Forecasting the fishery for pink shrimp, *Penaeus duorarum*, on the Tortugas Grounds, Florida

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Abstract.—In this report I review the biology of and fishery for pink shrimp, *Penaeus duorarum*, harvested from the Tortugas Grounds off southwest Florida, and present models used to forecast annual pink shrimp landings in this area. Pink shrimp spawn all year, and larvae recruit to nurseries in the seagrass-mangrove ecosystem surrounding Everglades National Park and Florida Bay. Juveniles move out of the nurseries all year, but catch per unit of effort for smallest size classes generally exhibits March and September peaks. Total landings usually rise sharply in November and taper off after April. The fishery was relatively stable during 1960–85, averaging 4,350 metric tons annually, but it has shown a singular decline and potential recovery since 1985. In 1987, I began forecasting annual landings by using multiple regression analyses of fishery catch statistics and environmental factors that could affect survival, growth, and recruitment. Potential predictor variables from May through October were investigated in order to release a timely annual forecast by November. Each year, the updated data set from 1966 onwards was examined to derive the "best" forecast models. Important predictor variables included indices of fishing activity during the waning months of the fishery (May–July) and surface and ground water levels within Everglades National Park during June-September. Forecasts were within ±20% of actual landings for five of eight years, whereas forecast direction (increase or decrease over the prior year) was usually correct. Cause-effect relationships between predictor variables and pink shrimp recruitment to the fishery remain to be determined.

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The pink shrimp, *Penaeus duorarum*, fishery over the Tortugas Grounds, southwest of Florida, averaged 4,525 metric tons (t) of shrimp tails per year during 1960–80 (Nance and Patella, 1989). Landings began to decline in the mid-1980's, collapsed to 2,000 t during 1988–91 for no apparent reason, and rebounded to over 4,000 t in 1994.[1,2] Coincident with this unprecedented decline, the Gulf of Mexico Fishery Management Council (GMFMC) requested that the National Marine Fisheries Service (NMFS) evaluate the possibility of forecasting annual landings for the Tortugas pink shrimp fishery. The Gulf of Mexico Fishery Management Council and NMFS expected that such a model could aid in the planning and evaluation of management actions and could assist shrimp fishermen in preparing for the upcoming fishing season. NMFS has been forecasting annual brown shrimp, *P. aztecus*, landings for Texas since 1962 (Berry and Baxter, 1969; Baxter and Sullivan, 1986) and for Louisiana since 1985.[2] Annual forecasts are released to the fishing industry in newsletters and direct mailings. Forecasting models for the Tortugas pink shrimp fishery have been proposed previously (Yokel et al., 1969; Browder, 1985). However, Yokel et al. never implemented their model, and Browder's annual models provided relatively poor forecasts for the three years beyond her base data set (estimated from Fig. 9 in Browder [1985] to be –24%, +53%, and +56% of actual 1981, 1982, and 1983 landings, respectively).

In this report I review both the biology of and the fishery for pink shrimp in southern Florida. I then present empirical models used by NMFS since 1987 to forecast annual Tortugas pink shrimp landings. These models are based on environmental conditions in the primary pink shrimp nurseries of Florida Bay, Everglades National Park, and adjoining coastal waters. Pink shrimp production is likely linked to survival and growth of juveniles in these habitats. For example, high water levels in Everglades National Park during October–December and January–March were associated with subsequent high pink shrimp catches in January–March and April–June, respectively (Browder, 1985). A disruption in nursery habitat functions, such as those resulting from seagrass mortality (Robblee et al., 1991) or freshwater diversion (Light and Dineen, 1994), may have been causes of previously noted fluctuations in pink shrimp harvest.

[1] Nance, J. M. 1994. A biological review of the Tortugas pink shrimp fishery through December 1993. Unpublished report to the Gulf of Mexico Fishery Management Council, National Marine Fisheries Service, 4700 Avenue U, Galveston, TX 77551, 11 p.

[2] National Marine Fisheries Service. 1985–1994. 4700 Avenue U, Galveston, TX 77551. Unpubl. data.

The predictive model(s) was intended to provide an estimate of a future 12-month total pink shrimp catch with a forecast issued in advance of the main shrimping season. For the Tortugas fishery, monthly catches generally rise sharply in November and taper off after April (Nance and Patella, 1989). Ideally, the forecast should be released to the industry no later than October. In practice, however, there are time delays between data collection for a given month and availability of final data. My goal was to release a forecast by October $Y_{t,t}$ for the November $Y_{t,t}$ through October $Y_{t,t+1}$ "fishing year."

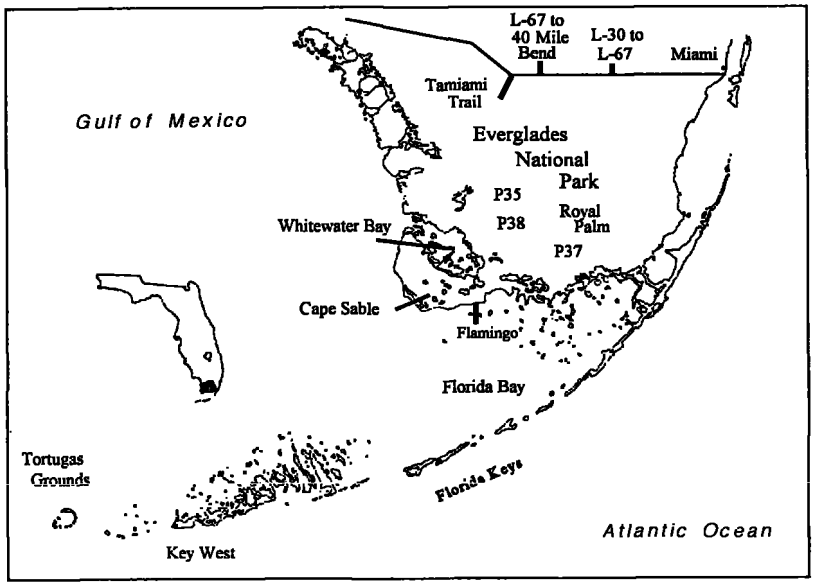

Figure 1

Location of the Tortugas pink shrimp grounds in relation to the southern Florida environmental data sources. P35, P37, and P38 are wells in Everglades National Park. Rain gauges are located at Flamingo, Royal Palm, and Tamiami Trail. Surface water discharge gates are located at L-67 to 40-Mile Bend and at L-30 to L-67.

Since the fishery's inception in 1949, researchers have postulated that landings from the Tortugas Grounds were dependent on survival and growth of postlarval and juvenile pink shrimp in primary nursery habitats of Florida Bay and Whitewater Bay (Fig. 1). Female shrimp in spawning condition were found all year on the Tortugas Grounds west of Key West, with the highest frequency of ripe females occurring April through July (Ingle et al., 1959; Cummings, 1961). Larval stages were found all year in waters west and south of Florida Bay but were generally most abundant in the same months as ripe females (Munro et al., 1968; Jones et al., 1970). Postlarval stages also were found all year, but late postlarval stages were found primarily near the coast and in Florida Bay and Whitewater Bay (Tabb et al., 1962; Jones et al., 1970; Roessler and Rehrer, 1971; Allen et al., 1980). Larval and postlarval stages were first thought to migrate into Florida Bay by riding surface waters on the eastward tidal excursion and by dropping to the bottom either during westward tidal movement (Koczy et al., 1960) or after detecting lower salinities (Hughes, 1969). Alternatively, currents were hypothesized to sweep larvae south and east of the spawning grounds and along the south side of the Florida Keys until larvae entered Florida Bay through passes between the keys (Rehrer et al., 1967; Munro et al., 1968). Recent research on larval shrimp distributions in relation to currents has indicated that both immigration methods may be effective (Criales and Lee, 1995).

Postlarvae reaching coastal seagrass and mangrove nurseries encounter several distinctive environments: Florida Bay seagrass beds are frequently hypersaline, the Whitewater Bay ecosystem is estuarine, and the Florida Keys are oceanic (Tabb et al., 1962; McIvor et al., 1994). Catches of postlarval and juvenile pink shrimp were highest in seagrasses of western Florida Bay and the middle Florida Keys, moderate in central Florida Bay and the lower Keys, and low to absent in eastern Florida Bay (Costello et al., 1986; Holmquist et al., 1989). Pink shrimp also recruit to the mangrove-lined Whitewater Bay system and were found to be more abundant in submerged aquatic vegetation than in nonvegetated areas during trawl surveys (Idyll and Yokel, 1970). Higher densities of pink shrimp are associated with seagrass (*Thalassia testudinum* and *Halodule wrightii*) habitats than with algal, red mangrove (*Rhizophora mangle*) prop root, or nonvegetated habitats (Sheridan, 1992; Sheridan et al.[3]). Widespread mortality of seagrasses (Robblee et al., 1991) thus might be expected to reduce subsequent pink shrimp harvests.

Juvenile pink shrimp exhibit early spring and late summer peaks in abundance in western Florida Bay (although only a single summer peak has been observed for the last decade[4]) and move out of coastal habitats on ebb tides, at night, during full and new moons (Tabb et al., 1962; Hughes, 1968; Yokel et al.,

[3] Sheridan, P., G. McMahan, G. Conley, A. Williams, and G. Thayer. 1996. Response of macrofaunal communities to seagrass mortality in Florida Bay (Florida, USA). I. Shallow bank-top habitats. In review.

[4] Robblee, M. 1995. National Biological Service, Southeastern Research Program, Florida International University, Miami, Fl 33199. Unpubl. data.

1969). Rapid salinity changes, as might be experienced during rainy season floods, may also force shrimp out of nearshore habitats (Hughes, 1969). Emigration of juvenile pink shrimp from nurseries in summer and fall has been postulated to form the fall and winter landings of new recruits by the fishery (Higman et al., 1972). Juvenile and subadult pink shrimp marked and released in southwest Florida coastal habitats were primarily recaptured on the Tortugas fishing grounds (Costello and Allen, 1966; Gitschlag, 1986). Apparent pink shrimp movement speeds were 1–2 km/day (Costello and Allen, 1966); thus pink shrimp could reach the fishing grounds 100 km southwest of Cape Sable (Fig. 1) in 50–100 days, as postulated by Higman et al. (1972).

Environmental determinants of pink shrimp growth and survival have not been examined extensively. Most available information consists of pink shrimp abundance and size by season or habitat, with coincident measurements of temperature and salinity. Pink shrimp have wide tolerances for salinity and temperature (0–65‰ and 11–40°C; Costello and Allen, 1970; Costello et al., 1986). Maximum growth of postlarval pink shrimp (7.8–10.1 mm total length [TL]) was found at 30–35°C under constant salinity (28–32‰, Teinsongrusmee, 1965). The only experimental analyses of pink shrimp survival versus combined temperature and salinity variations was conducted by Williams (1960). Survival of juveniles (35–100 mm TL) was highest (77–100%) at 15–30‰ and 8.8–28.4°C but was significantly lower (62–67%) at 10‰ and 8.8–28.4°C due to impaired osmoregulation. Higman et al. (1972) conducted enclosure experiments to determine pink shrimp growth in the field but felt that poor water quality conditions confounded their results. Neither Williams (1960) nor Teinsongrusmee (1965) addressed the hypersaline conditions often experienced in Florida Bay (up to 70‰; McIvor et al., 1994).

The Tortugas fishery began in 1949, and since 1956 monthly catch and effort data have been collected by NMFS personnel using standard methods (Nance and Patella, 1989). The fishery has landed an average of 4,350 metric tons (t) annually during 1960–85 (NMFS[2]) and was relatively stable (coefficient of variation=17%; Nance and Patella, 1989). Since that time, however, the fishery has shown a singular, and as yet unexplained, decline and apparent recovery (Fig. 2). In conjunction, the bimodal trend in monthly catch per unit of effort (CPUE) of the smallest pink shrimp size class (≥68 tails to the pound, or "68-count") has changed (Fig. 3). The fall peak in recruitment of 68-count pink shrimp that dominated in early years (1960–69) has shifted in favor of a spring peak. This shift may have been the result of management measures enacted during 1961–81 to restrict the catch of small shrimp (Caillouet and Koi, 1981; Gulf of Mexico Fishery Management Council, 1981).

Materials and methods

Fishery yield forecasts often depend upon indices of larval or juvenile abundance as indicators of recruitment into a fishery. Forecasting brown shrimp yield off Texas depends upon landings of juveniles by the Galveston Bay bait shrimp industry immediately prior to their emigration from the bay (Berry and Baxter, 1969; Baxter and Sullivan, 1986). Forecasting western rock lobster, *Panulirus cygnus,* yield is based on seasonal settlement of the final planktonic stage (puerulus) on collectors at a single site, Seven Mile Beach, Western Australia (Phillips, 1986). In Florida, however, there are no long-term fishery-independent data sets describing larval or juvenile pink shrimp abundance in coastal habitats. Thus, my models are based on fishery-dependent catch statistics and on environmental variables that could affect the survival, growth, and recruitment of pink shrimp, even though causal mechanisms may be

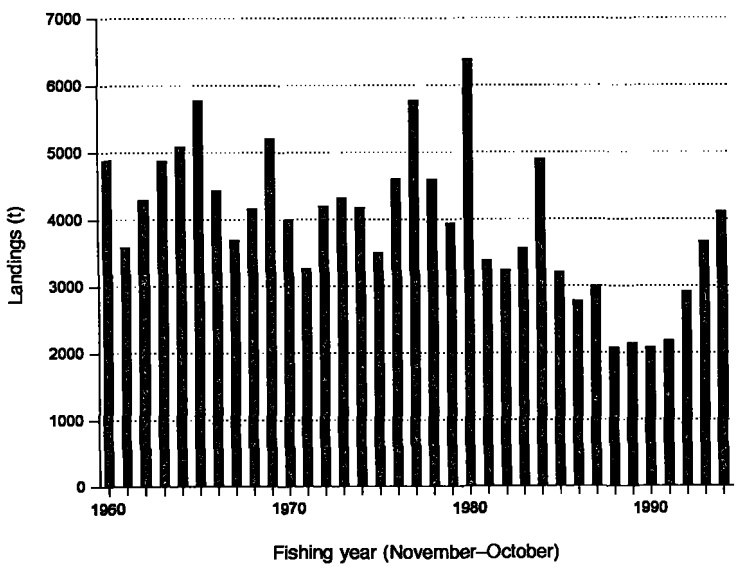

Figure 2

Annual landings by the Tortugas pink shrimp fishery (NMFS, Footnote 2 in the text).

unknown. The above review of the literature indicated that factors affecting larval and juvenile pink shrimp abundance and survival during the months of May–October were most likely to affect recruitment to the next fishing year.

Data sources

Development of forecasting models requires sets of long-term data collected in a consistent manner. There are no long-term environmental or biological data sets from within Florida Bay per se (Schmidt and Davis, 1978), with the exception of an historical salinity data set that has been compiled by the National Biological Service.[4] Thus, the primary sources of long-term data used in my models were those with physical or biological factors for May–October in locations near Florida Bay. These sources were the U.S. Department of Commerce (National Weather Service [NWS]; National Ocean Service [NOS]; and NMFS) and the U.S. Department of the Interior (Everglades National Park [ENP]).

National Weather Service stations in Key West and Miami, Florida, bracket Florida Bay and Everglades National Park (Fig. 1). The NWS collects data that provide hourly, daily, and monthly maxima, minima, means, and totals for climatic factors.[5] Monthly values at each site were compiled for the following variables: mean air temperature; total heating and cooling degree days (on any given date, one degree day accrues for each °F that the mean temperature falls below or above 65°F [18.3°C], respectively); total days with air temperatures ≤55°F (13°C) and ≥90°F (32°C) to examine effects of temperature extremes; mean wind speed; mean cloud cover; and total rainfall.

NOS records monthly sea level data at Miami Beach and Key West, Florida. I compiled monthly mean sea level data for Key West (station number 8724580), the tide gauge used by NOS to develop tide tables for Florida Bay.[6]

ENP maintains a series of ground water wells, surface water discharge gates, and rain gauges to monitor hydrology within the park.[7] I compiled the following data: mean monthly water level at three wells closest to the coast (P35 and P38 in Shark River Slough flowing into Whitewater Bay and the Gulf of Mexico, and P37 in Taylor Slough flowing into central Florida Bay); monthly total surface water discharge into northern ENP via two sets of water control structures (Canal L-67 to 40-Mile Bend and Canal L-30 to Canal L-67, later referred to as L-67 and L-30) along the Tamiami Trail, U.S. Highway 41; and total monthly rainfall at three gauges within the park (from south to north: Flamingo, Royal Palm, and Tamiami Trail; Fig. 1). In 1987, a correlation analysis of the ENP, Key West, and Miami monthly rain data was conducted for the period 1963–86. Although all five gauges were significantly correlated (r=0.514–0.792, P<0.05), the Royal Palm gauge had the highest correlations with gauges other than Key West (r=0.773–0.792). Lowest correlations were found between Key West and other gauges (r=0.514–0.609). For these reasons, Royal Palm was selected as the primary rainfall indicator (Miami was substituted directly in 1993 because of disruptions in ENP data availability caused by Hurricane Andrew).

Finally, NMFS collects monthly catch and effort data (and thus catch per unit of effort, CPUE) by various size classes for shrimp fisheries in the Gulf of Mexico.[8]

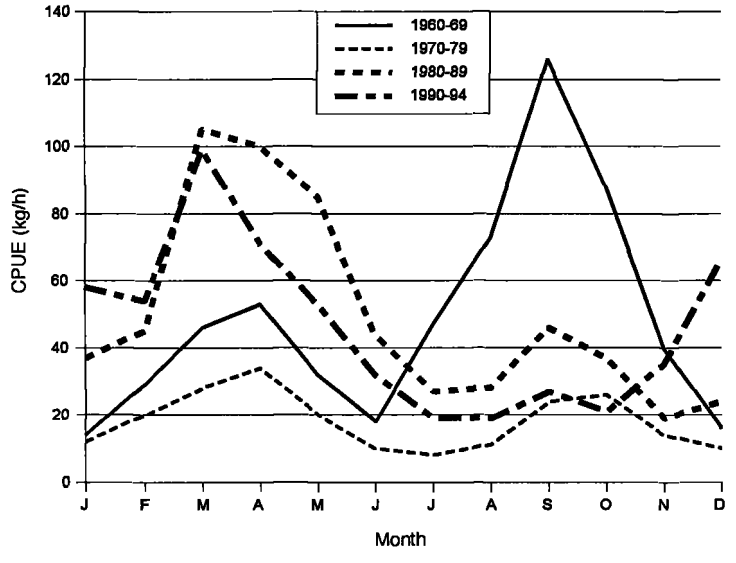

Figure 3

Decadal average monthly catch per unit of effort (CPUE) of 68-count pink shrimp (NMFS, Footnote 2 in the text).

[4] National Weather Service. 1963–1994. Local climatological data, monthly summaries for Miami and Key West, Florida. NOAA, National Climatic Data Center, Asheville, NC 28801.

[6] National Ocean Service. 1963–1994. Tides, high and low waters. NOAA, National Ocean Service, Tidal Analysis Branch, Silver Spring, MD 20910.

[7] Sikkema, D., and G. Schardt. 1987–1994. Hydrological Section, South Florida Research Center, Everglades National Park, Homestead, FL 33034. Unpubl. data.

[8] National Marine Fisheries Service, Statistics Operation Team. 1960–1994. 75 Virginia Beach Drive, Miami, FL 33149. Unpubl. data.

I compiled monthly pink shrimp catch, effort, and CPUE for all sizes combined and for the smallest size category (≥68 tails to the pound or "68-count") in NMFS statistical subareas 1–3 off southwestern Florida.

In addition to monthly values for these 29 variables, two quarterly means or totals for each variable (May–July and August–October) were created. These data resulted in a suite of 232 variables (29 variables × 6 months plus 29 variables × 2 quarters) as potential predictors. All data were received and analyzed in American system units (e.g. shrimp in pounds, rainfall in inches). Actual and predicted landings are presented in metric equivalents. Analyses began with the year 1966 because it was the approximate completion date for the system of major water control structures that influence ENP and Florida Bay (Light and Dineen, 1994).

Statistical analyses

The statistical relationships of annual pink shrimp catches in NMFS statistical subareas 1–3 with environmental and biological variables were examined by multiple linear regression. The tentatively entertained models were of the form

$$C = b_0 + b_1x_1 + b_2x_2 + \ldots b_kx_k,$$

where C = total November$_{Yr.\ t}$–October$_{Yr.\ t+1}$ pink shrimp catch;
x_k = variables measured during May–October;
b_k = regression coefficients; and
k = number of variables in the model.

For the first forecast (released in November 1987), environmental and biological data for May–October 1966–86 were used to develop descriptive ("hindcast") models, whereas data for May–October 1987 were reserved for the forecast. Initial regression analyses employed the "R-square" option of the SAS regression procedure (SAS Institute Inc., 1985) to capitalize on the power of Mallow's test statistic C_p. This option produces regression equations and multiple R^2 values for all possible subsets of p variables, allowing the investigator to choose the "best" linear model(s) based on R^2. Mallow's C_p statistic detects a "best" set of explanatory variables that minimizes both error due to too few variables and variance of predictions due to too many variables (Daniel et al., 1971). Regression equations with $C_p > p$, where p = number of variables in the equation, have increased bias whereas equations with $C_p < p$ have increased error. Regression equations including more than one form of a variable, such as those with a quarterly variable plus one or more of its component months, were not allowed. For models with $C_p \cong p$, stepwise regression (F-to-enter=0.25 and F-to-stay=0.25) was used to determine all partial and full statistics. The Durbin-Watson statistic was used to assure that autocorrelation in the selected models was minimal (i.e. that errors in regression were independent; Draper and Smith, 1981). The relationship between residuals and fitted values was examined to assure constant variance. Residuals were checked against Cook's statistic to assure that outliers did not unduly influence model coefficients (Draper and Smith, 1981). Models passing all these tests were employed for the annual forecast. Model performance was assessed by examining the direction of the forecast (whether landings increased or decreased over the prior year) and the accuracy of the forecast (expressed as percent above or below actual landings). Forecasts in the same direction and with accuracies of actual landings ±20% were termed successful.

After 1987, data sets were updated regularly and the regression procedures were repeated each year for the annual forecast, beginning with development of new descriptive models.

Results

Of the 232 possible predictors, only 30 monthly variables and two quarterly variables have ever appeared in the 26 forecast models generated since 1987 (Table 1). Only a few of these variables have occurred on a regular basis, including in decreasing frequency: 1) days fished during July; 2) ENP L–67 discharge during September and June; 3) ENP groundwater level in wells P38 during August and P37 during September; 4) CPUE of 68-count pink shrimp during May, and 5) Key West wind speed in September. Relationships of these variables to subsequent fishing year landings are illustrated in Figures 4–7. Five- and six-variable models incorporating four or more of these variables provided the most accurate forecasts.

Single forecast models were used in 1987 and 1988, whereas all other forecasts employed 2–4 models (Table 2). In multiple-model years, models usually differed by a single variable, and tests for selecting those models (Mallow's C_p and R^2) gave little reason for favoring one model over another. One exception occurred in 1989 when two sets of models with different independent variables were developed (models 3 and 4 versus models 5 and 6 in Table 2). Forecasts released to the industry stated whether landings were expected to improve or decline and gave high and low landing estimates from the models. A set of revised models for 1993 (forecasts were not

Table 1

Variables included in at least one regression generated for 1987–95 Tortugas pink shrimp landings forecasts. Variables are monthly means or totals (month 5=May) except RRain57 and MRain57 which are summed over months 5–7. NMFS = National Marine Fisheries Service; ENP = Everglades National Park; NWS = National Weather Service; NOS = National Ocean Service. Data are received from sources in American system units (in parentheses). Abbreviations are used in Table 2. ac-ft = acre feet.

			Frequency of occurrence by month					
Source	Variable	Abbreviation	5	6	7	8	9	10
NMFS	Total pink shrimp catch (lb)	Pink		8				1
	Total fishing effort (days)	Days	1	1	20		2	
	Catch per unit of effort of 68-count pink shrimp (lb/day)	CPUE68	11	1		1	3	
ENP	Mean water level in well P35 (ft)	P35	1			3	4	
	Mean water level in well P37 (ft)	P37				1	9	
	Mean water level in well P38 (ft)	P38		1	1	15	1	5
	Total rainfall, Royal Palm (in)	RRain		1				
	Total rainfall during May–July, Royal Palm (in)	RRain57	3					
	Total surface water discharge, L-67 to 40-Mile Bend (ac-ft)	L67		14		2	19	2
NWS	Total rainfall during May–July, Miami (in)	MRain57	1					
	Mean air temperature, Key West (°F)	KAir						4
	Mean wind speed, Key West (mi/h)	KWind	3		2		9	
NOS	Mean sea level, Key West (ft)	Sea	1					

released to the industry) is included as well (Table 2) because Hurricane Andrew impacted south Florida in August 1992 and disrupted ENP data collection through the remainder of 1992 and into 1993. All data were held until ENP had verified that recording instruments had not been disturbed by the hurricane or that instruments had been resurveyed and appropriate corrections had been applied to data sets.[7] These revised forecasts are presented in Table 2 because ENP data figured prominently in every other model.

All models derived in 1987, 1990, 1991, 1992, and 1994 produced forecasts that were within ±20% of actual landings (Table 2). All 1990 and 1991 models (models 7–12) contained the same first five variables. Models 13 and 14 (1992) and models 22 and 23 (1994) contained similar independent variables as did successful 1990–91 models. Forecast models for 1989 included two relatively successful ones (models 3 and 4, –10% and +18% of actual landings) and two poor ones (models 5 and 6, +45% and +44% of actual landings). None of the 1989 models approached the Mallow's test criterion of $C_p = p$, but models 3 and 4 had relatively high R^2 values compared with those of models 5 and 6. Model 2 (1988) and models 15–17 (1993) produced unsuccessful forecasts. Model 2 was the only forecast equation that had no variable directly associated with the Tortugas fishery, although all other unsuccessful models did have such variables. Models 15–17 were derived without access to ENP data which had been incorporated in all other models, successful or otherwise. Had ENP data been available, models 18–21 would have been generated with all but model 19 producing successful forecasts. Models generally forecasted increases or decreases in future landings correctly, with exceptions in 1989, 1991, and 1993. In both 1989 and 1993, three of four models correctly forecasted increased landings, whereas in 1991 only one of three models correctly forecasted decreased landings. Finally, the forecast models for 1995 (for which actual landings will not be available until late 1996) are presented for comparison with previous models and as documentation of the wide range in forecasts (2,858–4,581 t) seen previously only in 1989.

Every model contained at least one independent variable measured in September, and some models included October measurements. These data were usually unavailable until November, thus my goal of releasing each forecast in October was never achieved.

The fact that several variables consistently entered forecast models that were generated annually argues for selecting a single model with fixed variables. This strategy was assessed by applying monthly data, collected in years after generating each model, to those models in order to determine accuracy, if a given

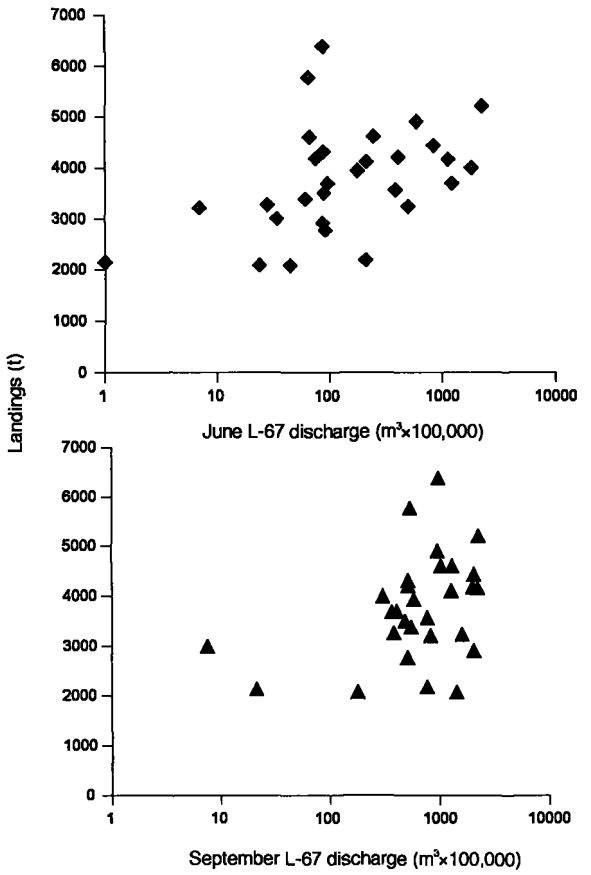

Figure 4

Scatterplots of surface water variables against subsequent fishing year landings, 1966–94.

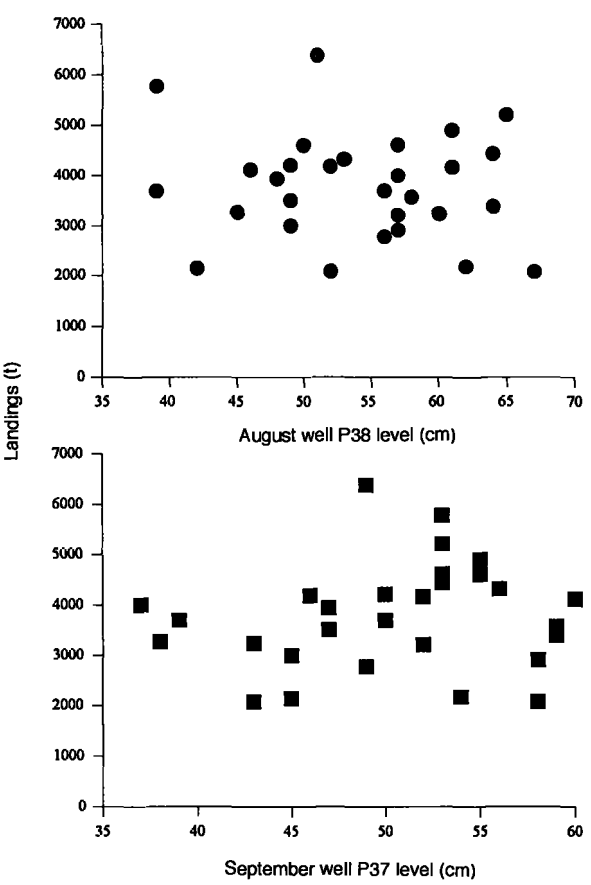

Figure 5

Scatterplots of well water levels against subsequent fishing year landings, 1966–94.

year's model had become "the" forecast model (Table 3). The results indicate that a model that successfully forecasts for the year it was developed does not always function well in succeeding years (e.g. models 1, 3, and 9) and that initially poor models can later become successful (e.g. models 5 and 6). Generating new forecast models each year from updated databases appears to be more accurate than using a fixed forecast model.

Discussion

These models were quite accurate at forecasting whether landings would increase or decrease and only moderately accurate at forecasting amounts landed, but they did not address cause-effect relationships between environmental variables and pink shrimp recruitment. The regular selection of only a few variables in the regression models, however, implies that determining the mechanisms behind selected variables describing Florida Bay and adjacent waters could provide the requisite data for more accurate forecasting of pink shrimp landings. Two classes of data regularly occurred as forecast variables: 1) measurements of upland freshwater supply during the rainy season, and 2) fishing activity on the Tortugas grounds during the waning months of a given fishing year.

Correlation between penaeid shrimp production and freshwater inputs have been recorded worldwide, even though the exact relationship between landings and freshwater may be site- or species-specific. In a previous study of the Tortugas pink shrimp fishery, quarterly landings were found to be either positively or negatively correlated with ENP ground water levels (Browder, 1985). Elsewhere, correlations between penaeid shrimp landings and rainfall, river discharge, or well-water levels have been positive (Hildebrand and Gunter, 1953; Gunter and Edwards,

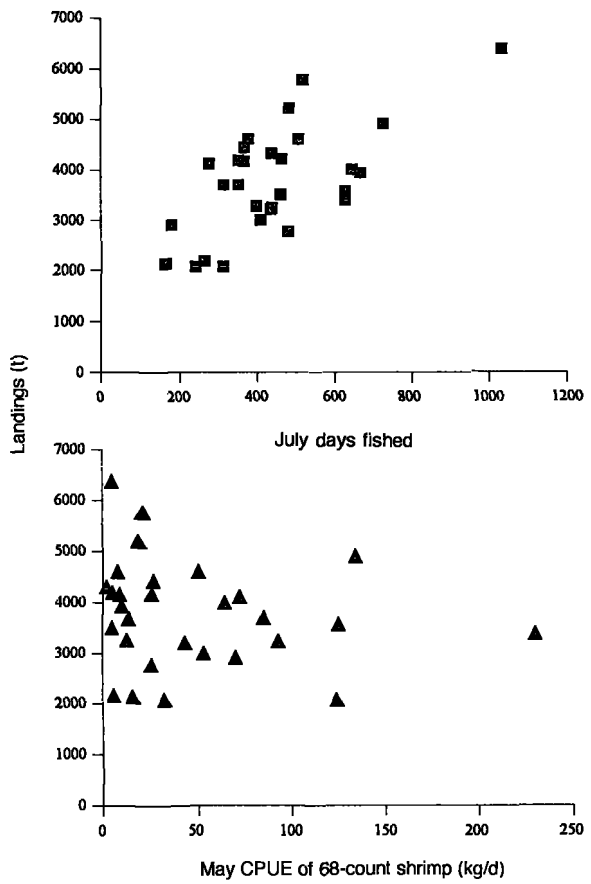

Figure 6

Scatterplots of fishery variables against subsequent fishing year landings, 1966–94.

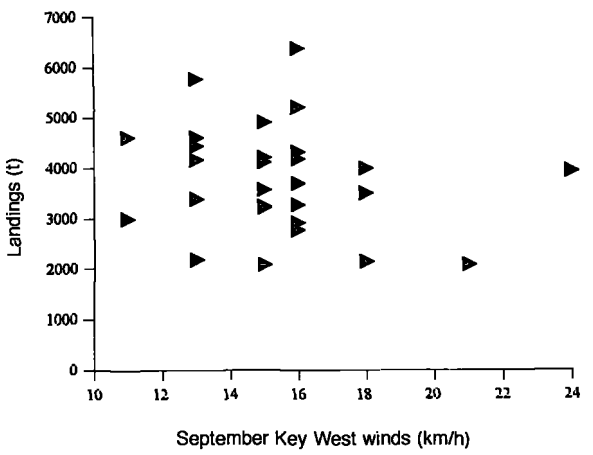

Figure 7

Scatterplot of September Key West winds against subsequent fishing year landings, 1966–94.

1969; Ruello, 1973; Edward, 1978; Glaister, 1978; annual model of Browder, 1985; Vance et al., 1985; Gracia, 1989), negative (Barrett and Gillespie, 1973, 1975; Barrett and Ralph, 1977), or absent (Glaister, 1978; Hettler and Chester, 1982).

In this analysis, freshwater indices exhibited both positive and negative influences on pink shrimp forecasts. Coefficients for L-67 surface water discharge into ENP were always positive, although the nature of the relationship is not as clear for September as it is for June (Fig. 4). The two years with highest landings (1980 and 1977) both occurred when there was moderate L-67 water discharge. Lowest pink shrimp production was associated with extremely low L-67 discharges during the drought of 1989–90. Coefficients for groundwater at well P37 (flowing toward Florida Bay) were always positive whereas those for well P38 (flowing toward Whitewater Bay) were always negative, but again the relationships to landings are not clear (Fig. 5). In most cases, including the present one, the mechanisms behind any relationship between freshwater and penaeid shrimp landings have not been determined experimentally. It has been postulated that excessive freshwater may prevent habitat utilization by postlarval penaeids (Barrett and Gillespie, 1973, 1975) or may initiate early movement of juvenile penaeids out of estuaries (Vance et al., 1985). Hypersalinity is a more frequent condition in Florida Bay (McIvor et al., 1994). Although the direct effects of hypersalinity on pink shrimp are unknown, low surface water discharges are associated with low landings. Examples of the linkage of freshwater inputs to other marine organisms include positive correlation with sea nettle, *Chrysaora quinquecirrha*, abundance in Chesapeake Bay (Cargo and King, 1990) and positive or negative correlation with production by several commercial fisheries in Maryland (Ulanowicz et al., 1982).

Another class of variables typically included in penaeid shrimp forecast models are indices of fishing activity or standing crop prior to the forecast period. The Texas brown shrimp forecast covers the July–June period and is based on average weekly CPUE by the Galveston Bay live bait shrimp fishery during April–June, just prior to emigration of the shrimp into the offshore fishery (Baxter and Sullivan, 1986). The Louisiana brown shrimp forecast also covers July–June, but it is based on inshore and offshore landings from the western half of the state during May.[2] Descriptive models for Tortugas pink shrimp (Browder, 1985) included indices for fishing effort and CPUE that were usually positive in nature and appeared to influence landings up to four

Table 2

Regression models and forecast versus actual Tortugas pink shrimp landings during fishing years 1987–95. See Table 1 for definitions of abbreviations of variables (V1–V6), listed with signs and in order of inclusion by stepwise regression. n = number of variables; Cp = Mallow's test; % = accuracy = 100 (forecast-actual)/actual.

		Variables in regression						Statistics			Landings (t)		
Year	Model	V1	V2	V3	V4	V5	V6	n	Cp	Mult. R^2	Forecast	Actual	%
1987	1	–KAir10	+P379	–CPUE688	+P386	+RRain6	—	5	5.20	0.849	3454	3000	15
1988	2	+RRain57	–L678	+P389	–P388	+L679	+P387	6	6.36	0.775	2857	2075	38
1989	3	–CPUE685	+Pink6	+L6710	+P379	+L676	—	5	6.53	0.883	1917	2141	–10
	4	–CPUE685	+Pink6	+L6710	+P379	+L676	–P3810	6	5.77	0.911	2516	2141	18
	5	+Days7	+RRain57	–P388	+L679	–KWind7	—	5	6.21	0.746	3100	2141	45
	6	+Days7	+RRain57	–P388	+L679	–KWind7	+P359	6	5.22	0.792	3081	2141	44
1990	7	+Days7	+L679	–P388	+L676	+P379	—	5	5.28	0.809	1904	2078	–8
	8	+Days7	+L679	–P388	+L676	+P379	+Pink6	6	6.31	0.819	1786	2078	–14
	9	+Days7	+L679	–P388	–P359	+P379	+L676	6	6.36	0.811	1911	2078	–8
1991	10	+Days7	+L679	–P388	+L676	+P379	—	5	5.16	0.810	2153	2179	–1
	11	+Days7	+L679	–P388	+L676	+P379	–P355	6	6.25	0.830	1993	2179	–9
	12	+Days7	+L679	–P388	+L676	+P379	–L678	6	6.02	0.822	2006	2179	–8
1992	13	+Pink6	–Cpue685	+P359	+Days9	–P3810	—	5	5.37	0.873	2830	2914	–3
	14	+Pink6	–Cpue685	+P359	+Days9	–P3810	+L679	6	6.02	0.897	3066	2914	5
1993	15	+Days7	–KAir10	–CPUE685	–KWind5	–CPUE689	+MRain57	6	6.16	0.880	1982	3696	–46
	16	+Days7	–KAir10	–CPUE685	–KWind5	–CPUE689	–Days6	6	6.01	0.861	1574	3696	–57
	17	+Days7	–KAir10	–CPUE685	–KWind5	–CPUE689	+Sea5	6	6.03	0.858	2106	3696	–43
1993	18	+Days7	+L679	–P388	–KWind9	+L676	+P378	6	6.20	0.898	3237	3696	–12
Revised	19	+Days7	+L679	–P388	–KWind9	+L676	–P3810	6	6.04	0.884	2531	3696	–32
	20	+Days7	+L679	–P388	+L676	–KWind9	+Days5	6	6.37	0.884	3738	3696	1
	21	+Days7	+L679	–P358	+L676	–KWind9	+Pink10	6	6.02	0.878	3483	3696	–6
1994	22	+Days7	+L679	–P388	–KWind9	+Pink6	–CPUE685	6	6.08	0.867	4517	4127	9
	23	+Days7	+L679	–CPUE685	+Pink6	–KWind9	–P3810	6	6.27	0.866	3709	4127	–10
1995	24	+Days7	–KWind9	–P358	+L676	+L679	–CPUE685	6	6.03	0.863	2858	—	—
	25	+Days7	–KWind9	–P358	+L676	+L679	–P388	6	6.00	0.861	3266	—	—
	26	+Days7	–KWind9	–P388	+Pink6	+L679	–CPUE685	6	6.16	0.861	4581	—	—

quarters (12 months) in advance of a given fishing year, thus covering new recruits and spawning stocks. In my models, fishing activity on the Tortugas Grounds during the waning months of a given fishing year (May–July) may be related to the status of the spawning stock and its future production of larvae during the summer and fall months. Catch and effort variables in these models had positive effects on forecasted landings, although CPUE variables had negative coefficients. These indices may be related to prerecruits or to potential parent spawning stocks, although there are no statistically significant parent stock-recruitment relationships for Gulf of Mexico *Penaeus* (Nance, 1993).

In a descriptive model for the North Carolina pink shrimp fishery (Hettler and Chester, 1982; Hettler, 1992), landings during February–July were positively correlated with water temperatures during the coldest two weeks of the preceding winter. Severe cold temperatures were postulated to have reduced landings by killing postlarvae and juveniles overwintering in estuaries (Hettler and Chester, 1982). The model successfully described landings within ±20% of actual landings in five of 10 years (Hettler, 1992). The opposite effect was seen in Florida (Browder, 1985), where mean January–March air temperature,

Table 3

Accuracy (% above or below actual landings) of Tortugas pink shrimp forecasts if forecast equations had become fixed in the year generated. Model = model number from Table 2. Boldface values are ±20% of actual landings.

		Accuracy (%)							
Year	Model	1987	1988	1989	1990	1991	1992	1993	1994
1987	1	**15**	153	55	72	109	87	**3**	**-17**
1988	2		38	56	56	58	119	**-1**	55
1989	3			**-10**	-29	39	-29	53	22
	4			**18**	**-13**	57	**14**	71	46
	5			45	25	31	**4**	**-20**	-32
	6			44	**17**	42	**18**	**-18**	-26
1990	7				**-8**	**-1**	29	**-14**	**-13**
	8				**-14**	**-12**	26	-23	**-15**
	9				**-8**	**-14**	22	-38	-25
1991	10					**-1**	29	**-13**	**13**
	11					**-9**	25	**-18**	-26
	12					**-8**	35	**-11**	**-4**
1992	13						**-3**	23	23
	14						**5**	22	28
1993	15							-46	-63
	16							-57	-73
	17							-43	-40
1993	18							**-12**	-28
Revised	19							-32	-33
	20							**1**	**-9**
	21							**-6**	**-17**
1994	22								**9**
	23								**-10**

as a proxy for water temperature, was negatively correlated with Tortugas pink shrimp landings during the following July–September. The present analyses for the Tortugas fishery rarely included air temperature as a predictor variable, perhaps because predictors were limited to the warmest months of May–October. Costello and Allen (1970) listed no known negative impacts of high summer temperatures on pink shrimp. Air and water temperature have been found to be potential predictors in a variety of other fisheries (Fogarty, 1989).

One final type of data consistently entered my models, i.e. September wind speed at Key West. Wind speed and direction were postulated by Vance et al. (1985) to affect recruitment and settlement of postlarval *Penaeus merguiensis* and thus subsequent harvest. Off Florida, high winds in September, associated with passage of tropical storms, could break up advective processes that deliver planktonic pink shrimp to the nursery areas during the summer. However, concurrent studies of oceanographic features and larval pink shrimp abundance remain to be conducted during this period (Criales and Lee, 1995). It is also possible that high winds in September reduce fishing effort and thus subsequent harvest, but high winds occur during the low point of the fishing year.

My forecasting method involves generating new prediction equations each year, rather than employing a single fixed equation, because 1) the models do not describe cause and effect relationships, 2) causal relationships between most variables and subsequent recruitment to the fishery are not well known (leading to the "hazards of correlative studies" noted by

Hannah (1993), and references cited therein), and 3) changes occur in the database used to make predictions. In time, new environmental, biological, or fishery conditions are encountered. For example, the database for the Tortugas pink shrimp fishery now reflects (directly or indirectly) results of massive seagrass mortality in Florida Bay which began in 1987, a prolonged drought in south Florida during 1989–91, and the four worst fishing years on record. None of these factors would have influenced the first forecast model derived in 1987, and assessment of that model indicated it would have been a failure if used in most future years. Even the durable Texas brown shrimp forecast, first released to the public in 1962 and accurate within ±20% of actual landings for 22 of its first 29 forecasts, was modified in 1994 to reflect the changing nature of the Galveston Bay live bait shrimp fishery after 1980.[2]

Incorrect fishery forecasts can have negative economic impacts on fishermen and processors (Bocking and Peterman, 1988; Walters, 1989), especially if the fishery in question is actively regulated on a short-term basis like the salmonid fisheries of the northeastern Pacific. The penaeid shrimp fisheries of the U.S. Gulf of Mexico are managed to prevent the harvest of undersized shrimp (Gulf of Mexico Fishery Management Council, 1981; Klima et al., 1986). Shrimp management strategies are assessed annually and are accomplished by seasonal closure of Federal and state waters off Texas and by areal closure of shallow Federal waters off southwest Florida. Flexible, in-season adjustments are possible but rare, and to date shrimp management has not been altered in response to forecasts of high or low harvests. As yet, no assessment of the utility and economic effects of either pink shrimp or brown shrimp forecasts have been made among members of the fishing community.

This study indicates that landings of Tortugas pink shrimp might be forecast reliably with some advance knowledge of environmental conditions and abundance of juvenile pink shrimp in nursery areas. Cause-effect relationships are not yet known, and mechanisms describing pink shrimp responses to predictor variables need to be determined through experimental analyses.

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