Abstract—Historical and retrospective comparisons of Atlantic menhaden virtual population analyses (VPA) from 1955 to 1995 revealed substantial inconsistency in estimates of management variables in the last year of stock assessments. Estimates of management variables from several historical stock assessments were generally consistent throughout most of the time series. In the last two years, however, historical estimates have deviated from revised estimates. Relative performance of alternative ad hoc methods for estimating fully recruited fishing mortality (F) in terminal years showed that all methods were imprecise, but conventional catch-curve estimates were unbiased and had the least retrospective inconsistency. Retrospective differences in terminal estimates of age-1 F by separable VPA ranged widely for eight alternative settings but were clearly minimized by using seven years of catch data. The general magnitude of retrospective difference was ±1.2 billion recruits (46% relative difference), ±9,000 metric tons of spawning stock biomass (33% relative difference), and ±4.7 percent maximum spawning potential (106% relative difference). Retrospective differences in recruitment, spawning stock biomass, and spawning potential were positively skewed but not biased, indicating that the frequency of positive and negative inconsistencies are equal but that the positive differences are much greater in magnitude. The skewed distribution of retrospective inconsistency should be considered for managing the Atlantic menhaden fishery.

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Retrospective analysis of virtual population estimates for Atlantic menhaden stock assessment

Steven X. Cadrin
Massachusetts Division of Marine Fisheries
50 A Portside Drive
Pocasset, Massachusetts 02559
Present address: Northeast Fisheries Science Center,
National Marine Fisheries Service, NOAA
Woods Hole, Massachusetts 02543-1097

Douglas S. Vaughan
Beaufort Laboratory, National Marine Fisheries Service
Beaufort, North Carolina 28516

The Atlantic menhaden, *Brevoortia tyrannus*, is a planktivorous clupeid that schools in coastal waters off the east coast of the United States. Atlantic menhaden dominated total U.S. fishery landings from 1946 to 1962 (Ahrenholz et al., 1987), yielding approximately 600,000 metric tons (t) per year 1953–62 (Henry, 1971), after which landings steadily declined to 162,000 t in 1969 owing to recruitment failure and subsequent overfishing. Since then, catch has increased to an average of 330,000 t per year 1970–95 (AMAC, 1992).[1] The Atlantic menhaden fishery is currently managed according to six fishery and population thresholds that indicate overfishing in relation to historic production (AMAC, 1992). Three of the minimum population thresholds (2 billion recruits, 17,000-t spawning stock biomass, and 3% maximum spawning potential) are derived from virtual population analysis (VPA) (Megrey, 1989).

Atlantic menhaden landings have been reported from processing plants since 1940 and have been sampled for length, weight, and age since 1955 according to a two-stage cluster sampling design in which fish were sampled weekly from each port where menhaden were processed (Nicholson, 1975; Chester, 1984; Smith et al., 1987). The frequency of fishery samples and the consolidated nature of the fishery provide an extremely reliable 41-year series of catch at age, ages 0–6$^+$, for estimation of abundance and mortality through VPA (Table 1). Unfortunately, no independent indices of relative abundance are available to calibrate abundance estimates for the last year of catch: commercial catch per unit of effort is a biased index because commercial catchability is inversely related to abundance (Schaaf, 1975; Ahrenholz et al., 1987; Vaughan and Smith, 1988; Atran and Loesch, 1995) and fishery-independent survey indices are not correlated with abundance (Ahrenholz et al., 1989). In the absence of reliable abundance indices, and therefore of a formal statistical estimator for year-class abundance in the last year of the VPA, ad hoc estimation rules have been used to approximate abundance.

The error in estimates of abundance is progressively less in previous years than in the last year of

[1] 1992–95 landings from Joseph Smith, Beaufort Laboratory, National Marine Fisheries Service, Beaufort, NC. Personal commun.

Table 1

Age-based stock assessments of Atlantic menhaden. Y_t indicates the terminal year the VPA.

Y_t	Source
1976	AMMB, 1981; Powers, 1983
1981	Vaughan et al., 1986; Ahrenholz et al., 1987
1984	AMMB, 1986; Vaughan and Smith, 1988
1988	Vaughan, 1990; Vaughan and Merriner, 1991
1990	AMAC, 1992 (p. 40–50); Vaughan, 1993
1992	AMAC, 1992 (p. 17–30)
1993	Vaughan, 1994[1]
1994	Vaughan, 1995[1]
1995	Vaughan, 1996[1]

[1] Vaughan, D. S. Trigger variables for Atlantic menhaden. Natl. Mar. Fish. Serv., NOAA, Unpubl. AMAC reports.

the VPA, provided that catch at age and natural mortality (M) are well estimated and fishing mortality (*F*) is at least moderate (Jones, 1961; Tomlinson, 1970; Pope, 1972; Ulltang, 1977; Megrey, 1989). As stated in the Atlantic menhaden fishery management plan, "Trigger estimates for recent years from VPA are subject to large uncertainty, while estimates 2 to 3 years old are more reliable" (AMAC, 1992). Consistency in successive stock assessments can be evaluated by using "historical analysis," which compares estimates from the most recent assessment with contemporary estimates from prior stock assessments (Sinclair et al., 1985),[2] but historical assessments of the menhaden stock were not conducted with a common estimation rule. Consistency of the current estimation rule can be evaluated by using "retrospective analysis," which recreates a historical series of VPA's with a single estimation rule (Sinclair et al, 1990).[2]

The first objective of the current investigation was to report the general magnitude and potential bias of retrospective differences for guidance on interpreting current estimates and for providing fishery management advice. The second objective was to attempt alternative estimation rules to improve consistency of estimates.

[2] Examples of historical and retrospective analyses, interpretation, and discussion can also be found in the following two refererences:

Int. Counc. Explor. Sea. 1991. Report of the working group on methods of fish stock assessments. ICES Council Meeting Assess., p. 25.

Northeast Fisheries Science Center. 1994. Report of the 18th Northeast Regional Stock Assessment Workshop (18th SAW). NEFSC Ref. Doc. 94-22.

Methods

Historical comparisons

Three Atlantic menhaden management variables derived from VPA (age-1 abundance [R], spawning stock biomass [SSB], and percent maximum spawning potential [%MSP]) were compared among ten reported stock assessments (Table 1). The number of historical estimates of each variable differed because some reports did not document all three population estimates.

Consistency of successive stock assessments was measured by comparing historical estimates with revised estimates (from the 1995 VPA), which are more reliable. Inconsistency may result from historical estimation error or inaccurate estimates for prior years in the current VPA (Sinclair et al., 1990). The population thresholds used to define overfishing are subject to some uncertainty because they are also VPA estimates; but they are converged estimates, which are much more certain than current estimates. In comparing current VPA estimates with these overfishing thresholds for an annual assessment of stock status, converged and current estimates are assumed to be consistent. Estimates in the last year (Y_t), and back-calculated years (Y_{t-1}, Y_{t-2}, etc.) were compared with the time series of estimates derived in 1995. Differences between historical estimates and revised estimates were calculated as follows:

$$\Delta R_{t,t+k} = R_{t,t+k} - R_{t,1995},$$

where $R_{t,1995}$ = the most recent estimate of recruitment in year t;
$R_{t,t+k}$ = recruitment in year t as estimated when $t+k$ was the last year in the assessment; and
k = is the retrospective lag between year t and the last year of the historical VPA.

For example, $R_{1990,1993}$ is the 1993 estimate of 1990 recruitment, which has a three-year retrospective lag (i.e. k=3). When k = 0, $R_{t,t}$ is an estimate of recruitment for the last year in an assessment and is referred to as a terminal estimate. Historical differences in SSB and %MSP were similarly calculated:

$$SSB_{t,t+k} = SSB_{t,t+k} - SSB_{t,1995}$$
$$\Delta\%MSP_{t,t+k} = \%MSP_{t,t+k} - \%MSP_{t,1995}.$$

Root mean square (RMS) difference was used as a measure of dispersion of historical estimates from converged estimates for the additive properties of mean square difference. Sample sizes for historical differences were low, because of the limited number of historical stock assessments, but the following retrospective analyses have greater sample size for estimating RMS difference (n>30).

Retrospective comparisons

Retrospective analysis was performed in two stages to investigate consistency of both elements of the estimation rule: 1) estimation of fully recruited F by ad hoc methods and 2) estimation of partial recruitment to the fishery at ages 0 and 1 by separable VPA (SVPA; Pope and Shepherd, 1982). Both analytical stages assumed that menhaden were fully recruited to the fishery at age 2 and that M was 0.45 for all ages, over the entire time period.

Fully recruited F was approximated by using three alternative ad hoc methods for the first element of the analysis. Conventional catch curves (Beverton and Holt, 1957; Ricker, 1975; Gulland, 1983) and modified catch curves (Chapman and Robson, 1960; Robson and Chapman, 1961) were used to estimate mortality of the age-5 cohort over the four terminal years of the catch record (i.e. ages 2–5). These two catch-curve methods assumed that F in the current year was similar to F experienced by that cohort over the previous three years. The third ad hoc method, log catch ratios (Ricker, 1975; Gulland, 1983), derived fully recruited F from the negative log ratio of age-3^+ abundance in the terminal year to age-2^+ abundance in the previous year and assumed that F in the last year was similar to F in the previous year. All three ad hoc methods assume that menhaden are fully recruited and equally available to the fishery at age-2^+, which was confirmed through inspection of back-calculated F from the 1995 VPA.

The second element of the assessment, estimation of partial recruitment, was performed by using SVPA on a fixed number of years. For example, a retrospective series of 5-year SVPA's was produced with the following algorithm.

- Step 1 SVPA was run on an initial time series of catch-at-age data (e.g. 1955–60) with the appropriate estimate of fully recruited F in the terminal year.
- Step 2 Catch data in the starting year (e.g. 1955) were deleted, and catch data from a new terminal year (e.g. 1961) were appended.
- Step 3 SVPA was rerun on the revised time series with the appropriate estimate of fully recruited F in the new terminal year.

Steps 2 and 3 were repeated until 1995 was the terminal year.

Significance of retrospective bias was tested with a conventional t-ratio test (H_0: mean difference=0). Normality was tested by using the Shapiro and Wilk (1965) method. Results of t-ratio tests were confirmed by using nonparametric chi-square and sign tests. Dispersion of retrospective estimates from converged estimates was compared among alternative assessment rules by using RMS of retrospective differences. Retrospective estimates of fully recruited F in terminal years were compared with back-calculated estimates of fully recruited F from the 1995 VPA, as the average of ages 2–5 (weighted by abundance), to derive retrospective differences:

$$\Delta F_{t,t} = F_{t,t} - F_{t,1995}.$$

Note that there is no k subscript, as there were in the formulae for historical comparisons, because all retrospective estimates of fully recruited F were for terminal years (i.e. k=0). The relative retrospective difference ($\Delta F_{t,t}/F_{t,1995}$) was also calculated to remove the magnitude of the estimate from estimates of general inconsistency.

Back-calculated estimates of fully recruited F from the 1995 VPA were used in terminal years to compare retrospective inconsistency of SVPA settings without including retrospective inconsistency from ad hoc estimates of terminal F. The fixed number of years in each series of retrospective SVPA's was varied from three to ten years by using the algorithm described for the five-year example above. Retrospective consistency was compared among the eight series of retrospective SVPA's according to RMS difference of age-1 F estimates. Full recruitment of age- 2 and oldest age (6^+) menhaden was confirmed through inspection of back-calculated F at age from the 1995 VPA and was not adjusted for retrospective comparison.

Final SVPA runs were performed with seven years of catch-at-age and catch-curve estimates of terminal F to emulate more realistic inconsistency and describe the general magnitude and direction of retrospective differences. Retrospective estimates of R were derived directly from SVPA terminal estimates of age-1 abundance. SSB was estimated from terminal SVPA estimates of age-3^+ abundance and estimated weight at age of spawners. Percent MSP was calculated according to egg production per recruit (Vaughan, 1990; AMAC, 1992). Retrospective differences and relative differences of management variable estimates were log transformed [e.g. loge (R+ constant)] to test bias, and geometric mean square was used to estimate mean square difference because differences had skewed distributions.

Results

Historical comparisons

Management variable estimates from past stock assessments were generally consistent throughout most of the time series, except for the last two years of each assessment, when some historical estimates deviated from revised estimates from the 1995 VPA (Fig. 1). Terminal estimates of age-1 abundance were greater than revised estimates for five assessments and less than revised estimates for three assessments, but positive historical differences (i.e. historical estimate > revised estimate) were greater. For ex-

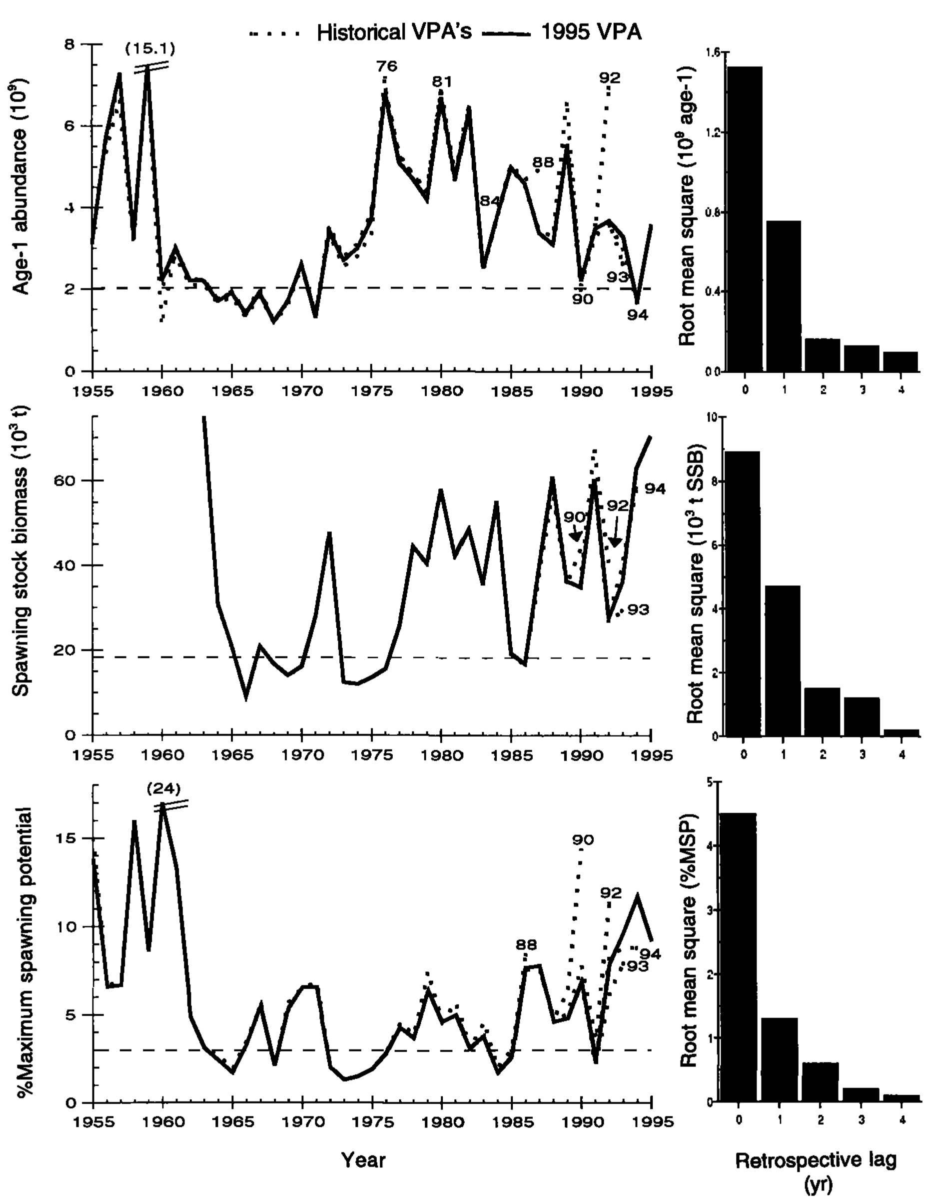

Figure 1

Comparison of historical estimates of Atlantic menhaden recruitment, spawning stock biomass, and percent maximum spawning potential. In the left charts, terminal years of historical stock assessments are labeled at the end of each series, overfishing thresholds are indicated by broken horizontal lines, and values in parentheses are not plotted. Convergence of estimates is illustrated by reduction in root mean square of historical differences over time in the charts on the right.

ample, in 1992, recruitment was estimated to be 3.4 billion greater than the 1995 estimate of 1992 recruitment. Estimates converged to within 160 million recruits of 1995 VPA estimates, when the retrospective lag (k) was greater than one year.

Only five terminal estimates of SSB and %MSP were available, including 1995 estimates. Two historical estimates of SSB were greater than revised estimates and two were less than revised estimates. Historical estimates of SSB converged to within 1,500 t of 1995 VPA estimates when k>1 year.

Historical estimates of %MSP were greater than revised estimates for three assessments and less than revised estimates for two assessments. The 1992 estimate of 1991 %MSP (i.e. backcalculated one year) was 3.6, but subsequent estimates of 1991 %MSP were below the overfishing threshold of 3 %MSP. Therefore, an overfishing trigger fired, but it was not detected until two years later. Estimates of %MSP converged to within 0.6 of 1995 VPA estimates when k>1 year.

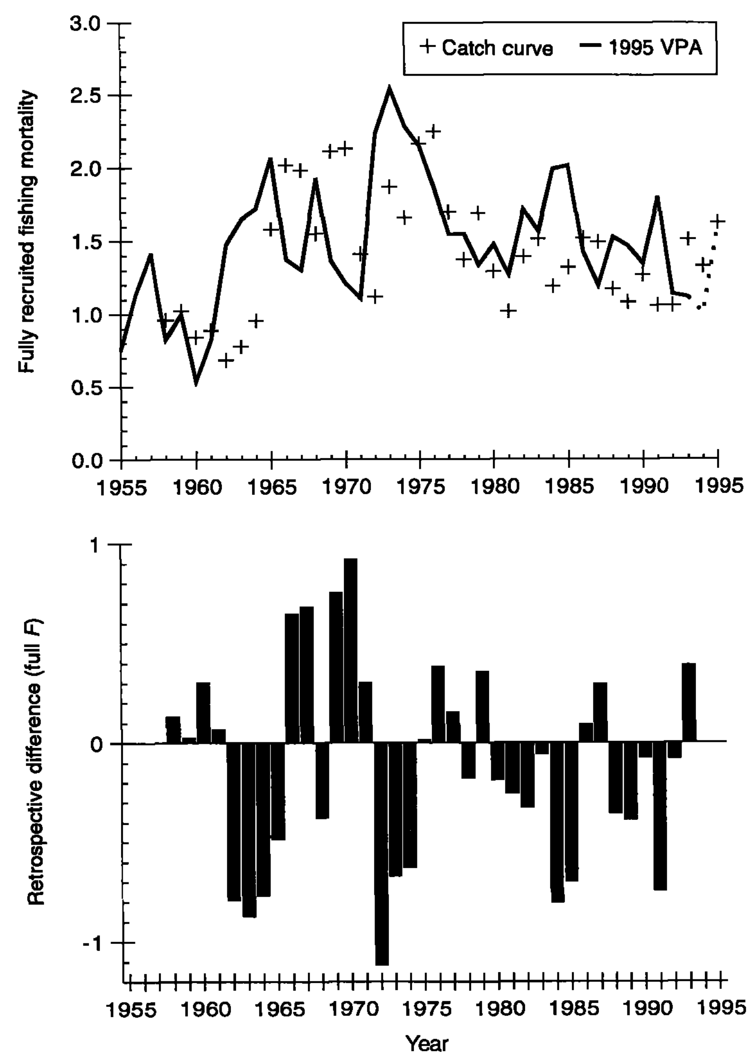

Figure 2

Retrospective catch-curve estimates of Atlantic menhaden fishing mortality and back-calculated estimates from the 1995 VPA (above) and retrospective differences (below). The broken line in the upper chart indicates provisional estimates.

Retrospective comparisons

Conventional catch curves produced the most consistent estimates of fully recruited F among the three ad hoc methods used. Retrospective differences from catch-curve estimates in terminal years ranged from −1.12 to 0.92 (Fig. 2). The RMS difference was 0.51 and the RMS relative difference was 33% (n=36). The mean retrospective difference in fully recruited F was not significantly different from zero. Therefore, although terminal estimates were imprecise, they were not biased. Retrospective differences in catch-curve estimates were negatively correlated with back-calculated F from the 1995 VPA (r=−0.62)(i.e. when F was low, catch-curve estimates were generally greater than revised estimates; when F was high, catch-curve F was generally less than the revised estimate). Retrospective differences in fully recruited F produced opposite inconsistencies in SSB and %MSP. For example, in 1993, catch-curve F was greater than the revised F (Fig. 2), and initial VPA estimates of SSB and %MSP were less than revised estimates (Fig. 1). Alternative methods of estimating fully recruited F produced even greater inconsistency. The RMS retrospective difference from modified catch curves was 0.60 (49% relative difference), and log catch ratios produced a RMS difference of 0.61 (52% relative difference) (n=36 for both methods).

Retrospective differences in estimates of age-1 F from SVPA ranged from −0.59 to 0.45 for all retrospective SVPA's and were not significantly different from zero (n=31 for each series). RMS difference was minimized when seven years of catch-at-age data were used and increased regularly as the number of years deviated from seven (Fig. 3). The RMS retrospective difference for estimates of age-1 F was

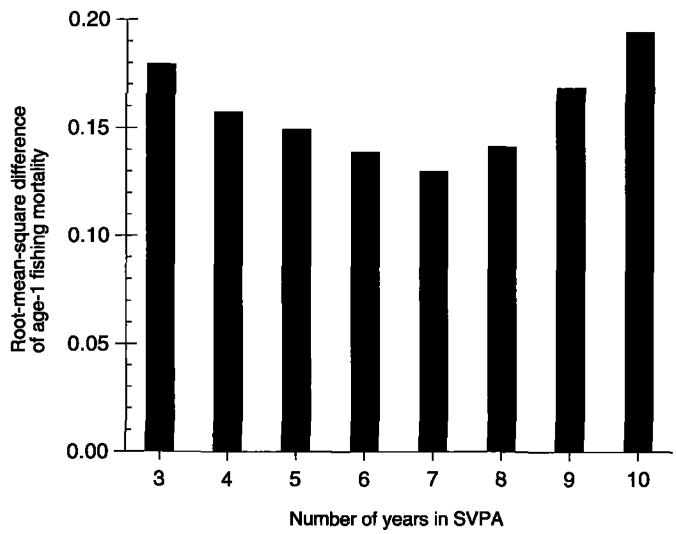

Figure 3

Root-mean-square retrospective difference of fishing mortality estimates for age-1 Atlantic menhaden from SVPA's with three to ten years of catch at age.

0.13 (33% relative difference) with back-calculated values of fully recruited *F* and increased to 0.18 (45% relative difference) with catch-curve estimates (Fig. 4).

Retrospective differences in age-1 abundance ranged from –2.4 billion to 11.5 billion individuals in terminal years (Fig. 5). There was no significant bias in log-transformed differences, and the RMS difference was 1.2 billion recruits (n=34). The RMS relative difference for estimates of age-1 abundance was 46%.

Retrospective differences in terminal SSB estimates ranged from –72,000 t to 448,000 t (Fig. 6). The large positive differences in 1962 and 1963 SSB were primarily due to large negative differences in fully recruited *F* (Fig. 2). Log-transformed retrospective differences were not significantly biased, and the RMS difference was 9,000 t SSB (n=34). The RMS relative difference for estimates of SSB was 33%. Retrospective differences in %MSP ranged from –5.5 to 19.5 in terminal years (Fig. 7).

The RMS difference was 4.7 %MSP, and there was no significant bias in log-transformed differences (n=34). The RMS relative difference for estimates of %MSP was 106%, because inconsistencies were larger than the estimated level of %MSP. Retrospective differences in %MSP were negatively correlated with retrospective differences in fully recruited *F* (r=–0.79).

Discussion

This case study illustrates how retrospective comparisons can provide useful data for analytical decisions and reveal important insights for management advice, especially in situations where statistical estimates of uncertainty are not available. For example, SVPA with seven years of catch data clearly provided more consistent results than SVPA of longer or shorter time series (Fig. 3). A time period of seven years appears to be long enough to smooth annual variation in partial recruitment, while including only years which represent the current schedule of *F* at age. By including more years in the analysis, there is a likelihood that catches from substantially different exploitation patterns will be incorporated. Performance of alternative intervals of catch data was judged according to general conditions over three decades. Although such guidance is valuable, specific SVPA runs should be examined to confirm the assumption of separability. For example, targeting specific cohorts, such as the superabundant 1958 year class, may change fishing patterns. Abrupt changes should be reflected in patterns of log catch-ratio residuals (Pope and Shepherd, 1982) and may necessitate a longer or shorter time series of catch at age for SVPA.

Retrospective inconsistency can result from a host of systematic problems, including errors in the cur-

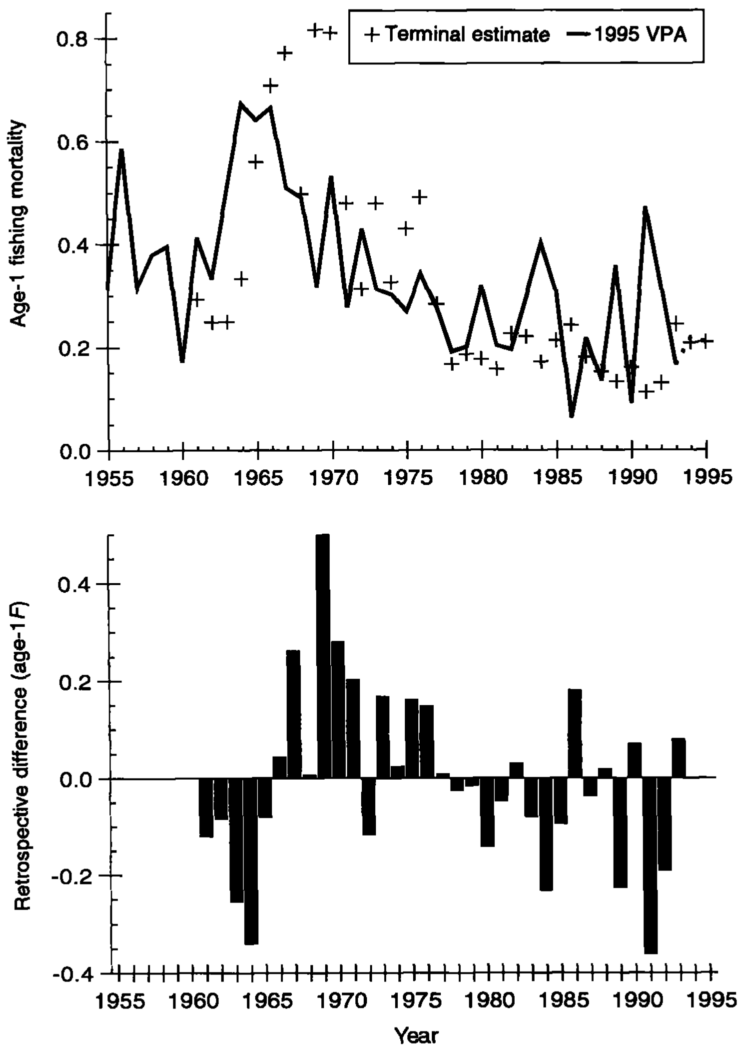

Figure 4

Estimates of fishing mortality for age-1 Atlantic menhaden from the 1995 VPA and terminal estimates from retrospective SVPA's (above) and retrospective differences (below). The broken line in the upper chart indicates provisional estimates.

rent VPA (Sinclair et al., 1990). For example, Lapointe et al. (1989) simulated Atlantic menhaden catch for VPA's to show that 50% underestimates of M produced 12% overestimation of recruitment and 6% overestimation of biomass and that overestimation of M produced similar underestimates of recruitment and biomass. Therefore, the assumption that M is constant when M varies among years and ages may cause VPA inconsistency. It appears that the inability to estimate fully recruited F accurately in terminal years accounts for a substantial portion of the retrospective differences in management variables reported here. Inaccurate estimates of terminal F may result from abrupt changes in F or M. Catch-curve estimates of terminal F are not sensitive to changes in current mortality because they reflect the average mortality over the last three years more than mortality in the terminal year.

Retrospective differences in management variables were positively skewed, and log transformation was necessary to test for bias. Skewed retrospective differences with no bias imply that positive and negative differences occur with equal frequency, but positive differences are generally greater in magnitude. Theoretically, normally distributed errors in F will produce lognormally distributed errors in R,

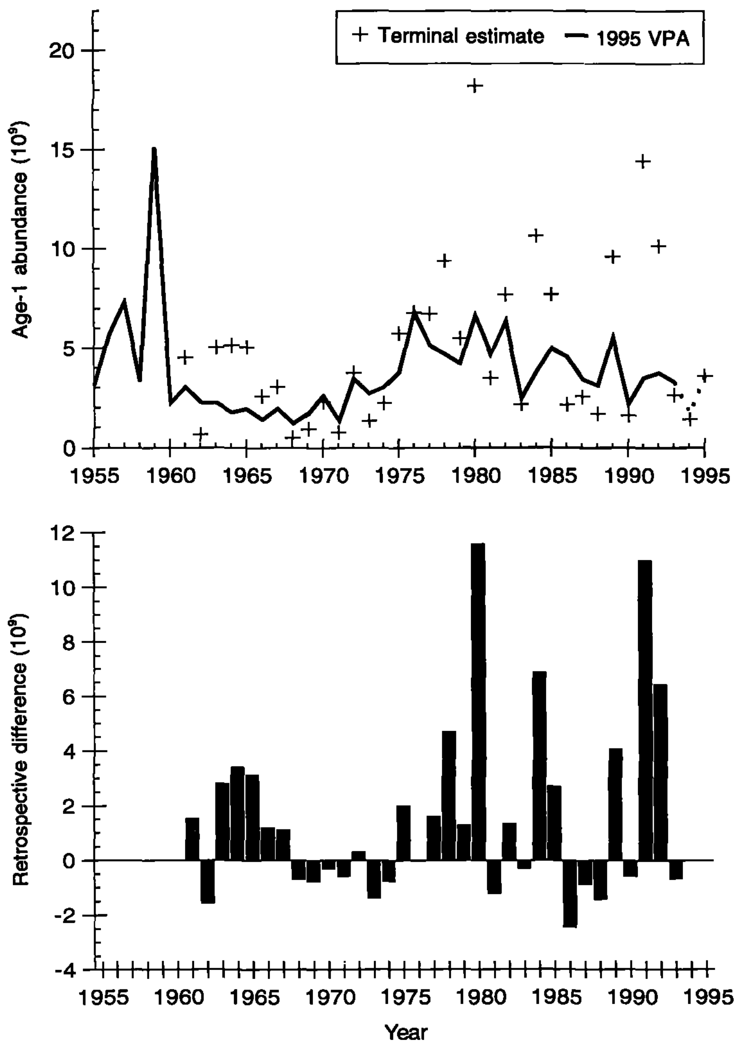

Figure 5
Estimates of Atlantic menhaden recruitment from the 1995 VPA and terminal estimates from retrospective SVPA's (above) and retrospective differences (below). The broken line in the upper chart indicates provisional estimates.

SSB, and %MSP because they are based on estimated abundance, biomass, and egg production, respectively, which have a negative exponential relation with fishing mortality. Therefore, small underestimates in F can produce large overestimates of abundance. Retrospective differences may also be skewed because negative values of R, SSB, and %MSP are not possible. Despite the conclusion that log-transformed retrospective differences were not biased, the positive skewness of retrospective differences and relative differences has important implications for management of the fishery. A skewed distribution of inconsistency from converged estimates may be considered a characteristic feature of terminal estimates from future menhaden VPA's. Therefore, management advice should account for the equal likelihood of moderate underestimation and substantial overestimation of R, SSB, and %MSP.

Management decisions must consider the difference between converged estimates, which are used to define overfishing thresholds, and terminal estimates, which are used to determine current status. Although inconsistency does not quantify uncertainty of estimates, the large retrospective differences re-

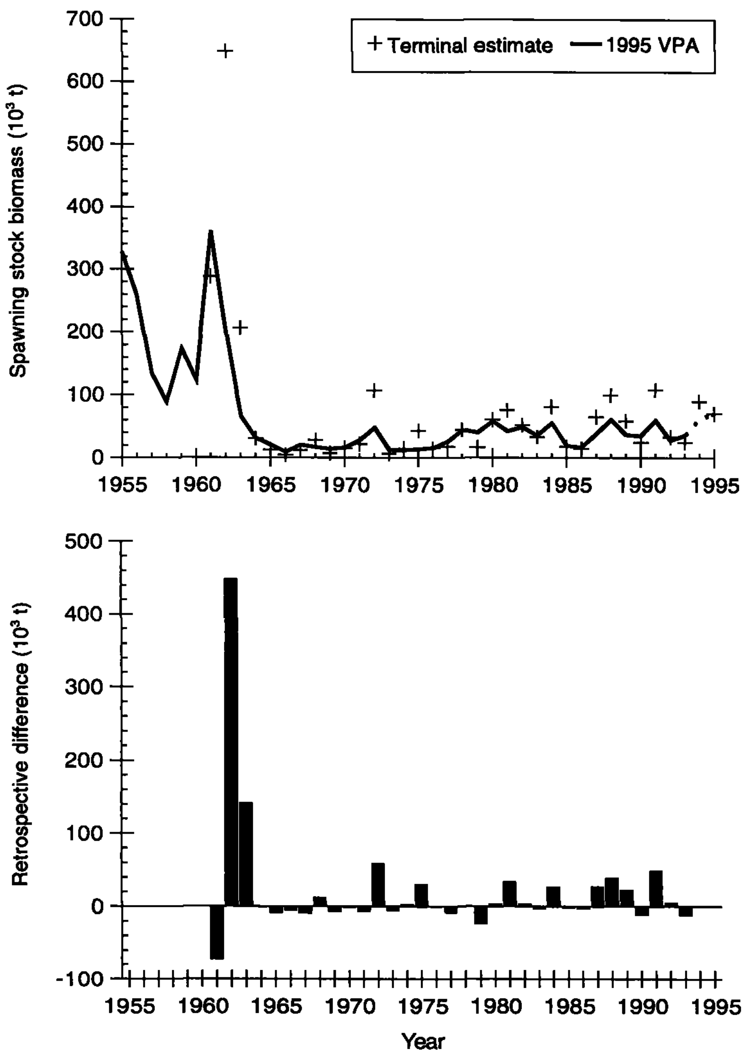

Figure 6

Estimates of spawning stock biomass of Atlantic menhaden derived from the 1995 VPA and terminal estimates from retrospective SVPA's (above) and retrospective differences (below). The broken line in the upper chart indicates provisional estimates.

ported here suggest large uncertainty in terminal estimates. Fredrick and Peterman (1995) simulated uncertainty in Atlantic menhaden VPA's to show that much more conservative overfishing thresholds would be needed to incorporate high levels of uncertainty into risk-averse management decisions. An alternative to incorporating uncertainty adjustments is to make management decisions based on converged estimates that indicate conditions of two years earlier (AMAC, 1992). If more timely management is desirable, methods to calibrate terminal estimates of abundance are necessary.

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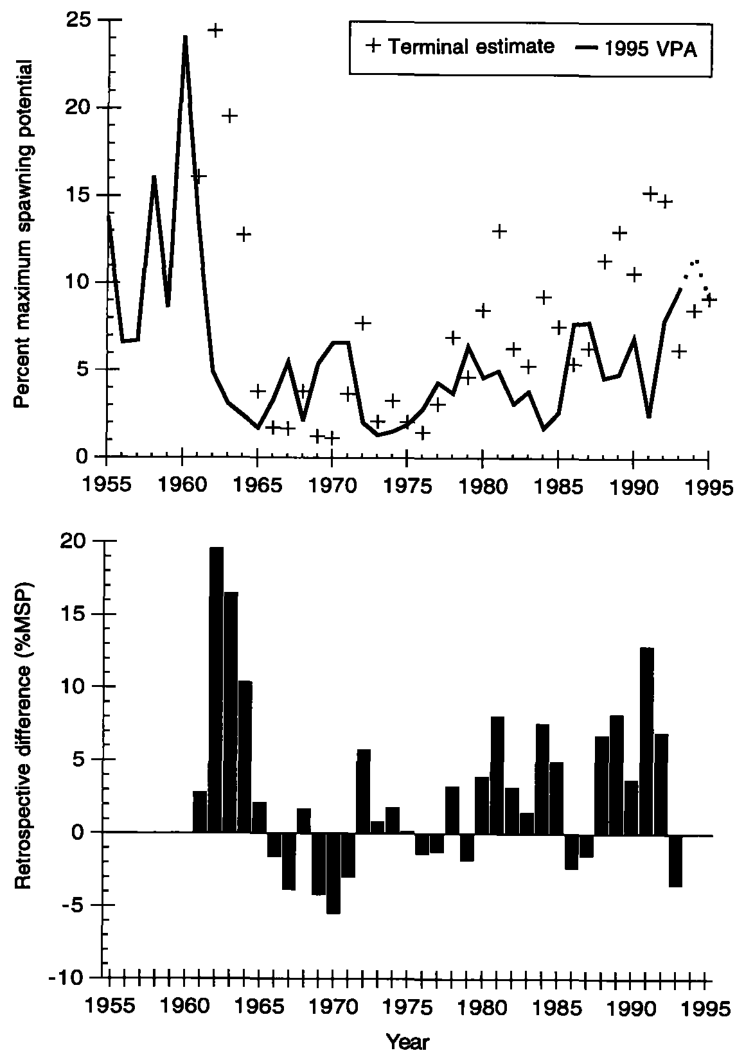

Figure 7

Estimates of percent maximum spawning potential of Atlantic menhaden derived from the 1995 VPA and terminal estimates from retrospective SVPA's (above) and retrospective differences (below). The broken line in the upper chart indicates provisional estimates.

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