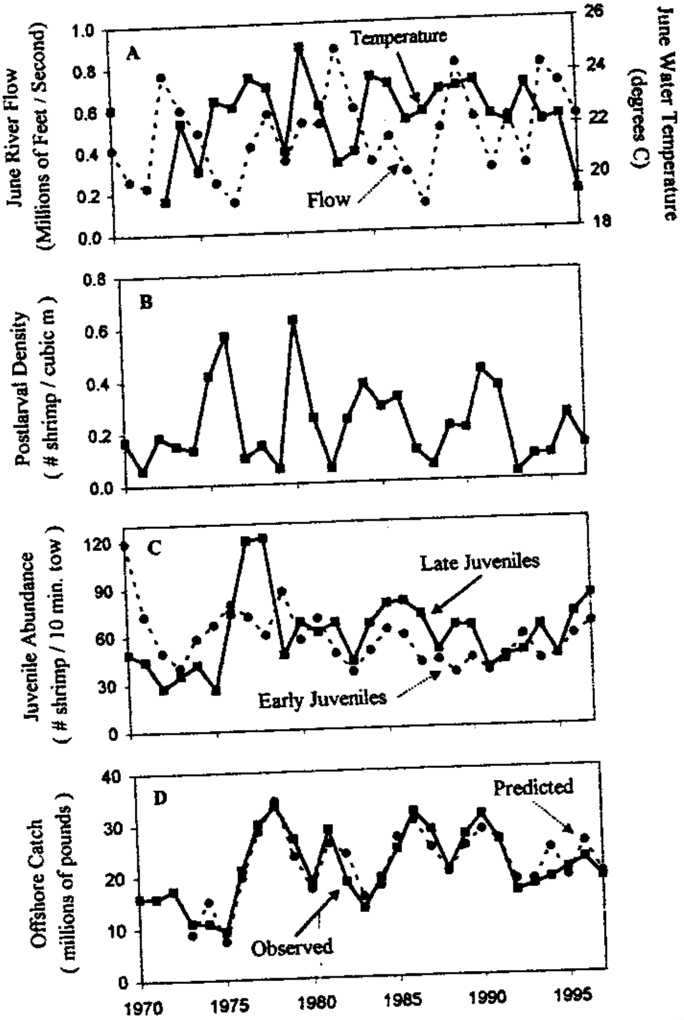

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