ABSTRACT

LEE, LAURA MALEDA. Population Dynamics of Atlantic Croaker Occurring Along the U.S. East Coast, 1981 – 2002. (Under the direction of Peter S. Rand and Joseph E. Hightower)

Atlantic croaker are one of the most plentiful inshore, demersal fishes from the Chesapeake Bay to Florida. A coastwide assessment of the stock based on landings, fishery-dependent and fishery-independent length data, and survey abundance information was performed using the stock synthesis model. Landings have generally increased since the 1950s, with most of the catch occurring in North Carolina and Virginia. Major commercial gears are gill net, trawl, haul seine, and pound net. The recreational fishery has become increasingly important over time. Indices of relative abundance generated from fishery-independent surveys show that year-class strength has varied considerably among years. Patterns for year-class strength were consistent within each state, and fairly consistent among states. There is evidence for a potential rebuilding of the stock from both the observed data and model predictions. Coastwide length samples from the recreational fisheries and length samples from NC commercial fisheries demonstrated an increase in the maximum length in recent years. Observed and predicted mean lengths for the gill net, trawl, and recreational fisheries also suggest an increase in the proportion of older and larger fish in recent years. Observed trends in relative abundance and model predictions of recruitment reflect the presence of several recent strong year classes. The model results suggest that the population is highly recruitment-driven and that recruitment is variable. This dynamic is likely reflected in the harvest as variability in catch, which has shown fluctuations for at least the past 50 years. Estimates of fishing mortality have been high, particularly during the late 1980s when abundance was estimated to be low. Evaluation of the uncertainty in model estimates demonstrated that the model was fairly insensitive to changes in source data, but did appear sensitive to changes regarding assumptions about *M* and assumptions about the error associated with survey abundance indices. The yield-per-recruit analysis results suggested that a significant gain in yield would result if age-at-entry was delayed, which, in turn, would allow for relatively higher *F*s. Comparison of age-0 abundance indices between Virginia and North Carolina revealed similar patterns in annual recruitment. Age-0 abundance indices also exhibited significant spatial autocorrelation for both states. In general, sampling stations in close proximity tended to have more similar observations of age-0 abundance. Positive spatial autocorrelation typically occurred at distances less than 30-km, while negative spatial autocorrelation was more often detected at distances of 40-km or greater. Accounting for spatial patterns in recruitment indices should result in a better measure of recruitment for use in future stock assessments.

POPULATION DYNAMICS OF ATLANTIC CROAKER OCCURRING ALONG THE U.S. EAST COAST, 1981 – 2002

by

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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

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DEDICATION

For mom.

PERSONAL BIOGRAPHY

I was born in Reading, Pennsylvania in 1975. I grew up in a small community in the mountains with an older sister and younger brother. After high school, I attended Millersville University, located near Lancaster, PA. Though I entered as a chemistry major and then switched to pre-med, my academic interests extended beyond the requirements for the curriculum. I became more interested in learning as much as possible than locking myself into a particular career path, and took just about every class that piqued my interest in hopes of finding a course of study that challenged me. Oceanography was the first class that presented me with a real challenge and just a few weeks into the class, I enrolled in the Earth Sciences program as a Biological Oceanography major.

In my senior year, I decided to do a senior thesis. The title of my project was "Tidal Exchanges of Plankton in the Chincoteague Inlet". I looked at the diurnal exchanges of blue crab larvae between the ocean and Chesapeake Bay. The study had a substantial field component - taking day and night samples with plankton nets and a CTD from a 40' research vessel. I presented the results to my committee and a handful of students who weren't busy studying for finals or packing up their dorm rooms. During the completion of this project, I began to seriously think about graduate school.

After graduation, I was offered a full-time position as an education specialist at the science museum I had been working at part-time. I decided to take at least a brief break from school while working and spent time looking into graduate programs and other opportunities. I ended up applying and being accepted to several great, but very different programs. I decided that NC State's Fisheries and Wildlife program was the best fit for me. My committee was very supportive and helped me develop a project in my main area of interest – population assessment. A couple years into the program, I got married in the beautiful Smoky Mountains. Shortly after, my co-advisor suggested I started looking into job opportunities while writing my thesis. I took his advice and, much to my surprise, was offered the first job I applied to - a stock assessment scientist with ASMFC. My job has been very demanding in terms of workload and travel. I owe a large part of my success to my graduate courses, thesis project, and the support of a great committee.

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1 INTRODUCTION

The Atlantic croaker, *Micropogonias undulatus*, is found from the Gulf of Maine to Argentina along the western Atlantic Ocean (Chao and Musick 1977). It is one of the most plentiful, inshore demersal species from the Chesapeake Bay to Florida (Joseph 1972; Nelson et al. 1991; Stone et al. 1994). Atlantic croaker are a valuable resource, supporting substantial commercial and recreational fisheries (ASMFC 1987). Atlantic coast commercial fisheries have landed an average of 5,500 metric tons of Atlantic croaker a year from 1950 to 2002. Of this, North Carolina and Virginia were responsible for over 90% of the harvest combined. From 1981 to 2002, the total recreational catch of Atlantic croaker has ranged from 2.8 to 13.2 million fish per year.

Atlantic croaker spawn in the fall and winter in the Mid- and South Atlantic Bights (Hildebrand and Cable 1930; Wallace 1940; Haven 1957; Bearden 1964; Setzler 1977; White and Chittenden 1977; Colton et al. 1979; Morse 1980; Warlen 1980; Barbieri et al. 1994b). Spawning activity has been detected in habitats ranging from estuaries to marine waters over the outer continental shelf (Hildebrand and Cable 1930; Welsh and Breder 1923; Haven 1957; Bearden 1964; Hoese 1973; Morse 1980; Norcross 1991; Barbieri et al. 1994b; Govoni and Pietrafesa 1994). After the pelagic eggs hatch, larvae are advected inshore by wind-driven transport mechanisms. Advanced larval stages then migrate to estuarine and freshwater nursery areas (Hildebrand and Cable 1930; Wallace 1940; Haven 1957; Warlen 1980; Lewis and Judy 1983; Setzler-Hamilton 1987; Norcross 1991). Juveniles can be found in shallow open water areas of large bays (Parker 1971; Yakupzack et al. 1977; Knudsen and Herke 1978; Copeland et al. 1984), small tidal streams (Turner and Johnson 1974), and tidal riverine habitats (Raney and Massmann 1953). However, most studies have demonstrated that juvenile Atlantic croakers prefer the deep, main channels of estuaries and avoid shallower areas (Haven 1957; Weinstein et al. 1980; Thomas 1981). It seems that the suitability of shallow areas diminishes for juvenile Atlantic croakers as daily fluctuations of water level increase (Diaz and Onuf 1985). Juveniles remain in estuarine nursery areas through June depending on location and year (Parker 1971; Chao and Musick 1977; Yakupzack et al. 1977; Weinstein 1983; Copeland et al. 1984; Miller and Able 2002; Ross 2003).

The timing of emigration is variable. Juvenile Atlantic croakers have been found to remain in nursery areas of the Chesapeake Bay until temperatures begin to decline (Wallace 1940). Movement out of the nursery habitat can be direct to open marine waters (Parker 1971; Yakupzack et al. 1977; Knudsen and Herke 1978). Other studies found emigration to occur gradually through the late summer and fall, with larger individuals occurring in more saline waters near the mouth of estuaries (Haven 1957; Bearden 1964). Atlantic croaker reach maturity by age 2 and may live ten years or more (White and Chittenden 1977; Morse 1980; Barbieri et al. 1994b).

In 1987, the Atlantic States Marine Fisheries Commission (ASMFC) adopted a fishery management plan (FMP) for Atlantic croaker. The ASMFC is responsible for coordinating the conservation and management for a number of fishery resources along the US East Coast. Many of the ASMFC member states monitor their marine resources through one or more fishery-independent surveys that target species of recreational and/or commercial importance. Data collected from these programs are used with fishery-dependent information to support stock assessments and develop management advice. The fishery-independent surveys are especially important for characterizing parts of the population that may not be available or vulnerable to the fisheries. Incorporating data from both fishery-dependent and independent sources facilitates understanding of stock changes, which lends to more effective management. But before an effective management plan can be devised, there needs to be an understanding of the population structure and dynamics.

The primary objective of this study is to evaluate the available fisheries-dependent and independent data for Atlantic croaker and incorporate these data into a coastwide population assessment using the stock synthesis model developed by Methot (1989, 1990, 2000). The model can incorporate diverse auxiliary information to model both the dynamics of the population and the processes by which we observe them. The synthesis model generates a time series of estimates of population size and fishing mortality. Uncertainties in the results of the assessment model will be explored through profiling techniques and sensitivity analysis. A yield-per-recruit analysis will be used to investigate the effects of varying fishing pressure and age-at-entry to the fishery. Spatial analyses of fishery-independent recruitment indices will be done in order to gain a better understanding of recruitment patterns.

2 POPULATION ASSESSMENT

2.1 Methods

2.1.1 Data Sources

A summary of the data sources and types is given in Table 2.1.

2.1.1.1 Harvest

<u>National Marine Fisheries Service</u>

The Marine Recreational Fisheries Statistics Survey (MRFSS) provided recreational harvest and length frequency data for Atlantic croaker caught along the Atlantic Coast (National Marine Fisheries Service, Fisheries Statistics and Economics Division, Silver Spring, MD, pers. comm.). MRFSS estimates generally are divided into three catch types depending on availability for sampling. Fish brought to the dock in whole form, which are identified and measured by trained interviewers, are classified as landings (Type A). Fish that are not brought ashore in whole form (used as bait, filleted, or released dead) are classified as discards (Type B1). Type B1 removals are reported to the interviewer, but identified to species by the angler. The sum of Types A and B1 provides an estimate of total harvest for the recreational fishery. Estimates of landings or harvest provided by the MRFSS are minimum values and so may not accurately reflect the true total removals. Total weight of recreational fisheries harvest of Atlantic croaker was summarized for the Atlantic Coast by year. Length distributions for each year were also computed based on the MRFSS Atlantic Coast data. The MRFSS data were not available prior to 1981 so this stock assessment began in that year.

Commercial fisheries data are available from the Fisheries Statistics and Economics Division of the National Marine Fisheries Service (NMFS) through their online website query at http://www.st.nmfs.gov/index.html (NMFS, pers. comm.). The NMFS has performed in-depth surveys of all coastal states since 1951 through a joint state-federal cooperative program. The NMFS largely relies on the state fishery agencies to provide commercial fisheries landings data. The majority of states obtain landings information from monthly reports submitted by seafood dealers. Many states have initiated mandatory tripticket programs in which dealers and fishermen report their landings by species at the conclusion of every fishing trip. Individual states may also require additional information such as effort and/or area fished. While survey methods may vary between states, the NMFS takes measures to ensure that data from the various states are comparable. Atlantic Coast commercial landings for Atlantic croaker were available by year, gear, and state from 1950-2002. Virginia and North Carolina were responsible for approximately 91% of the harvest for Atlantic croaker over the assessment period, 1981-2002. For this reason, these states were the focus for auxiliary age and length information.

2.1.1.2 Surveys

North Carolina Division of Marine Fisheries

The North Carolina Division of Marine Fisheries (NCDMF) carried out the fishery-independent monitoring surveys in North Carolina. In 1971, NCDMF established a statewide Estuarine Trawl Survey, also known as Program 120 (K. West, NCDMF, pers. comm.). The main objectives were to identify primary nursery areas and produce annual recruitment indices for economically important species, including Atlantic croaker. Currently, sampling is conducted in primary nursery areas throughout the state during May and June, except for July sampling of weakfish. The survey is done using a two-seam otter trawl with a 10.5' headrope, 0.25" bar mesh wings and body, a 0.125" bar mesh cod end, six-foot bridle, and 18" by 30" doors. The trawl is towed for one minute by small outboard boats at about a speed of 75 yards per minute at 105 core stations. Economically important species, such as Atlantic croaker, are counted and a subsample (30 – 60 individuals) of each age group is measured. Bottom type, depth, occurrence of submerged aquatic vegetation and bottom and surface temperature and salinity are also recorded at each station.

The Pamlico Sound survey, also known as Program 195, was initiated by the NCDMF in 1987 (K. West, pers. comm.). The initial objective of this survey was to assemble a long-term fishery-independent database for the waters of Pamlico Sound, eastern Albemarle Sound, and the lower Neuse and Pamlico rivers. The survey employs a random stratified design. Samples are taken during the first through third weeks in June and September using a 44' double-rigged trawler, the R/V *Carolina Coast*. Two 30' mongoose trawls with 24" by 28" doors, 0.875" bar mesh body, and 0.75" bar mesh codends are towed for 20 minutes over 50 to 53 randomly selected one minute grids. The grids are chosen from seven strata, based on depth and geographic location, with each stratum having at least three stations. Stations are distributed among strata based on previous sampling in the same time frame in order to provide the most accurate abundance estimates for target species, including Atlantic croaker. All Atlantic croaker are counted, weighed and measured, except for extremely large samples, which are subsampled. Environmental data including surface and bottom temperature and salinity, wind speed, and wind directions are also taken.

Survey data for Atlantic croaker must be interpreted carefully because spawning can occur from about August through January (Warlen 1980) and fish grow rapidly over the first year. The peak spawning months for Atlantic croaker are reported to be September and October in the Middle Atlantic Bight (Ross 1988; Barbieri et al. 1994a). Following Barbieri et al. (1994a), a January 1 birth date was assumed, so fish that were spawned in late fall were considered age-0 fish the following year. The pattern is well illustrated by the 1988 results from the NC195 deep water trawl survey, which was done in several months during the first few years but only June and September after 1990 (Figure 2.1). The March 1988 length distribution contained mostly age-1 fish, with a mode of 16.5 cm. The June distribution had two modes representing age-0 fish (mode at 9.5 cm) and age-1 fish (mode at 18.5 cm). The mode for age-0 fish shifted to 14.5 cm in September and 15.5 cm in December. Age-1 fish were not apparent in the September and December samples.

The NCDMF survey data used in the stock synthesis model were chosen based on the consistency of sampling in different months over the period of interest. For the NC120 survey, the only months consistently sampled from 1981 through 2002 were May through September. The NC195 survey has been conducted during June and September since 1987. To allow for comparison between the two surveys, June data from the NC120 survey and both NC195 June and September data were used. Annual catch-per-unit-effort (CPUE) values were calculated for each survey (NC120, NC195 June, NC195 September) as the average number of fish caught per tow. Only age-0 fish were captured in the NC120 June shallow water trawl survey and the NC195 September survey (Figures 2.2, 2.3). Each of those CPUE series was used in the model as an index of year-class strength by shifting each series forward by one year to serve as an index of age-1 abundance. Length composition data from these survey sources were not included in the model. CPUE and length composition data from the NC195 June survey were used because a mode was present for age-1 fish (Figure 2.3). For that survey, CPUE values and length distributions were based on fish 14 cm and larger.

NCDMF is also responsible for sampling the dominant commercial finfisheries of North Carolina. The aim of this program, started in 1982, was to obtain relevant biological and fisheries data on economically important fishes to be incorporated into management evaluations. Species-specific information includes size and age, landings, and weights for the major finfisheries (NCDMF 1997). For Atlantic croaker, weighted length frequencies from 1985 through 2002 were available. Fish less than 18 cm were excluded to restrict the analysis to fish age-1 and older. Age data from scales were available for 1988-1998 and from otoliths for 1996-2002.

Virginia Institute of Marine Science

The Virginia Institute of Marine Science (VIMS) Juvenile Trawl Survey has been in effect since 1955. The main objective of this survey is to monitor trends in seasonal distribution and abundance of juvenile fish for about twenty recreationally, commercially, or ecologically important finfish and invertebrates. The trawl includes sites from the mouth of the Chesapeake Bay up to the freshwater interface at the fall line of the James, York, and Rappahannock rivers. The R/V *Fish Hawk* collects samples from about 60 stations every month each year. At each station, a 30' semi-balloon otter trawl (1½" stretch mesh body, a ¼" mesh cod liner, two steel china-v doors (28" x 19"), and an attached tickler chain) is towed for five minutes using a 60' bridle. The catch is sorted by species, the number of fish of each species is counted, 20 – 30% are measured and all are released (VIMS website: http://www.fisheries.vims.edu/trawlseine/mainpage.htm).

For the VIMS survey, sampling was done in almost every month since 1981, but tows and numbers of Atlantic croaker collected were very low in some months (Appendix 7.1). October survey data were chosen because of the relatively high catches and number of tows. Annual CPUE values for the October survey were calculated as the average number of fish caught per tow. October length distributions generally contained two modes: one for newly spawned fish (2-3 cm) that will be age-0 fish the following year, and one for late age-0 fish at about 18 cm (Figure 2.4). This survey was treated as an additional index of year-class strength (by eliminating length classes < 12 cm and shifting the CPUE values forward a year) in the model; length distributions from this survey were not included.

Virginia Marine Resources Commission

The Virginia Marine Resources Commission (VMRC) Stock Assessment Program has collected finfish biological data (length, weight, sex, and age) since 1988. Recently, the sampling protocol was modified to include the removal of otoliths from 13 important finfish species, including Atlantic croaker. Old Dominion University's Center for Quantitative Fisheries Ecology Laboratory is responsible providing the VMRC age data for these finfish species (VMRC website: http://www.state.va.us/mrc/). Age data for Atlantic croaker were only available for 1998.

Northeast Fisheries Science Center

The Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service conducts bottom trawl surveys over a large portion of the Atlantic Shelf (Azarovitz 1980). The surveys began in 1963 in order to develop a time series of abundance and distribution data for fishery-related ecological studies. Stations are selected within each sampling stratum, which are determined by depth. The catch is sorted and weighed by species. Larger catches are sub-sampled by weight or volume and later expanded to represent the entire catch. Scales, otoliths or other hard parts are collected from selected species for age and growth studies, and stomachs, tissue samples, and ovaries are routinely collected. Temperature, bottom salinity, oxygen, weather, sea state, and position are noted when possible. The NEFSC survey typically occurred in September and October and rarely in November or December. Catches of Atlantic croaker were higher and more consistent in September compared to October, so September length composition and CPUE data were used in the model. Annual CPUE estimates were obtained as the average catch per tow for the NEFSC data. The September length distributions sometimes contained a mode at about

12-16 cm that appeared to be age-0 fish (Figure 2.5), so fish less than 18 cm were excluded from the CPUE values and length distributions.

2.1.2 Model Structure

The assessment was carried out using the full size/age version of the stock synthesis model software (Methot 1989, 1990). In this version the population is characterized by age and size with an integrated growth curve. That software is similar in purpose to other stock assessment programs but is sufficiently flexible to handle multiple fisheries, multiple surveys, and both length and age composition data. Identification of major gear types is important because different gears tend to capture fish of different sizes and ages. The model can allow up to ten sample types (fisheries and surveys combined).

For Atlantic croaker, age data were not available from the fishery-independent surveys or from the recreational fishery. Age data from North Carolina commercial fisheries were available for 1988-1998 based on scales and 1996-2002 based on otoliths. Virginia commercial fishery age data (using otoliths) were available for 1998 only. Mean size-at-age estimated from NC fishery samples were used within the synthesis model as an additional source of information about gear selectivity and the age-length relationship. The synthesis model is designed for fish age-1 and older, so length distributions for each of the fisheries and surveys were examined in an attempt to exclude age-0 fish (see 2.1.1 Data Sources). Fish that appeared to be age-0 generally comprised a small fraction of the commercial catch length distributions.

The synthesis model estimates growth parameters using the Schnute (1981) parameterization of the von Bertalanffy growth curve. In this model, the von Bertalanffy growth curve used parameters for length at age-0.75, length at age-10, and the growth rate. The parameter for length at age 0.75 was fixed in order to constrain the lower portion of the curve, where size-selective fishery samples tend to overestimate population size-at-age. The mean size at age-0.75 from the NC195 September survey was used (14.1 cm).

A key parameter in any stock assessment model is the natural mortality rate (M). In a yield-per-recruit analysis for Atlantic croaker in the Middle Atlantic Bight, Barbieri et al. (1997) used M values ranging from 0.20 to 0.35. Those values were based on the maximum ages and total instantaneous mortality rates (Z) observed in previous age and growth studies. Barbieri et al. (1994b) reported a maximum age of 8 years for Atlantic croaker in Chesapeake Bay (based on otolith ages), and estimated Z values ranging from 0.55 to 0.63. Their mortality estimates were obtained using pooled age composition data from pound-net, haul-seine, and gillnet samples. For Atlantic croaker in North Carolina, Ross (1988) reported a maximum age of 7 years (based on scale ages) and an estimated Z of 1.3, based on haul-seine catches.

A regression equation developed by Hoenig (1983) can also be used to predict Z from the observed maximum age. Using that method, maximum ages of 7-8 correspond to predicted annual Z values of 0.58-0.67. Those Z values are the combined total of M and the instantaneous fishing mortality rate, F. However, information on size or age from a period when Atlantic croaker were unexploited or lightly exploited are not available, so estimates of M based on maximum age or size may be biased. In this assessment, M was assumed to equal 0.35.

2.1.3 Parameter Estimation

The "best fit" of the synthesis model is determined in terms of log-likelihood (Methot 1989, 1990). The likelihood function is composed of independent terms from each type of fishery or survey. In this model the likelihood components are expressed in terms of harvest (L_1), CPUE (L_2), size composition of fishery (L_3) and survey samples (L_4), mean size-at-age (L_5), and spawner-recruitment (L_6). Parameter values are estimated through numerical calculation of parameter derivatives and application of a modified Newton method in order to maximize the total log-likelihood.

The individual log-likelihoods (ignoring constant terms) were as follows:

where $C_{f,y}$ and $\hat{C}_{f,y}$ are observed and predicted catch biomass values by fishery and year, and σ_f is the assumed normal SE of log [fishery catch biomass];

$$L_2 = \sum_y -0.5 \left\{ \frac{\log\left(\frac{\hat{C}_{s,y}}{C_{s,y}}\right)}{\sigma_{s,y}} \right\}^2$$

where $C_{f,y}$ and $\hat{C}_{s,y}$ are observed and predicted CPUE by survey and year, and $\sigma_{s,y}$ is the measured SE of log [survey CPUE] in year y;

$$L_3 = \sum_y A_{f,y} \left(\sum_l P_{f,l,y} \log \hat{P}_{f,l,y} \right)$$

where $A_{f,y}$ is the sample size for a fishery length distribution in year y (up to a maximum of 200), and $P_{f,l,y}$ and $\hat{P}_{f,l,y}$ are observed and predicted proportions in length class l;

$$L_4 = \sum_y A_{s,y} \left(\sum_l P_{s,l,y} \log \hat{P}_{s,l,y} \right)$$

where $A_{s,y}$ is the sample size for a survey length distribution in year y (up to a maximum of 400), and $P_{s,l,y}$ and $\hat{P}_{s,l,y}$ are observed and predicted proportions in length class l;

$$L_5 = \sum_y \sum_a -0.5 \left\{ \frac{\log \frac{\hat{L}_{f,a,y}}{L_{f,a,y}}}{\sigma_{f,L@A}} \right\}^2$$

where $L_{f,a,y}$ and $\hat{L}_{f,a,y}$ are observed and predicted mean length-at-age a by fishery and year, and $\sigma_{f,L@a}$ is the estimated normal SE for mean size-at-age in fishery f, based on sample size;

$$L_6 = \sum_y -0.5 \left\{ \frac{\log\left(\frac{\hat{R}_y}{R_y}\right)}{\sigma_{SRR}} \right\}$$

where R_y and $\hat{R}_y$ are observed and predicted recruitments based on a stock-recruitment relationship estimated internally by the model. Giving this likelihood component moderate emphasis provides a constraint on estimated annual recruitment values (Methot 1990). The maximum sample sizes for fishery and survey length composition data were assumed values, to prevent large samples from dominating the fit (Fournier and Archibald 1982; Methot 1990).

2.1.4 Uncertainty

Uncertainty in model results can be investigated by examining the influence of input parameters. This method, termed profiling, involves setting one parameter at a time to different fixed values and measuring to what degree the model output is affected (Mittertreiner and Schnute 1985; Hilborn and Walters 1992; King 1995). This approach is especially useful when there are a large number of parameters to be estimated. A useful parameter to explore is the recruitment value of a particularly large year-class (R. Methot, NMFS, pers. comm.). Uncertainty can also be explored by assessing the contribution of each source of information (Methot 1990). The contribution of a data source or other parameter can be manipulated by changing the weight, or emphasis, of the associated likelihood component. For instance, the emphasis of the stock-recruitment relationship can be reduced to see how well the model can perform in estimating recruitment without this information. A number of alternative population models were run to examine how the performance of the synthesis method depended on the different fishery-independent surveys and how it was affected by different assumptions related to mortality and recruitment.

The contributions of the NC120, NC195 (June and September), VIMS, and NEFSC surveys were examined through a series of model runs in which one survey at a time was given an emphasis of 0.001 (compared to a default emphasis of 1.00). Other runs gave low

(0.001) emphasis to all North Carolina surveys (NC120 and NC195 June and September) and to the stock-recruitment relationship. The model's performance under different assumptions regarding *M* was evaluated, because of the uncertainty associated with that parameter. In addition to the base run at *M*=0.35, the model was fit using *M*=0.20, the lower assumed value used by Barbieri et al. (1997). A value of *M*=0.50 was also explored to investigate the potential implications of a higher natural mortality rate. Finally, alternative options regarding the variance estimates of the survey indices, $\sigma_{s,y}$, were considered. Maunders and Starr (2003) recommended that population models be run using both time-invariant as well as variable estimates of imprecision for the survey index components of the log-likelihood equation. While those authors were evaluating fishery-dependent catch rates, here the suggestion is applied to the fishery-independent indices. The preferred method uses standard errors estimated from sampling statistics for each survey and year (Methot 2000); this approach was applied in the base run. Synthesis also allows the user to specify a level of error for each data series, which is assumed constant for the time series; this option is more commonly used. If external estimates of survey variance are not available and a constant error is not provided, the synthesis model does an iterative re-weighting of the root mean squared error (RMSE) of the current fit, which provides an error estimate for each survey series. Estimates from the base run were compared to model runs where the variability for each survey series was specified prior to the fitting procedure and where the error assigned to each survey is estimated within the model through iterative re-weighting.

2.2 Results

2.2.1 Population Trends

Annual commercial landings of Atlantic croaker along the Atlantic coast have varied for at least the past 50 years (Figure 2.6). Virginia and North Carolina have accounted for nearly the entire harvest with the proportion due to each state varying through time. Five gear types dominate harvest of Atlantic croaker: haul seines, pound nets, trawls, gill nets, and recreational gears (Figure 2.7). Commercial fishing activity is linked to the seasonal migration of Atlantic croaker (ASMFC 1987). As the fish move north and inshore during the warmer months, they are exploited by haul seines and pound nets. Trawls and gill nets target

Atlantic croaker during the cooler months as the fish move southward and offshore. The recreational fishery has also become increasingly important in recent years.

Length-frequency distributions of Atlantic croaker samples obtained from different commercial fishing gears in North Carolina suggest different selectivity patterns (Figure 2.8). The smaller Atlantic croaker were captured by pound nets and haul seines, which are primarily inshore gears. Trawl and gill net fisheries operate offshore and typically catch larger Atlantic croaker. The recreational fishery, which is both in and offshore, expectedly captures the most diverse size range (Figure 2.9).

One interesting result was the observed increase in maximum length of Atlantic croaker, especially in recent years. This is most apparent in the coastwide length samples from the recreational fishery (Figure 2.9), but is also evident in the length composition samples from the North Carolina commercial fisheries. A closer look at the recreational length data reveals that this increase is evident in the Virginia samples and to a lesser degree in the North Carolina samples (Figure 2.10).

The fishery-independent surveys provide information about relative abundance. The NC120, VIMS, and NEFSC surveys provide evidence that recruitment was poor during the late 1980s (Figure 2.11). Information about year-class strength was reasonably consistent between the fishery-independent surveys (Figure 2.12).

Samples from NCDMF and VMRC indicated similar growth patterns and so these data were combined to generate parameter estimates of the von Bertalanffy growth curve (Figure 2.13). Previous estimates of these parameters have shown large variation, likely due to the differences in time frame and area investigated (Barbieri et al. 1994a; Barger 1995; Ross 1998). Estimates here (L_∞=45 cm, K=0.25) fall into this diverse range (L_∞=31-65 cm, K=0.20-0.36; Table 2.2), and provide external estimates of the parameters that can be compared to the growth parameters estimated by the synthesis model.

2.2.2 Stock Assessment

The synthesis model was structured to have five fisheries (pound nets, gill nets, haul seines, trawls, recreational) and five surveys (NC120 June, NC195 June, NC195 September, VIMS October, and NEFSC September). Preliminary runs of the stock synthesis model that allowed for estimation of all gear selectivity patterns resulted in poor parameter estimates that were dependent on the starting values. Kimura (1989) noted that auxiliary data are sometimes insufficient to constrain a model and suggested that fixing additional selectivity parameters may produce more reliable model results. For this study, the selectivity of the recreational fishery was fixed to an asymptotic pattern in order to get more stable (better constrained) parameter estimates. Larger fish are well represented in the recreational length composition data (Figure 2.14). Also, evidence of stock recovery is most apparent in the recreational length samples. A tabular summary of population estimates from the base run is given in Appendix 7.2.

Selectivity patterns varied among surveys and fisheries in a predictable fashion, based on where the survey or fishery occurs (Figure 2.15). The estuarine NC195 June survey selected age-1 fish, whereas the NEFSC offshore survey caught larger fish but generally smaller than those occurring in the five commercial fisheries. The pound net fishery was estimated to select somewhat smaller fish than the other gears, whereas larger fish were estimated to be more vulnerable to the gillnet fishery than the other commercial gears.

There was reasonable agreement between the observed and predicted CPUE values for the five surveys (Figure 2.16). The patterns for year-class strength were generally similar for the three surveys of age-0 abundance (NC120 June, NC195 September, and VIMS), the age-1 mode of the NC195 June survey, and the NEFSC survey (even though the NEFSC survey selects a broader range of sizes). There is some indication of poor recruitment in the late 1980s compared to more recent years. Predicted estimates of survey CPUE suggest strong 1994 and 1998 year-classes.

Trends in estimated biomass were linked to recruitment variation through time (Figure 2.17). Estimated biomass declined to a low point around 1990 then increased sharply in recent years, due to the estimated strength of the 1994 year-class. The 1996 and 1997 year-classes were estimated to be of average strength but the 1998 year-class was relatively large. As in most stock assessments, the biomass estimates for the most recent years are the most uncertain, so the predicted decline in 2000-2002 must be re-examined with additional data. Estimated instantaneous fishing mortality rates (summed over fisheries, averaged over ages 1-10) have been high historically, particularly during the late 1980s when biomass was estimated to be low (Figure 2.17). The most recent *F* estimates indicate fairly high fishing mortality rates, but as terminal year estimates are associated with a higher degree of uncertainty, they should be interpreted with caution.

The stock synthesis model estimates of the von Bertalanffy growth parameters were L_∞ = 44.82, $L_{age\text{-}10}$ = 41.67, and *K*=0.25. These values are consistent with the external estimates predicted from the external fit of the von Bertalanffy growth function based on the NCDMF and VMRC age samples (Table 2.2).

There was moderate agreement between observed and predicted mean total length from the various surveys and fisheries (Figure 2.18). It was not possible to fit the patterns from all data sources with this model structure because the patterns were inconsistent. For example, mean lengths generally increased over the past few years in the gill net, trawl, and recreational fisheries. The model interpreted this as a rebuilding process (increasing proportion of older and larger fish). However, the fishery-independent NEFSC survey did not show an increasing pattern over time. In some cases (*e.g.*, 1994 and 1999-2001 pound net, 1994-1995 and 1999 haul seine), changes in mean total length from year to year were greater than would be expected due to variation in age composition. The consistent differences between observed and predicted mean length in 1998-2002 commercial gill net and trawl samples could indicate a recent change in gear selectivity.

2.2.3 Uncertainty

In addition to a base stock assessment, a number of alternative models were fitted in order to evaluate the sensitivity of results to survey data and different assumptions about population parameters (Table 2.3). Results of the base stock assessment (Appendix 7.2) suggested that 1994 was a relatively large year-class, estimated at a value of 291 million fish (Figure 2.17). A profiling technique was used to explore the sensitivity of the model results by fixing this parameter at values ranging from 10 to 900 million individuals and re-fitting the stock synthesis model. Compared to the best fit, the model fit is degraded (lower negative log-likelihood values) at higher and lower values of 1994 year-class strength (Figure 2.19). Estimated annual biomass and recruitment levels prior to 1994 (Figure 2.20) were essentially unaffected by changes in the strength of the 1994 year-class. Trends in biomass estimates for years after 1994 were similar, though the relative magnitude was directly proportional to the value assumed for the 1994 year-class. Intuitively, this makes sense because increasing the strength of a recent year-class would increase biomass numbers in subsequent years.

Eliminating various sources of information had little effect on the performance of the synthesis model, in general. The emphasis values assigned to individual likelihood components in the sensitivity runs as compared to the base run are given in Table 2.4. Patterns of estimated *F*s were generally similar to that estimated in the base assessment regardless of which source of data was given reduced emphasis (Figure 2.21). Annual estimates of recruitment and biomass also exhibited similar patterns regardless of which data sources were de-emphasized (Figure 2.21). The relaxation of the stock-recruitment relationship had a negligible effect on the synthesis model results compared to the base model results. Estimates of recruitment and *F* were similar to those predicted in the base run (Figure 2.22). Predicted biomass was somewhat higher than the base run from the mid-1990s through 2002 (Figure 2.22). When the synthesis model was re-fitted with an assumed *M* of 0.20, estimated recruitment values were similar to the base run for most of the time series whereas biomass estimates were higher and *F*s were lower for M=0.20 (Figure 2.23). Assuming M=0.50 produced estimates of recruitment that were generally similar to the base run (Figure 2.23). Biomass estimates based on M=0.50 were lower in earlier and later years and comparable over the middle of the time series. Estimates of *F* based on M=0.50 were higher than for the base run.

Model runs based on different assumptions regarding the variance of survey relative abundance produced similar patterns in annual recruitment, biomass, and *F* (Figure 2.24). Estimates of *F* over time were the most variable between the methods - especially in the earlier part of the time series where the two alternative survey variance methods estimated average *F* rates that were consistently higher than the base run. The *F* estimated for the final year was similar between the base run and the run with a fixed level of survey error, but the terminal *F* was 60% higher for the iterative re-weighting run than the base run.

3 YIELD-PER-RECRUIT ANALYSIS

3.1 Background

The purpose of a yield-per-recruit (YPR) analysis is to investigate how different levels of fishing influence a population (Beverton and Holt 1957; Ricker 1975; Gulland 1983). Chittenden (1977) applied a YPR model to Atlantic croaker based on data from the northwestern Gulf of Mexico, but indicated that the results were not necessarily applicable to other regions. Barbieri et al. (1997) performed a YPR analysis for Atlantic croaker using stock assessment data from the Chesapeake Bay (years 1988-91; Barbieri et al. 1994a) and North Carolina (years 1979-81; Ross 1988). Here, a YPR model is applied to the stock assessment results to investigate a range of fishing mortalities and ages-at-entry on the potential yield of Atlantic croaker harvest. This allows for exploration of potential management scenarios that would maximize yield of fish after they have recruited. Different assumptions about natural mortality are considered.

3.2 Methods

Yield calculations were calculated using Ricker's (1975) approach, a flexible method that is easily set up in spreadsheet format:

$$Y = \sum_a N_a W_a \left(\frac{F_a}{Z_a} \right) A_a$$

where N_a, W_a, F_a, Z_a, and A_a are cohort size, mean weight, instantaneous fishing mortality rate, instantaneous total mortality rate, and total mortality rate for age a fish.

The assessment model estimates of von Bertalanffy growth parameters were used to calculate length-at-age for ages 1 – 10, and weight-at-age values were calculated using a length-weight relationship provided by Ross (1988). Average Fs by age over the 1981-2002 time interval were rescaled to a maximum of 1 to estimate an overall selectivity pattern for all gears combined (Figure 3.1). Estimates of YPR were calculated for different assumed ages-at-entry and Fs. This allowed for evaluation of the gains or losses in yield by varying those management options. Due to the uncertainty associated with estimates of M, trials were conducted using the three M values (and resulting synthesis model estimates) considered in the stock synthesis model sensitivity analyses.

3.3 Results

The results suggest that YPR of Atlantic croaker could be maximized if age-at-entry were delayed to age 4 assuming M=0.35, age 5 or 6 for M=0.20, and age 3 for M=0.50, depending on F (Figure 3.2). Current age-at-entry is age 1 or lower; thus, these results suggest that a significant gain in yield could be made if harvest was delayed. The F that maximized YPR for age-at-entry of 1 year was 0.25 at M=0.20, 0.35 at M=0.35, and 0.55 at M=0.50 (Figure 3.3). Higher Fs would maximize YPR if age-at-entry were increased.

4 SPATIAL DISTRIBUTION OF RECRUITS

4.1 Background

Survey indices of abundance, such as mean catch per tow, are assumed to reflect changes in population abundance. However, estimates of mean catch per tow can also vary due to factors such as catchability, spatial heterogeneity, changes in survey design, and environmental influences (Pennington 1985). A statistically sound survey design is one of the primary methods for reducing the variance in survey estimates. The distribution of the target species determines the level of precision that can be attained (Gunderson 1993). The spatial pattern of a distribution is defined by the arrangement of individual entities in space and the geographic relationships among them. The capability of evaluating spatial patterns is a prerequisite to understanding the complicated spatial processes underlying the distribution of a phenomenon. Identifying spatial distributions can improve the design and efficiency of a survey for a target species (Barange and Hampton 1997). Sites that are too close together may yield duplicate information, reducing efficiency. Likewise, sampling sites that are too far apart may not provide an adequate representation of the attribute that is being measured.

The amount of variance in survey estimates attributed to spatial patterns can be assessed by evaluating the degree of spatial variation associated with the variable of interest. Spatial autocorrelation is a measure of the relationship between the value of a variable and the location of that variable in space (Oden and Sokal 1986; Legendre and Fortin 1989). It indicates the extent to which the occurrence of one feature is influenced by similar features in neighboring areas. The intensity and extent of spatial autocorrelation can be quantified using spatial statistics (Cressie 1991; Legendre and Legendre 1998; Brunt 2000). The correlogram is one method for evaluating the correlation of data with distance (Oden and Sokal 1986; Legendre and Legendre 1998). Correlograms provide an index of spatial autocorrelation at defined distance intervals to describe spatial trends and to test for the presence of spatial autocorrelation in the distribution pattern of a variable.

The primary goal of this exploratory analysis was to describe spatial patterns in age-0 abundance indices, including the degree of spatial autocorrelation. A secondary goal was to determine the level of agreement between recruitment patterns for Virginia and North Carolina.

4.2 Methods

4.2.1 Data

Data from surveys the NC195 September and VIMS October surveys were among the indices of year-class strength used in the stock synthesis model. Recall that the CPUE values were shifted forward by one year and considered indices of age-1 abundance in the following year within the model. Observations for 2002 are included in the exploratory spatial analyses. The observations of age-0 Atlantic croaker in these surveys along with geographic coordinates were used to evaluate the spatial distribution of recruits in the Pamlico Sound and Chesapeake Bay, including the tributaries and creeks of those water bodies (Figure 4.1). The NC120 June survey was not considered for the spatial analysis, as it is restricted to shallow water, occurs at a different time of year, and so may not provide a suitable comparison. Refer to Section 2.1.1.2 for description of survey designs and methods.

4.2.2 Analysis

The NC195 September and VIMS October recruitment indices (number of fish per tow) were z-transformed to provide a uniform scale for comparison. The transformed values were plotted against time to provide a visual comparison of temporal trends. The strength of the relationship between the indices was evaluated using Spearman's ρ correlation coefficient ($\alpha = 0.05$).

Latitude and longitude coordinates for each tow location (recorded at time of survey tow) were provided for both surveys. Availability of the geographic coordinates for the sampling stations allowed for determining the number of age-0 Atlantic croaker observed at each station by year for both survey regions. All counts were log-transformed (ln[count+1]) prior to analysis. For both surveys, the spatial distributions of age-0 Atlantic croaker observed at each sampling station were plotted for each year.

Moran's I statistic was applied to test for the presence of spatial autocorrelation in the distribution of age-0 Atlantic croaker by year in each region (Moran 1950; Legendre and Legendre 1998). The Moran statistic is a weighted correlation coefficient used to measure the degree of spatial autocorrelation in a variable over a series of distance classes, or lag increments. Moran's I is computed as:

$$I(d) = \frac{\frac{1}{W}\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad \text{for } j \neq i$$

where y_i and y_j are the observed values of the variable under evaluation, n is the number of observations, w_{ij} is the weight of distance class d, and W is the sum of w_{ij} for the particular distance class. The statistic is similar to Pearson's r in that the estimated values usually range from -1 to +1, though values outside this range may be obtained.

In order to define distance classes, a matrix of geographic distances between all pairs of tow locations must be computed. Here, geographic distance matrices were developed for all pairs of samples by year for each survey. Moran's I was calculated for equidistant lags of 5-km (Sokal 1979; Oden and Sokal 1986). The Moran statistics were then plotted against distance intervals within the range of reliability to form correlograms. The range of reliability is considered to be half the maximum distance for all pairs (Journel and Huijbregts 1978). A general rule of thumb suggests that each interval within the range of reliability should contain at least 30 pairs of points (Journel and Huijbregts 1978; Legendre and Fortin 1989; Rossi et al. 1992).

The significance (α = 0.05) of the Moran test statistics was evaluated by random data permutation, whereby the log-transformed abundances were randomly redistributed among the spatial coordinates for each of 1,000 permutations (Sokal 1979; Legendre 1993; Edgington 1995). Moran's I is recomputed during each permutation and compared to the value of I calculated from the original data. When determining significance simultaneously for multiple comparisons, an adjustment is needed because the tests are not independent. Legendre and Legendre (1998) recommend Holm's correction procedure (Holm 1979) for assessing significance of the individual lag increments. The correlogram is considered globally significant if at least one of the individual values is significant after applying Holm's correction.

4.3 Results

A marginally significant correlation was found between the z-transformed NC195 September and VIMS October indices of recruitment ($\rho = 0.4871$, Prob > $|\rho| = 0.0557$). Both series showed a period of relatively weak year-class strength from about 1987 – 1990 (Figure 4.2). Recruit strength in 1996 and 2001 was relatively weak in both areas. Years of stronger recruitment occurred in 1993, 1994, 1997, and 1998.

The spatial distribution of age-0 abundance exhibited year-to-year variation with both the VIMS October and NC195 September surveys. Relative abundance of recruits was usually greater in the three major tributaries extending west from the Chesapeake Bay based on the VIMS October survey data (Figure 4.3). In some years, this pattern extended from the tributaries into the main part of the Bay. In the NC195 September survey, recruit abundance tended to have larger values in the northeast portion of Pamlico Sound and in the major tributary extending west from the Sound (Figure 4.4). In both surveys, strong year classes resulted in high catch rates throughout the surveyed area.

The results of the Moran's test for spatial autocorrelation varied within and between surveys. The 1987 VIMS October survey had the fewest number of tows in the time series and all of these tows occurred within tributaries (Figure 4.3). The number of pairs of points per distance class ranged from 10 to 32 within the range of reliability, where only three intervals provided the recommended minimum of 30 pairs. As such, the correlogram for that year is not considered reliable, though it is included for presentation (Figure 4.5). Only five of the remaining years contained a distance interval with fewer than 30 pairs of points; in all of these cases, this occurred at the shortest lag, 5-km. The average number of pairs per distance class within the range of reliability varied between 108 and 499, not including 1987 where 23 was the average. The maximum distance between pairs of tow locations ranged from 105 to 147-km from 1987 to 2002. As such, ranges of reliability varied between 52 and 73-km. The Moran correlograms for the VIMS October survey indicated positive spatial autocorrelation at smaller distance intervals and negative autocorrelation at greater distances for most years (Table 4.1; Figure 4.5). Moran's tests indicated log-transformed abundance values at the shortest lag were significantly positively correlated in 1991, 1998, 1999, 2001 and 2002. Few negative correlation coefficients that were significant were found. There was no obvious pattern in the occurrence of significant correlation coefficients among distance classes and between years. All correlograms were determined to be globally significant, with the exception of the 1987 and 1989 correlograms, which revealed no significant correlation at any distance.

Few tows were available for analysis based on the 1999 NC195 September survey. The size intervals used provided between 1 and 17 point pairs per lag increment within the range of reliability. While the correlogram for 1999 for this survey is not considered reliable, it is included for presentation (Figure 4.6). In all other years, the number of pairs of points exceeded 30 for all but the shortest distance class within the reliable range. The only exception was 1997, where there were 32 pairs of points within the 5-km distance interval. The average number of pairs per lag ranged from 60 to 78 between 1987 and 2002, excluding 1999. The maximum distance between all pairs in the NC195 September survey from year to year varied from 113 to 152-km, which resulted in ranges of reliability between 56 and 76-km. Similar to the VIMS October survey, the correlograms for the NC195 September survey data tended to show positive spatial correlation at smaller increments and negative autocorrelation with increasing distance between locations (Table 4.2; Figure 4.6). Likewise, no obvious pattern in the occurrence of significant correlation coefficients among distance classes and between years emerged. The correlograms for 1987 and 1989 showed significant positive autocorrelation within the 5 and 10-km lag increments. In 1991, 1993, and 1995, the first three distance intervals showed statistically significant correlation. The 2000 correlogram for the NC195 September survey exhibited significant positive spatial correlation in the first five distance classes (through 25-km). The correlograms for 1989 and 1993 showed significant negative autocorrelation for a series of intervals at larger distances. Correlograms for 1988, 1990, 1992, 1999, and 2001 were not found to be globally significant.

5 DISCUSSION

Assessment of Atlantic croaker is complex due to the five major fisheries (with different selectivity patterns) and the numerous fishery-independent surveys that were available. The assessment made use of both length and age data in order to characterize growth and the selectivity of each fishery and survey. A strictly age-based assessment could be done, but it would be for a shorter time frame (1988-2002 compared to 1981-2002) and would not have information about the size/age composition of the recreational fishery, which is of considerable importance in recent years. Length composition data from surveys also contain considerable information about growth that would be sacrificed in an age-based assessment.

The fitted von Bertalanffy growth curve obtained from the synthesis model was similar to the curve generated externally from pooled Virginia-North Carolina age data. Parameters for the synthesis model curve were: $L_{age\text{-}0.75}$ = 14.13 (fixed); $L_{age\text{-}10}$ = 41.67; L_{∞} = 44.82; and K=0.25. The synthesis model was used to estimate the coefficients of variation (CV) for length-at-age. The estimated CVs (0.23 at age-1, 0.06 at age-10) differed somewhat from estimates produced externally from NCDMF scale (CV=0.12) and otolith (CV=0.14) age data. Some difference would be expected, given that the various fisheries result in a size-selective sample that understates population variability in length-at-age. The predicted age-length distribution from the fitted synthesis model was consistent with observed length modes from surveys and published reports (Ross 1988).

Results of the base assessment, as well as the profiling and sensitivity analysis, strongly suggest that the Atlantic croaker population is recruitment driven. Trends in recruitment are reflected by patterns in biomass. Low recruitment in the mid- to late 1980s caused a decline in estimated biomass. Also, the synthesis model indicated the presence of strong recent year-classes that caused estimated biomass to increase. There is some uncertainty in biomass and fishing mortality estimates due to uncertainty about *M*. While the estimated patterns in recruitment were similar over the range of *M* explored, assuming a lower *M* resulted in overall higher biomass and assuming a higher *M* resulted in lower biomass and higher fishing mortality estimates.

Estimates of *F* were generally consistent with the results from North Carolina and the Gulf of Mexico, but higher than expected based on results from the Chesapeake Bay. In

2002, F was estimated at 1.11 (averaged over ages 1-5), which would imply that the total instantaneous mortality rate (Z) was about 1.5. Ross (1988) used catch curve analyses on North Carolina data and calculated a Z of 1.3 for ages 1-5. A Z value of 0.96 was reported for Atlantic croaker in the Gulf of Mexico (White and Chittenden 1977). These estimates are considerably higher than the range of 0.55 to 0.63 for Z estimated for the Chesapeake Bay from a catch curve analysis (Barbieri et al. 1994a). The differences in estimates may be due to differences in geographic location, methods, time period, or gear selectivity, which is not accounted for in the catch curve analysis.

The synthesis model performance was variable when assumptions regarding M changed. Overall trends in recruitment were similar for all assumed values of natural mortality. The range of M values explored resulted in generally similar recruitment estimates for the time series. The model with lower M (M=0.20) estimated an especially strong peak in recruitment in 1994, which was not seen in the base run. Assuming higher M predicted strong 1994 and 1998 year-classes like the base run, but the relative strength of those year-classes was estimated to be higher based on the larger M. Lowering M resulted in higher biomass estimates while predicted Fs were correspondingly smaller. Assuming a higher value of M (M=0.50) produced lower biomass than the base run for most of the time series. Estimates of F were consistently higher than the base run estimates assuming the larger M.

A YPR analysis suggested that yield could be substantially increased if harvest was restricted to at least age 2 and older. At the current age-at-entry (age 1 or lower) F_{MAX} is 0.35 for M=0.35, 0.25 for M=0.20, and 0.55 for M=0.50. Estimated total F for age-1 Atlantic croaker in 2002 was 0.79, suggesting a reduction in fishing pressure may increase yield. Another study suggested that the abundance and size of adult Atlantic croaker could be increased through reductions in bycatch (Diamond et al. 1999).

The seasonal patterns of the commercial fisheries for Atlantic croaker, based on their migration patterns, also complicate the assessment process. The ocean gillnet and trawl fisheries occur during winter months, so summaries on an annual basis combine catches that are widely separated in time (*e.g.*, January-March combined with October-December). This introduces error into the length composition and size-at-age data, especially for age-1 fish that are growing rapidly. Developing a model that is based on a biological year, rather than an annual time scale, might be more appropriate. This would require agencies to put landings and commercial fishery samples together using a biological year. This should reduce some of the inconsistencies between the surveys and fisheries regarding size-at-age-1.

Careful consideration should be given to the specification of error associated with auxiliary indices of relative abundance. The precision of assessment results is a function of the precision of input information. While trends in population estimates were similar among the models assuming different error for the survey indices, there was evidence that the method used to specify error can result in highly divergent estimates of F in the terminal year. Sampson and Yin (1998) found that using a time-invariant high estimate of survey biomass variability versus a low estimate had a significant effect on terminal year F in simulated assessments using the stock synthesis model. Their results also showed that differences in the error of the survey indices had a substantial influence over the variation in ending year estimates of biomass, exploitable biomass, and recruitment. Similar results were reported in a recent extension of that study (Yin and Sampson 2004). Maunder and Starr (2003) performed Monte Carlo simulations to evaluate the results of a surplus production model that incorporated constant versus variable error between years for fishery-dependent indices. They concluded that not accounting for between year variability can introduce bias into the model and lead to less precise population estimates. Uncertainty in terminal year estimates of F and biomass is an important management concern, as these parameters are often used for updating stock status and setting management regulations.

Spatial autocorrelation was detected for age-0 Atlantic croaker abundance observed in the NC195 September and VIMS October surveys. In general, sampling stations in close proximity tended to have more similar observations of age-0 abundance. Likewise, abundance values were more dissimilar between locations at greater distances. Positive spatial autocorrelation typically occurred at distances less than 30-km, while negative spatial autocorrelation was more often detected at distances of 40-km or greater. Ecological variables are more likely to have similar magnitude at sites that are closer in space than sites that are farther apart (Cressie 1991; Legendre 1993; Brown et al. 1995; Koenig 1999; Rivoirard et al. 2000). The analysis of spatial variation of age-0 abundance suggests that spatial distance could explain a proportion of the variation in the counts among stations. As physical processes driving spatial patterns can vary at different scales, the degree of spatial variation can also vary at different scales. The trends in spatial autocorrelation of Atlantic croaker recruits found here may differ from analyses of spatial variation on a more global scale (*e.g.*, across systems) or on a finer scale (*e.g.*, distances less than 5-km apart). Statistics based on spatial sampling are often confounded by autocorrelation, due to the assumption that variables are independent and identically distributed in space (Legendre and Fortin 1989; Horne and Smith 1997; Rivoirard et al. 2000). Failure to consider underlying spatial structures may result in inaccurate estimates of relative abundance (Swartzman et al. 1992; Booth 2000). Further research to investigate the underlying causes of spatial patterns could result in better estimates of year-class strength that would then result in a more reliable stock assessment. Using information about spatial variation to design future surveys should also improve efficiency and reduce duplication of information. Sampling sites that are optimally distributed in space reduce the variances of estimates derived from observations and so reduce bias introduced into the model.

It is likely that we have a poor understanding of the population characteristics of Atlantic croaker in the absence of fishing. Historical landings of Atlantic croaker in North Carolina averaged around 6 million pounds in the late 1920s through early 1930s which suggests that Atlantic croaker have been significantly exploited for a long time (Chestnut and Davies 1975). This reduces confidence in the perception of maximum age and estimates of *M*. Uncertainties about *M* introduce uncertainties in estimates of biomass and mortality rates, and recommendations about target *F*s (Vetter 1988).

The potential for spatial differences in the stock structure of Atlantic croaker further complicates the population model. In 2004, the ASMFC's Atlantic Croaker Technical Committee and Stock Assessment Subcommittee performed an assessment for the mid-Atlantic region (ASMFC 2003, 2004). A separate assessment of the south Atlantic region was also attempted, but was considered unacceptable by the Technical Committee (ASMFC 2003). A peer review panel stated that there was inadequate support for applying regional assessments and recommended further investigation into the question of stock structure. The current management plan assumes a single stock for the Atlantic coast (ASMFC 1987).

The suggestion of spatial differences in the population dynamics of Atlantic croaker has been debated in the literature for some time. White and Chittenden (1977) found a number of aspects of the life history of Atlantic croaker in the warm-temperate waters of the Carolina Province that were different than those of fish found in the cold-temperate waters north of Cape Hatteras. These included differences in spawning season, size and age at maturity, and maximum size. Ross (1988) supported those results, finding evidence of two groups of Atlantic croaker overlapping in North Carolina. Though he considered Cape Lookout as the zoogeographic boundary, his data were consistent with the proposed northern group life history (larger sizes and older ages). He inferred that population dynamics data and the resulting fishery management may be confounded by a possible mixing of Atlantic croaker until adequate separation techniques are produced. In contrast, Barbieri et al. (1994a) disputed the existence of a group of larger, older Atlantic croaker in the Chesapeake Bay as compared to more southern waters and suggested that the hypothesis of different groups occurring above and below Cape Hatteras should be reevaluated. However, they stated that surveys of the age and size composition of Atlantic croaker over time are needed to fully assess this inquiry. An analysis of otolith microchemistry detected no significant differences between juvenile Atlantic croaker from North Carolina and Virginia, suggesting larvae from north and south of Cape Hatteras may come from a single spawning sites (Thorrold et al. 1997). A study of genetic population structure found no evidence that Atlantic croaker from North Carolina and Virginia are from different genetic stocks using mitochondrial DNA analysis (Lankford 1997; Lankford et al. 1999). More recently, Lankford and Targett (2001) investigated adaptive variation in growth capacity and cold tolerance of young-of-year Atlantic croaker and found no geographic variation in these physiological traits, lending further support to hypothesis of a single stock along the Atlantic coast. The model developed here used commercial fishery length and size-at-age data from the North Carolina sampling programs to represent coastwide landings, even though Virginia was responsible for a significant portion of the landings. The only data source from Virginia used was CPUE information from the VIMS fishery-independent survey. Creating a coastwide model using both Virginia and North Carolina fishery data may not be practical (at least using a separable model) because one would need to account for 8 commercial gears and the recreational fishery, not to mention the number of fishery-independent surveys available. Performing separate assessments for both North Carolina and Virginia is more feasible; however migration of Atlantic croaker would not be accounted for and would increase uncertainty. The survey data suggest that patterns in year-class strength are similar for Virginia and North Carolina, adding support to the coastwide approach.

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Table 2.1 Summary of data sources and types used in Atlantic croaker stock assessment model.

	DATA TYPE	SOURCE	YEARS
Harvest	Commercial East Coast landings by year, gear, state	NMFS	1981-2002
	Recreational East Coast landings by year, state	MRFSS	1981-2002
Size	Length composition by year - commercial gear (haul seine, gill net, pound net, trawl)	NCDMF	1986-2002
	Length composition by year - recreational fishery	MRFSS	1981-2002
	Length composition by year - surveys	NCDMF 195	1987-2002
		NEFSC	1981-2002
Age	Mean size-at-age by year - commercial gear (haul seine, gill net, pound net, trawl)	NCDMF	1988-2002
		VMRC	1998
Abundance	CPUE by year - surveys	NCDMF 120	1980-2002
		NCDMF 195 (June)	1987-2002
		NCDMF 195 (Sept)	1987-2001
		VIMS	1980-2001
		NEFSC	1981-2002

Table 2.2 Parameter estimates of the von Bertalanffy growth curve from this and previous studies.

L_∞ (cm)	*K*	REGION	SOURCE
45	0.25	North Carolina / Virginia	NCDMF & VMRC
42	0.25	US Atlantic Coast	Stock Synthesis Model estimates (this study)
31	0.36	Chesapeake Bay	Barbieri et al. (1994a)
65	0.20	North Carolina	Ross (1998)
42	0.27	N. Gulf of Mexico	Barger (1995)

Table 2.3 Overview of alternative model structures used in evaluating uncertainty of base model results.

METHOD	SOURCE OF UNCERTAINTY	RUN LABEL	DESCRIPTION
Profiling	1994 Recruitment Level	10	Recruitment in 1994 fixed at 10 million individuals
		50	Recruitment in 1994 fixed at 50 million individuals
		100	Recruitment in 1994 fixed at 100 million individuals
		200	Recruitment in 1994 fixed at 200 million individuals
		400	Recruitment in 1994 fixed at 400 million individuals
		500	Recruitment in 1994 fixed at 500 million individuals
		700	Recruitment in 1994 fixed at 700 million individuals
		900	Recruitment in 1994 fixed at 900 million individuals
Sensitivity	Data Source	No NEFSC	Reduced emphasis of NEFSC survey observations
		No VIMS	Reduced emphasis of VIMS survey observations
		No NC120	Reduced emphasis of NC120 survey observations
		No NC195 June	Reduced emphasis of NC195 June survey observations
		No NC195 Sept	Reduced emphasis of NC195 September survey observations
		No NC	Reduced emphasis of NC120, NC195 June, and NC195 September survey observations
	Stock-Recruitment	Relaxed S-R	Reduced emphasis on the fitted stock-recruitment curve
	Survey Variance	Iterative re-weighting	Iterative re-weighting of the root mean square error used to estimate the standard error of each survey time series
		Fixed	A constant fixed value specified for the standard error of each survey time series
	Natural Mortality	$M = 0.20$	Natural mortality rate fixed at $M = 0.20$ for the population
		$M = 0.50$	Natural mortality rate fixed at $M = 0.50$ for the population

Table 2.4 Likelihood components and corresponding emphasis factors for the base model run and sensitivity analyses.

SENSITIVITY	SOURCE	KIND	RUN LABEL							
			Base	No NEFSC	No VIMS	No NC120	No NC195 June	No NC195 Sept	No NC	Relaxed S-R
Data Source	Gill Net	Catch	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Size-at-Age	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Haul Seine	Catch	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Size-at-Age	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Trawl	Catch	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Size-at-Age	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Pound Net	Catch	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Size-at-Age	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Recreational	Catch	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	NEFSC	CPUE	1.000	**0.001**	1.000	1.000	1.000	1.000	1.000	1.000
		Length	1.000	**0.001**	1.000	1.000	1.000	1.000	1.000	1.000
	VIMS	CPUE	1.000	1.000	**0.001**	1.000	1.000	1.000	1.000	1.000
	NC120	CPUE	1.000	1.000	1.000	**0.001**	1.000	1.000	**0.001**	1.000
	NC195 June	CPUE	1.000	1.000	1.000	1.000	**0.001**	1.000	**0.001**	1.000
		Length	1.000	1.000	1.000	1.000	**0.001**	1.000	**0.001**	1.000
	NC195 Sept	CPUE	1.000	1.000	1.000	1.000	1.000	**0.001**	**0.001**	1.000
Stock-Recruitment	S-R Curve	Stock-Recruit Indiv	1.000	1.000	1.000	1.000	1.000	1.000	1.000	**0.001**
		Stock-Recruit Mean	1.000	1.000	1.000	1.000	1.000	1.000	1.000	**0.001**

Table 4.1 Summary of distance classes where statistically significant positive (+) or negative (-) spatial autocorrelation was detected in the VIMS October survey data based on Moran's *I* statistics. Distance classes outside the range of reliability are shaded.

Year	DISTANCE CLASS (km)															
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
1987																
1988						+										
1989																
1990									-							
1991	+		+								-					
1992				+	+					-						
1993			+		+											
1994			+								-					
1995						+										
1996		+			-											
1997													-			
1998	+	+											+			
1999	+					-								-		
2000		+														
2001	+	+	+							-				-	-	
2002	+		+		-			+				-				

Table 4.2 Summary of distance classes where statistically significant positive (+) or negative (-) spatial autocorrelation was detected in the NC195 September survey data based on Moran's *I* statistics. Distance classes outside the range of reliability are shaded.

Year	DISTANCE CLASS (km)															
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
1987	+	+										-				
1988																
1989	+	+								-	-		-			
1990																
1991	+	+	+					+	+					-		
1992																
1993	+	+	+					-	-	-	-	-	-			
1994	+															
1995	+	+	+										+			
1996		+						-	-							
1997				+	+			-			-	-		-		
1998		-														
1999																
2000	+	+	+	+	+							-	-			
2001																
2002			+													

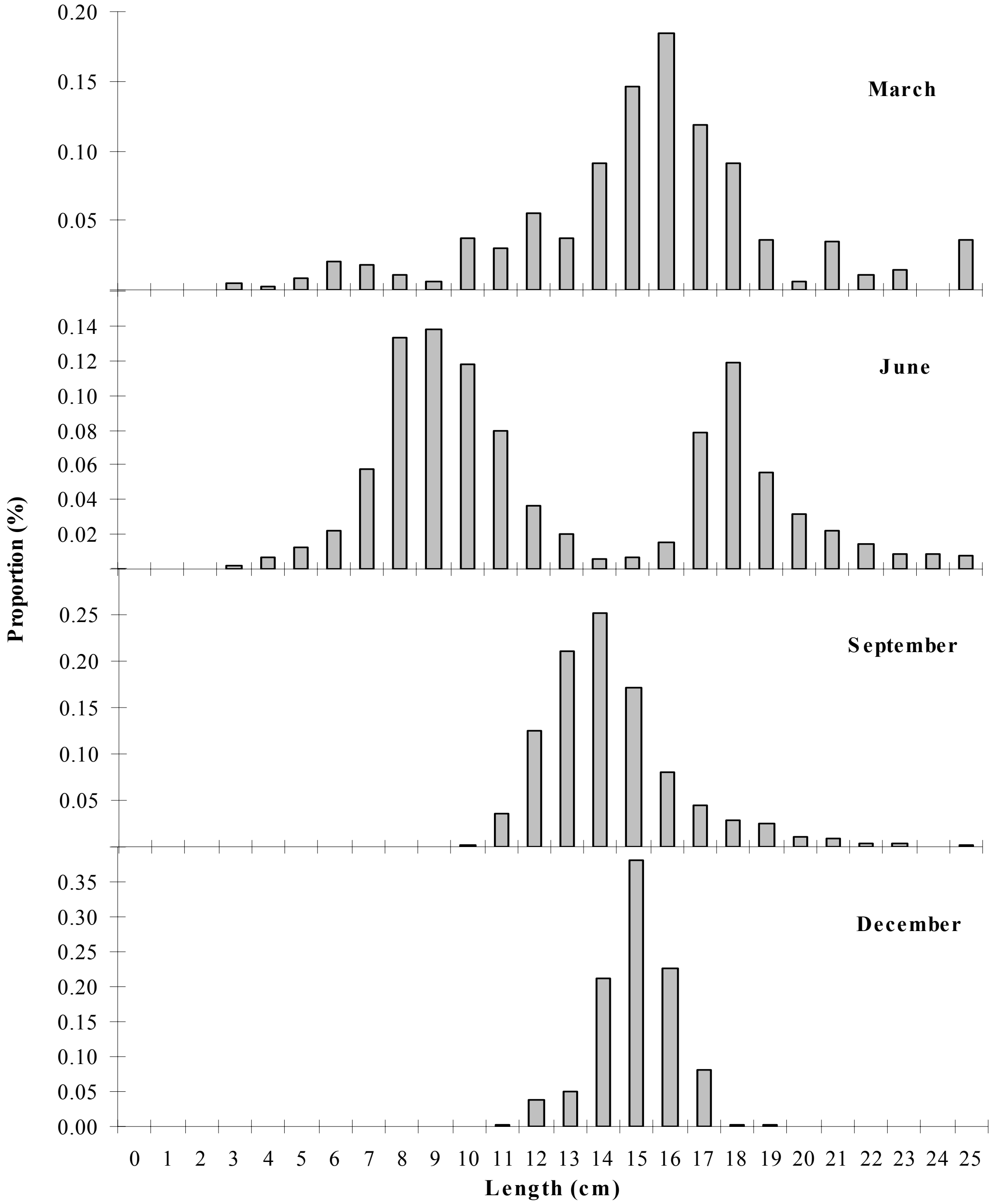


Figure 2.1 Length-frequency distributions of Atlantic croaker in 1988 from the NC195 survey.

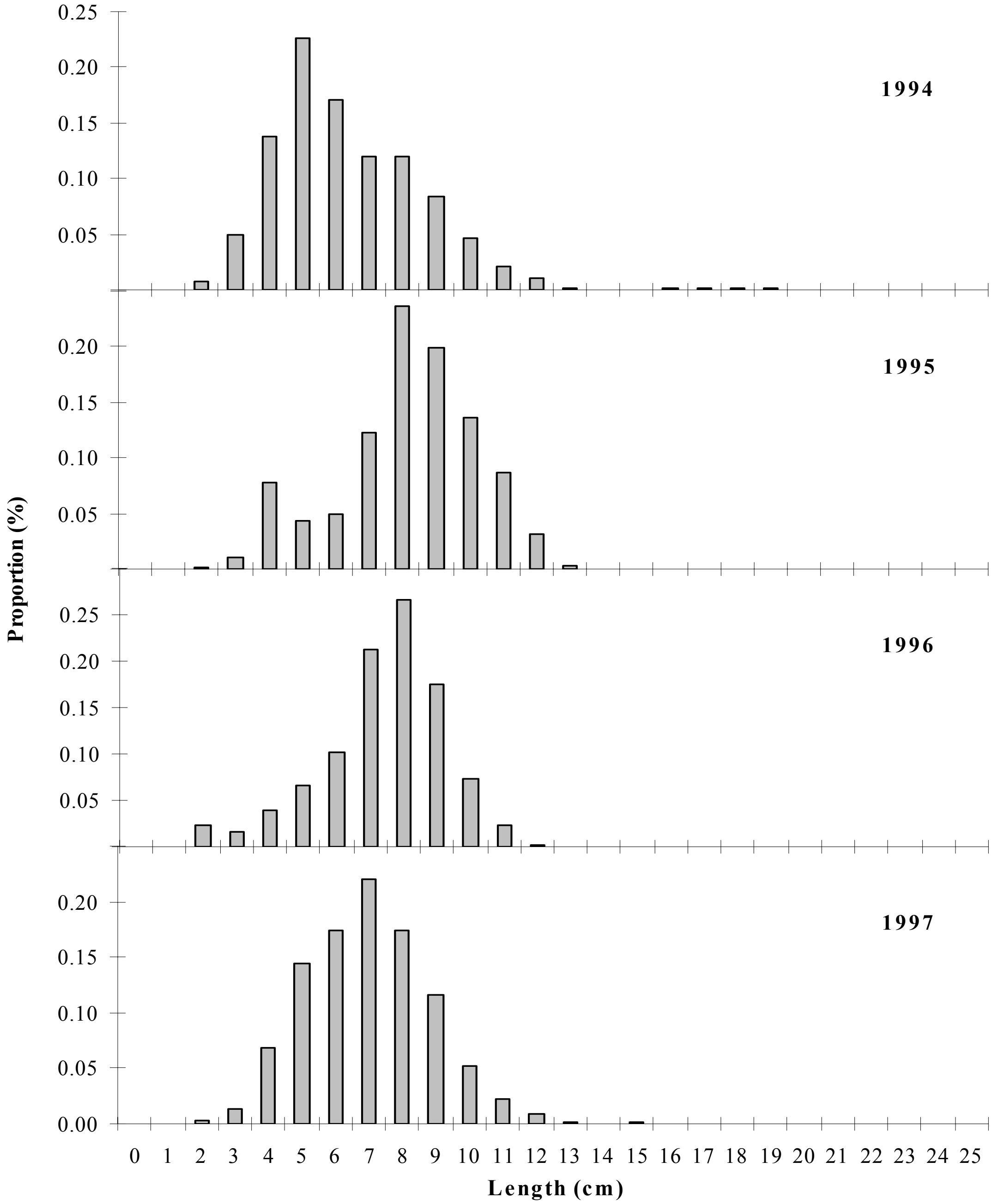


Figure 2.2 Atlantic croaker length distribution samples from the NC120 June survey for representative years.

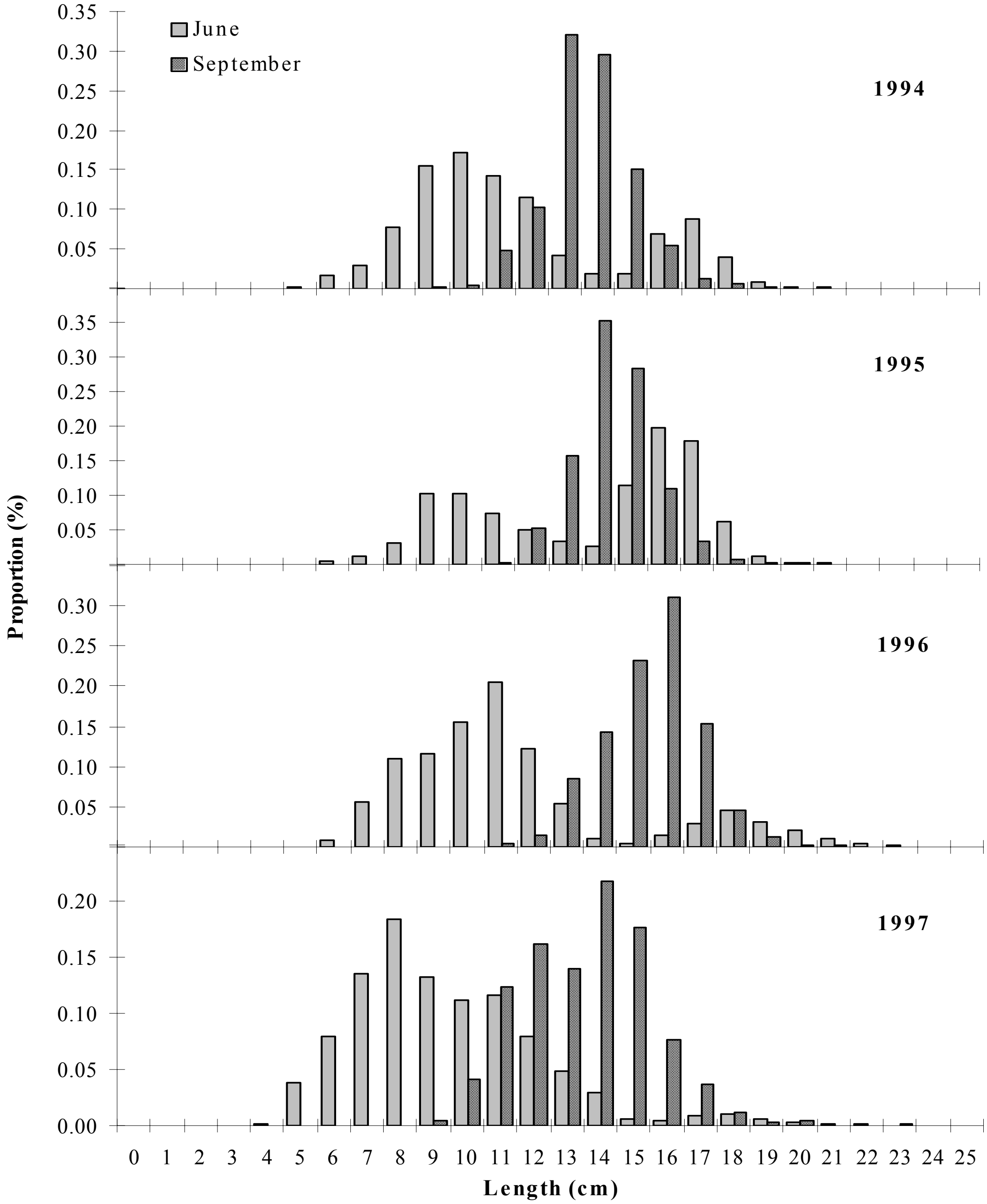


Figure 2.3 Atlantic croaker length distribution samples from the NC195 June and September surveys for representative years.

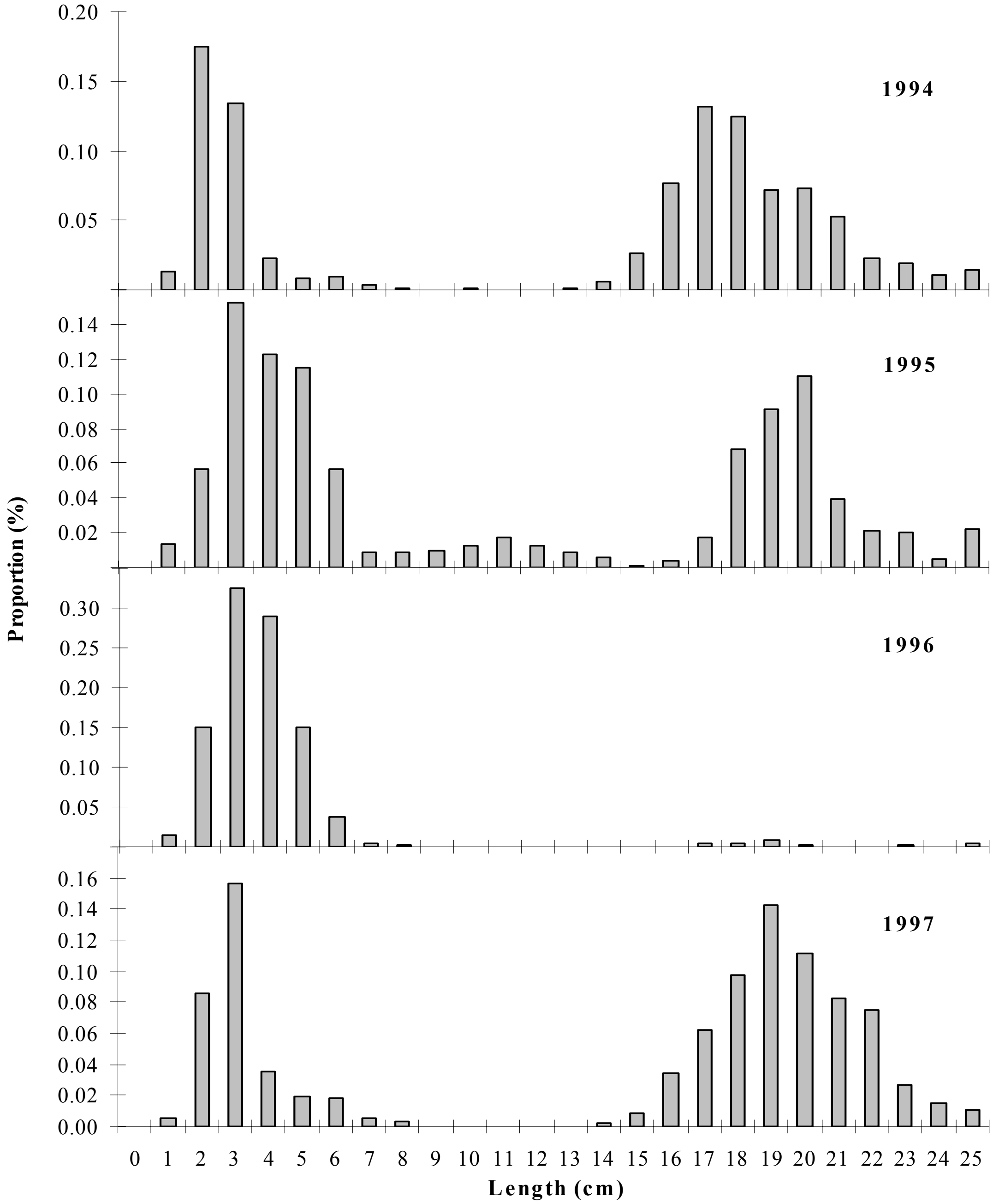


Figure 2.4 Atlantic croaker length distribution samples from the VIMS October survey for representative years.

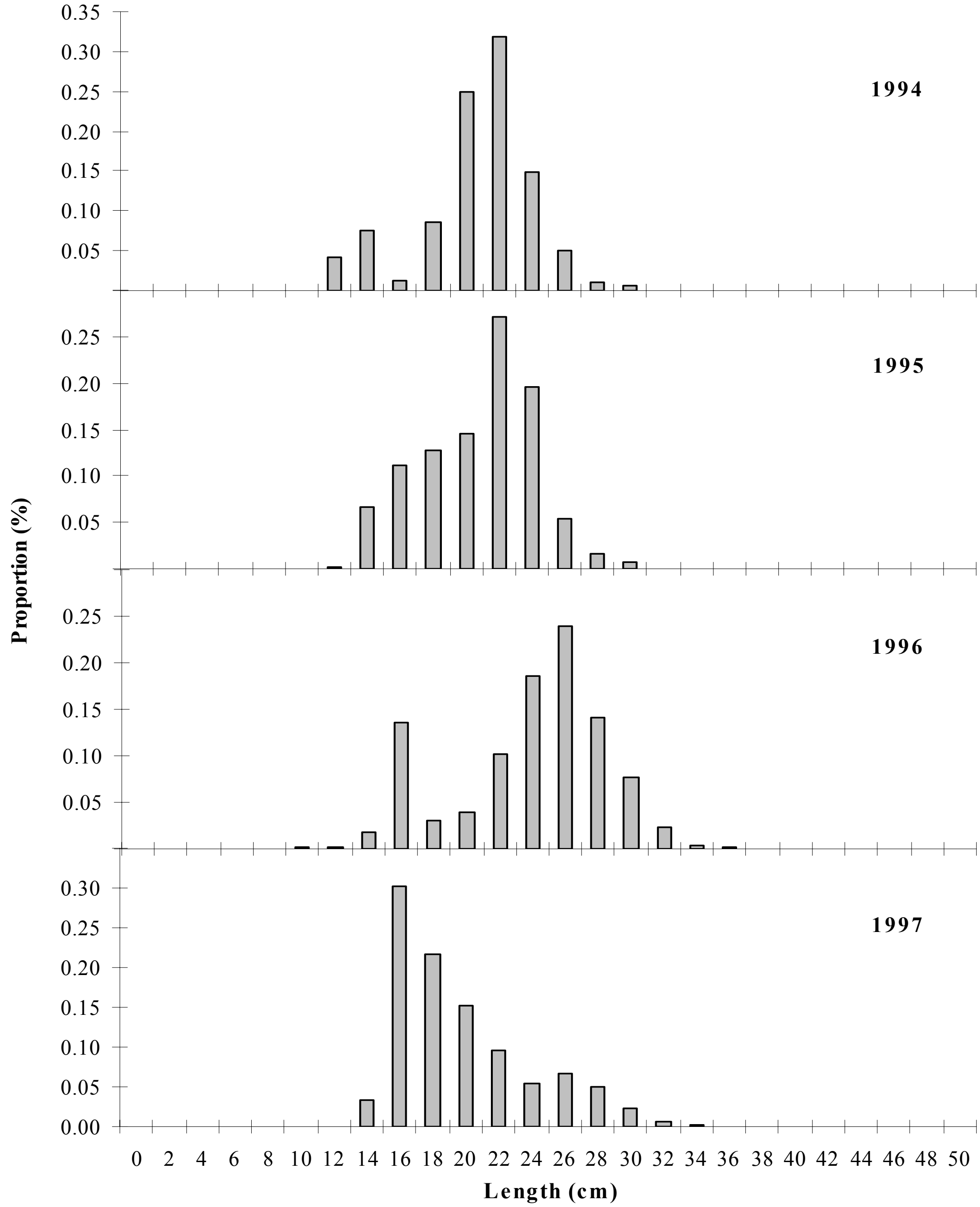


Figure 2.5 Atlantic croaker length distribution samples from the NEFSC September survey for representative years.

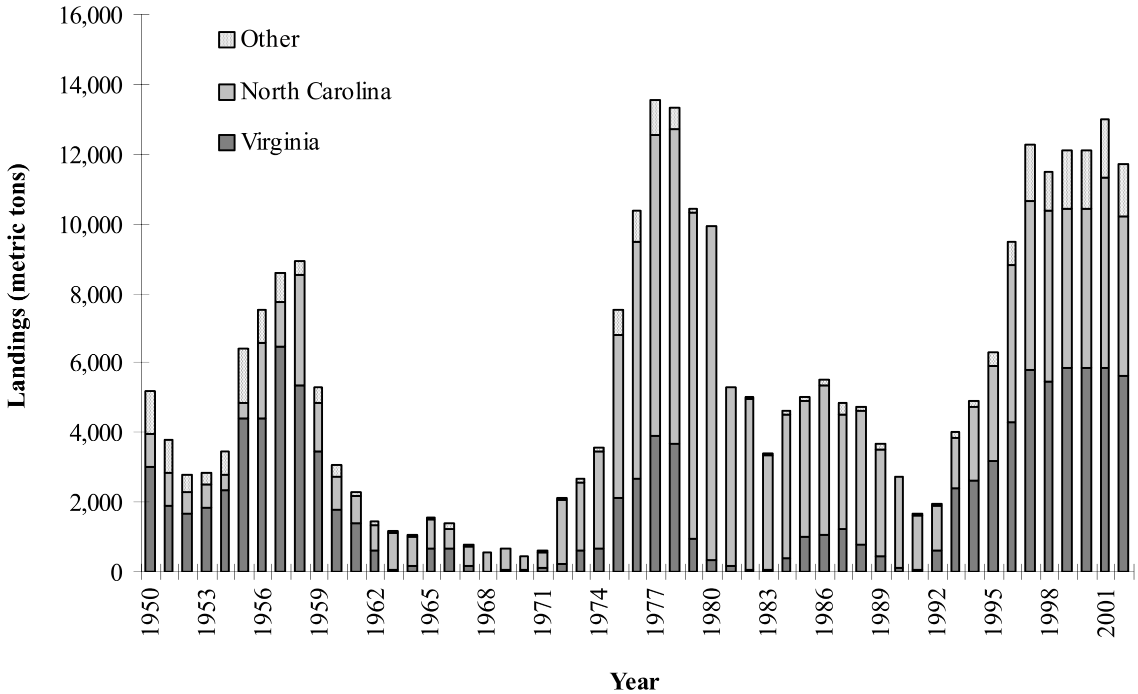


Figure 2.6 Annual commercial landings of Atlantic croaker for North Carolina, Virginia, and all other Atlantic coastal states combined.

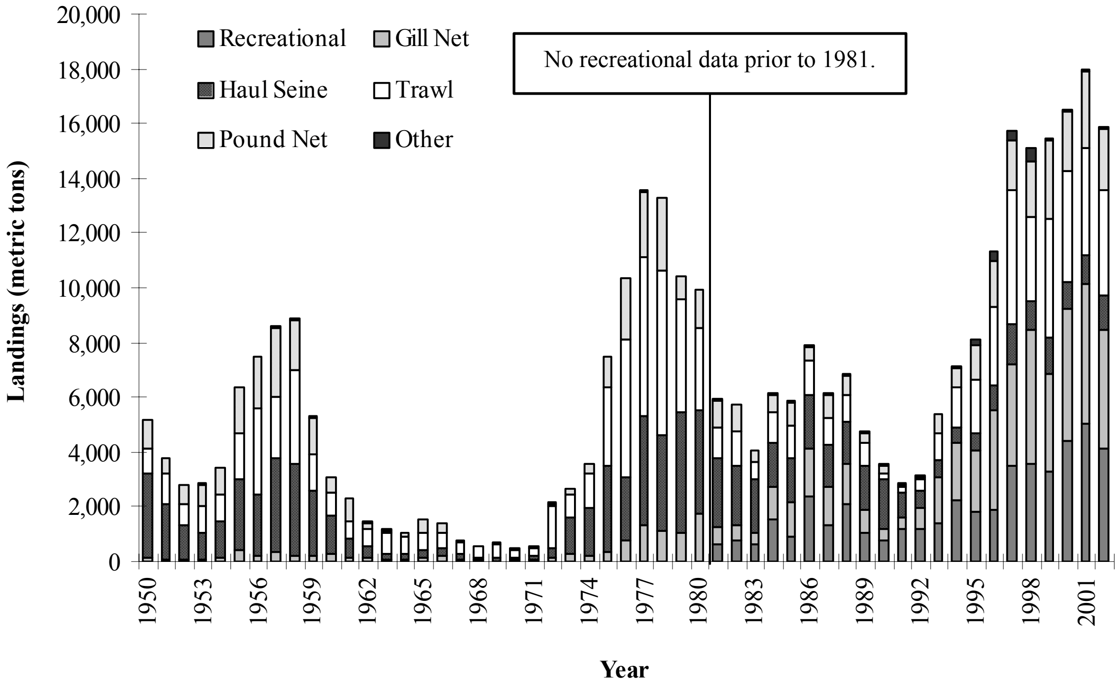


Figure 2.7 Harvest of Atlantic croaker by major gear and year. Landings from the recreational fishery were not available prior to 1981.

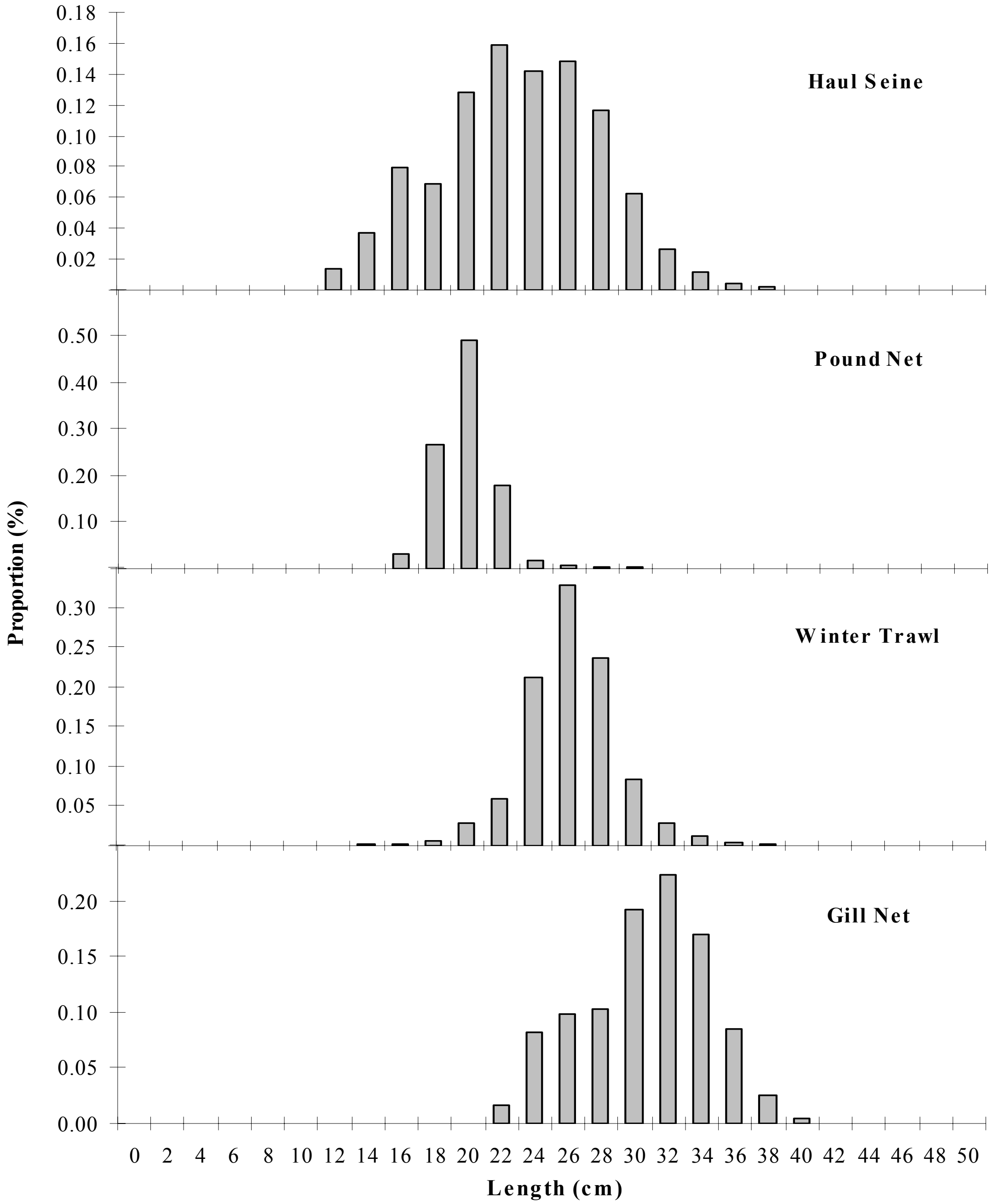


Figure 2.8 Weighted length-frequency distributions of Atlantic croaker by major gear in North Carolina. Here, data from 1996 are shown as a representative example.

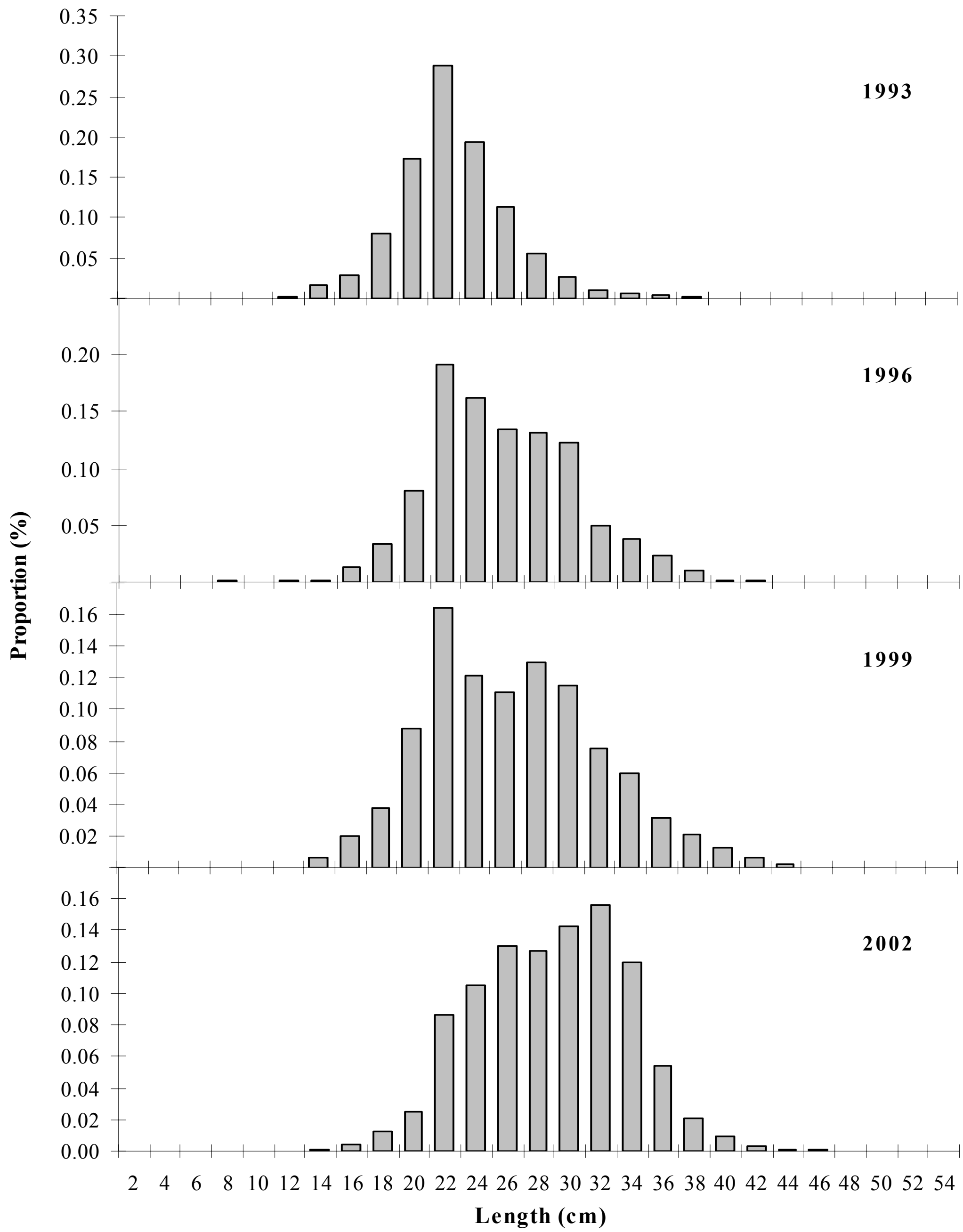


Figure 2.9 Length-frequency distributions of Atlantic croaker coastwide recreational fishery samples. Intermittent years were chosen to demonstrate the increase in maximum total length in recent years.

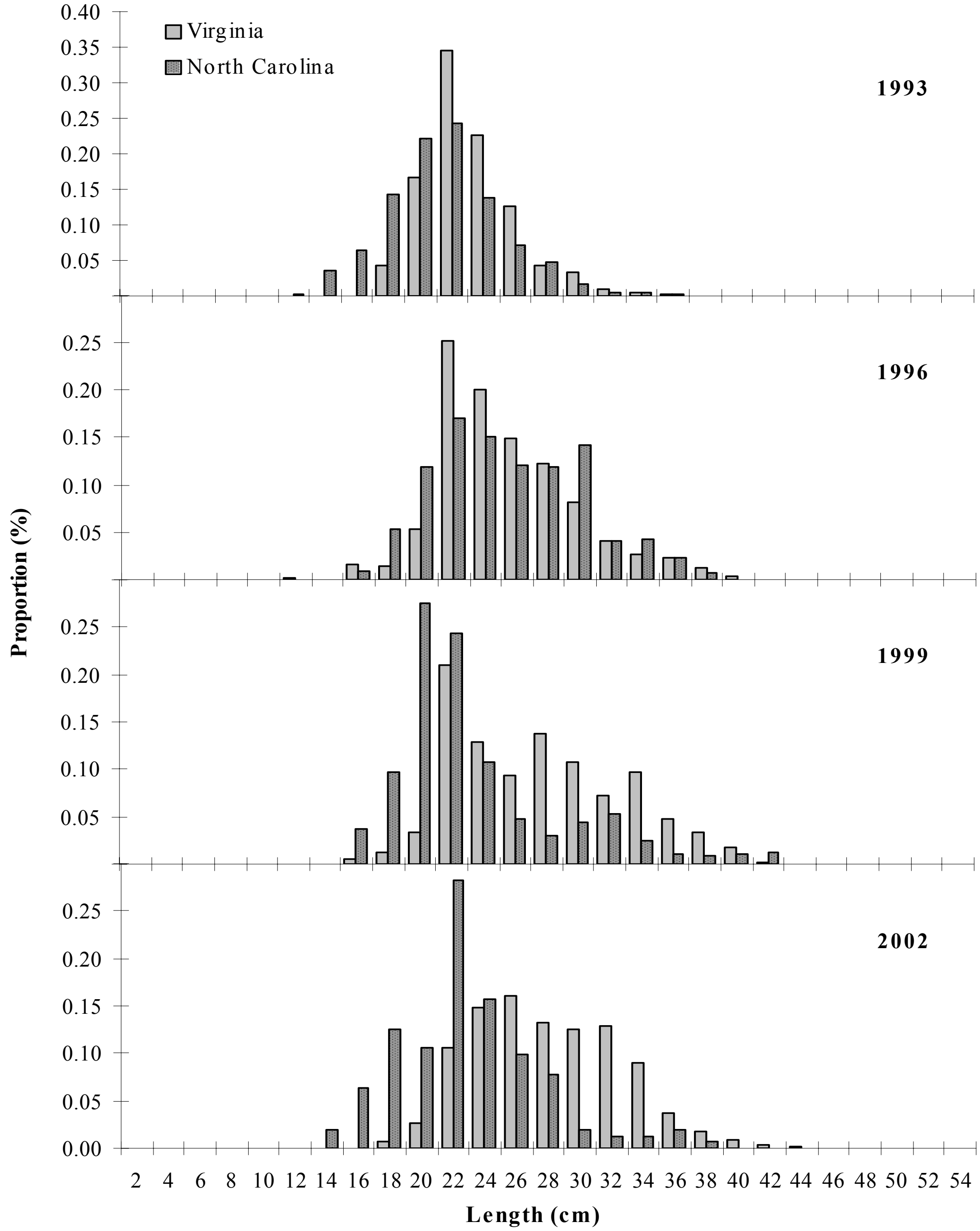


Figure 2.10 Length-frequency distributions of Atlantic croaker from North Carolina and Virginia recreational fishery samples. Intermittent years were chosen to demonstrate the increase in maximum total length in recent years.

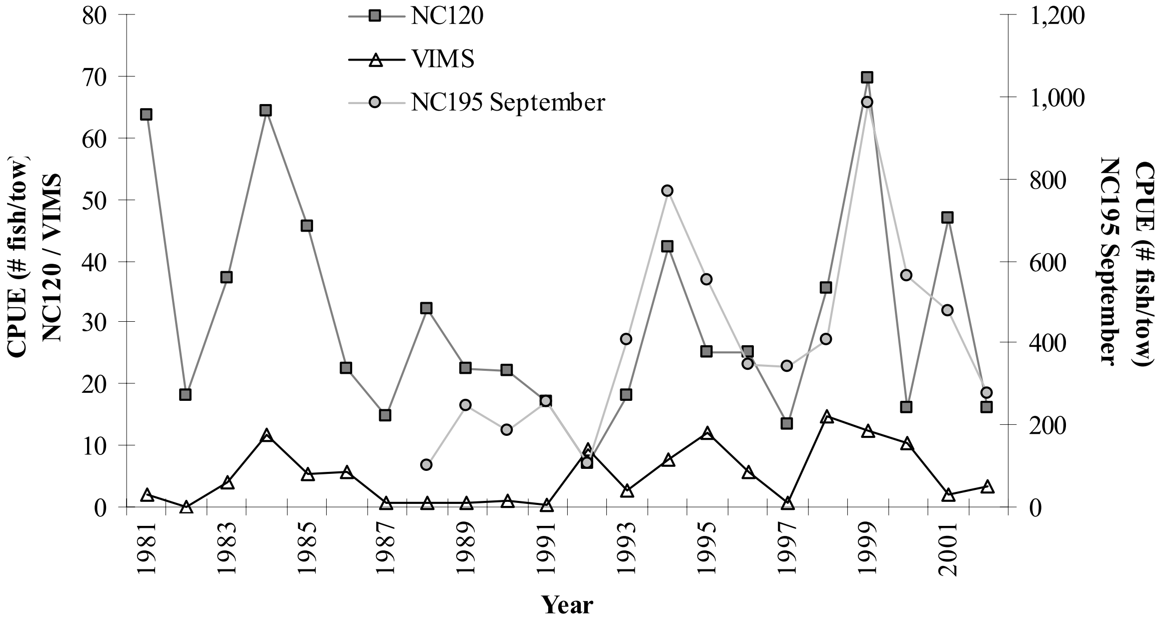


Figure 2.11 Year-class strength information (measured in terms of CPUE) for age-1 Atlantic croaker based on NC120 June, NC195 September, and VIMS October survey data. CPUE values are shifted by one year to serve as a relative index of age-1 abundance.

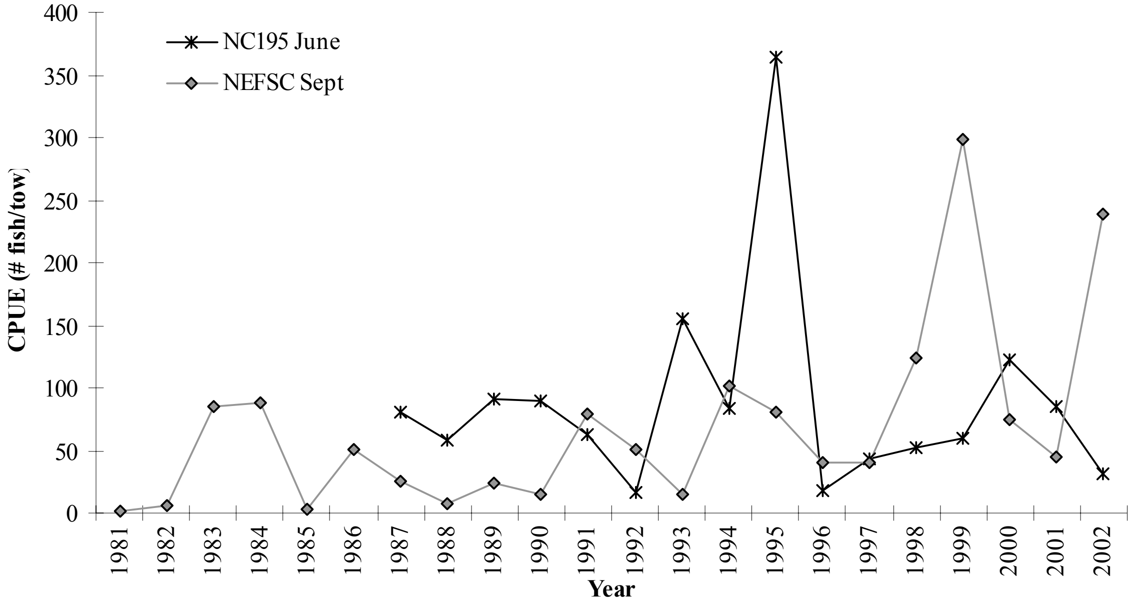


Figure 2.12 Relative abundance (measured in terms of CPUE) of Atlantic croaker from NEFSC September and NC195 June survey data.

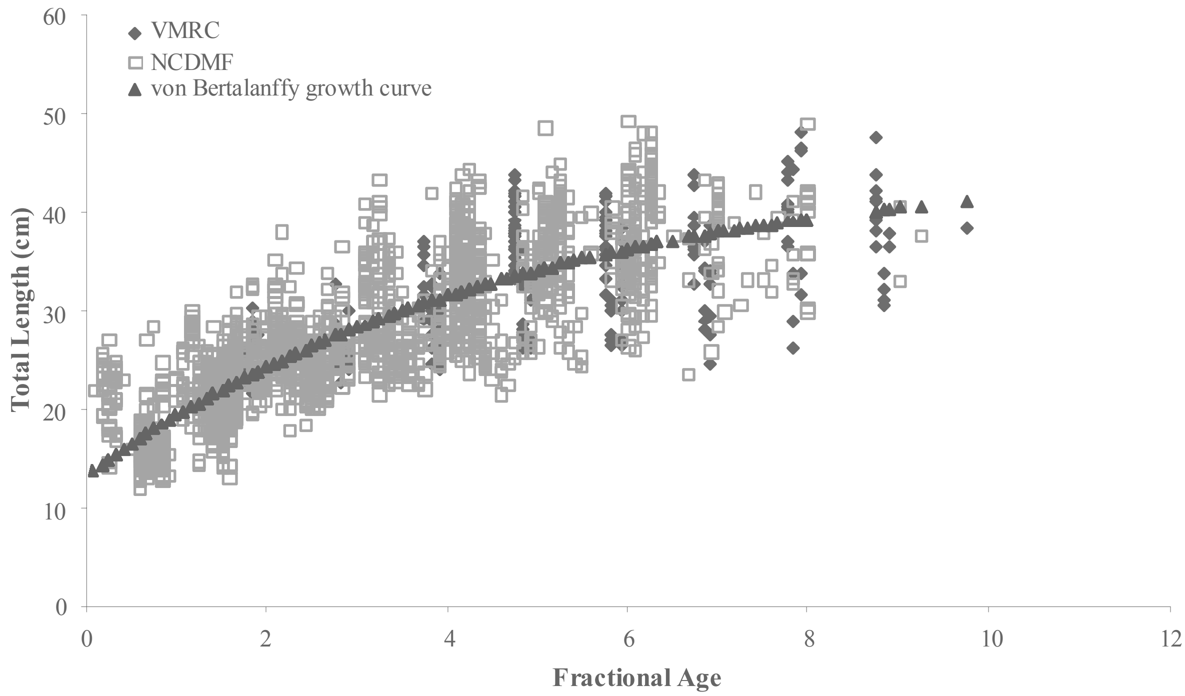


Figure 2.13 Age samples from NCDMF and VMRC fitted with a von Bertalanffy growth curve.

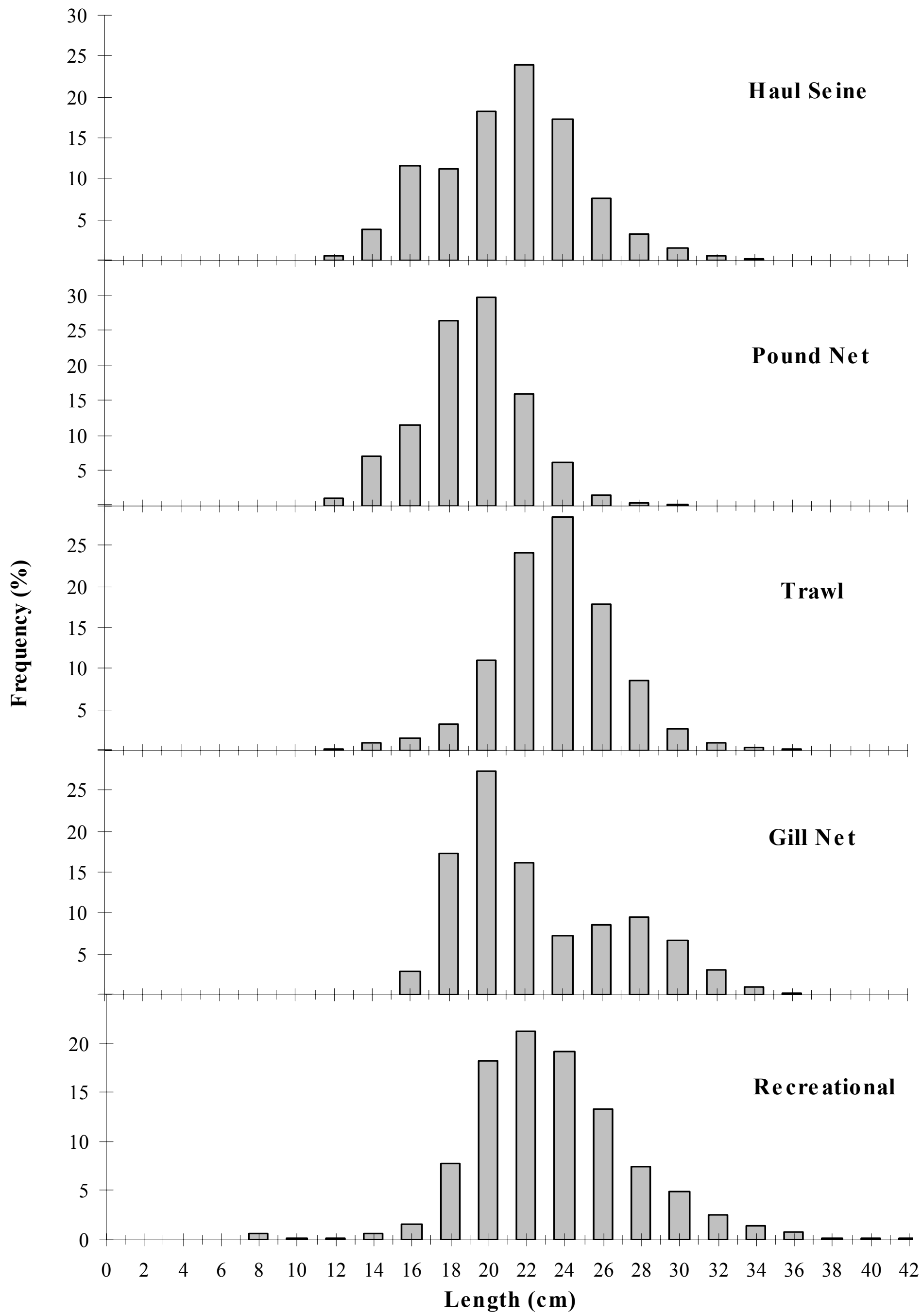


Figure 2.14 Length-frequency distributions of Atlantic croaker by major gear. Here, length composition data from North Carolina commercial samples and coastwide recreational samples (averaged over years, 1991-1996) are shown.

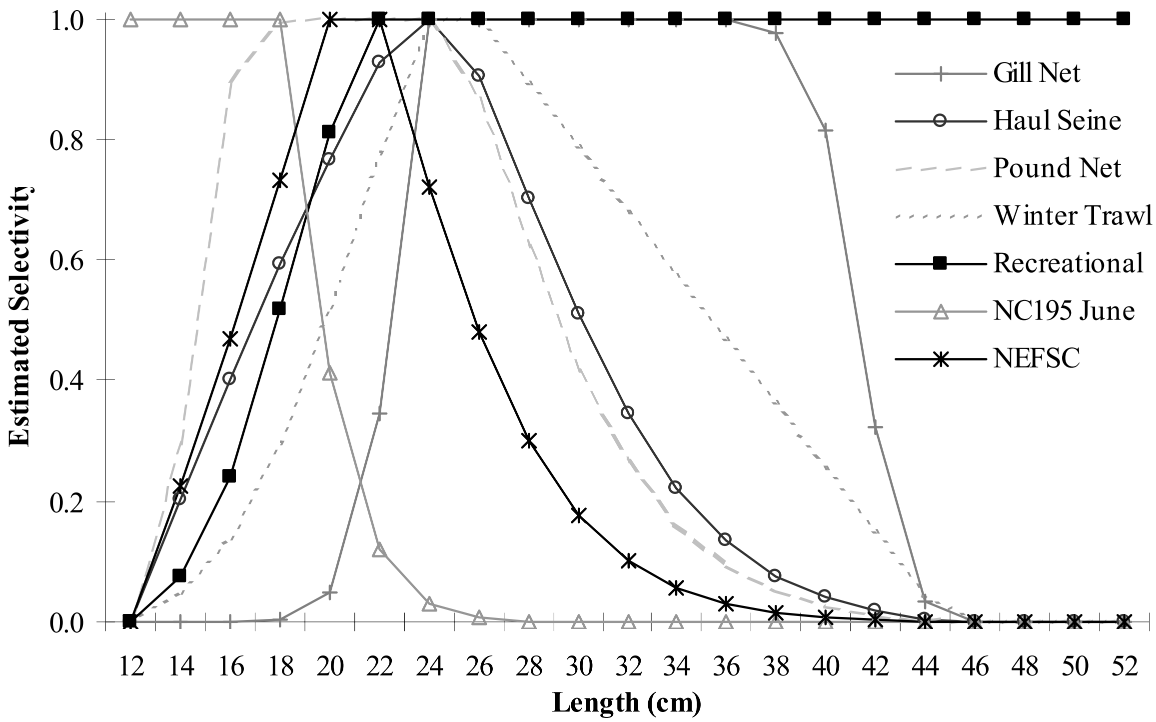


Figure 2.15 Synthesis model estimates of selectivity patterns for major gears and surveys. The selectivity pattern for the recreational fishery was assumed to be asymptotic.

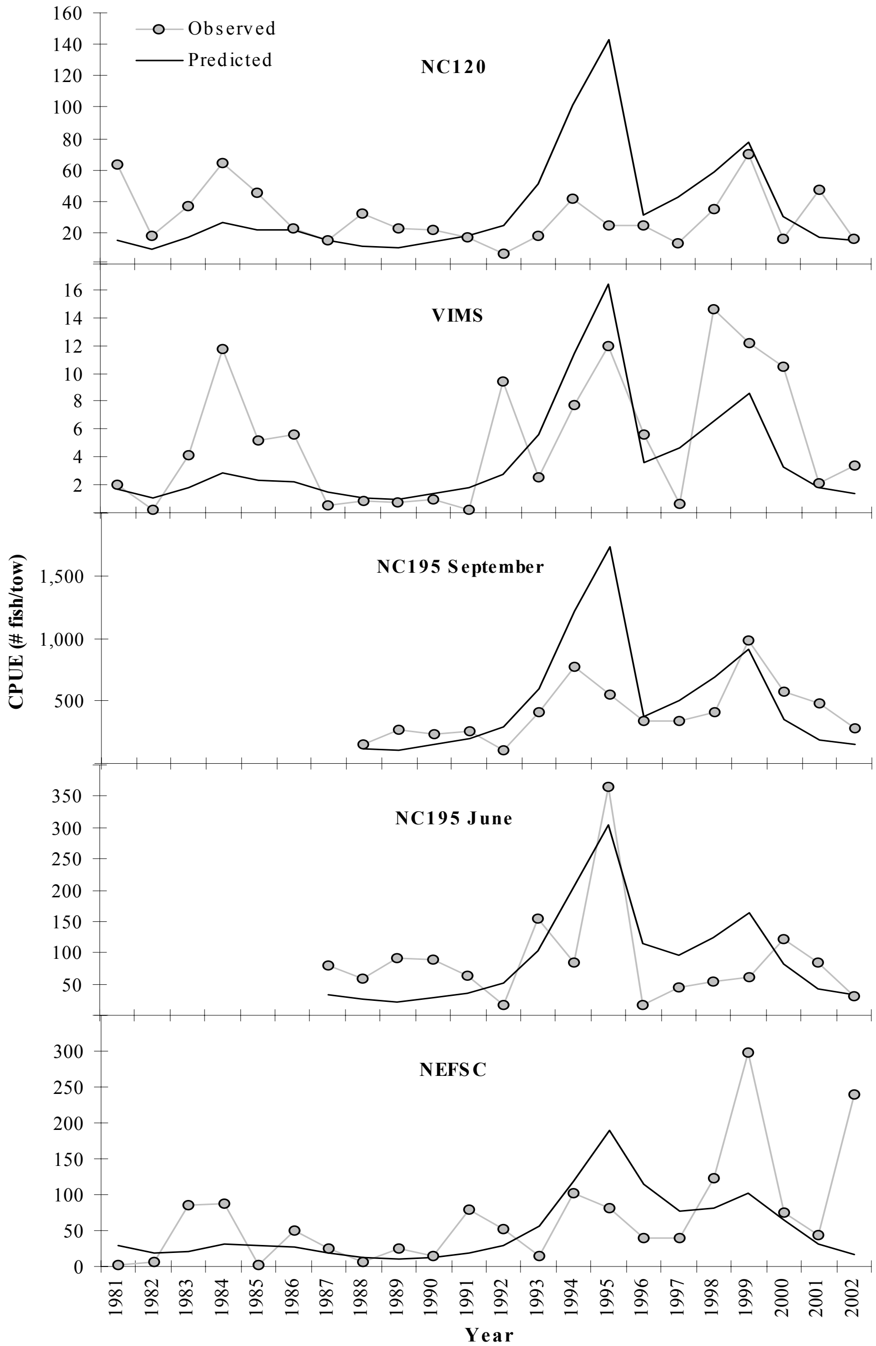


Figure 2.16 Observed and predicted annual CPUE values for each of the fishery-independent surveys.

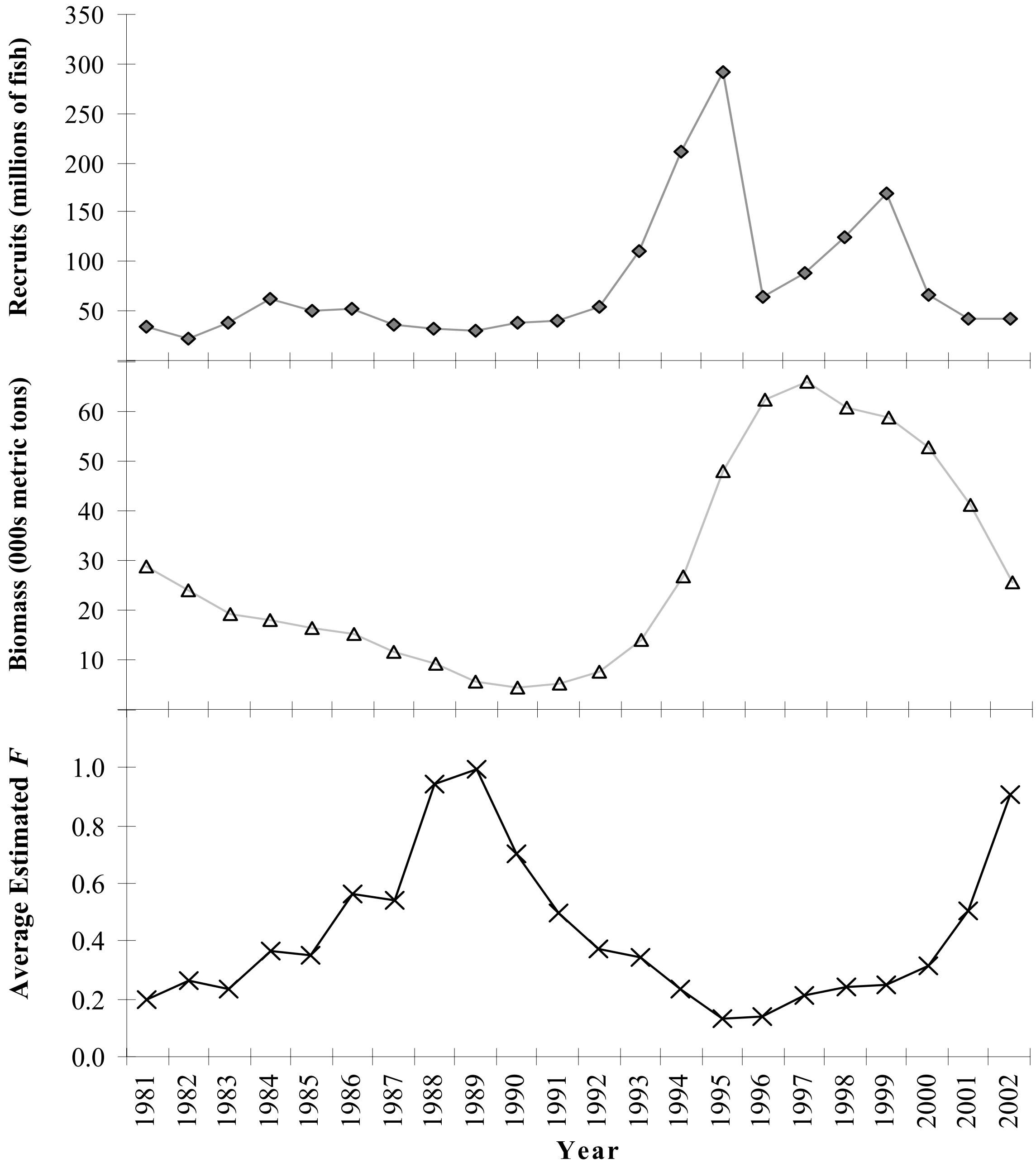


Figure 2.17 Annual recruitment, biomass, and *F* (averaged over ages 1-10) for Atlantic croaker estimated from the stock synthesis model base run.

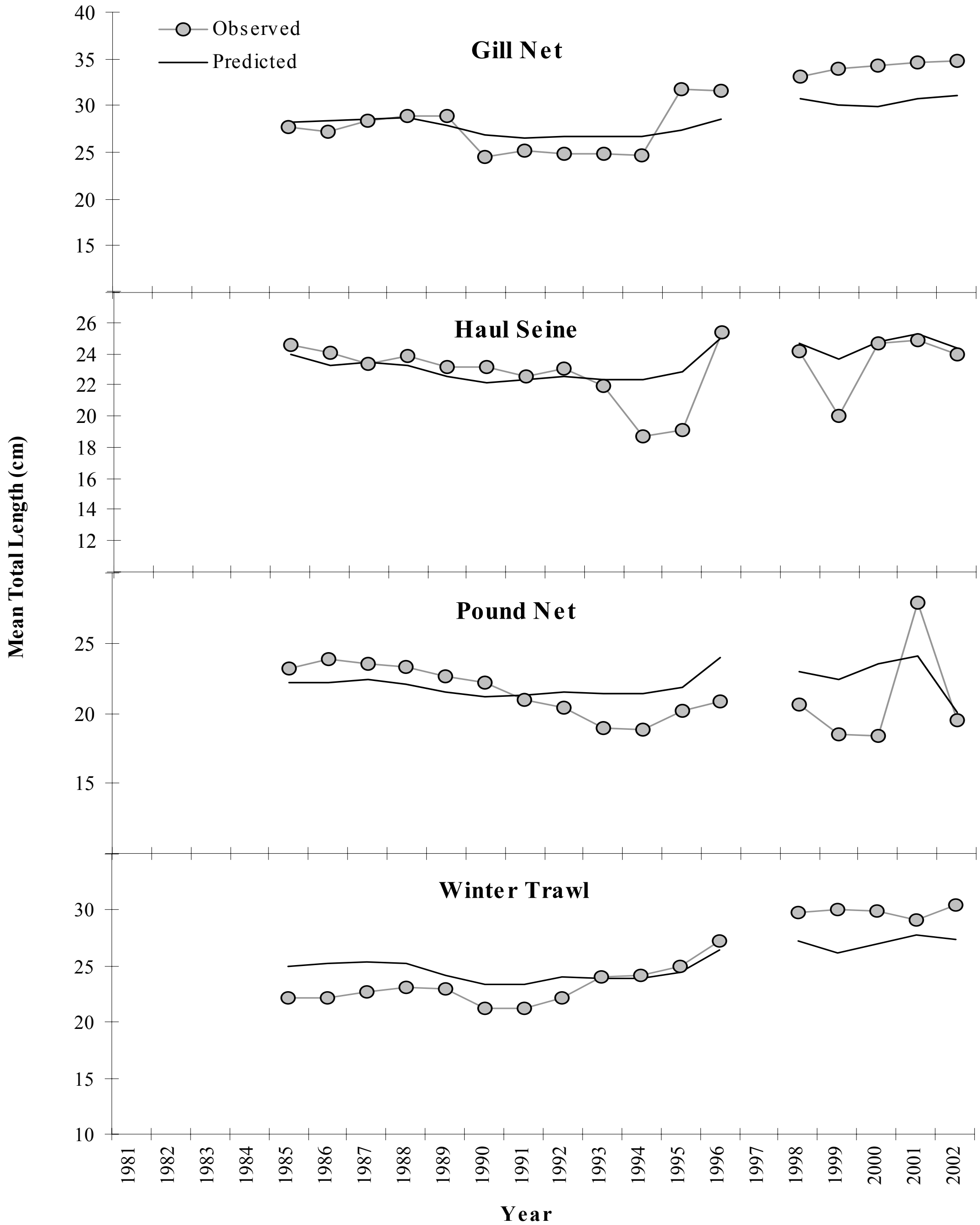


Figure 2.18 Observed and predicted mean total length (cm) of Atlantic croaker for major fisheries and fishery-independent surveys.

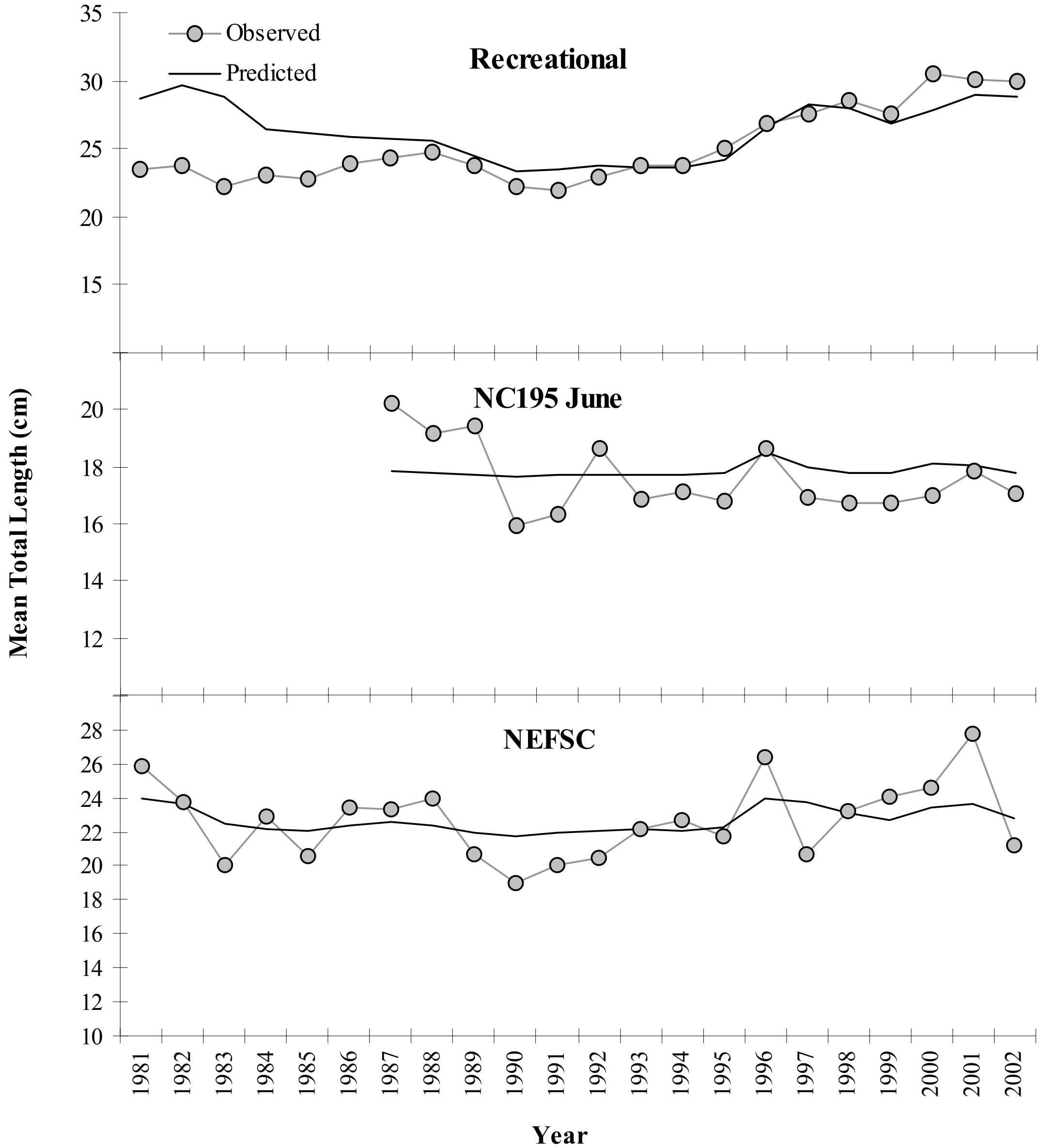


Figure 2.18 (*continued*) Observed and predicted mean total length (cm) of Atlantic croaker for major fisheries and fishery-independent surveys.

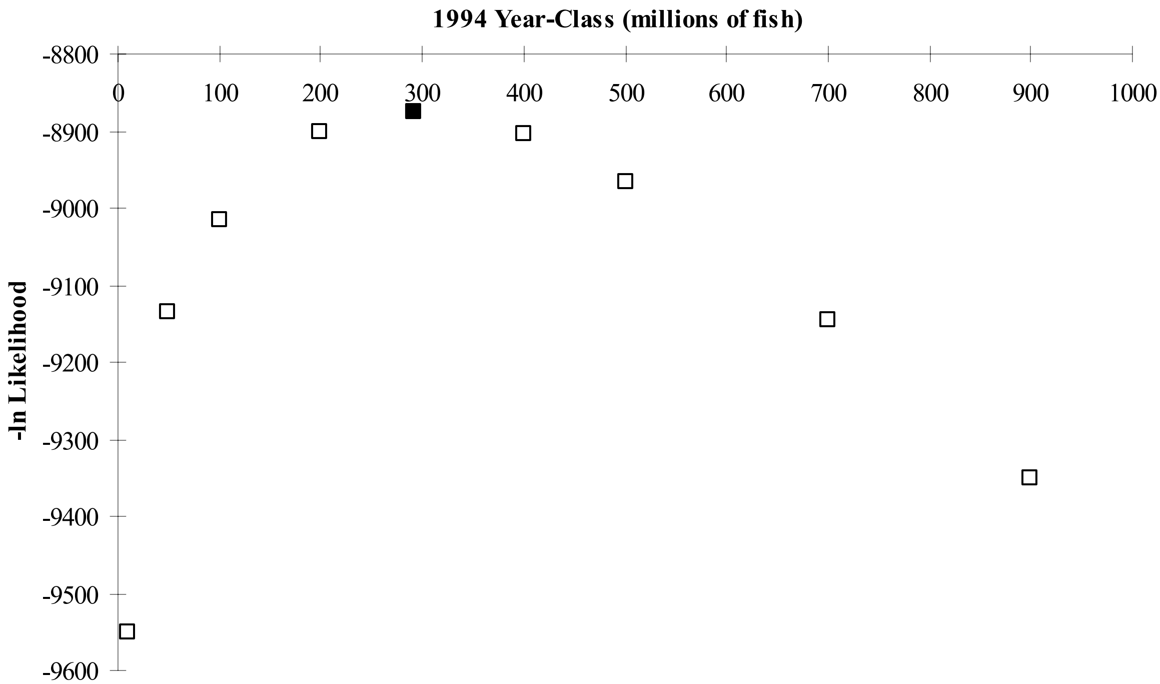


Figure 2.19 Likelihood profile for various fixed values of the 1994 year-class. The solid black square represents the likelihood value from the base model run.

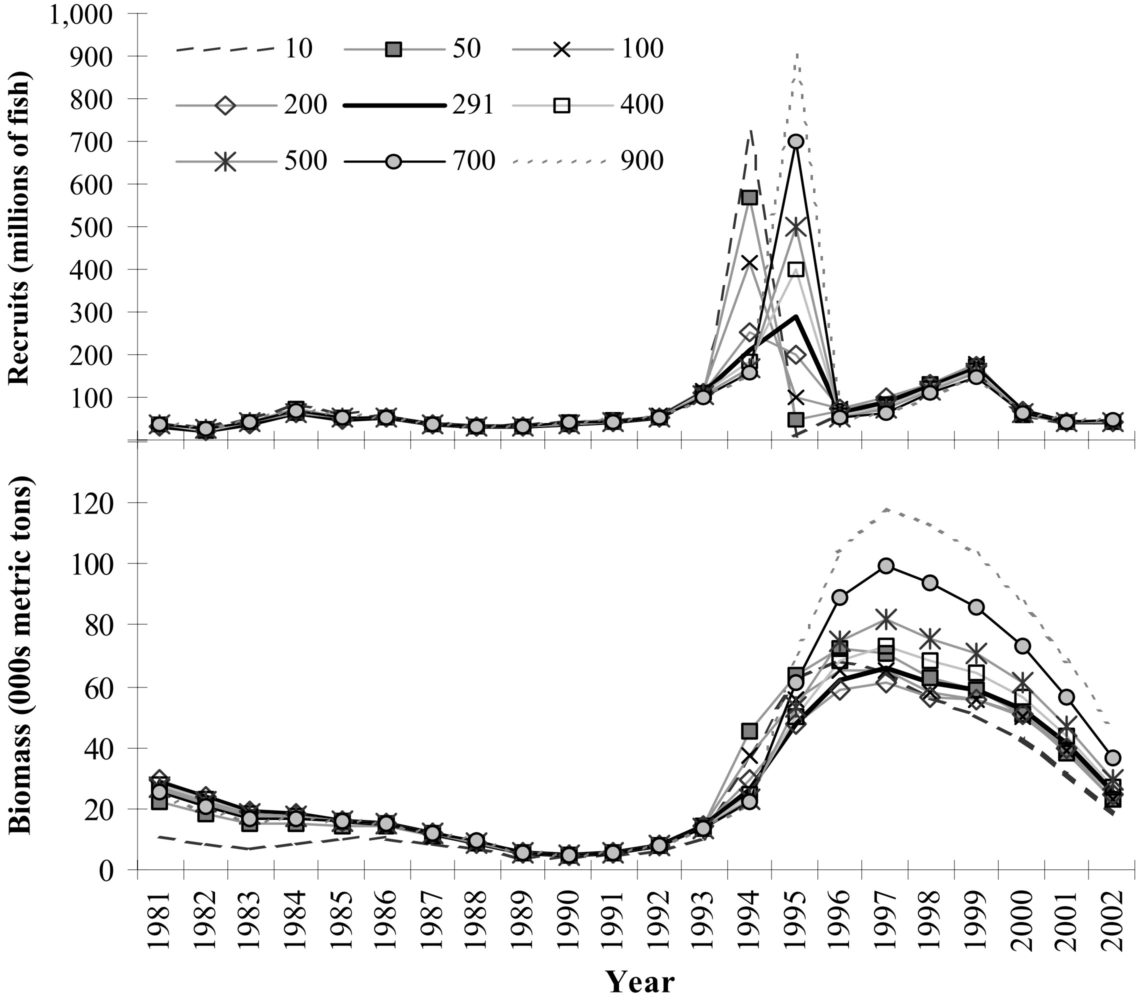


Figure 2.20 Estimated recruitment and biomass of Atlantic croaker assuming different values (in millions of fish) for the size of the 1994 year-class.

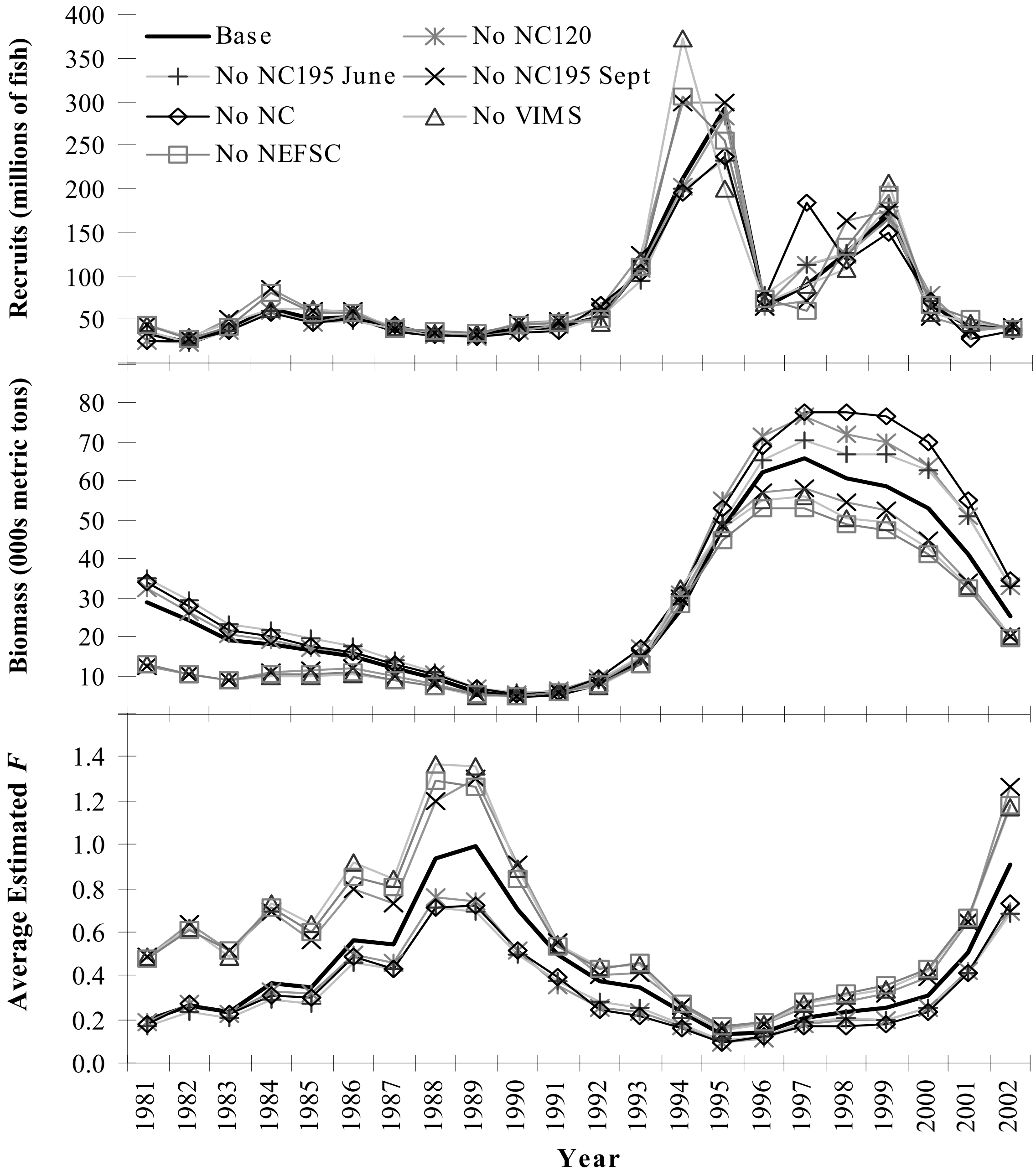


Figure 2.21 Comparison of annual recruitment, biomass, and F (averaged over ages 1-10) estimates for Atlantic croaker between the stock synthesis model base run and model runs with reduced emphasis of different survey sources.

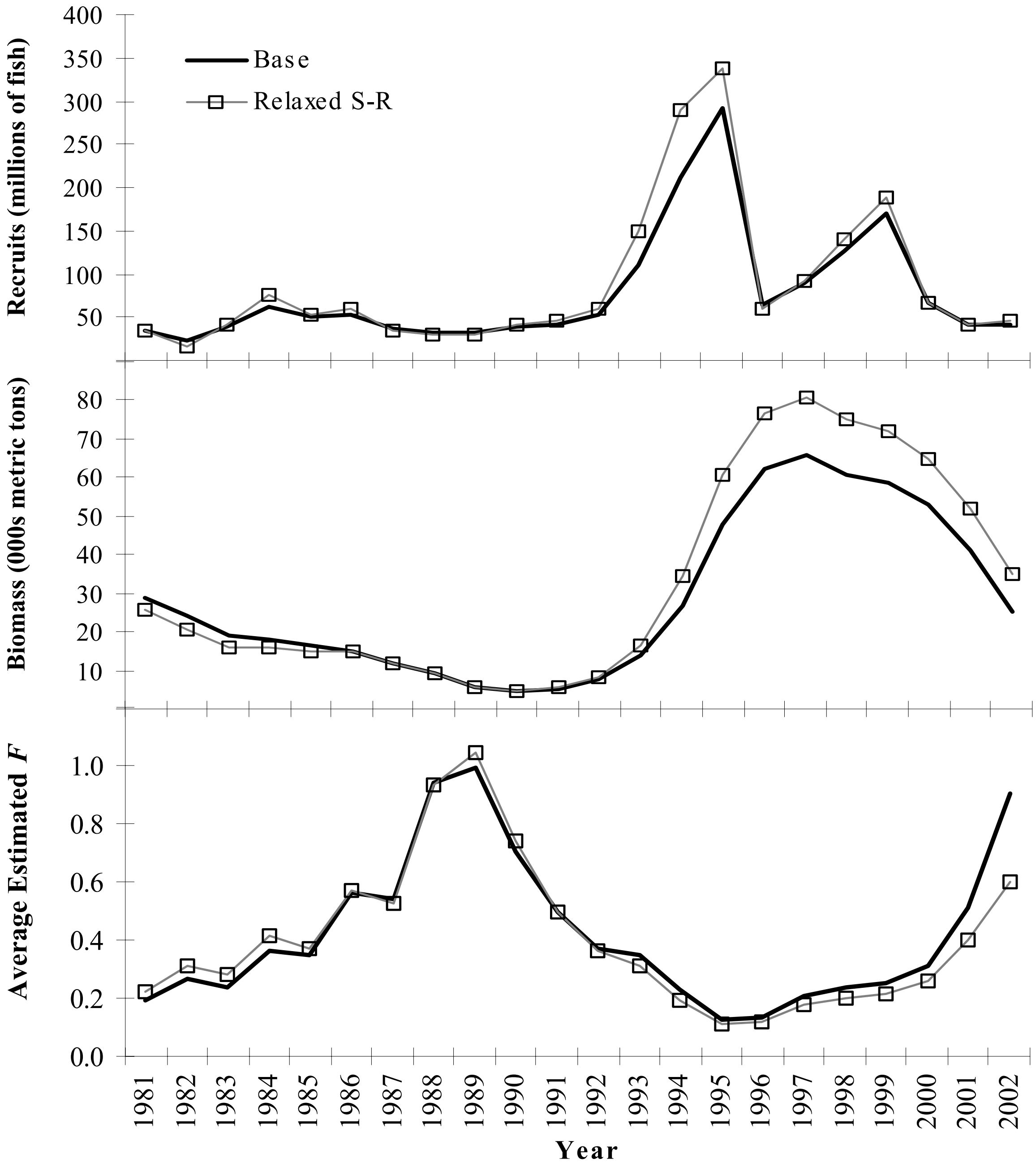


Figure 2.22 Comparison of annual recruitment, biomass, and *F* (averaged over ages 1-10) estimates for Atlantic croaker between the stock synthesis model base run and model with a relaxation of the stock-recruitment relationship.

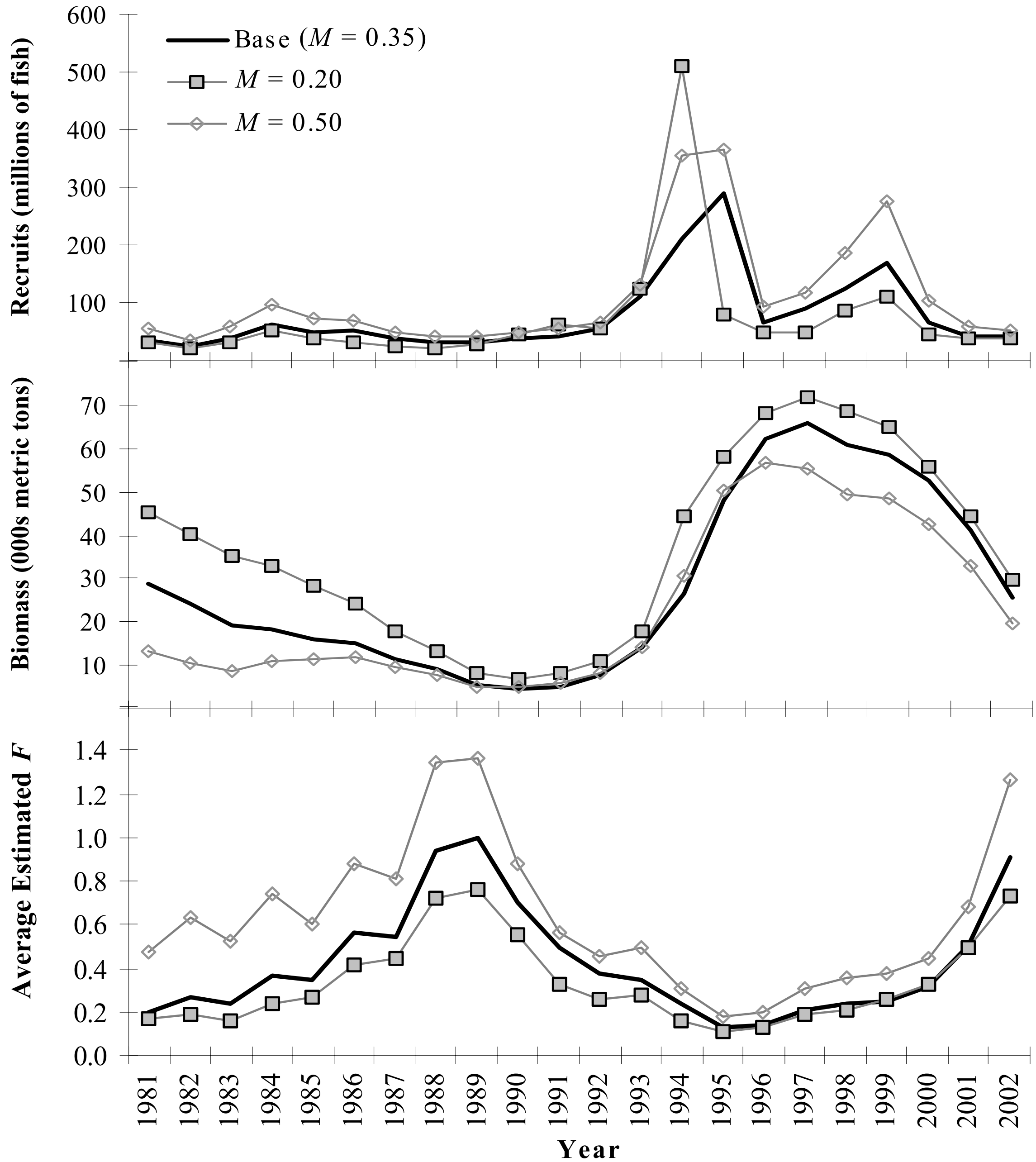


Figure 2.23 Comparison of annual recruitment, biomass, and F (averaged over ages 1-10) estimates for Atlantic croaker between the stock synthesis model base run and models assuming different values for the natural mortality rate, M.

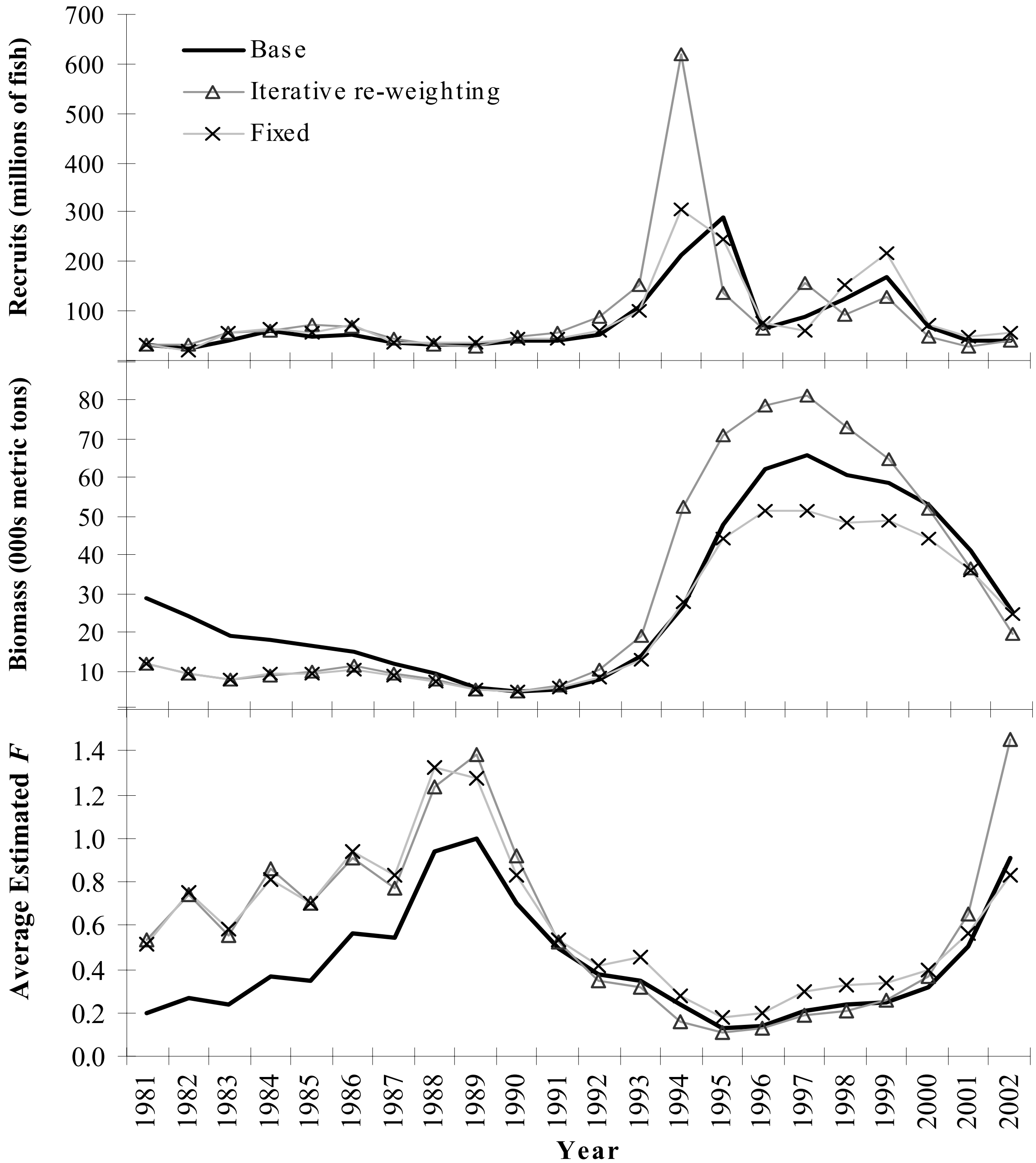


Figure 2.24 Comparison of annual biomass, recruitment, and *F* (averaged over ages 1-10) estimates for Atlantic croaker between the stock synthesis model base run and models assuming the iterative re-weighting option and fixed values for the error of survey relative abundance.

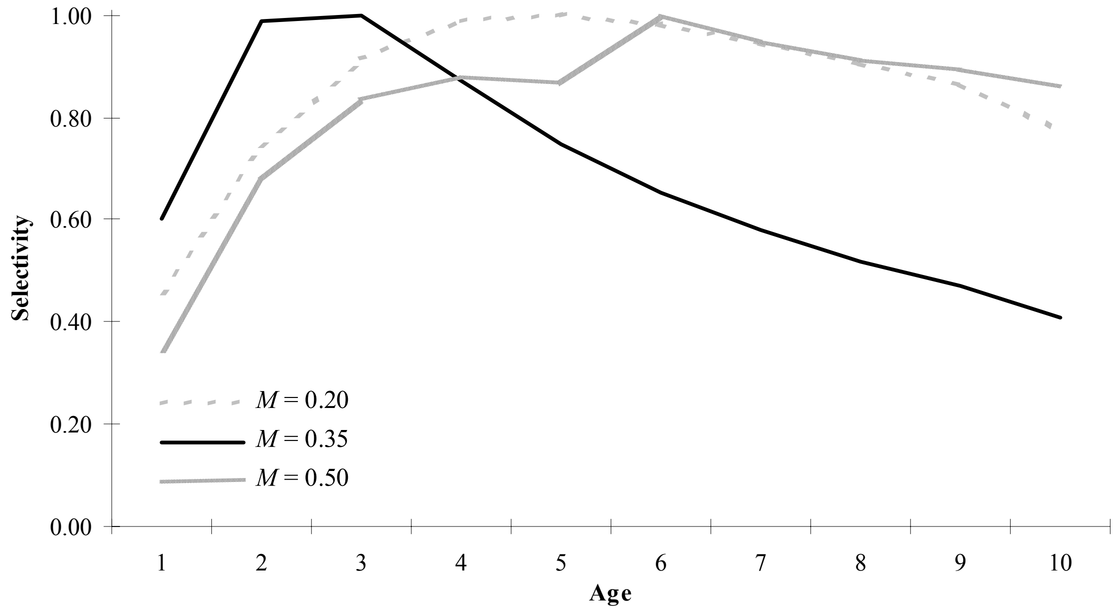


Figure 3.1 Selectivity patterns (all gears combined, based on 1981-2002 *F*s), based on assessment results for *M*=0.20, *M*=0.35, and *M*=0.50.

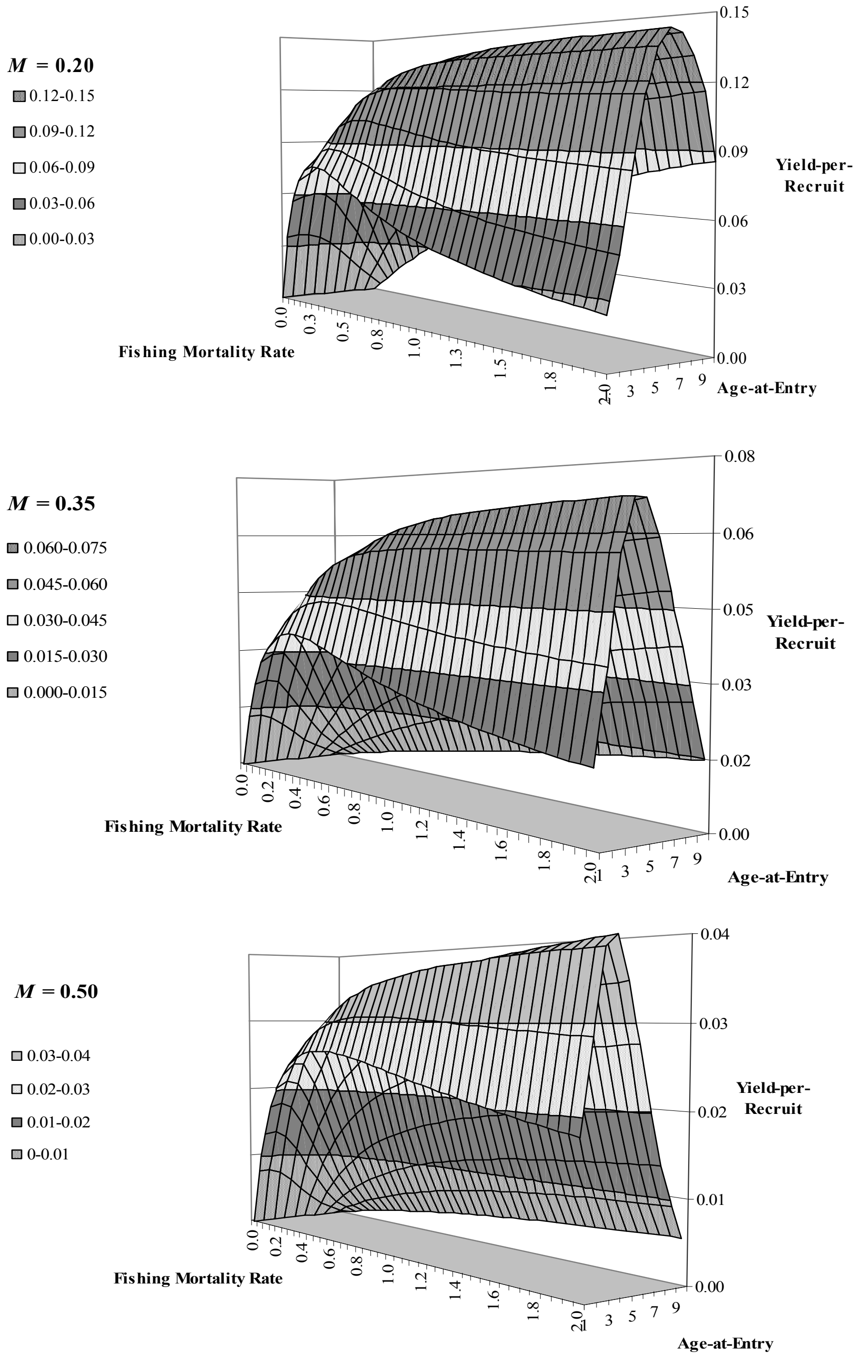


Figure 3.2 Estimates of yield-per-recruit for Atlantic croaker at different *F*s and different ages-at-entry for different assumed values of *M*.

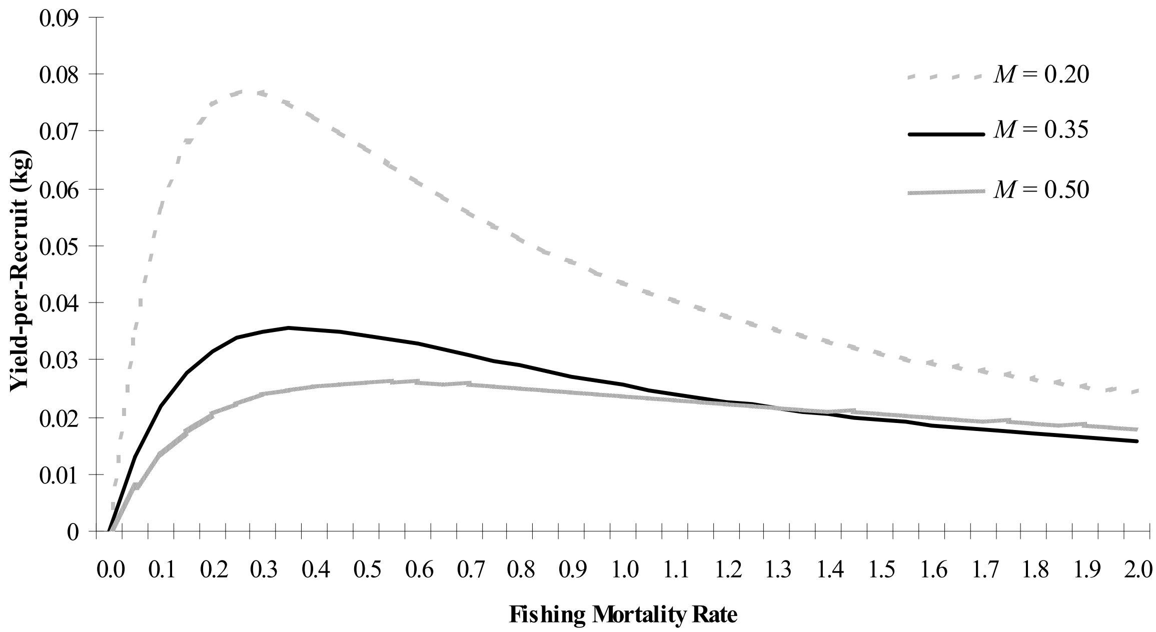


Figure 3.3 Estimates of yield-per-recruit for age-at-entry of 1 year based on different assumed values of *M*.

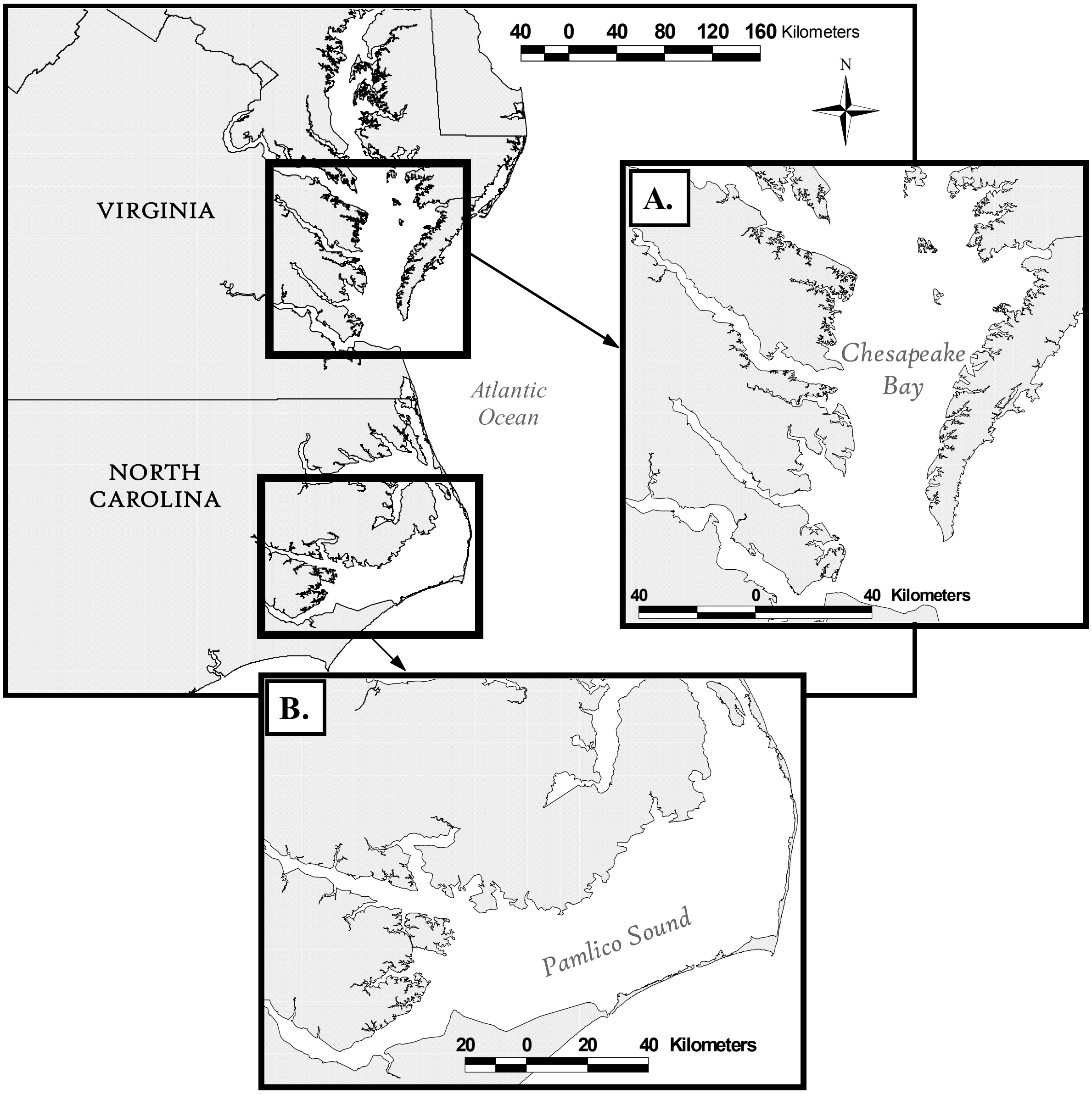


Figure 4.1 Map showing locations of the (A.) VIMS trawl survey of the Chesapeake Bay and tributaries as well as the (B.) NCDMF Program 195 survey of Pamlico Sound.

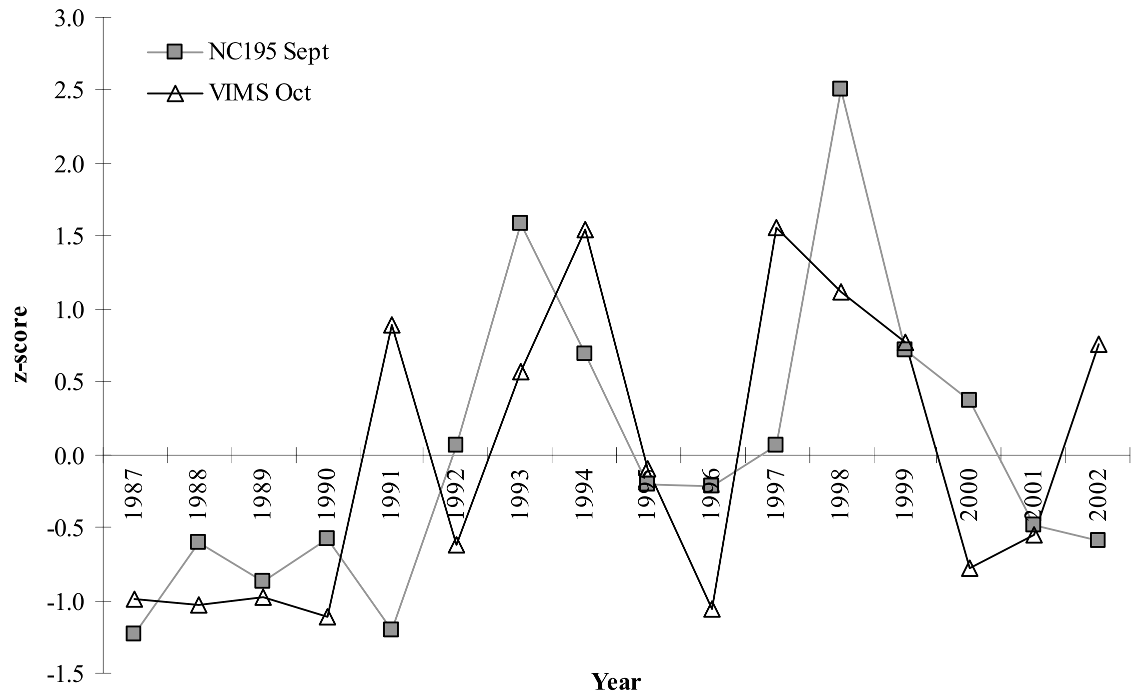


Figure 4.2 Z-transformed indices of relative abundance (measured in terms of CPUE) of age-0 Atlantic croaker based on NC195 September and VIMS October survey data, 1987 - 2002.

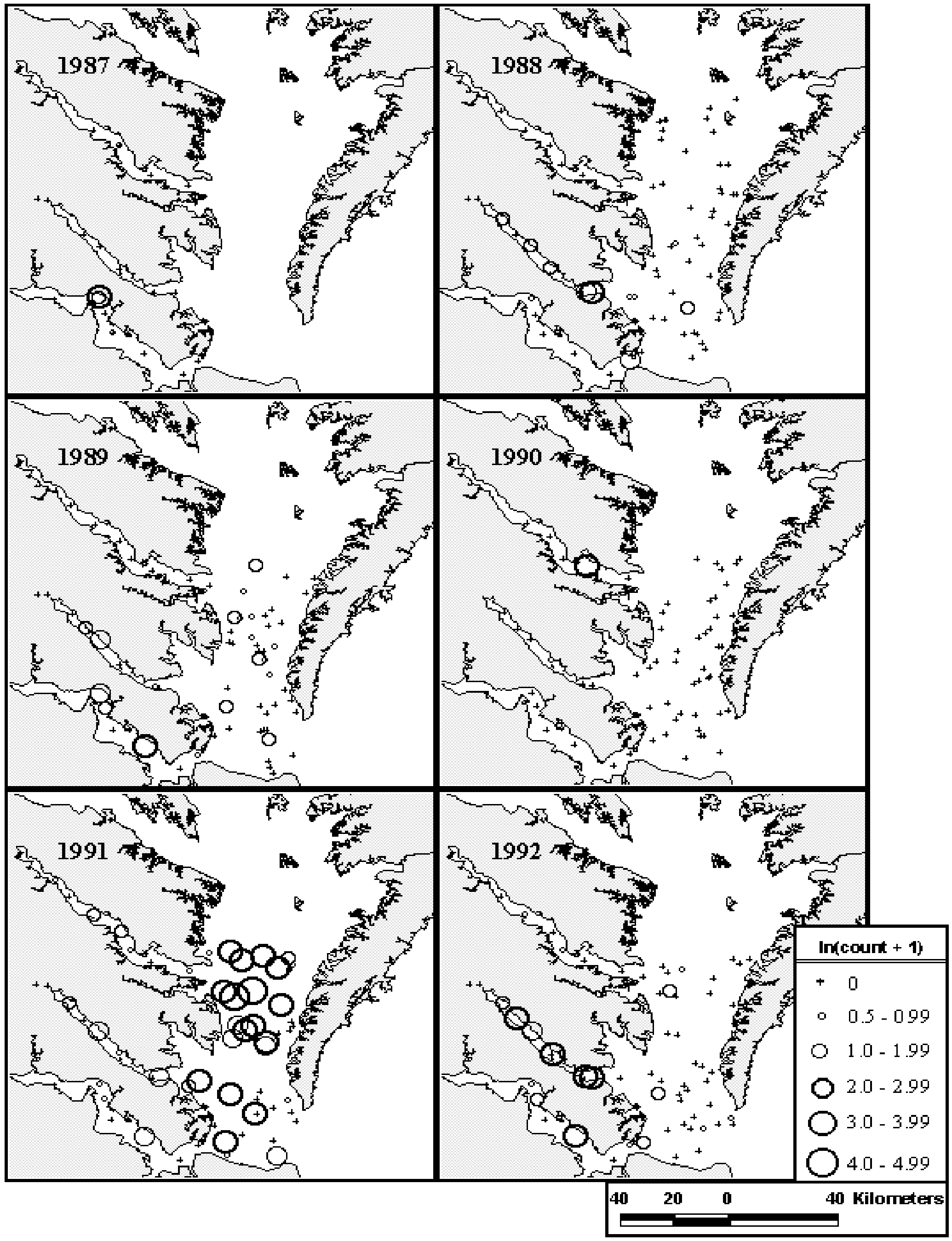


Figure 4.3 Plots of abundance for age-0 Atlantic croaker observed in the VIMS October survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

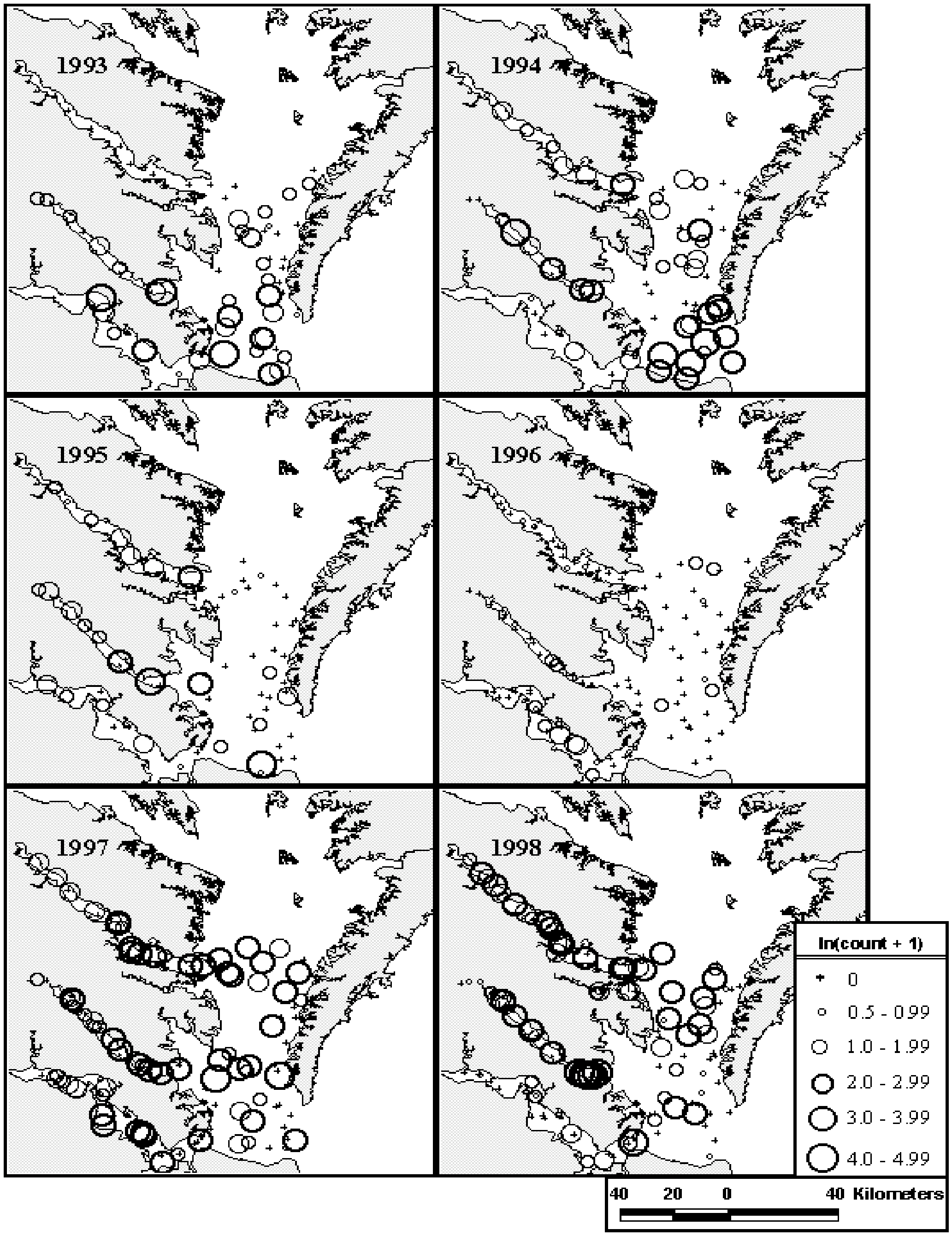


Figure 4.3 (*continued*) Plots of abundance for age-0 Atlantic croaker observed in the VIMS October survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

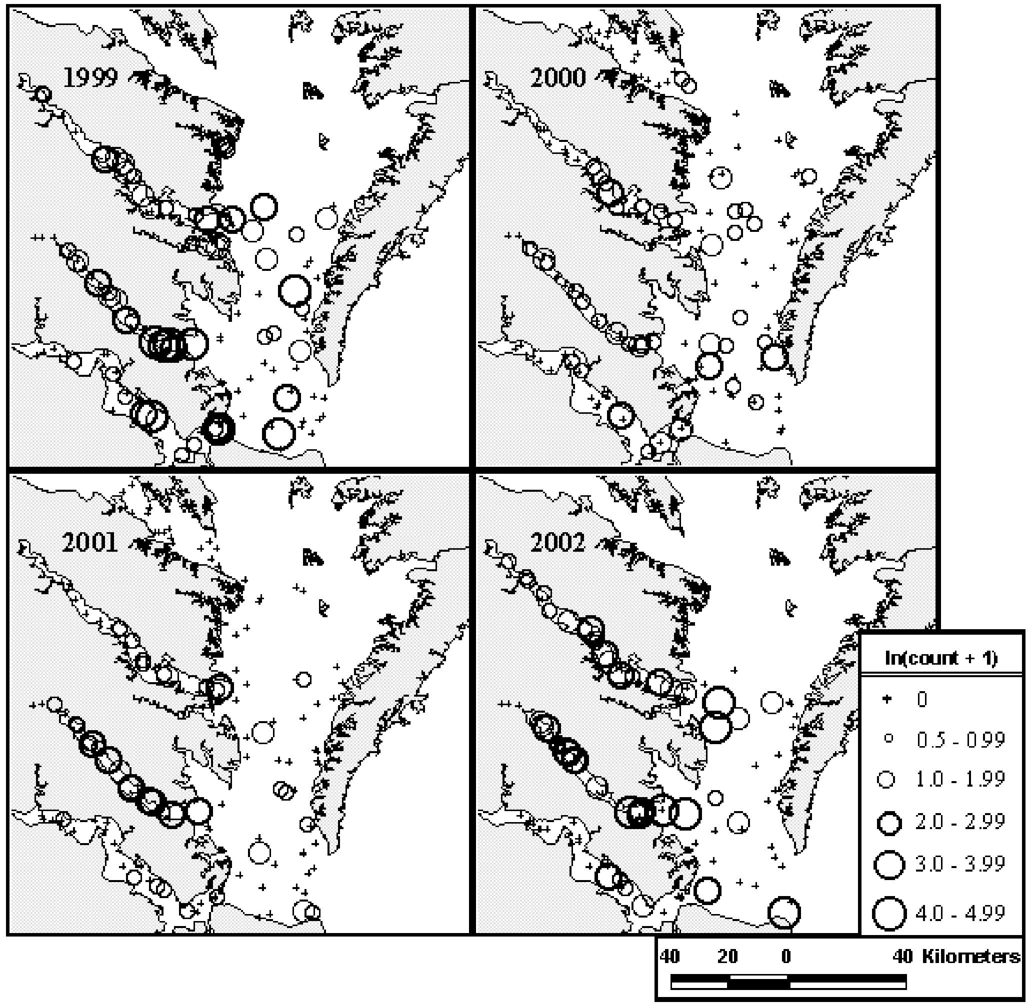


Figure 4.3 (*continued*) Plots of abundance for age-0 Atlantic croaker observed in the VIMS October survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

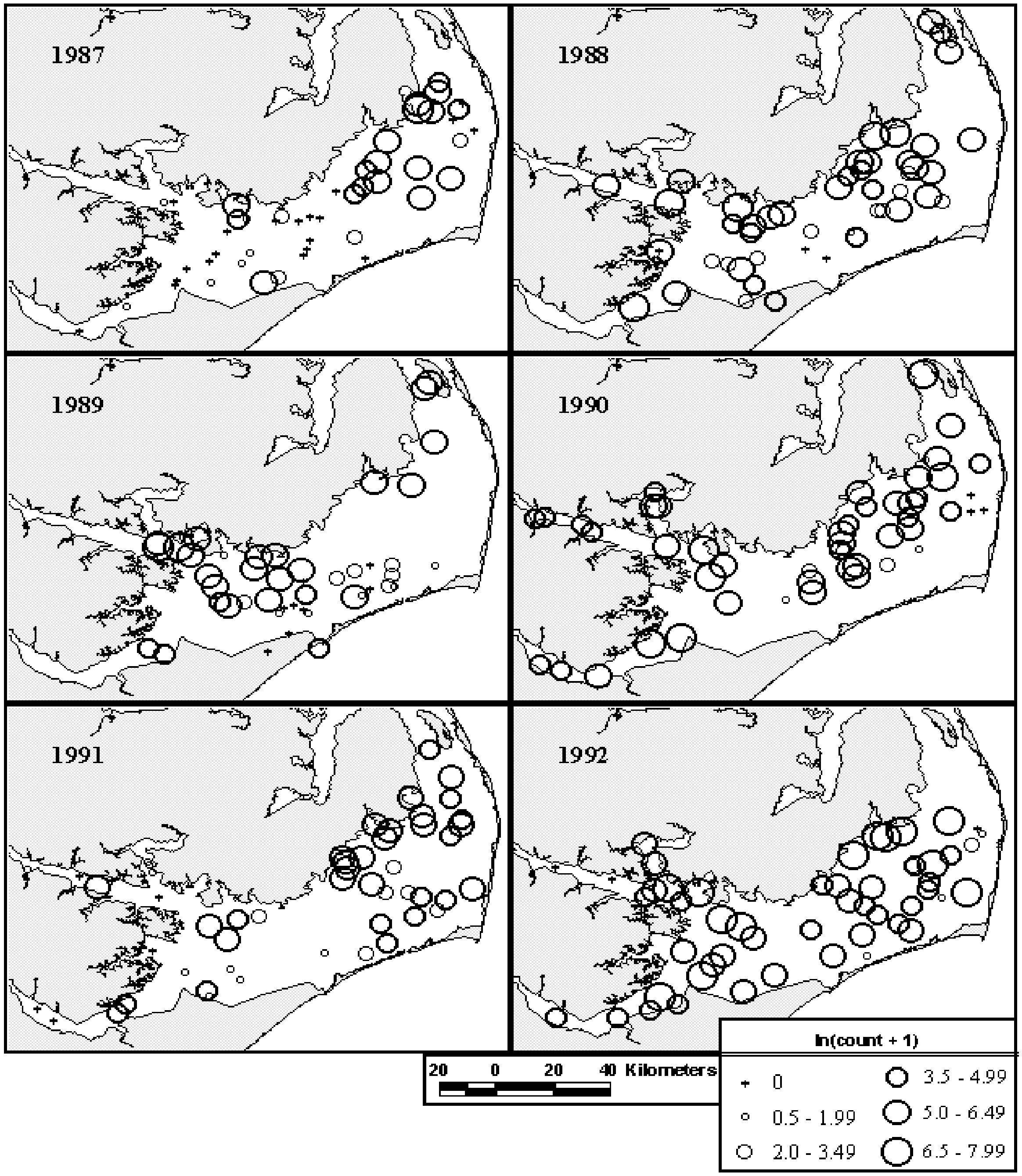


Figure 4.4 Plots of abundance for age-0 Atlantic croaker observed in the NC195 September survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

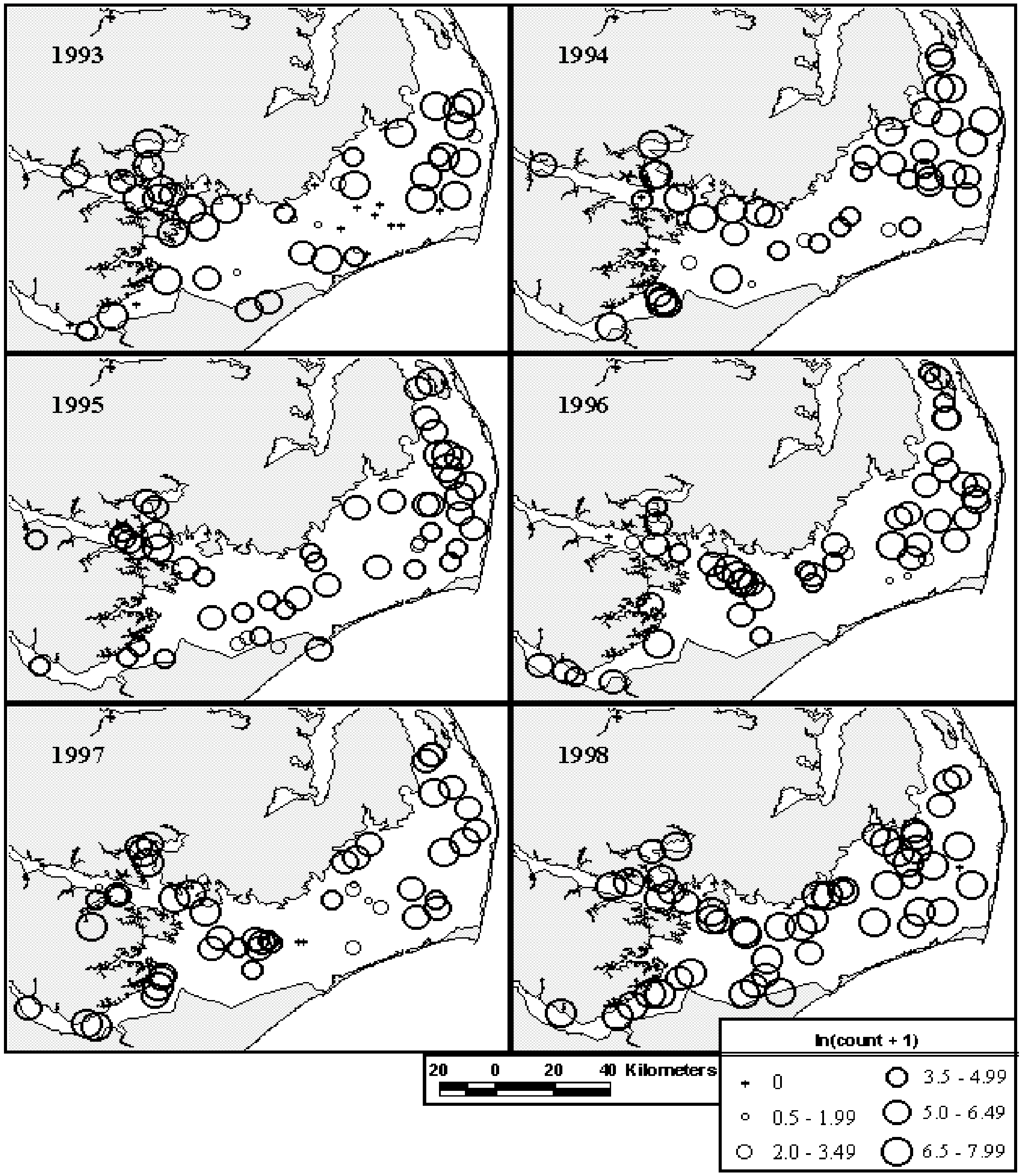


Figure 4.4 (*continued*) Plots of abundance for age-0 Atlantic croaker observed in the NC195 September survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

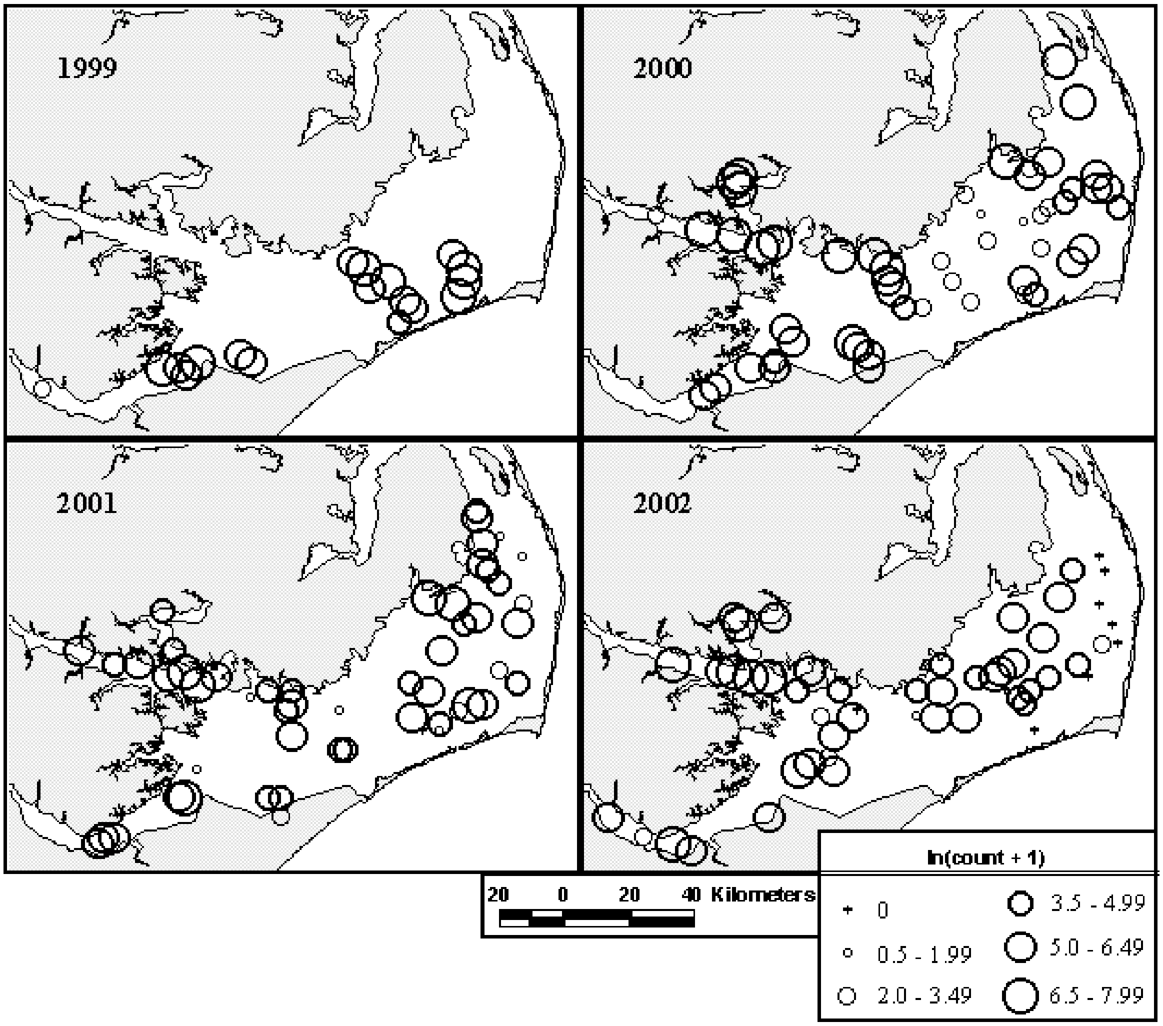


Figure 4.4 (*continued*) Plots of abundance for age-0 Atlantic croaker observed in the NC195 September survey. The crosses (+) represent zero catches; circles are proportional to the log-transformed counts.

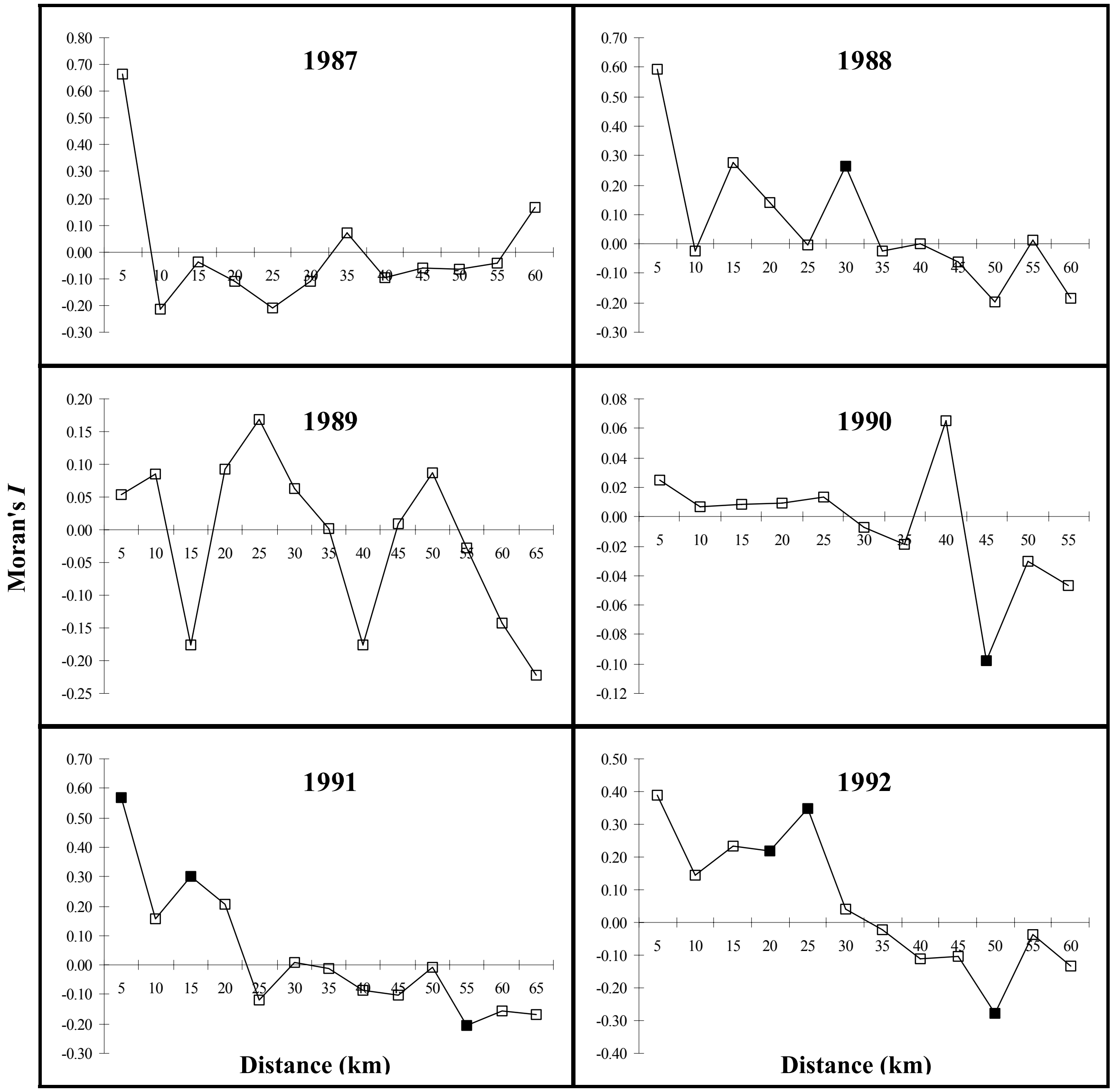


Figure 4.5 Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the VIMS October survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

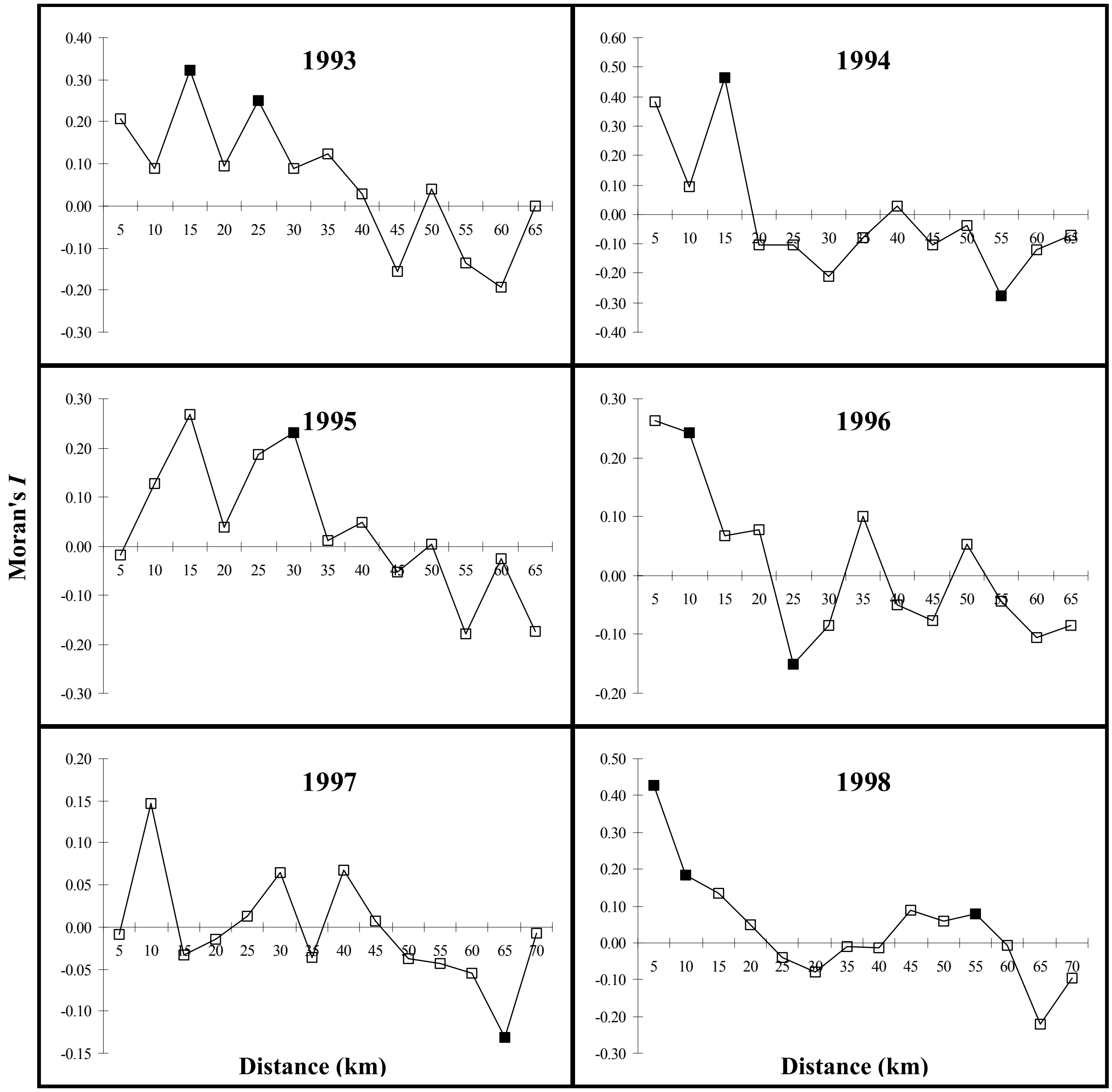


Figure 4.5 (*continued*) Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the VIMS October survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

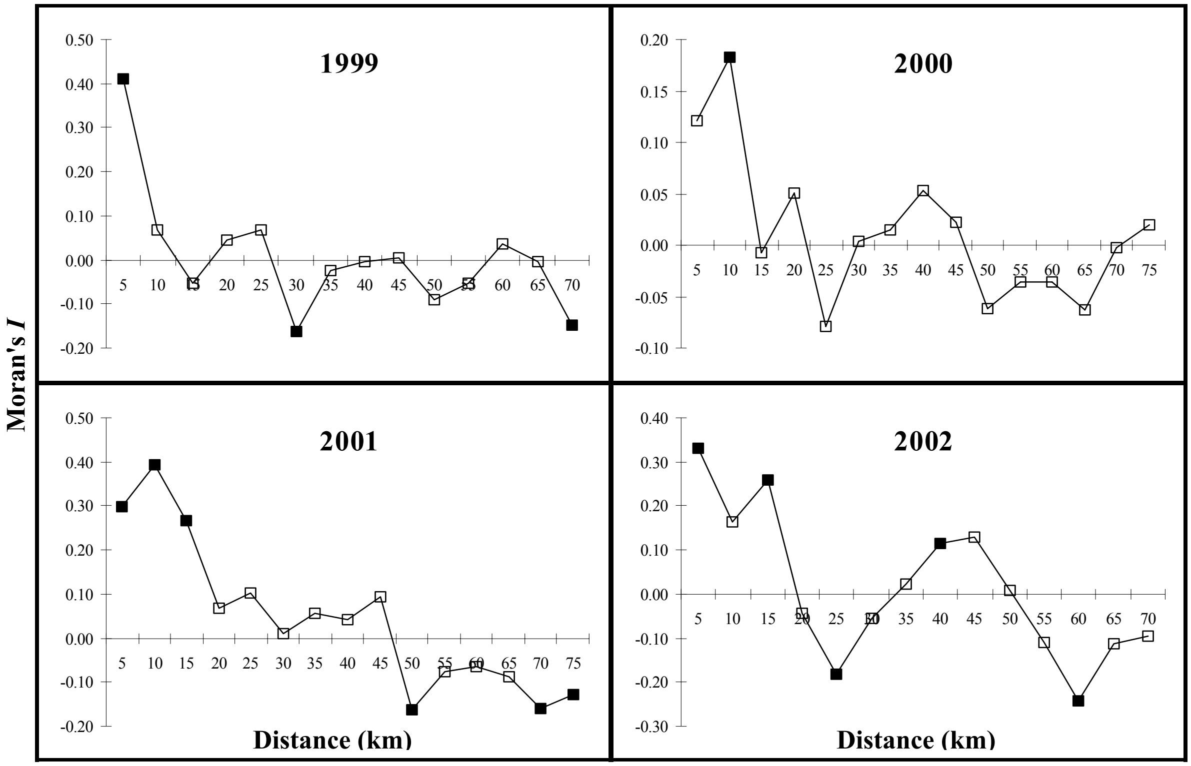


Figure 4.5 (*continued*) Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the VIMS October survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

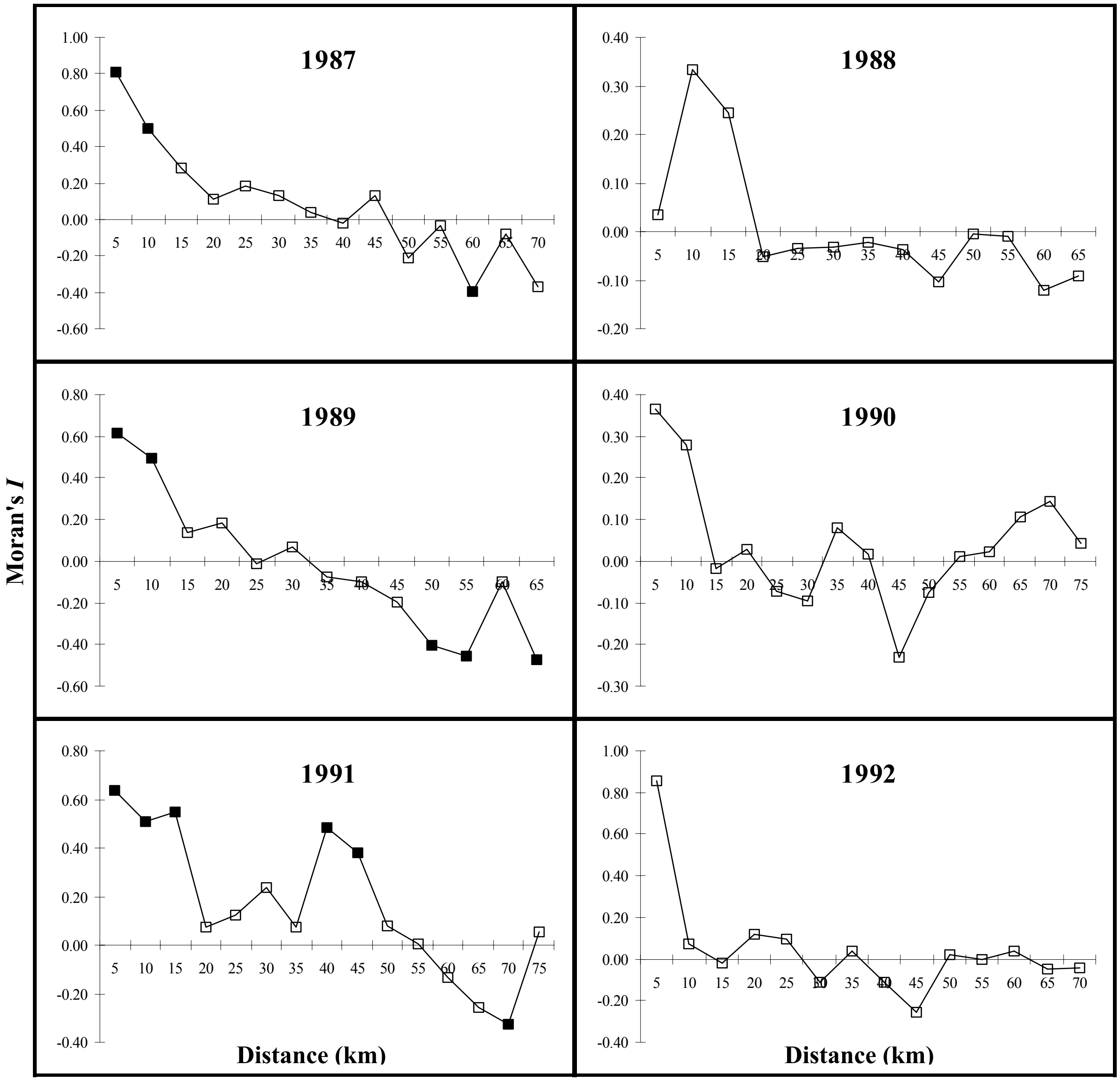


Figure 4.6 Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the NC195 September survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

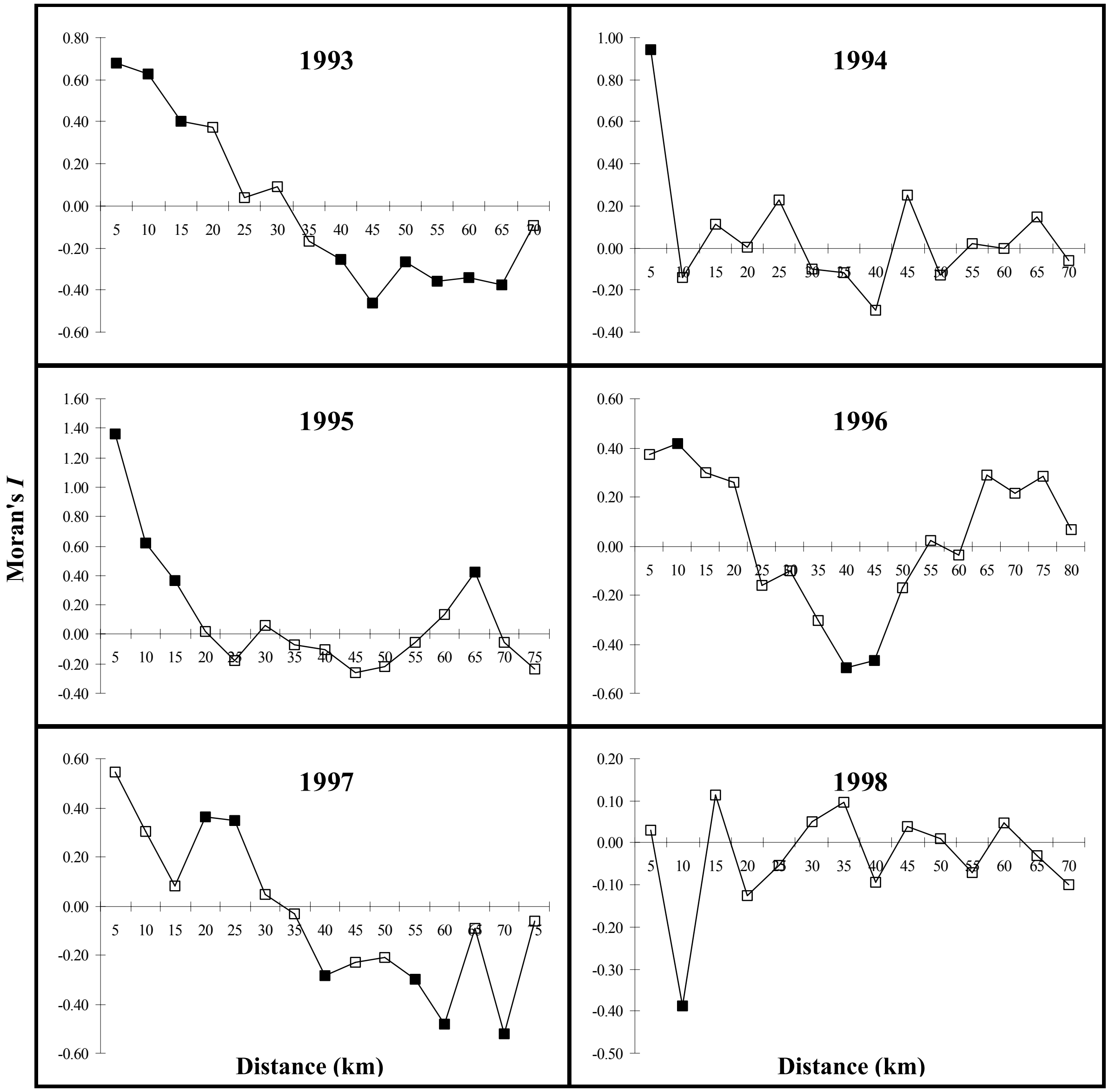


Figure 4.6 (*continued*) Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the NC195 September survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

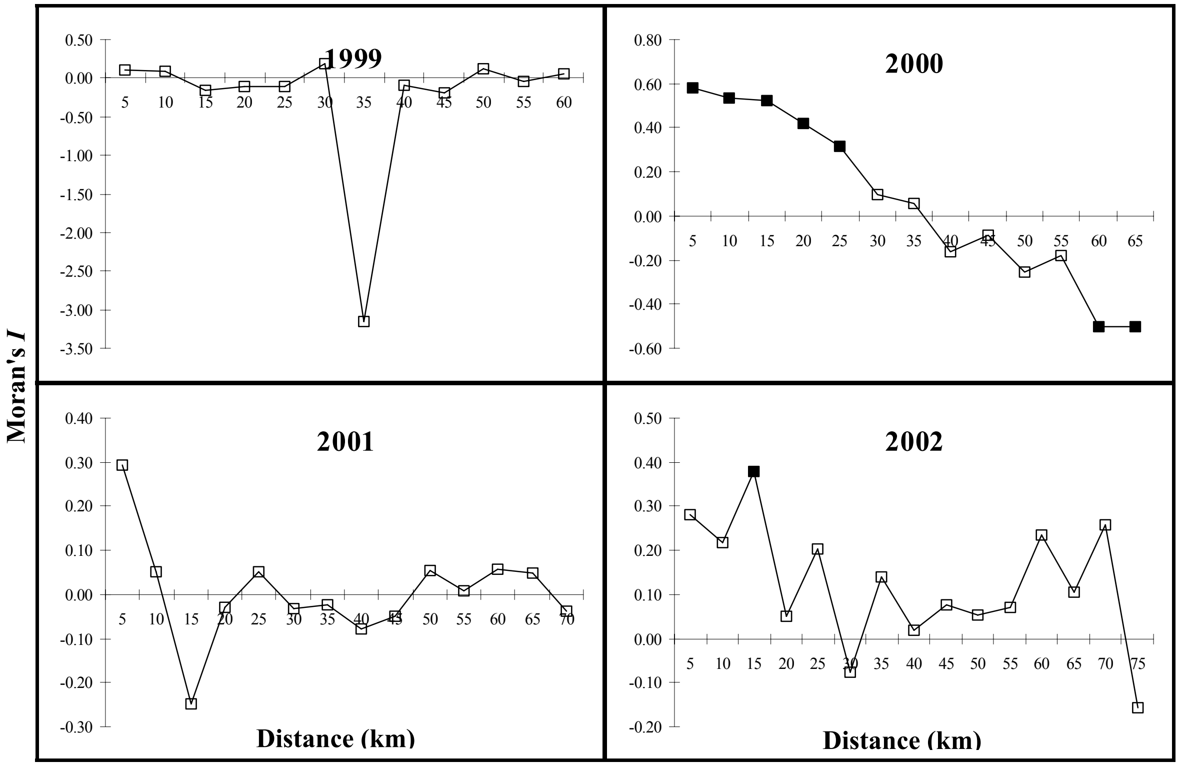
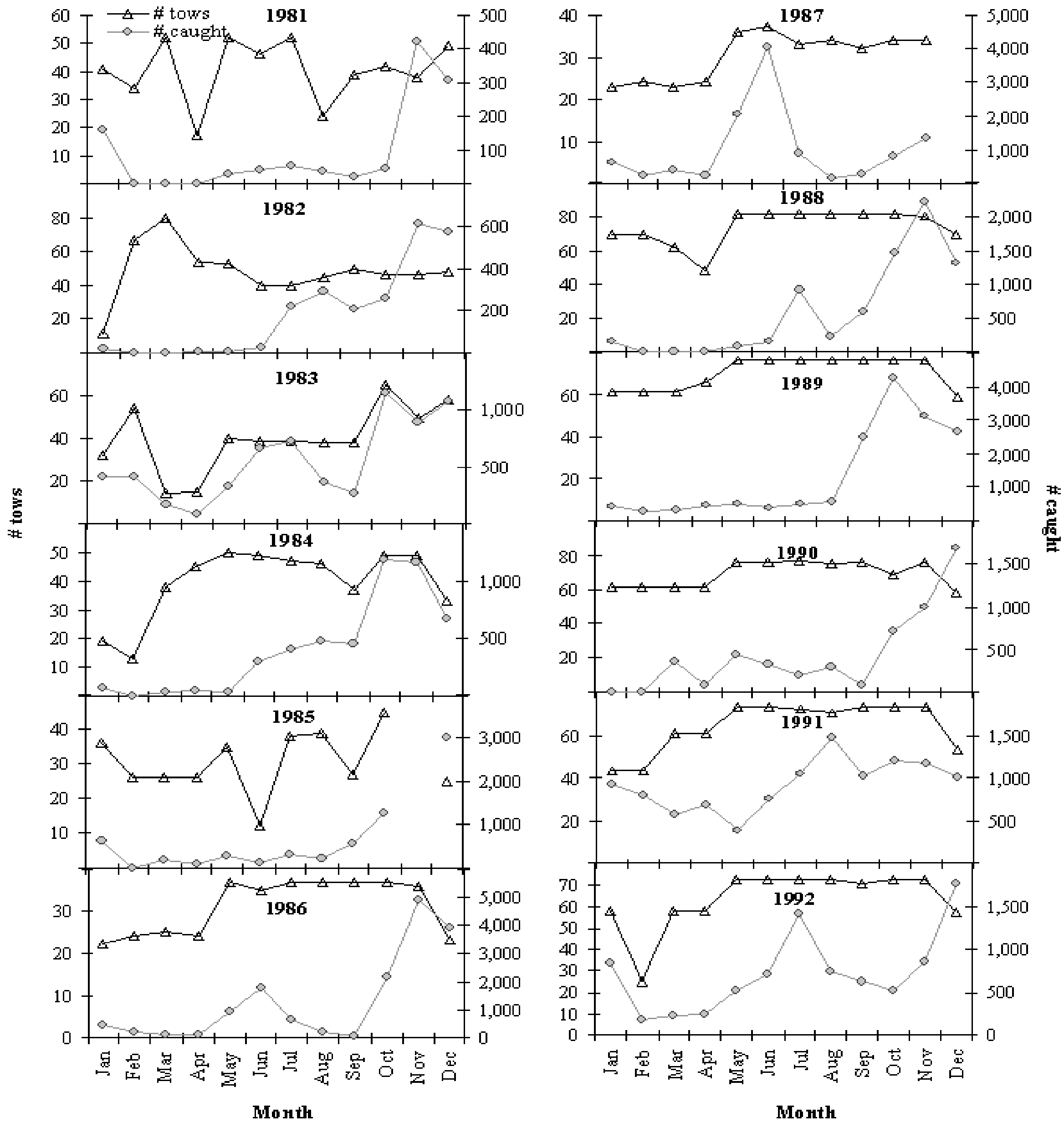


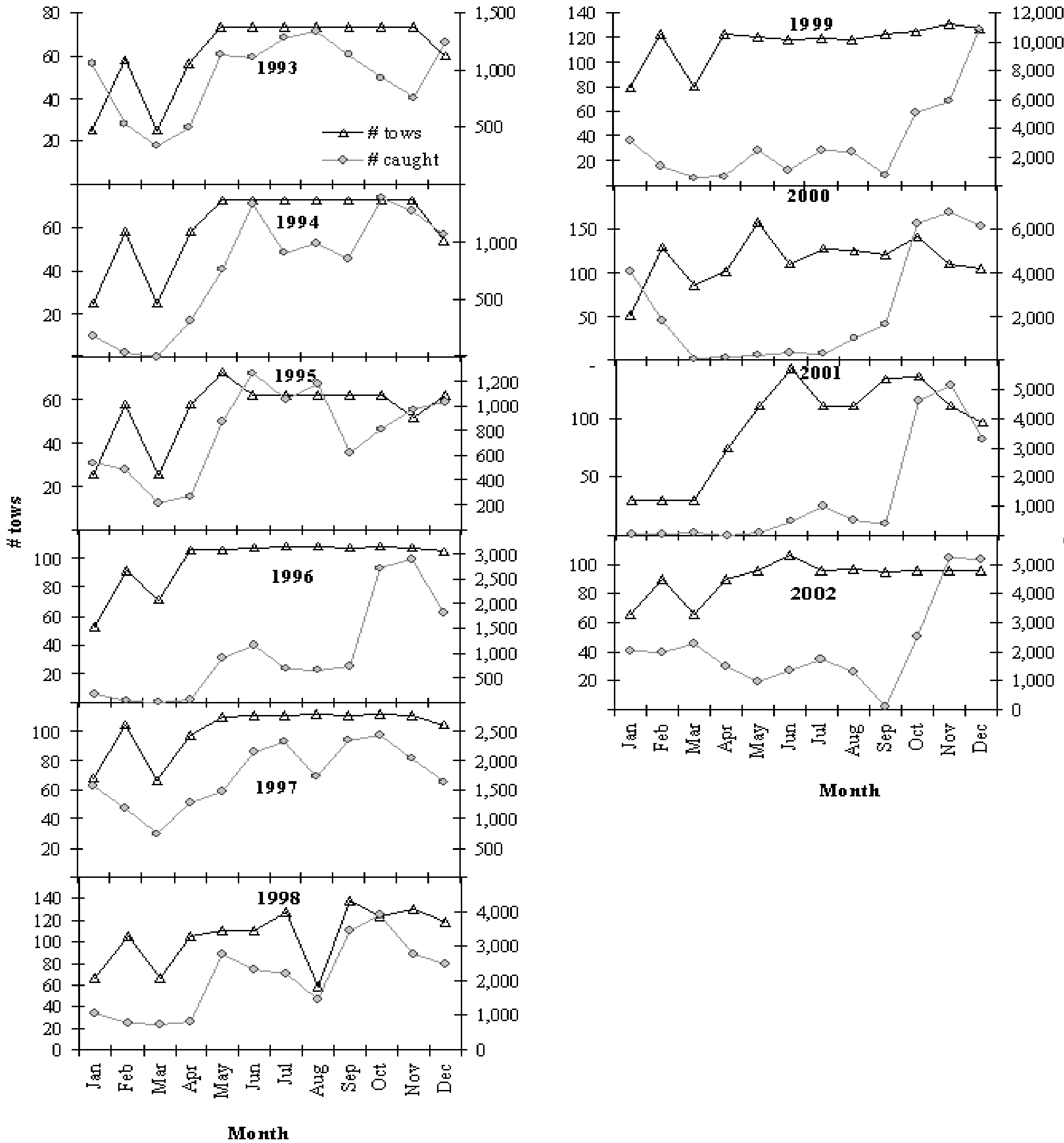
Figure 4.6 (*continued*) Moran correlograms for log-transformed counts of age-0 Atlantic croaker observed in the NC195 September survey. A solid point indicates significant spatial autocorrelation based on Holm's correction.

7 APPENDICES

7.1 Plots of number of tows and number of Atlantic croaker caught by month in the VIMS survey.



7.1 (*continued*). Plots of number of tows and number of Atlantic croaker caught by month in the VIMS survey.



7.2 Estimates of population status of Atlantic croaker from the stock synthesis model base run.

TABLE B.1 Annual estimates of biomass, recruitment, and spawning stock biomass for Atlantic croaker from the stock synthesis model.

	Biomass (000s metric tons)	Recruits (millions of fish)	Spawning Stock (10^9 eggs)
1981	28.8	33.8	13.9
1982	24.0	22.8	11.7
1983	19.1	38.4	9.1
1984	18.1	61.4	8.3
1985	16.2	49.7	7.4
1986	15.2	51.9	6.9
1987	11.7	37.0	5.3
1988	9.1	32.4	4.1
1989	5.6	31.1	2.4
1990	4.5	38.5	1.8
1991	5.2	41.0	2.1
1992	7.7	53.6	3.2
1993	14.0	110.5	5.6
1994	26.6	211.5	10.7
1995	48.1	290.9	20.3
1996	62.3	64.0	29.5
1997	65.9	89.4	31.7
1998	60.9	125.5	28.8
1999	58.6	169.1	27.1
2000	52.7	66.8	25.2
2001	41.3	41.2	20.0
2002	25.4	41.8	12.2

7.2 (*continued*). Estimates of population status of Atlantic croaker from the stock synthesis model base run.

TABLE B.2 Annual estimates of population size (millions of fish) by age and year from the stock synthesis model.

	Age-1	Age-2	Age-3	Age-4	Age-5	Age-6	Age-7	Age-8	Age-9	Age-10
1981	33.8	35.8	20.3	11.4	6.6	3.9	2.4	1.5	1.0	2.0
1982	22.8	18.2	17.2	10.2	6.2	3.8	2.4	1.5	1.0	2.0
1983	38.4	11.1	7.6	7.6	5.1	3.4	2.2	1.4	0.9	1.9
1984	61.4	19.8	5.0	3.6	4.0	2.8	2.0	1.3	0.9	1.8
1985	49.7	30.5	8.0	2.0	1.6	1.9	1.4	1.0	0.7	1.5
1986	51.9	24.7	12.3	3.2	0.9	0.8	1.0	0.8	0.6	1.3
1987	37.0	23.1	8.0	3.9	1.1	0.3	0.3	0.4	0.3	0.9
1988	32.4	15.9	7.3	2.5	1.4	0.4	0.1	0.1	0.2	0.7
1989	31.1	10.5	3.1	1.4	0.5	0.3	0.1	0.04	0.05	0.3
1990	38.5	9.0	1.7	0.5	0.3	0.1	0.1	0.04	0.02	0.1
1991	41.0	13.5	2.1	0.4	0.1	0.1	0.05	0.04	0.02	0.1
1992	53.6	20.0	5.0	0.8	0.2	0.1	0.04	0.02	0.02	0.05
1993	110.5	30.0	9.1	2.2	0.3	0.1	0.03	0.02	0.01	0.03
1994	211.5	62.7	14.0	4.0	1.0	0.2	0.04	0.01	0.01	0.02
1995	290.9	129.8	33.8	7.2	2.1	0.5	0.1	0.02	0.01	0.02
1996	64.0	187.4	77.6	19.9	4.3	1.3	0.3	0.1	0.01	0.02
1997	89.4	40.7	109.8	44.9	11.7	2.6	0.8	0.2	0.03	0.02
1998	125.5	52.8	21.3	57.0	24.2	6.5	1.5	0.5	0.1	0.03
1999	169.1	73.1	26.9	10.7	29.7	13.1	3.6	0.9	0.3	0.1
2000	66.8	95.0	35.8	13.1	5.5	15.9	7.3	2.1	0.5	0.2
2001	41.2	36.9	44.1	16.2	6.2	2.7	8.2	3.9	1.1	0.4
2002	41.8	18.7	12.8	15.1	6.0	2.5	1.2	3.7	1.8	0.8

TABLE B.3 Annual estimates of total *F* by age (shown for ages 1-5) from the stock synthesis model.

	Age-1	Age-2	Age-3	Age-4	Age-5		Age-1	Age-2	Age-3	Age-4	Age-5
1981	0.27	0.38	0.34	0.26	0.19	**1992**	0.23	0.44	0.49	0.46	0.43
1982	0.37	0.52	0.46	0.35	0.26	**1993**	0.22	0.41	0.47	0.44	0.41
1983	0.31	0.45	0.41	0.31	0.23	**1994**	0.14	0.27	0.31	0.29	0.27
1984	0.35	0.56	0.56	0.47	0.39	**1995**	0.09	0.16	0.18	0.17	0.15
1985	0.35	0.56	0.55	0.46	0.38	**1996**	0.10	0.18	0.20	0.18	0.16
1986	0.46	0.78	0.81	0.72	0.62	**1997**	0.18	0.30	0.31	0.27	0.23
1987	0.50	0.80	0.80	0.69	0.59	**1998**	0.19	0.32	0.34	0.30	0.27
1988	0.78	1.29	1.33	1.18	1.03	**1999**	0.23	0.36	0.37	0.32	0.27
1989	0.89	1.47	1.48	1.28	1.09	**2000**	0.24	0.42	0.44	0.40	0.35
1990	0.70	1.10	1.07	0.90	0.74	**2001**	0.44	0.71	0.72	0.64	0.56
1991	0.37	0.63	0.66	0.61	0.55	**2002**	0.79	1.29	1.31	1.16	1.00

7.3 Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.1 Synthesis model estimates of annual biomass (000s metric tons) of Atlantic croaker from model runs assuming different values for the size of the 1994 year-class.

	10	**50**	**100**	**200**	**291**	**400**	**500**	**700**	**900**
1981	10.9	22.6	26.2	29.1	28.8	27.9	27.2	25.4	24.2
1982	9.0	18.7	21.8	24.2	24.0	23.2	22.6	21.1	20.1
1983	7.2	15.1	17.4	19.3	19.1	18.5	18.1	16.9	16.2
1984	8.9	15.5	17.0	18.2	18.1	17.7	17.4	16.8	16.4
1985	10.0	14.7	15.6	16.3	16.2	16.0	15.9	15.7	15.5
1986	10.6	14.3	14.8	15.2	15.2	15.1	15.1	15.0	15.0
1987	8.7	11.1	11.4	11.7	11.7	11.7	11.7	11.7	11.8
1988	6.8	8.7	8.9	9.1	9.1	9.1	9.1	9.2	9.2
1989	4.2	5.4	5.5	5.6	5.6	5.6	5.6	5.7	5.7
1990	3.7	4.6	4.6	4.5	4.5	4.6	4.6	4.7	4.8
1991	4.7	5.6	5.4	5.2	5.2	5.3	5.3	5.5	5.7
1992	6.7	8.1	8.0	7.7	7.7	7.8	7.8	8.0	8.2
1993	10.6	14.1	14.4	14.2	14.0	13.8	13.6	13.5	13.5
1994	37.1	45.4	37.6	29.2	26.6	24.7	23.4	22.2	21.5
1995	62.9	63.3	55.4	47.7	48.1	50.4	53.4	61.6	71.0
1996	68.1	72.6	65.0	59.2	62.3	68.1	74.4	88.9	104.2
1997	65.3	71.0	64.9	61.5	65.9	73.5	81.6	99.5	118.5
1998	56.3	62.9	58.5	56.8	60.9	68.0	75.9	93.9	113.6
1999	50.6	58.7	56.0	55.6	58.6	64.1	70.5	85.9	103.7
2000	43.3	50.6	49.9	50.8	52.7	56.4	61.1	73.0	87.8
2001	31.9	38.5	38.7	40.0	41.3	43.7	47.1	56.2	68.3
2002	18.2	23.0	23.4	24.5	25.4	27.2	29.7	36.8	46.5

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.2 Synthesis model estimates of annual biomass (000s metric tons) from the base run and model runs with reduced emphasis of different survey sources.

	Base	No NC120	No NC195 June	No NC195 Sept	No NC	No VIMS	No NEFSC
1981	28.8	32.5	34.8	12.4	34.1	12.6	12.6
1982	24.0	26.4	29.3	10.2	28.0	10.5	10.5
1983	19.1	20.6	23.3	8.5	21.8	8.8	8.5
1984	18.1	19.2	21.7	10.6	20.0	9.8	10.2
1985	16.2	17.0	19.4	11.2	17.7	10.0	10.5
1986	15.2	15.9	17.6	11.8	16.2	10.4	10.9
1987	11.7	12.6	13.7	9.6	12.9	8.5	8.8
1988	9.1	10.1	10.8	7.8	10.4	7.0	7.3
1989	5.6	6.5	6.9	5.1	6.6	4.8	5.0
1990	4.5	5.3	5.4	4.6	5.2	4.5	4.7
1991	5.2	6.1	5.8	5.6	5.6	5.5	5.6
1992	7.7	9.5	8.5	8.4	9.2	7.3	7.6
1993	14.0	17.0	14.8	14.6	16.9	13.0	12.8
1994	26.6	31.1	28.1	29.6	31.0	32.2	28.1
1995	48.1	55.0	49.5	48.5	52.8	47.8	45.0
1996	62.3	71.7	65.5	57.2	68.9	55.1	52.8
1997	65.9	76.5	70.6	57.9	77.7	56.0	53.0
1998	60.9	71.9	67.0	54.6	77.7	50.4	48.6
1999	58.6	69.7	66.7	52.4	76.5	49.4	47.4
2000	52.7	64.0	62.7	44.8	69.8	42.5	41.3
2001	41.3	50.9	50.7	33.8	54.9	32.8	32.2
2002	25.4	32.8	32.9	19.8	34.7	20.1	19.8

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.3 Synthesis model estimates of annual biomass (000s metric tons) from the base run (M=0.35), run with relaxed stock-recruitment relationship, runs assuming different values of M, and runs assuming the iterative re-weighting option and fixed values for the error of survey relative abundance.

	Base	**Relaxed S-R**	***M*=0.20**	***M*=0.50**	**Iterative re-weighting σ_s**	**Fixed σ_s**
1981	28.8	25.6	45.5	13.2	11.6	12.0
1982	24.0	20.7	40.4	10.6	9.3	9.2
1983	19.1	16.1	35.3	8.8	7.9	7.7
1984	18.1	16.0	32.9	10.9	9.0	9.1
1985	16.2	15.1	28.4	11.4	9.8	9.3
1986	15.2	15.1	24.1	11.9	11.1	10.4
1987	11.7	12.0	17.8	9.6	9.5	8.5
1988	9.1	9.3	13.1	7.7	7.8	7.1
1989	5.6	5.7	8.4	5.2	5.0	5.0
1990	4.5	4.6	7.0	4.9	4.6	4.8
1991	5.2	5.5	8.4	6.0	6.1	5.6
1992	7.7	8.3	11.2	8.4	10.3	8.0
1993	14.0	16.6	17.8	14.1	18.8	12.9
1994	26.6	34.3	44.4	30.5	52.4	28.0
1995	48.1	60.8	58.2	50.4	70.8	44.0
1996	62.3	76.7	68.3	56.8	78.9	51.6
1997	65.9	80.5	71.8	55.3	81.3	51.6
1998	60.9	75.1	68.7	49.4	72.9	48.3
1999	58.6	72.1	64.8	48.6	64.7	49.0
2000	52.7	64.8	55.7	42.4	51.8	44.3
2001	41.3	51.9	44.2	32.7	36.3	35.9
2002	25.4	34.9	29.8	19.8	19.7	24.6

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.4 Synthesis model estimates of annual recruitment (millions of fish) of Atlantic croaker from model runs assuming different values for the size of the 1994 year-class.

	10	**50**	**100**	**200**	**291**	**400**	**500**	**700**	**900**
1981	43.5	37.2	35.0	33.5	33.8	34.6	35.5	37.8	39.8
1982	30.6	25.1	23.5	22.4	22.8	23.4	24.1	25.8	27.4
1983	51.1	43.8	40.7	38.1	38.4	39.7	40.8	43.7	45.8
1984	83.6	71.4	66.2	61.2	61.4	63.3	64.8	69.0	71.9
1985	61.1	54.8	52.0	49.4	49.7	50.8	51.8	54.0	55.3
1986	58.2	54.6	53.1	51.7	51.9	52.6	53.0	54.1	54.4
1987	38.5	36.5	36.7	36.9	37.0	37.2	37.3	37.5	37.7
1988	33.9	32.2	31.9	32.3	32.4	32.4	32.5	32.6	32.7
1989	34.4	32.5	31.7	31.1	31.1	31.3	31.5	32.0	32.4
1990	43.5	41.4	40.3	38.4	38.5	39.1	39.4	40.6	41.3
1991	48.2	46.1	44.3	41.0	41.0	41.7	42.2	44.2	45.8
1992	53.1	54.7	55.3	53.9	53.6	53.5	53.1	53.6	53.9
1993	100.5	112.7	116.0	113.1	110.5	108.0	104.9	102.5	100.4
1994	718.6	567.3	414.4	251.1	211.5	186.3	170.7	157.2	150.1
1995	10.0	50.0	100.0	200.0	290.9	400.0	500.0	700.0	900.0
1996	65.4	70.4	75.0	72.5	64.0	57.3	53.4	50.6	50.3
1997	69.1	81.8	91.9	98.6	89.4	79.8	73.0	64.1	58.9
1998	132.1	133.4	133.6	129.9	125.5	119.9	115.0	108.6	105.8
1999	162.6	173.2	177.7	174.7	169.1	161.9	155.9	149.1	148.2
2000	58.0	60.4	63.7	67.5	66.8	65.0	63.6	61.9	62.1
2001	44.1	42.0	41.7	41.3	41.2	41.2	41.4	42.8	45.0
2002	43.2	42.3	42.2	41.6	41.8	42.3	43.0	45.3	48.0

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.5 Synthesis model estimates of annual recruitment (millions of fish) from the base run and model runs with reduced emphasis of different survey sources.

	Base	**No NC120**	**No NC195 June**	**No NC195 Sept**	**No NC**	**No VIMS**	**No NEFSC**
1981	33.8	25.2	35.8	43.2	26.2	43.6	44.5
1982	22.8	24.0	24.1	28.1	24.8	29.1	28.2
1983	38.4	37.6	37.4	49.6	37.0	47.1	40.8
1984	61.4	59.3	60.1	84.4	58.2	62.9	79.4
1985	49.7	45.6	46.8	60.5	46.1	61.8	56.7
1986	51.9	55.0	47.5	59.2	51.6	56.9	56.6
1987	37.0	40.3	40.0	39.0	44.1	41.5	38.2
1988	32.4	32.8	31.3	33.4	32.1	34.5	36.8
1989	31.1	30.1	30.4	31.9	28.9	34.8	34.1
1990	38.5	36.6	35.0	45.2	35.5	42.6	42.7
1991	41.0	42.8	37.5	48.1	37.9	47.4	44.9
1992	53.6	58.8	52.6	65.4	67.3	46.1	50.2
1993	110.5	108.8	95.3	124.4	102.8	117.7	110.4
1994	211.5	201.2	199.7	300.0	195.3	371.7	304.8
1995	290.9	282.9	232.6	299.2	237.1	199.3	255.0
1996	64.0	65.1	78.5	64.9	74.5	69.0	72.5
1997	89.4	113.7	113.2	70.6	183.6	90.6	60.3
1998	125.5	124.9	126.3	163.8	117.7	108.3	133.7
1999	169.1	166.6	179.3	174.1	150.0	206.5	192.4
2000	66.8	77.6	71.6	53.2	71.3	56.4	67.4
2001	41.2	35.7	41.4	39.2	28.5	47.0	49.5
2002	41.8	42.1	40.1	40.7	36.6	41.4	38.8

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.6 Synthesis model estimates of annual recruitment (millions of fish) from the base run (M=0.35), run with relaxed stock-recruitment relationship, runs assuming different values of M, and runs assuming the iterative re-weighting option and fixed values for the error of survey relative abundance.

	Base	**Relaxed S-R**	***M*=0.20**	***M*=0.50**	**Iterative re-weighting σ_s**	**Fixed σ_s**
1981	33.8	34.2	30.2	54.7	33.8	32.3
1982	22.8	16.1	21.6	34.3	33.6	21.7
1983	38.4	41.4	32.1	57.7	55.6	57.4
1984	61.4	75.1	52.1	96.3	59.6	66.2
1985	49.7	53.5	36.2	71.2	73.7	55.7
1986	51.9	60.3	30.4	70.4	69.6	70.5
1987	37.0	34.3	23.0	49.4	43.6	35.7
1988	32.4	30.3	21.7	40.8	33.4	36.9
1989	31.1	30.5	27.5	39.7	30.1	35.5
1990	38.5	41.1	45.8	49.8	46.8	43.8
1991	41.0	45.2	60.9	55.7	56.6	43.9
1992	53.6	59.3	55.4	66.6	88.2	58.5
1993	110.5	148.5	122.9	131.9	152.9	102.2
1994	211.5	289.9	509.1	354.4	618.2	305.6
1995	290.9	338.0	80.8	364.1	136.2	246.3
1996	64.0	60.1	49.7	94.7	63.7	76.0
1997	89.4	91.9	46.7	116.1	158.8	60.4
1998	125.5	140.4	86.6	184.5	93.9	154.1
1999	169.1	188.5	111.4	275.0	128.0	218.8
2000	66.8	67.6	44.2	102.9	47.3	73.3
2001	41.2	42.0	39.1	57.8	29.3	50.1
2002	41.8	45.9	38.4	53.4	38.8	56.4

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.7 Synthesis model estimates of annual spawning stock (10^9 eggs) of Atlantic croaker from model runs assuming different values for the size of the 1994 year-class.

	10	**50**	**100**	**200**	**291**	**400**	**500**	**700**	**900**
1981	4.5	10.7	12.5	14.0	13.9	13.4	13.0	12.1	11.4
1982	3.8	8.9	10.5	11.8	11.7	11.2	10.9	10.1	9.6
1983	2.7	7.0	8.2	9.2	9.1	8.8	8.5	7.9	7.5
1984	3.0	6.8	7.7	8.3	8.3	8.1	7.9	7.5	7.3
1985	3.8	6.5	7.0	7.5	7.4	7.3	7.2	7.0	6.9
1986	4.2	6.4	6.7	6.9	6.9	6.8	6.8	6.8	6.7
1987	3.5	5.0	5.2	5.3	5.3	5.3	5.3	5.3	5.3
1988	2.8	3.9	4.0	4.1	4.1	4.1	4.1	4.1	4.1
1989	1.5	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4
1990	1.1	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9
1991	1.5	2.2	2.2	2.1	2.1	2.1	2.1	2.2	2.3
1992	2.4	3.3	3.3	3.2	3.2	3.2	3.2	3.3	3.4
1993	3.6	5.7	5.8	5.7	5.6	5.6	5.5	5.5	5.5
1994	7.8	16.3	14.0	11.6	10.7	10.0	9.5	9.1	8.8
1995	27.7	28.8	25.2	20.9	20.3	20.3	20.7	22.7	25.2
1996	31.8	34.8	31.1	28.1	29.5	32.2	35.0	41.4	48.2
1997	30.9	34.2	31.1	29.4	31.7	35.5	39.5	48.4	57.6
1998	25.8	29.7	27.4	26.7	28.8	32.4	36.4	45.4	55.2
1999	22.2	27.0	25.6	25.5	27.1	29.9	33.2	40.9	49.8
2000	19.9	24.0	23.6	24.2	25.2	27.0	29.4	35.3	42.7
2001	14.8	18.5	18.6	19.3	20.0	21.2	22.9	27.4	33.3
2002	8.2	10.9	11.1	11.7	12.2	13.0	14.3	17.8	22.5

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.8 Synthesis model estimates of annual spawning stock (10^9 eggs) from the base run and model runs with reduced emphasis of different survey sources.

	Base	No NC120	No NC195 June	No NC195 Sept	No NC	No VIMS	No NEFSC
1981	13.9	15.8	16.9	5.4	16.7	5.5	5.5
1982	11.7	12.9	14.3	4.5	13.7	4.7	4.7
1983	9.1	9.9	11.3	3.6	10.5	3.8	3.7
1984	8.3	8.9	10.2	4.1	9.4	4.0	4.1
1985	7.4	8.0	9.1	4.6	8.3	4.1	4.3
1986	6.9	7.3	8.3	4.9	7.5	4.3	4.6
1987	5.3	5.8	6.4	4.1	5.9	3.6	3.7
1988	4.1	4.7	5.0	3.3	4.8	2.9	3.1
1989	2.4	2.9	3.1	2.1	3.0	1.9	2.0
1990	1.8	2.2	2.3	1.7	2.2	1.7	1.8
1991	2.1	2.6	2.5	2.1	2.4	2.1	2.2
1992	3.2	4.1	3.7	3.2	3.8	3.0	3.0
1993	5.6	7.3	6.3	5.6	7.3	5.0	5.0
1994	10.7	13.3	11.8	10.9	13.3	11.6	10.3
1995	20.3	24.2	22.0	19.4	23.6	19.8	18.2
1996	29.5	34.5	31.5	25.9	33.2	25.1	23.8
1997	31.7	36.9	33.9	27.2	36.8	26.1	24.8
1998	28.8	34.4	32.0	24.8	37.4	23.3	22.2
1999	27.1	32.9	31.3	23.3	36.5	21.8	20.9
2000	25.2	30.9	30.3	20.8	33.9	19.5	18.8
2001	20.0	24.9	24.8	15.9	27.0	15.3	15.0
2002	12.2	15.9	16.0	9.2	16.9	9.3	9.1

7.3 (*continued*). Atlantic croaker population estimates from stock synthesis model sensitivity runs.

TABLE C.9 Synthesis model estimates of annual spawning stock (10^9 eggs) from the base run (M=0.35), run with relaxed stock-recruitment relationship, runs assuming different values of M, and runs assuming the iterative re-weighting option and fixed values for the error of survey relative abundance.

	Base	**Relaxed S-R**	***M*=0.20**	***M*=0.50**	**Iterative re-weighting σ_s**	**Fixed σ_s**
1981	13.9	12.2	21.6	5.7	5.2	5.3
1982	11.7	10.1	19.4	4.7	4.1	4.2
1983	9.1	7.5	16.9	3.6	3.2	3.1
1984	8.3	7.1	15.5	4.2	3.7	3.6
1985	7.4	6.8	13.3	4.6	3.9	3.8
1986	6.9	6.7	11.3	4.9	4.5	4.2
1987	5.3	5.5	8.3	4.0	4.0	3.6
1988	4.1	4.2	6.1	3.2	3.4	3.0
1989	2.4	2.4	3.7	2.1	2.1	2.0
1990	1.8	1.8	2.9	1.8	1.7	1.8
1991	2.1	2.2	3.3	2.2	2.3	2.2
1992	3.2	3.4	4.5	3.3	4.0	3.1
1993	5.6	6.5	7.0	5.3	7.4	5.0
1994	10.7	13.5	15.8	10.8	18.9	10.2
1995	20.3	25.7	24.5	19.7	30.8	17.8
1996	29.5	36.4	31.1	25.5	37.0	23.2
1997	31.7	38.8	33.8	25.4	38.1	24.1
1998	28.8	35.6	32.3	22.0	34.5	21.9
1999	27.1	33.5	30.2	20.4	30.3	21.3
2000	25.2	31.0	26.2	18.9	24.6	20.1
2001	20.0	25.2	20.9	15.1	17.5	16.7
2002	12.2	16.8	14.0	9.0	9.3	11.3