1992

Fisheries Assessment and Management Synthesis: Lessons for Chesapeake Bay

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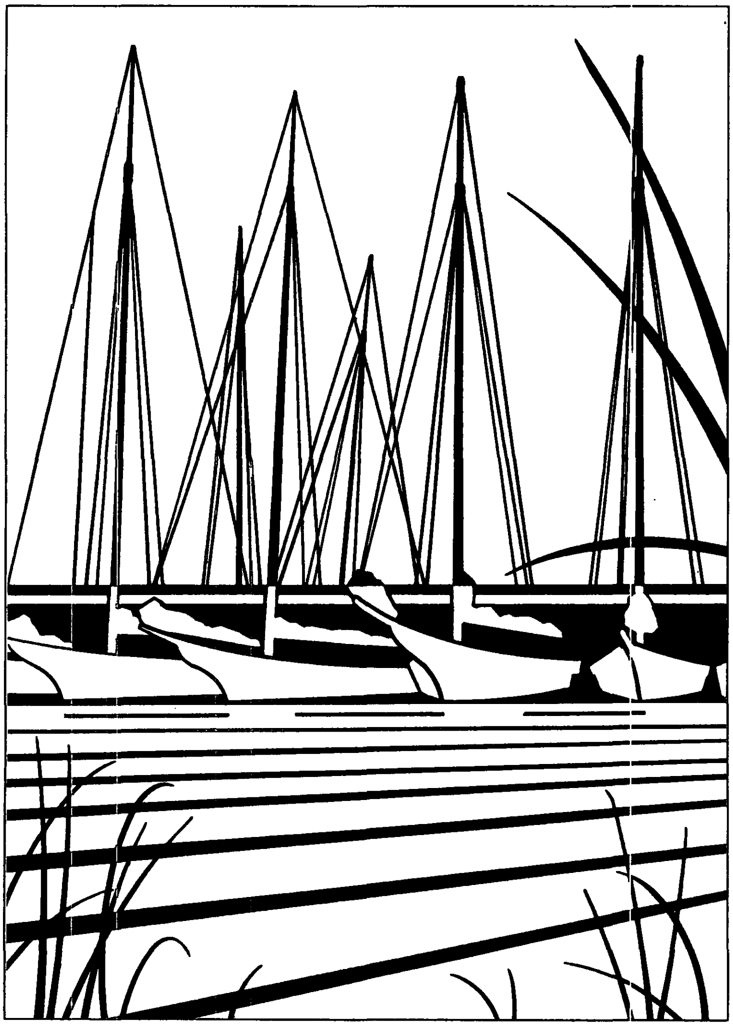
Perspectives on Chesapeake Bay, 1992: Advances in Estuarine Sciences



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Scientific and Technical Advisory Committee
Chesapeake Bay Program

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ACKNOWLEDGMENTS

Perspectives on Chesapeake Bay, 1992 was coordinated and edited by the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC). Acknowledgments include:

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CRC Publication No. 143

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Introduction

Perspectives on Chesapeake Bay, 1992 is the third in a series of research volumes that have been published by the Chesapeake Bay Program's Scientific and Technical Advisory Committee (STAC) since 1988. The purpose of these literature syntheses is to provide managers, scientists, legislators, and other interested people with summaries of research findings, key management issues, and other information on a range of Chesapeake Bay–oriented topics—all presented at a technical level comprehensible to the generalist. Each volume, therefore, is intended to make a useful contribution to a better understanding and the improved management of the Bay's ecosystem—and ultimately to the restoration and sustained well-being of what is the nation's largest estuary.

This volume consists of four papers, each of which focuses on a specific research topic:

- "Ecological Functions and Values of Nontidal Wetlands," by Carl Hershner, reviews our current understanding of the functions of nontidal wetlands, assesses the problems of assigning values to wetland functions, and surveys the use of these functions and values in management programs of the mid-Atlantic states. Although the author discusses nontidal wetlands in general, he makes it clear that the findings and implications of numerous wetlands research studies are directly applicable to all wetlands in the Bay.

The focus on nontidal wetlands is timely and relevant. Even though they account for over two-thirds of the Bay area's wetland acreage, research generally has been limited to specific wetland types and functions; it has not yet led to an equal understanding of all potential wetland functions. Among the functions described in the paper are groundwater recharge and discharge, flood storage and desynchronization, shoreline anchoring and the dissipation of erosive forces, sediment trapping, nutrient retention and removal, food chain support, provision of habitat for fisheries and wildlife, and recreational opportunities.

Currently, wetlands managers are faced with a dilemma of competing interests: the preservation of these irreplaceable resources versus the demand for development of natural areas by our rapidly expanding population. Given the "fundamental incompatibility" of these two interests, the author declares, it is essential to have "a generally accepted method for determining the value of a wetland and for comparing the value of one wetland with that of another." However, as he concludes, such a method is not yet available, although considerable progress could be made in the Chesapeake Bay region "if the efforts of multiple research and funding agencies could be . . . [incorporated into a] well-planned research strategy."

- "Groundwater Discharge in Coastal Systems: Implications for Chesapeake Bay," by William G. Reay and George M. Simmons, Jr., examines the role of groundwater as both a source and transport mechanism of nutrients and other contaminants. As the authors demonstrate, that role is a significant one in many coastal regions, but it needs to be better understood in the Chesapeake Bay watershed, where most research to date has concentrated on the contributions of point-source contaminants and non-point source surface runoff. Furthermore, the studies reviewed by the authors mostly concentrate on dissolved inorganic nitrogen; however, there are other groundwater contaminants, such as synthetic toxic compounds and pesticides, that also should be studied closely.

Drawing from their analysis of the leading studies, the authors conclude their paper with several broad research recommendations that are designed to provide a more complete scientific understanding of the Bay region's groundwater discharge processes and groundwater/wetland interactions, a more comprehensive system of groundwater monitoring, and the development of so called best management practices that take into account groundwater contamination and the transport of such groundwater-borne pollutants to aquatic systems.

- "Low-Level Effects of Toxic Chemicals on Chesapeake Bay Organisms," by David A. Wright, Jacqueline D. Savitz, and S. Ian Hartwell, focuses on the low-level effects that toxic substances have on certain Bay species. These effects are generally less obvious and more pervasive than the lethal responses measured in the laboratory and observed in the Bay waters. The authors describe the principal toxological approaches used by researchers and summarize the findings of numerous field and laboratory studies. They conclude that, although there is strong evidence that toxic substances do have adverse effects on the Bay's biota (tumors in fish have been correlated with exposure to toxicants, for example), more research is needed to ascertain the precise linkages that may or may not exist between low-level exposures and various effects, such as the decline of a fish stock. Furthermore, most of the studies to date have concentrated on the Elizabeth River, which is the most heavily polluted portion of the Bay system, and those studies have been useful in establishing a reliable connection between contaminant and effect. Accordingly, the authors call for a systematic approach to a Baywide determination of toxicity.

- "Fisheries Assessment and Management Synthesis: Lessons for Chesapeake Bay," by William A. Richkus, Steven J. Nelson, and Herbert M. Austin, describes the basic approaches that are used for stock assessment of the fish and shellfish stocks of the Chesapeake Bay system. The authors summarize the principal methods of stock assessment and fisheries management that have been—and are being—applied to Bay fisheries, with particular emphasis on data collection and the use of models. They then present case studies of three critical species: (1) the striped bass, a Bay-spawning pelagic predator that has suffered a serious stock decline during the past two decades but holds promise of being restored through the current use of a vigorous and effective management strategy; (2) the blue crab, a benthic scavenger that has been the basis of the Bay region's most valuable fishery for almost a decade but now faces the possibility of undergoing a serious stock collapse caused by overfishing; and (3) the Eastern oyster, a native shellfish species that was long the basis of the Bay's leading fishery but, since the 1960s, has declined to the point where it is questionable that the fishery can continue.

Both in the body of their paper and in the three case studies, the authors summarize the findings of a variety of studies (including some that look at striped bass stocks elsewhere in the United States, for comparative purposes), and they also summarize the status of stock assessment efforts and the pros and cons of the various models that have been developed and applied to Bay species. Based on their review, the authors conclude that the data required for effective stock assessment are still not available, which seriously hampers the use of models and other useful analysis and management tools. Accordingly, they state, "current fisheries management priorities for the Bay must continue to be focused on recruitment-related issues."

Solomons Island, MD
June, 1992

Fisheries Assessment and Management Synthesis: Lessons for Chesapeake Bay

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Introduction

For centuries, Chesapeake Bay has been one of the most productive estuaries in the world for fish and shellfish. Fisheries—activities or industries devoted to the harvesting of fish or shellfish—have been part of the history of the Bay as long as humans have lived on its shores. Of the more than 200 species of fish and shellfish found in the Bay during some stage of their life cycles, as many as 40 have supported widespread and economically important fisheries in both Maryland and Virginia. In addition, they have provided extensive recreational fishing opportunities for Bay residents and visitors.

In recent decades, however, the stocks, or populations, of some Bay-spawning species, such as American shad, river herring, yellow perch, and striped bass have fallen significantly. Oysters also have shown dramatic declines in abundance [94, 78, 79]. The declines in important recreational and commercial species, especially striped bass and oysters, have hurt commercial and recreational Bay fisheries [107]. The trends for other species, though, have varied. For example, soft clam and blue crab stocks tend to fluctuate substantially from year to year but do not evidence any long-term decline, whereas some ocean-spawning species, such as spot, actually are more abundant in the Bay today than they were 5 to 10 years ago [154, 92, 188, 44, 19, 150, 20].

Background

Because of the economic and recreational value of many Bay species, the decline in fish stocks triggered both public concern and also remedial action by state and federal agencies starting in the early 1980s. One key outcome of that response was the establishment of the Chesapeake Bay Program, a multijurisdictional effort run by the U.S. Environmental Protection Agency (EPA) and operating at both the federal and state levels [188].

As part of the overall Bay restoration effort, state and federal resource managers developed stock assessment recommendations for the 1987 Chesapeake Bay Agreement. The agreement's purpose was to implement programs to restore depressed fish and shellfish stocks and to prevent the decline of currently abundant stocks [45, 20, 137].

Under the Chesapeake Bay Agreement, the Chesapeake Bay Stock Assessment Committee (CBSAC), a federal/state committee sponsored by the National Oceanic and Atmospheric Administration (NOAA), was assigned the task of developing a stock assessment plan. The objective of the plan is to develop a Baywide stock assessment of fishery resources so as to be able to gauge the impact of fishing mortality, natural mortality, and contaminants on the abundance of key Bay species. Such an assessment is intended to provide a basis for a scientific approach to restoring habitat and water quality, setting management goals for each stock, and devising necessary harvest regulations. The stock assessment plan, therefore, is designed to be a blueprint for action.

It is a complex task, however, to identify all of the factors that affect the status of exploited, or harvested, stocks and to quantitatively classify the relative impact of these factors. Figure 1 schematically illustrates the myriad interacting natural and anthropogenic factors that bear on the size of a fish or shellfish stock [159]. As is evident, it is difficult to predict adult stock size. Furthermore, when setting harvest regulations, managers must take into account not only the biological factors but also various social, political, economic, and jurisdictional factors [159]. These nonbiological factors, many of which are not based on science, often play a major role in management decisions. Consequently, the final decisions made about exploited stocks tend not to be wholly consistent with the biological data.

This paper reviews the stock assessment methods that are used as a basis for managing fisheries and examines their application to Chesapeake Bay. It summarizes the methods generally applied in fisheries management, with emphasis on basic data needs; the use of fisheries models and other analytical tools; and various management issues, especially nonbiological factors. The paper concludes with three case studies that examine how these methods have been used for managing three Chesapeake Bay stocks. One case study looks at the striped bass (*Morone saxatilis*), an example of a depressed stock that is being restored by balanced interstate fisheries management; the second case study focuses on the blue crab (*Callinectes sapidus*), a stock that is currently not in decline but possibly may be susceptible to overharvesting in the future; and the third case study examines the Eastern oyster (*Crassostrea virginica*), a stock that is now in serious decline.

Methods of Stock Assessment and Fisheries Management

Normally, the fisheries manager seeks to control the harvest of an exploited fish or shellfish stock such that the stock will sustain a desirable level of annual harvest, or yield, over an indefinite period of time. The goal is to harvest at such a rate that the resource is renewable, with the fishery taking a certain amount and the stock replenishing itself year after year. The assumption underlying the exploitation and management of a renewable resource is that stock abundance (population size) is regulated by internal feedback mechanisms; that is, when stock abundance decreases as a result of fishing activity, the species responds with increased growth and reproduction. Theoretically, this increased biomass in response to fishing activity allows a certain level of annual harvest to be sustained indefinitely [170].

Stock assessment is an important component of any fisheries management strategy. Specifically, management of a renewable resource is based on three major technical activities: (1) quantifying biologically appropriate levels of harvest; (2) monitoring the current and future resource status for comparison with harvest objectives; and (3) adjusting the resource status if necessary (and if possible) by making changes in the magnitude and nature of the harvest [45].

The first two activities (quantifying the harvest levels and monitoring the resource status) constitute the stock assessment, which involves preparing a description of the biology and status of a fish stock and its associated fishery. Such a description may range from accurate and broad quantitative characterizations to subjective estimates of critical stock and fishery parameters. However, an assessment must yield information on certain critical aspects of the species's biology and the associated fishery to contribute significantly to the third activity—the actual management of the exploited stock.

Clearly, management approaches and the stock assessments upon which they are based are developed from various types of biological and fishery data. These data are analyzed through the use of various mathematical models or analytical procedures, which describe the population dynamics of the species (e.g., recruitment, growth, and mortality); measure the impact of fishing on the

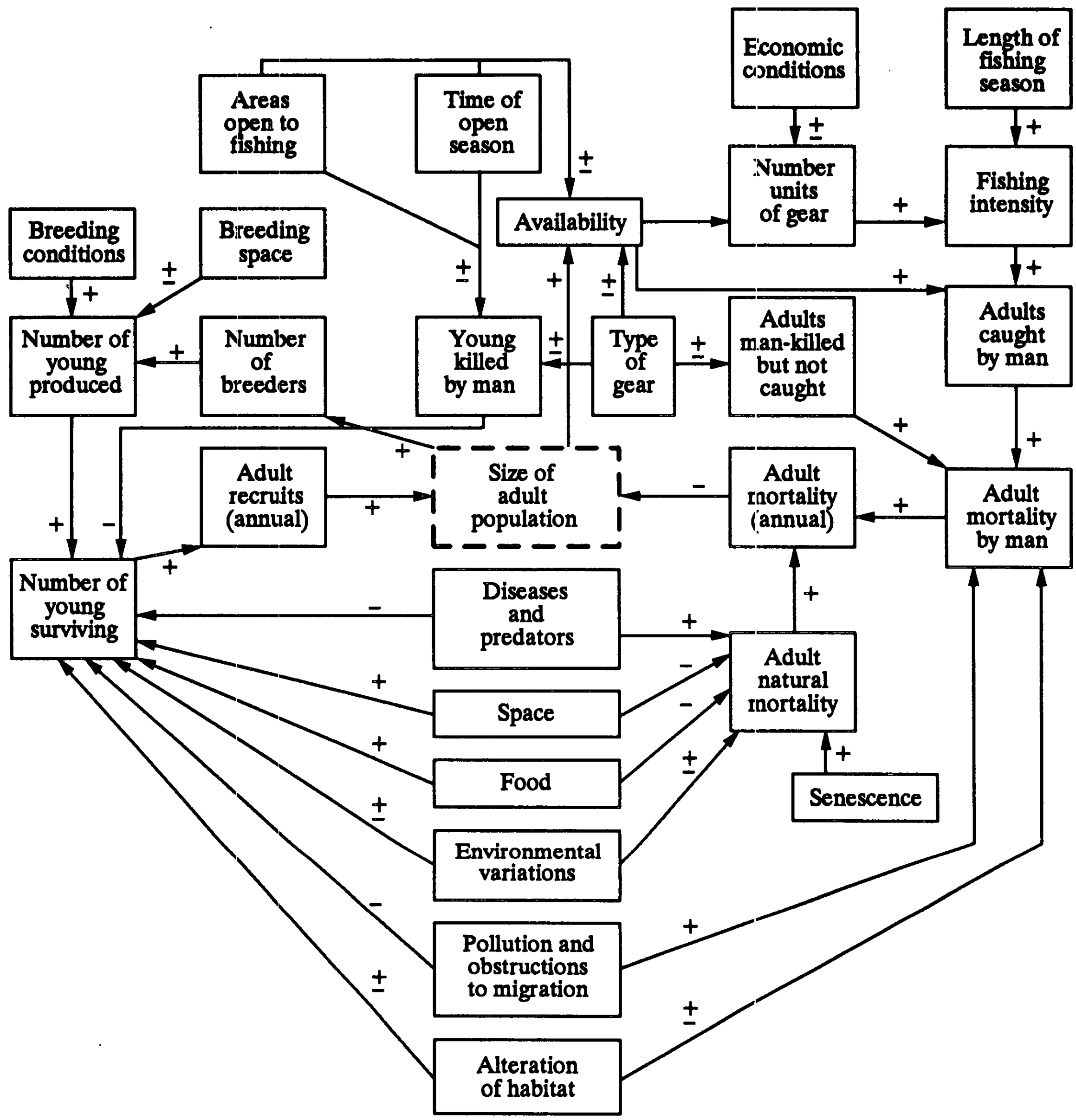

Figure 1. Factors involved in determining population size of exploited fish or shellfish stocks. The (+) and (-) signs refer to a positive or negative effect, respectively, of one factor or another. From Rounsefell, 1975 (159).

stock; and investigate the influence of anthropogenic and natural environmental modifications on the stock. The results of these analyses are then integrated with relevant socioeconomic factors to determine what management actions may be required to ensure the optimal level of harvest.

The following sections summarize the key concepts and elements of fisheries management and stock assessment that are critical to the long-term maintenance of a fish stock and the fishery that exploits it.

Stock Assessment Data

The data required for fisheries management analysis and modeling fall into two major categories. The first consists of *fishery-dependent data*, or data collected by monitoring ongoing commercial and recreational harvest activities. These data include specific information on the fishing effort (e.g., the amount of net fished, the number of active anglers, and the number of crab pots deployed); the temporal and geographic distribution of the fishing effort and harvest; and the amount of the harvest and its composition (e.g., species, age, and size).

The second category consists of *fishery-independent data*, or data obtained from studies unrelated to harvesting activities. Examples of such studies include annual surveys to document the abundance of juveniles (an indicator of spawning success) and the sampling of adults on the spawning grounds to establish the age and sex composition of the spawning stock. Fishery-independent studies are generally the source of much species biology information critical to a thorough stock assessment, including such population parameters as age of maturity, growth rates, migration patterns, fecundity, and natural mortality rates.

Figure 2 is a general diagram showing the various ways in which fishery-generated data and other research data are combined for use in stock assessments.

Historically, data collection activities in Chesapeake Bay have lacked precision, accuracy, and temporal continuity, and they have often failed to provide essential information [45]. A rare exception to this generality has been the data collection effort for striped bass. Temporal continuity for this species has been provided by two long-term time series data sets that have served as an underpinning for striped bass analyses. Annual juvenile abundance data (extending back to 1954) and annual commercial harvest data (extending back to the 19th century) have been used to investigate historical fishing rates, characterize critical relationships between spawning stock size and recruitment, document the extent and nature of variability in recruitment, and investigate the role of environmental factors in controlling that variability. However, the temporal continuity of these two data sets was not sufficient to develop all of the management tools presently used for striped bass. Striped bass modeling and management are now possible largely because of additional intensive, species-specific, fishery-independent sampling programs conducted throughout the Bay over the past decade. Management plans are currently being implemented or are in various stages of development for most other major Chesapeake Bay fish and shellfish species, although none are as technically well developed as the striped bass plan. Each plan identifies the critical data needs for one species [45].

In its discussion of stock assessment, the CBSAC concluded that stock assessments for Bay species must rely on available historical data and information [45]. The requirement that there be at least several years of data as inputs for models means that completely adequate stock assessments will not be ready for a number of years. The data from new or expanded collection efforts, combined with older archival information, and development of new or improved models, will result in more accurate and reliable stock assessments.

Figure 3 provides a summary of the quality and availability of data for 18 species of fish and shellfish found in Chesapeake Bay and mid-Atlantic coastal areas.

Fisheries Models and Other Management Tools

Over the past several decades, a variety of mathematical models and other analytical tools have been developed for use in managing fisheries. Following is a brief discussion of some of the models and other tools that have been tried, starting with the so-called yield models that rose to prominence in the 1950s and then proceeding to the recruitment models that were developed in the 1970s and 1980s.

Yield Models

The concept of manipulating a stock to produce a desired yield, or level of harvest, is embodied in the traditional fisheries management goals known as maximum sustainable yield (MSY), optimum

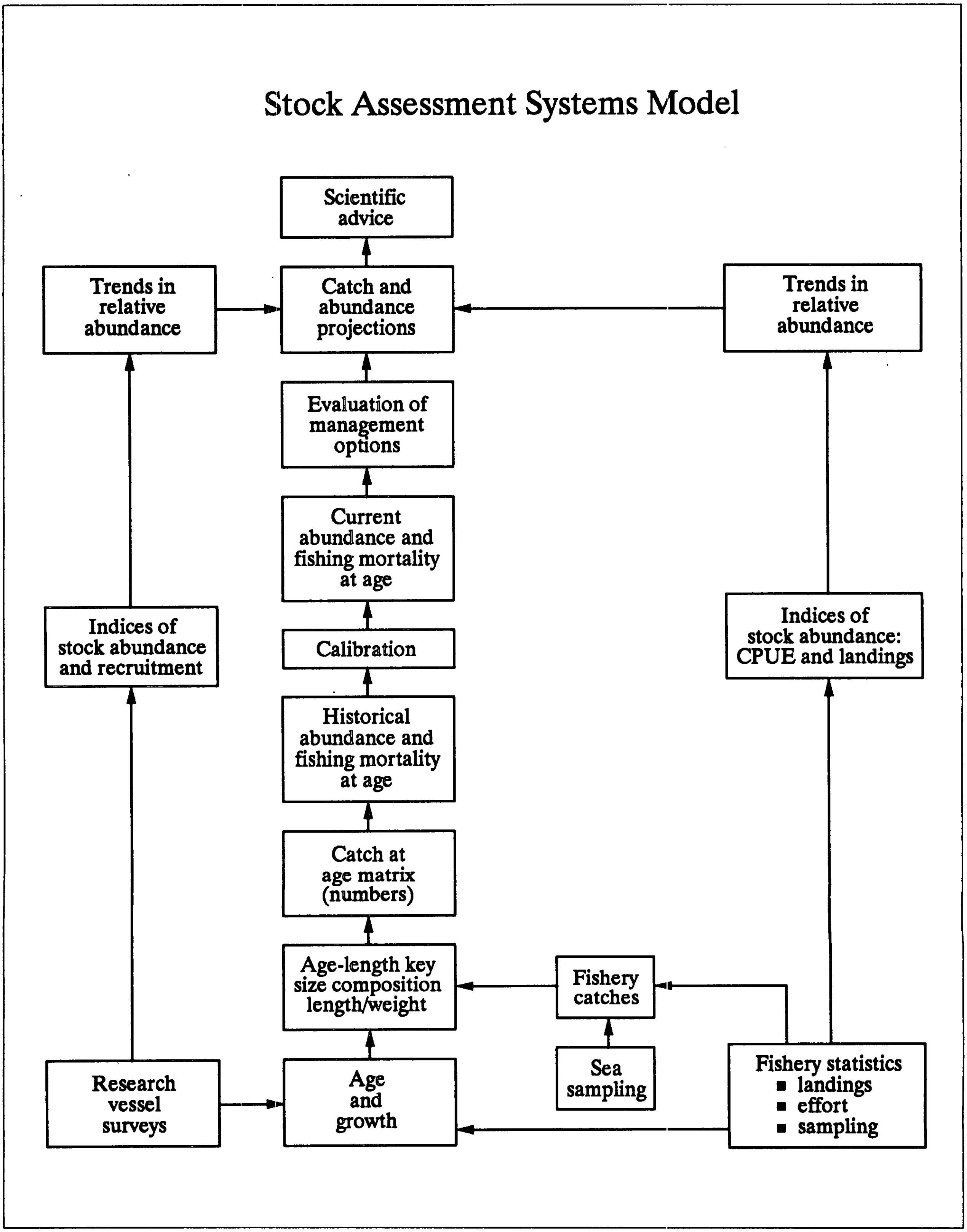

Figure 2. Diagram of alternate ways in which fishery-generated data and other research data are combined to constitute a stock assessment that provides a basis for developing scientific advice on the status of the species. From NOAA, 1990 (136).

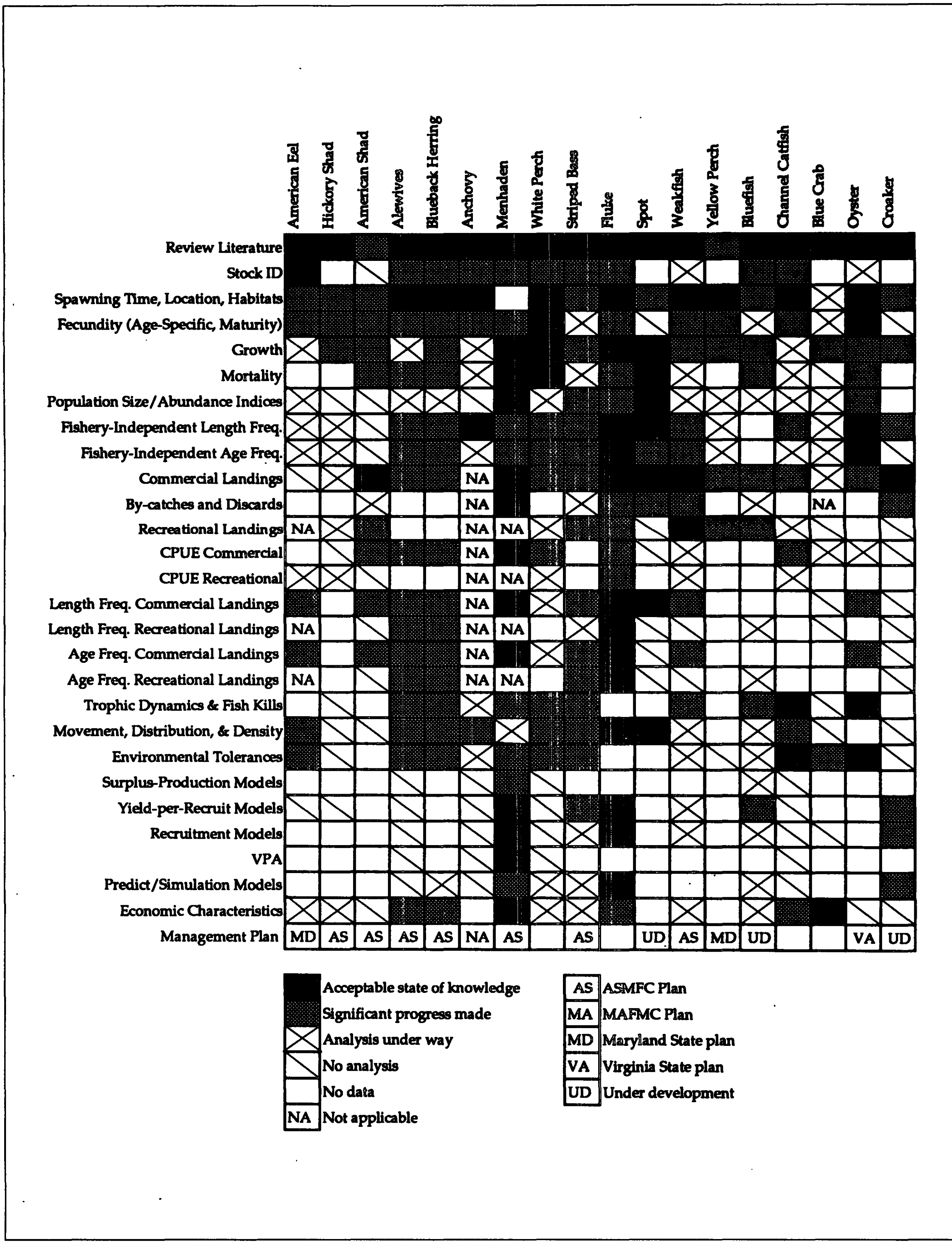

Figure 3. Stock assessment data and models for important Chesapeake Bay species. Modified from NOAA, 1990b (137).

sustainable yield (OSY), and maximum economic yield (MEY). These types of management goals were very attractive to fisheries managers in the past—especially in the 1950s and 1960s—in that all that was needed as inputs for the mathematical models used to set harvest targets were readily available data on annual harvest and fishing effort [151, 163, 164]. In recent decades, however, such goals have proven to be unrealistic for most heavily fished coastal or inshore species [152, 58, 170, 145].

The two principal types of yield model that have been used are the surplus-production model and the yield-per-recruit model. The salient features of these two model types are described briefly below.

Surplus-Production Model. The surplus-production model is based on the mathematical relationship between fishing effort and catch. The target stock is predicted to yield a given level of harvest when a certain level of fishing effort is applied, and the level of harvest is presumed to be in equilibrium with that effort based on the exploited stock's recruitment and growth. At lower levels of fishing effort, additions to the stock may exceed the harvest. At too high a level of fishing effort, harvesting may exceed the production capacity of the stock, resulting in overfishing and stock decline. Thus, the theoretical objective in applying this type of management model is to identify the level of fishing effort at which harvest is maximized (i.e., the point at which MSY is attained). Figure 4 summarizes the basic feature of the surplus-production type of model used to determine MSY.

Yield-per-Recruit Model. The yield-per-recruit model (which was initially developed more or less in parallel with the surplus-production model) is based on the idea that it is essential for fisheries managers to develop strategies that maximize the yield, in weight, obtainable from each recruit entering the exploitable portion of the population [58, 170]. Maximizing the yield is important primarily in commercial fisheries, in which the economic value of a harvest is linked principally to the total weight of the harvest.

The individuals that make up a given group of fish or shellfish added to the population each year—the yearclass, or age cohort—increase in mass as they age. A certain number of them also die each year, however. During the initial portion of their lifetime, the growth in weight of the total

Surplus-Production Model
The surplus-production model compares fishery yield (Y) with growth in biomass [F(B)] to determine maximum sustained yield (MSY). Thus,

$$\text{Yield} = F(f, q, B)$$

where F = a population function
f = fish. effort
q = catchability
B = total biomass of harvest

Subsequently, it can be shown that equilibrium yield (Y_E) depends on fishing effort:

$$Y_E = qF_E(B_{00} - q/kF_E)$$

where Y_E = yield
q = catchability
F_E = equilibrium effort
B_{00} = maximum population or carrying capacity

A plot of Y_E against equilibrium fishing effort yields a curve in the form of a parabola. The MSY of the resource occurs at an intermediate level of fishing effort; an increase in effort results in decreased yield.

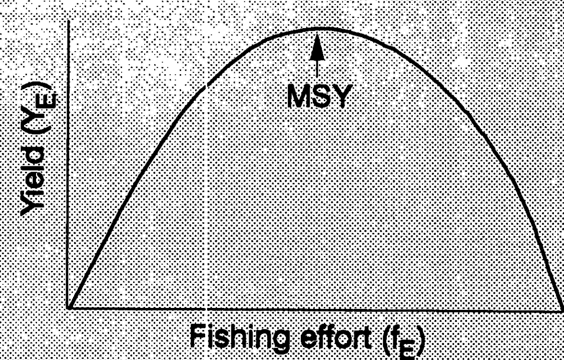

Figure 4. Surplus-production model.

Yield-Per-Recruit Model
The Thompson-Bell model is a common yield-per-recruit model. In this model, the mean age-specific weight in landings, W1, is used as an adequate measure of fish growth. The yield is simply the sum of the catches in each age group:

$$\text{Yield} = \sum_{i=r}^{n} E_1 N_{01} W_1$$

where E_1 = age-specific exploitation rate
N_{01} = number in age group i at beginning of season
W_1 = mean weight of age group i in landings
r = age of first capture
n = maximum age of capture

Assuming constant recruitment, yield (Y) varies according to age of first capture (r) and amount of fishing effort (E). Theoretically, fishery managers can vary r and E to determine a fishing strategy to produce optimum yield.

The relationship between yield per recruit and fishing mortality allows the optional fishing rate to be established.

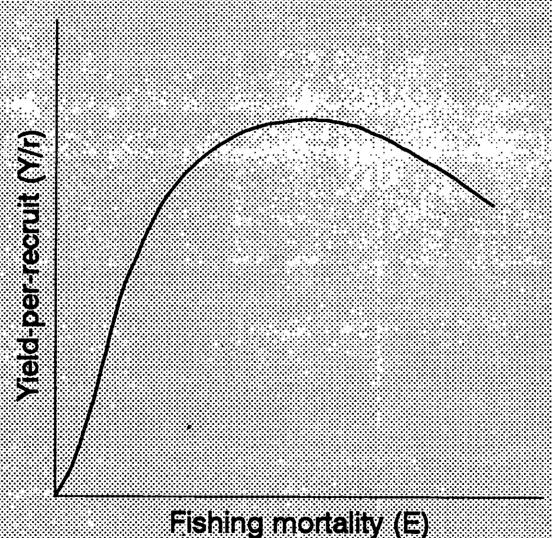

Figure 5. Yield-per-recruit model.

cohort exceeds the loss in weight attributable to the death of a portion of the total cohort. At older ages, as growth rates become asymptotic, the loss of weight owing to mortality exceeds the weight gain owing to growth.

The yield-per-recruit model (sometimes referred to as the dynamic-pool model) uses growth and mortality rates as inputs to establish the age (size) at which fish should be harvested and the optimum fishing rate required to maximize the yield from a given yearclass [30].

Harvesting too large a portion of a cohort at a less than optimal age results in a phenomenon known as *growth overfishing;* under such circumstances, a cohort is producing less yield in weight than would be the case if fishing pressure were reduced on the younger yearclasses.

Yield Models: Past, Present, and Future
The application of yield models—both surplus-production and yield-per-recruit models—to heavily exploited fish stocks has generally been unsuccessful, owing principally to the failure of the stock's recruitment to sustain imposed levels of fishing pressure [170]. (The role of recruitment prediction in fisheries management is discussed in detail below.) In addition, the species for which yield models were initially developed were generally open ocean or anadromous species, rather than coastal or estuarine residents. Such species are usually subject to less environmental variability and habitat change than are the estuarine species harvested in Chesapeake Bay.

Despite the widespread failure of yield models, the soundness of their basic concepts is evidenced by the fact that the mathematical formulations underlying surplus-production and yield-per-recruit models have served as the foundation upon which much more detailed and realistic models have since been constructed [74].

In Chesapeake Bay studies, yield models have remained virtually unused, primarily because of the lack of available data [45, 154]. To date, such models have been applied to only a few species, primarily menhaden (using both surplus-production and yield-per-recruit models) and fluke, striped bass, bluefish, and croaker (yield-per-recruit models), and that has been on a coastwide basis, without specific application to Chesapeake Bay populations. (See figure 3). Sophisticated models have recently been developed for a few of the most important exploited Bay species, such as striped bass [13] and Eastern oyster [158].

Tools for Solving the Recruitment Problem

Failure of MSY management (as evidenced by the decline or collapse of the exploited stock) has generally been attributed to the failure of the exploited population to respond reproductively in the manner that the yield models have predicted [58, 153, 170]. Both surplus-production and yield-per-recruit models assume a population in equilibrium, with predictable or constant recruitment. In reality, widely fluctuating annual production of juveniles (recruits) has generally been insufficient over the long term to compensate for the portion of the stock lost each year to relatively constant and high levels of natural and fishing mortality, causing the stock to decline. Continued harvest of a declining stock at a high level, a situation referred to as *recruitment overfishing*, results ultimately in stock collapse [170]. In some well-documented cases, however, stock collapse owing to recruitment overfishing, although definitely related to high levels of fishing pressure, has been triggered by an initial year of poor recruitment caused by natural or human-induced environmental change. One such case is that of the Peruvian anchoveta fishery [140].

The factors that determine the eventual fate of a heavily exploited stock appear to come into play primarily at the point when fishing mortality rates are approaching or modestly exceeding the long-term sustainable exploitation rate. The higher the exploitation rate, the greater the risk of a decline. The risk of decline is also directly related to the degree of variability in recruitment of the stock [169]. An inability to accurately predict recruitment because of its inherent variability is clearly the primary cause of fisheries management failures. Furthermore, it is evident from a study of numerous failed fisheries that recovery from stock collapse owing to recruitment overfishing is very slow and often incomplete. In many cases, stocks never return to former levels of abundance, even in the virtual absence of significant harvest pressure [140, 169]. This fact points out the critical need in fisheries management for *preventing* the occurrence of stock collapse in that the probability is low that postcollapse management will result in complete stock recovery.

Fisheries managers have attempted to overcome the obstacle of unpredictable variability in recruitment in several different ways. Obviously, if the managers could determine the magnitude of recruitment (i.e., determine the size of the yearclass), they could link this knowledge with a yield-per-recruit management approach to establish the level of harvest that could safely be taken from an individual yearclass. Allowable harvests from small yearclasses would be smaller than allowable harvests from large yearclasses. Thus, the level of annual harvest, while being sustainable, would not be constant.

There are three ways of solving the recruitment problem. They are to use (1) virtual population analysis, (2) a juvenile index, or (3) a stock-specific recruitment model. These methods—which may be used collectively—are discussed briefly below.

Virtual Population Analysis. Virtual population analysis (VPA) can be used to establish relative yearclass size by obtaining age composition data from annual catches to track the relative contribution of individual yearclasses to the annual harvest as each yearclass ages and moves through the fishery over a period of years [93, 131]. VPA, which is also known as cohort analysis or sequential population analysis, relies on assumptions about natural mortality rates and other population characteristics and is an effective means for assessing annual fishing mortality rates. VPA has been a mainstay of modern management in most major commercial fisheries throughout the world. However, its use requires reliable, representative data on the age composition of a catch, and such data are less available and more costly to acquire than the simple catch and effort data used in surplus-production models. Such catch and age data are available for only one or two Bay species [45].

Juvenile Index. Juveniles of a specific species can be directly sampled to produce a juvenile index that can then be used in conjunction with yield-per-recruit-type models to develop management strategies. This approach is used extensively in the management of Northwest Atlantic groundfish stocks, as well as Chesapeake Bay—and also Hudson River—striped bass [136, 13]. Sampling programs produce an index of abundance, which is a measure of the strength (in numbers) of a given yearclass relative to all other yearclasses for which indices are available. Generally, though, it is not possible to establish the absolute size of any single yearclass from such programs, and the cost of the sampling effort to produce quantitatively reliable data is often high.

Recruitment Models. The third and most elaborate method of addressing the recruitment problem is to develop stock-specific recruitment models. Such models attempt to mathematically character-

Recruitment Model

The basic Ricker stock recruitment model relates recruitment to stock size as:

$$R = \alpha P e^{-\beta P}$$

where R = number of recruits

P = size of parental stock (measured in numbers, weight, egg production, etc.)

α = a dimensionless parameter

β = a parameter with dimensions of $1/P$

Point A is any point on the curve, the distance AB representing the surplus reproduction that must be removed by fishing if the stock is to remain in equilibrium at this level. The distance AB becomes a maximum a little farther to the left on the curve.

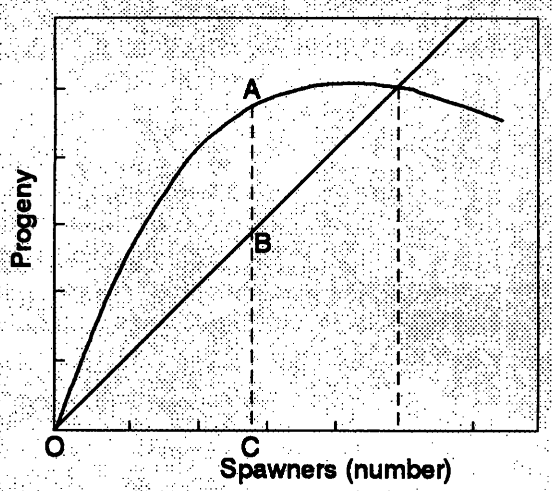

Figure 6. Recruitment model.

ize, in a predictable manner, the relationship between the amount of progeny produced and the size of the spawning stock.

The earliest recruitment models depicted a relationship in which the amount of progeny increased as the size of the spawning stock increased, up to a point at which some type of negative feedback would occur. After that point, a further increase in stock size would result in the same or a decreasing amount of progeny produced (see figure 6). This basic recruitment relationship was established for certain species, such as salmon, that use relatively stable environments for spawning and also require a specific type of habitat.

However, the application of this simple recruitment relationship to species using more variable environments, such as estuaries, usually proved to be unsuccessful, principally because of the major role that environmental variability plays in the reproductive success for such species.

Recent models of this type—which can basically be considered to be state-of-the-art models in fisheries management—attempt to take into account the manner in which environmental variability affects the interrelationship of spawning stock size, population fecundity, and juvenile production so as to be able to predict a stock's reproductive success in any given year.

The development of recruitment models often requires long time series of data on all pertinent environmental parameters (e.g., temperature and river flow), biological factors (e.g., mortality rates, fecundity, and growth rates), and fisheries characteristics (e.g., annual harvest and catch composition) [60, 169]. The extreme complexity of the stock/recruitment relationship, as it is affected by natural and anthropogenic environmental changes, has so far proven to be the most intractable obstacle to the reliable prediction of recruitment [153].

Stochastic and Simulation Models

Several approaches have been developed for attacking the recruitment problem in management. Sissenwine et al. [169] have described the application of stochastic, or random, harvesting models to account explicitly for the uncertainty of predicting future harvests and stock sizes. Brown and Patil [35] described the use of risk assessment as a means of addressing recruitment uncertainty in fishery management [35]. P. Rago and R. Dorazio have developed a probabilistic recruitment model to guide the interstate management of striped bass [13]. In recent years, investigators have developed a wide variety of species- or fishery-specific models in which the basic model types discussed above are linked or integrated with other model elements that represent a variety of factors influencing population dynamics and fisheries yields. Specialized simulation models can accommodate any peculiarities of specific fisheries and stocks while incorporating underlying population dynamics principles embodied in the basic model types. Gulland [74], for example, has presented numerous examples of such specialized models that have been developed in recent years. However, such complex models have yet to be regularly applied in the everyday management of most major exploited species.

Table 1. Types of fishing regulations and their impacts or intended effects.

Restriction	Impact or Intended Effect Recruitment	Harvesting	Mortality	Remarks
Minimum Size Limit	Control age when young recruit to fishery	Affects yield per recruit, and shelters young from harvest	May result in catch-and-release or by-catch mortality	Socially acceptable and enforceable
Recreational Creel Limit		Distributes catch across more anglers while restricting total catch. May not limit total catch if number of anglers or season not limited	Can cause high catch-and-release mortality	Socially acceptable and enforceable
Season/Area Closures		Reduces harvest, but degree of reduction uncertain owing to time/space variation in fishing effort	Reduce fishing mortality, but degree of reduction uncertain owing to annual variations in fish abundance and distribution	Socially acceptable and enforceable
Gear Restrictions	Can affect age when fish recruit to fishery	Shelter certain sizes from harvest; but restricting efficiency without limiting number of fisherman may not reduce harvest	Reduce by-catch mortality by prohibiting certain gear types	Social acceptability depends on importance of the restricted gear to user groups
Quotas		Places cap on total harvest	Implementation requires broad real-time harvest monitoring and extensive biological data	Difficult to enforce and often socially unacceptable
Limited Entry		Means of absolutely controlling total effort, in combination with other actions	Control fishing mortality when used with other restrictions	Often socially unacceptable with regard to basis for limiting licenses

Fishery Management

To meet sustainable harvest goals, fisheries managers attempt to adjust resource status through various management actions. Such adjustment has traditionally been accomplished by implementing harvesting regulations, which are intended to alter the amount, composition, or timing of the harvest to restore the stock to, or maintain it at, the desired status. In cases in which stock status is being affected by changes in habitat or water quality, fisheries managers may also act to protect or restore the habitat required to support or restore the target species.

This broader definition of fisheries management is not at present a practical reality, for two simple reasons. First, nearly all state, federal, and interstate agencies responsible for fisheries management are administratively distinct from the agencies responsible for the management of habitat and water quality. Consequently, they do not have regulatory authority over habitat issues. Second, the roles of habitat and environment in controlling stock abundance are not well understood. Thus, it is not known what kind and magnitude of habitat manipulation could reliably be expected to produce a desired change in stock status.

Typical categories of fisheries regulations, as well as their advantages and the stock characteristics intended to be altered, are presented in table 1. This table summarizes the effect of potential management actions used by agencies to achieve management goals.

The striped bass is yet another Bay species that has suffered a serious stock decline. Between the early 1970s and the late 1980s, total East Coast harvests of striped bass, which consisted primarily of fish produced in Chesapeake Bay, declined from roughly 10 million pounds a year to less than 1 million pounds a year. During the 10-year period beginning in 1973, Maryland's commercial harvest of Bay striped bass dropped from about 5 million pounds a year to less than 0.5 million pounds a year. Potomac River landings during the same period dropped from 1 million pounds a year to less than 0.2 million pounds a year [162]. These declines stimulated substantial management activity directed at saving the Bay's stock [11, 13]. However, that has not proved to be an easy undertaking; the life history of the Chesapeake Bay striped bass is complex and insufficiently understood, and that dual impediment has posed a major obstacle to rigorous quantitative stock assessment and effective management.

Striped Bass Life History

The striped bass is anadromous, spending most of its adult life in ocean coastal waters but returning to the low-salinity and freshwater portions of Chesapeake Bay and its tributaries to spawn [167]. Most mature adults return to the ocean within a short time after spawning, while their young remain in the Bay for 2 to 8 years before departing for the sea. The fraction of any single yearclass that remains in the Bay year-round differs with age and sex [160]. The geographical distribution of the fish remaining in the Bay may also vary with age. The youngest fish (up to 2 years in age) remain on the nursery grounds near the primary spawning locations, while older fish disperse throughout the Bay, exhibiting seasonal movements between deep and shallow habitats [106]. Striped bass overwinter in the Bay's deep waters and channels [105].

Major striped bass spawning locations in the Bay watershed include the upper Bay and the Potomac, Choptank, Nanticoke, James, York, and Rappahannock rivers. Some spawning is believed to also occur in the Patuxent and Wicomico rivers as well [150]. Based on relatively limited tagging and stock discrimination studies [167], it is generally believed that female striped bass return to their natal Bay tributaries to spawn, and that they possibly represent genetically distinct subpopulations of the Chesapeake Bay striped bass stock. Some of these same studies suggest that males exhibit a less refined homing instinct than females do.

Figure 7. Annual East Coast commercial landings of striped bass. (Total for region from Maine to North Carolina.)

Striped Bass Stock Assessment

Much of the data and information that has served as the basis for characterizing the life history of striped bass in the Bay also will contribute to a rigorous stock assessment of the species. However, most studies specifically instituted to develop a stock assessment for the species have been initiated only within the last decade.

To place in perspective the stock assessment status of the Chesapeake Bay striped bass, it is useful to review the basic types of data that are available for the species.

Fishery-Dependent Data. Fishery-dependent data, based primarily on the annual commercial harvest of a species, have been collected as far back as 1880 in much of the United States [181]. For Chesapeake Bay, reliable harvest data on striped bass have been available only since 1929.

Two compilations of Chesapeake Bay striped bass harvest data have been published. Bonzek and Jones [32] prepared the first complete Baywide synthesis of commercial landings. However, because numerous errors were subsequently discovered in many of the data sets included in that first summary, Jones et al. [92] have produced an expanded and corrected compilation of commercial harvest data on all major species, including striped bass. Jones et al. [92] also have presented a breakdown of harvest by fishing gear type, beginning with the year 1960. Data on amount of fishing effort were summarized in Bonzek and Jones [32]. However, the representativeness and reliability of those data were questioned by some researchers [154], so that those data generally have not been used in most fisheries management and stock assessment efforts in the Bay. Using the data sets summarized in Jones et al. [92], Richkus et al. [150] have developed regional breakdowns of annual commercial harvest beginning with the year 1960.

Prior to the 1980s, very little data were collected on the size, sex, or age composition of striped bass harvests in the Bay. Some commercial reporting of Maryland's striped bass harvest by fish size category (large, small) was required by the State of Maryland for a 10-year period during the 1960s but that reporting requirement was subsequently discontinued by the state [14]. Grant [73] documented the age composition of striped bass catches in Virginia for the years 1967-71.

In recent years, efforts have intensified to document commercial harvests, fishing effort, and catch composition. Catch composition in Maryland harvests was relatively well documented beginning in 1981 [174, 175], prior to the moratorium on harvesting striped bass that was imposed in 1984. After implementation of the 1981 ASMFC interstate management plan, composition of Virginia's commercial harvests was documented in a series of annual reports [15, 16, 17, 18, 108, 109]. However, commercial fisheries regulations changed markedly during the 1980s, and thus the information documented in those reports relate to fisheries that were very different from those prosecuted during the period of major striped bass harvests in the Bay (1960s and 1970s).

Detailed data on size, age, and sex were collected on the entire striped bass harvest when the Maryland season was reopened in 1990; all commercially harvested fish had to be checked in at established checking stations each day (H. Speir, pers. comm.). In Virginia, during the 1990 striped bass season, the Virginia Marine Resources Commission (VMRC) sampled 3.9% of the total commercial harvest for size (length and weight), 1.8% for sex, and 1.2% for age. Total harvest was documented through weekly written reports of the daily harvest, and on the basis of telephone reports from buyers and marketers [26].

During the past decade, sporadic surveys were conducted in Maryland waters to document to some extent the recreational harvest of striped bass [62, 173, 193]. More limited data are available on Virginia's past recreational fishery harvests [120]; most of those studies had numerous design flaws and provide only a gross characterization of the sport fishing harvest.

Coastwide marine recreational fishing surveys were conducted by the National Marine Fisheries Service in 1960, 1965, and 1970, and then annually starting in 1979 [14]. Although these surveys provide estimates of total fishing effort, total striped bass harvest, and harvest composition, they are designed for regional assessments of catches in marine waters and not for assessing harvests either in specific bodies of water or in inshore waters, such as the low-salinity portions of estuaries. Thus, annual recreational harvest data on striped bass in Chesapeake Bay are difficult to extract from these past studies.

Maryland instituted rigorous catch reporting requirements—access point checks and size data collection—for the recreational fishery when it was reopened in 1990. In Virginia, two recreational fishing surveys were conducted during the 1990 season: (1) a logbook program in which all striped bass anglers were required to obtain permits from the VMRC and return daily logs at the end of the season (the data included results from phone surveys of nonrespondents); and (2) an access intercept survey conducted at over 120 access sites. The sites were aggregated into 21 sampling routes throughout Tidewater Virginia, and size data were collected there [26]. Aerial boat counts were also conducted during the 1990 season.

Fishery-Independent Data. The scope of fishery-independent striped bass studies in Chesapeake Bay is much less comprehensive in time than that of fishery-dependent data collection. The fishery-independent study of the greatest importance for the present-day management of striped bass is Maryland's annual juvenile survey, which began in 1954 [55]. In this survey, haul seine samples are taken in late summer and early fall at 22 regular sampling sites distributed over the four major spawning areas in Maryland's portion of the Bay. The catch per haul of juvenile striped bass is considered to be an index of spawning success for the year. The index serves as a trigger mechanism for taking management action under the ASMFC's amendment 4 [13] to the interstate striped bass management plan issued in 1981. If the 3-year running average of the index exceeds 8.0, some exploitation of striped bass is permitted. The use of this index was the basis for lifting the Baywide striped bass harvest moratorium in 1990. Data from Maryland's annual juvenile survey have been used by numerous researchers and modelers investigating striped bass population dynamics [144, 14].

Virginia has conducted juvenile striped bass surveys using 30-foot trawls (1960-84) and seine nets (1967-73; 1980-present) [54, 53]. Researchers are now attempting to merge the Maryland and Virginia sampling programs to produce a single Baywide index of striped bass spawning success [53].

Recent results from the survey of juvenile striped bass conducted by the Maryland Department of Natural Resources (MDNR) are encouraging. In 1989, the juvenile index was 25.2, the second highest since the survey began in 1954. Virginia's survey results have shown steadily increasing values since 1981; the 1987 juvenile index of 15.8 was the highest on record for the lower Chesapeake Bay, and the three-year average for 1987 to 1989 was 11.6. This trend, together with the high Upper Bay index, could mean that the 1989 yearclass may be one of the strongest ever produced in Chesapeake Bay [137].

Very limited amounts of fishery-independent data (e.g., characterization of spawning stock composition) exist for the years prior to the 1970s (for many sources, see 106, 166, 167]. One major coordinated striped bass stock assessment effort—the Potomac River Fisheries Study —was conducted from 1974 to 1977 [194, 195, 91, 90]. In that study, experimental gill nets with a wide range of mesh sizes were deployed during the spawning season each year to sample all potential age and size groups of fish present. Size and age composition data were collected from the captured fish, together with fecundity information. Concurrently, extensive icthyoplankton (fish larvae and very young fish) surveys were conducted over the entire spawning period to document the timing, location, and success of spawning [143, 184]. In those surveys, integrated bottom-to-surface samples were collected using standard icthyoplankton nets towed at night over a set of randomly located stations in the spawning areas.

Fishery-independent studies comparable in scope to the Potomac River Fisheries Study were not initiated again until the early 1980s. Beginning in 1982, the MDNR began programs in most of the major spawning areas of the Bay. They include description of spawning stock based on sampling of spawning fish using experimental gill nets of many mesh sizes; determination of size and age of striped bass resident in the Bay year-round; sampling by means of hook-and-line fishing and experimental gill netting; ichthyoplankton surveys; estimates of egg deposition; bioassay studies to investigate factors influencing larval mortality rates; and studies of habitat factors that may be affecting reproductive success [121, 123].

Virginia's studies have been less comprehensive and have been linked to the state's fishery-dependent surveys (discussed above), as well as to tagging studies being conducted in cooperation with the U. S. Fish and Wildlife Service (USFWS) [108, 109, 110]. These efforts have generally consisted of sampling striped bass taken in commercial pound nets, and contracting with commercial gill netters to capture fish for tagging and release, and for stock characterization. Gear selectivity may limit the representativeness of some of the stock composition data collected in these studies. For example, pound nets may not capture larger fish as efficiently as they capture smaller fish; or the sizes of gill net mesh used may select against the capture of larger or smaller age groups.

The Recruitment Problem

Striped bass recruitment varies greatly over time and is unpredictable. Those are the primary underlying causes for the difficulties that have occurred in efforts to manage the Chesapeake Bay striped bass.

Historically, striped bass populations have displayed large annual variations, which are characterized by a phenomenon known as dominant yearclasses [69, 143, 71, 144, 96, 95]. As records of annual juvenile abundance show, there were low levels of juvenile recruitment in most years, with individual years of exceptionally high production—the dominant yearclasses—occurring on an intermittent basis, but generally every 4 or 5 years. Each dominant yearclass produced very large numbers of fish that supported both commercial and recreational fisheries for several years, generally until the next dominant yearclass was produced [132, 119, 126, 114].

This pattern of recruitment and harvest began to fail after the occurrence of the largest yearclass on record in 1970. Very large fisheries continued to heavily exploit the 1970 yearclass in the 1970s and into the 1980s, but another dominant yearclass failed to appear during that time. The result was a severe depletion of the spawning stock [14].

Studies of striped bass stocks during the 1970s, when spawning stocks were relatively large, suggested that recruitment (yearclass success) was largely independent of the size of the spawning stock. It was believed that environmental conditions during the developmental period of early life stages were the principal controlling factors in determining annual reproductive success [184, 112, 71, 186]. However, Goodyear and Christensen [70] pointed out that the impact of spawning stock size on reproductive success would be difficult to detect, given the magnitude of influence of environmental factors on larval survival. Subsequent analyses conducted in support of ASMFC's interstate management planning efforts suggested that spawning stock size becomes a critical factor in determining annual recruitment when that spawning stock has been severely reduced by overharvesting [14].

Numerous studies have been conducted to investigate the influence of both natural and anthropogenic factors on early life stage survival and ultimately recruitment in striped bass. Uphoff [187] has found that yearclass success is significantly related to minimum water temperature during peak spawn and mean river flow during the postlarval life stage. Low water temperatures reduce survival of eggs and prolarvae. Moderate to high river discharge rates apparently depressed postlarval survival and growth by diluting ionic concentrations and creating acidic, potentially stressful, and toxic conditions.

Hall [75, 76], Hall et al. [77], and Finger [63] have documented the effects of acidification and anthropogenic contaminants on the survival of early life stages, confirming that striped bass are very sensitive to such environmental perturbations. Houde and Rutherford [87] have reported that recruitment variability in Chesapeake Bay striped bass is strongly dependent upon temperature regimes that temporally structure spawning seasons, that can cause episodic losses of eggs and larvae, and that can affect larval growth rates. The large numbers of studies conducted to investigate the factors involved in striped bass recruitment variation in Chesapeake Bay have identified the principal one as being natural and anthropogenic water quality factors (e.g., temperature, salinity, pH, and contaminants), as well as the effect of exploitation on spawning stock size. None of these studies, however, have implicated other kinds of habitat modification, such as shoreline development, wetland loss, or sedimentation.

This brief literature review illustrates that numerous factors can significantly influence the survival rate of early life stages of striped bass and thus determine yearclass success. Unfortunately, the complexity of the interactions of these factors and their inherent variability virtually preclude accurate prediction of recruitment success for this species for any given year. For this reason, current management efforts rely for guidance on actual measures of annual reproductive success (i.e., juvenile abundance indices) [13, 14].

Models for Striped Bass Management

Efforts to apply traditional fisheries management models to the striped bass were long frustrated by the unpredictability of recruitment. However, the evolution of population dynamics modeling has lead to the development of new, species-specific simulation models that should prove to be useful tools for fisheries managers. In fact, the striped bass currently is the single Bay species that is managed in accordance with the outputs of mathematical models [68, 160, 13].

Two such models are now being used in directing the interstate management of striped bass along the East Coast. One was developed by V. Crecco of the Connecticut Division of Marine Fisheries, and the other was developed by P. Rago

Table 2. Comparison of three striped bass fisheries.

Species Fishery	West Coast Striped Bass	Gulf of Mexico Striped Bass (Coastal Waters)	Albemarle Sound/Roanoke River Striped Bass
Time Period	1958-84	1940s-present	1950s-present
Type of Fishery	Sport (no commerical after 1935)	Limited historical commercial, current sport	Commercial and recreational
Harvester Community	Charter boats 10-15% of harvest, shore and boat anglers 85-90% of harvest	Not well defined; large recreational fishery inland	Full-time diversified commercial watermen; extensive recreational fishery on Roanoke River
Market Factors	No information	No information	Local and east coast markets
Changes in Stock and Fishery	75% decline in stock size; 96% decline in catch; 50-90% decline in recruitment	Stocks occurred in the 1940s in all Gulf states; in 1980s, remnant stocks in Apalachicola River system in Florida, Georgia, and Alabama; stocking programs in most Gulf states	Commerical landings of about 700 thousand pounds in 1960s to 2 million pounds in early 1970s, to 100 thousand pounds in 1988; juvenile production declined 80-90%
Changes in Regulations	Until 1956, 12 in. minimum size, 5 fish bag; 1956-81, 16 in. minimum size, 3 fish bag; 1982, 18 in. minimum size, 2 fish bag	No restrictions on striped bass harvest in salt waters in any state except Florida (15 in. minimum size, 6 fish bag)	Until 1982, 12 in. minimum size, no bag limit on Roanoke, 25 fish bag on Neuse River, no commercial season; 1984, 8 fish bag on Roanoke, 2 month commercial closure on Roanoke; 1985, 14 in. minimum size and 3 fish bag; Roanoke commercial closure, 5 month commercial season in Albemarle
Explanations for Decline	Toxicity Entrainment loss in water diversion Reduced larval food Reduced adult stock	Dams Water quality decline Pollution Habitat degradation	Flow releases from dams Habitat quality Overfishing
Information Sources	Stevens et al. (1985)	Nicholson (1986)	ASMFC, 1990 Hassler et al. (1981)

and R. Dorazio of the USFWS. These models are described in detail in appendix A of ASMFC [14].

The Crecco model employs a yield-per-recruit function coupled with a stock recruitment function using a Shepherd approach. It incorporates a von Bertalanffy curve to predict mean length at age, assumes a stable age structure, presumes density-dependent population regulation, and takes into account seasonal migration and fishing rates that vary geographically [57].

The Rago/Dorazio model [148] is a Leslie matrix model of two interacting subpopulations, defined as Bay and coast subpopulations. This model uses the extensive data available for the Chesapeake Bay striped bass stock, such as migration rates, length-at-age data, maturation schedule, fecundity estimates, and egg variability.

Both the Crecco and Rago/Dorazio models have been used to investigate the likely consequences on future population status and growth of different management regimes, including such variables as geographically varying fishing rates and size limits. Both models played a role in determining that, when the striped bass fisheries were reopened in 1990, the instantaneous fishing rates should be maintained at a level of 0.25, with specified coastal and inshore size limits.

There is also a third model, developed by Rugolo and Jones [169], that has been used within the Maryland portion of Chesapeake Bay to establish an annual harvest quota consistent with the ASFMC-established target fishing rate of 0.25. This model uses the Maryland juvenile index as input, and it advances yearclasses through the years, incrementing available biomass based on established growth equations, and decrementing available biomass according to established sex- and age-specific migration rates and natural mortality. The model is used to establish the amount of fish (in pounds) that can be removed each year from the segment of the total coastal stock present in the Bay consistent with the target fishing rate of 0.25.

All of the models used in the management of striped bass are subject to revision and modification on a regular basis depending on the results of annual striped bass assessment studies.

Table 3. Management data and models for three striped bass fisheries.

	West Coast Striped Bass	Gulf of Mexico Striped Bass	Albemarle-Roanoke Striped Bass
Management Data	Charter boat catch and effort (1956-present); tag/recapture population estimates (1969-82); fishery indept. CPUE and juvenile trawl surveys (intermittent since late 1950s)	Commercial catch (intermittent and incomplete)	Juvenile index; spawning stock and population estimates; commercial and recreational harvest and effort; egg abundance and viability (all 1950s-present)
Management Models and Analysis	Trend analysis, regression population (Peterson) and mortality estimates	None	Regressional analysis; trend analysis; simulation models (under development)
Harvest Regulations	Size limits; recreational creel limits.	Size limits and recreational creel limits (geographically limited)	Size limit; recreational creel limits; seasons; gear restrictions; limited entry (recent)

Current Status of Striped Bass

The stock assessment and management status of the Chesapeake Bay striped bass can be placed in perspective by comparing it with the status of striped bass in three other parts of the United States: the West Coast; Gulf of Mexico; and Albemarle Sound/Roanoke River (see table 2).

The West Coast stock, which was established as a result of stocking juvenile striped bass from the East Coast in the Sacramento River in 1879, has shown declines during the last decade similar to those seen in Chesapeake Bay. Relative abundance indices of adult stock declined from values of above 20 during the 1960s to a low of about 5 in 1984 [178], with no recovery since that time.

Stock assessment data for this West Coast stock included some long-term data series on catch, fishing effort, tag-and-recapture population estimates, and juvenile abundance (table 3). However, these data were not analyzed in any detail until well after a very significant population decline, and no population or harvest models were developed for this stock on the basis of these data. In addition, fisheries managers did not make changes in harvest regulations or initiate any major management actions during the period of decline.

The factors that are believed to have been involved in the stock decline and the absence of recovery to date include water diversion effects, the presence of toxics, reduced food supply for larval fish, and reduced spawning stock [178]. However, stock assessment work to date has not identified the relative contributions of each of these factors.

Gulf of Mexico striped bass (table 2) occurred in coastal waters and tributaries of all of the Gulf states as recently as the 1940s. Although significant hatchery-supported freshwater fisheries for striped bass exist in reservoirs in most of these states at the present time, the coastal stocks have virtually vanished, except for a remnant stock in the Apalachicola River system [138].

Numerous environmental factors have been mentioned as possibly contributing to the decline and disappearance of these coastal stocks—the most prominent ones being the damming of spawning rivers and habitat degradation (water pollution). To date, however, there has been no definitive explanation for the causes of the decline, and no long-term data exist to document the way in which the status of the stocks has changed over time. In sum, there is a complete absence of stock assessment data (table 3). Commercial harvests reported for marine waters were historically very small and only intermittently reported; only anecdotal information exists on the nature of sport fisheries in coastal waters. Management efforts to restore these coastal stocks currently focus entirely on stocking programs [138].

The Albemarle Sound/Roanoke River striped bass stock has been the subject of study for many years [81] (table 2). This stock, which spawns in the nontidal waters of the Roanoke River, is currently believed to spend its entire life cycle in North Carolina's inland waters, and not to contribute significantly to coastal striped bass populations [14]. As occurred with the Chesapeake Bay and West Coast striped bass stocks, commercial landings, population size, and reproductive success of the Albemarle Sound/Roanoke River stock all declined by 80% to 90% during the late 1970s and early 1980s [81, 14].

Possible contributing factors in this decline have been identified as reductions in spawning stock size (owing to overharvesting) and habitat degradation (including changes in river flow regimes). Extensive long-term data sets have been available for many years (table 3); these data, however, were not used for management purposes until very recently, and no population or management models were developed until the late 1980s. Very restrictive harvest regulations are currently in place in North Carolina, and river flow regimes have been modified. However, recruitment success, while showing some improvement, has not yet approached the historical levels seen during the 1960s [14].

The striped bass stocks discussed above share a pattern of decline with little or no recovery. A lack of critical stock assessment data certainly has contributed to management failures with some of these stocks. The failure of management agencies to use available data also appears to have been a contributing factor. This review also suggests that management of the Chesapeake Bay striped bass stock is currently based on a more sound technical basis and employs more comprehensive management tools than are being applied to the other stocks.

Conclusion

The wide array of stock assessment data collected in various ongoing programs has been vigorously applied in current management regimes. For example, data from Maryland's programs have been used to establish age- and sex-specific migration rates, historical and current fishing mortality rates, natural mortality rates, and other important parameters incorporated into management models. Moreover, models are currently being applied to all coastal waters, and are being used to ensure Maryland's compliance with ASMFC management criteria [13, 160]. Prior to the 1980s, however, available stock assessment data and information appeared to have little bearing on the type and nature of harvest regulations applied to both the commercial and recreational fisheries. As a matter of fact, it appears that the limited nature of pre-1980s data prevented both the timely assessment of factors contributing to stock declines and the prompt regulatory actions that might have prevented those declines [167].

Blue Crab (Callinectes sapidus)

Introduction

Chesapeake Bay is the chief center of blue crab (*Callinectes sapidus*) abundance along both the Atlantic and Gulf coasts. It accounts for more than half of all East Coast blue crab landings each year, and is the source of most of the U.S. supply of soft crabs [45].

The blue crab commercial fishery has long been a major element of the Bay region's seafood industry, with annual landings—including those of hard crabs, peelers, and soft crabs—having generally increased over the decades from the 1930s to the present [46]. In fact, the blue crab fishery has been the region's most valuable fishery since 1983, when it surpassed the declining oyster fishery for the first time [72].

Furthermore, recreational, or sport, crabbing is a very popular pastime throughout the Bay region during the summer months, and the total annual recreational catch "is undocumented but believed to be large" [45].

Nevertheless, despite the fact that the blue crab has not shown evidence of the stock declines that have affected other Bay species, such as the striped bass and Eastern oyster, there has been widespread concern expressed about the future well-being of the Bay region's blue crab stock. That concern has been focused primarily on the potential for overfishing during years of relatively low crab abundance, given the fact that the species' abundance is known to fluctuate considerably from year to year [48].

Accordingly, the Chesapeake Bay Agreement of 1987 called for the blue crab to be recognized as a priority species that requires comprehensive Baywide management, and the agreement's signatories made a commitment to develop, adopt, and implement a management plan as soon as possible. The blue crab, in fact, was one of the first three Bay species (the other two being the Eastern oyster and American shad) for which management plans were to be prepared and put into effect.

Blue Crab Life History

Blue crabs occur from Nova Scotia to Uruguay and are commonly found in rivers, estuaries, and near-shore waters of the Atlantic Ocean. They are distributed throughout Chesapeake Bay and its tributaries. Blue crabs mate in the brackish middle waters of the Bay from mid-spring to September or October. Males reach sexual maturity after one year, usually before their final molt, and they may mate several times. Adult female crabs, called sooks, mate only once, during their second year of life. Extensive migrations are involved in the mating process [105]. In late fall, females migrate to the higher salinity waters of the lower Bay; males normally remain in the low- to mid-salinity waters year-round. In early spring, females swim up the Bay, and mate, just after completing their final molt to maturity. After mating, females return to the lower Bay where they also spawn.

The extruded egg mass is attached to the female's ventral surface ("sponge" crab stage) and may contain more than three million eggs. Spawning takes place from May to October, in the mouth of the Bay and in ocean waters near the Virginia capes [46]. Small zoeae larvae hatch from the eggs in about two weeks and are released into the water column, where they are subject to currents that may transport them out into the Atlantic Ocean and back into the Bay. Circulation patterns, environmental conditions, and predation affect larval survival and subsequent recruitment into the fishery [46, 189, 113].

After a series of seven molts during their first month, the zoeae metamorphose to the second, or megalopa, larval stage, and resemble small crayfish. Late-stage zoeae and megalopae are abundant in the waters of the lower Bay and in coastal shelf waters up to 40 miles from the mouth of the Bay [46]. The megalopae occur in the subsurface waters of the salt wedge, which aids their up-Bay transport and retention. By late summer and early fall, megalopae metamorphose into juveniles, and are abundant far up rivers, near the limit of the salt wedge. By November, they have grown to 25 to 60 mm in carapace width.

Young-of-the-year crabs are most abundant from June through August of their second summer [189]. Growth is rapid, and crabs hatched in May and June reach about 5 inches (130 mm) in width by August and September of their second summer [105, 177, 46]. From late spring through early fall, so-called peeler crabs are valued as bait for the recreational sport fish fishery. Peeler crabs are crabs over three inches (76 mm) wide and about to molt. After molting, they become the softshell crabs that are so prized as a seafood commodity.

While the blue crab is generally recognized for its food value, its role as both predator and prey in the Bay ecosystem must not be underestimated. Larval and juvenile crabs are important dietary constituents of most Bay sport and commercial finfish species, including striped bass, bluefish, red drum, black drum, spot, and croaker [189]. The blue crab is also an important predator on oyster spat [61] and the brackish water clam (*Macoma*).

The Blue Crab Management Plan

Published in July 1989, the blue crab management plan [46] draws on biological and fisheries data developed by Jones et al. [90] and declares that its goal is to "manage blue crabs in Chesapeake Bay to conserve and protect the ecological value of the stock and concurrently generate the greatest long-term economic and social benefit from using the resource."

The plan sets out a total of nine objectives that are intended to lead to achieving this goal. The first objective is to "[m]aintain the spawning stock at a size which eliminates low reproductive potential as a cause of poor spawning success"—that is, to eliminate the possibility of recruitment overfishing [46].

Clearly, meeting this objective is predicated on the availability of an effective blue crab stock assessment. However, such a stock assessment is not yet available, as is reflected in the plan's eighth and ninth objectives, which are, respectively, to "[p]romote research to improve the understanding of blue crab biology and population dynamics" and to "[p]romote studies to collect necessary economic, social, and fisheries data to effectively monitor the status of the blue crab fishery" [46].

What is more, specific stock assessment deficiencies constitute one of the five "problem areas" that are identified in the plan (the other four are ever-increasing fishing effort, wasteful harvest practices, habitat degradation, and certain regulatory matters) [46].

An effective blue crab stock assessment requires a combination of accurate fishery-dependent data on such measures as harvest and fishing effort and accurate fishery-independent data on such measures as recruitment and mortality. Accordingly, the management plan recommends various strategies designed to facilitate the collection of such data as a basis for effective stock assessment and fishery management.

Fishery-dependent Data Collection

Although some data on harvest and fishing effort are available for the Bay's commercial blue crab fishery, they are neither comprehensive nor specific enough. Data collection efforts are based on landing reports plus information on fishing gear used and licenses issued. However, managers need more detailed information on the distribution of harvest in terms of the crab's life history stages; specifically, they need better statistics on the catch of peelers and soft crabs [46].

Methods of documenting harvest and effort can have a dramatic effect on the reported catch figures. For example, Maryland changed its commercial harvest reporting system in 1981; although harvests appeared to double that year, the increase was simply attributable to the new sampling technique [179, 180]. Virginia on the other hand, while having the authority to require reporting, only asks for voluntary compliance.

There is also a need for accurate data on the recreational catch, as well as the impact of the catch on the Bay region's crab stock. There appears to be general agreement in the literature that the recreational catch is large [45].

That is consistent with estimates developed for Maryland's portion of the Bay and its tributaries for the years 1983 and 1988, when the recreational harvest was gauged as accounting for about 44% and 32.1%, respectively, of the total annual blue crab harvest [46]. However, some VMRC personnel believe that the Maryland estimates are too high and that a proportion of 20% would be more accurate (Smoller, pers. comm.).

On the other hand, Rothschild et al. [155] have suggested that the Bay region's annual recreational catch may actually equal, or even exceed, the commercial harvest. However, they have not presented any data in support of their view.

Fishery-Independent Data Collection

It is essential that a better understanding be developed of the blue crab stock's population dynamics [46], and that requires the use of fishery-independent data and analysis to focus on such key issues as recruitment and mortality.

Overall, what are the most effective ways of acquiring such data? Recently, Rothschild et al. [155] completed an evaluation of stock assessment methodologies to ascertain the most effective means of obtaining the needed kinds of information on population abundance and population dynamics. In their three-year study, they identified winter dredge surveys of overwintering crabs as the survey method most likely to provide reliable estimates.

However, they also pointed out that existing dredge-based survey design appears to have certain shortcomings that result in population abundance being underestimated, thereby precluding a clear determination of the magnitude of the potential overfishing problem.

Recruitment. Traditional assessments of larval stages of crustaceans (e.g., plankton tows) have never lent themselves well to recruitment monitoring. That is partly because of the patchiness and aggregating or swarming behavior of the larvae. Recent studies [190] have demonstrated the feasibility of monitoring larvae settled on artificial collectors. Collectors are more cost effective than monthly trawl surveys, and are subject to fewer outside variables. However, environmental factors, influencing yearclass strength, are significant not only at the larval and megalopal stages but also between the megalopal and juvenile stages, necessitating juvenile monitoring before final yearclass strength is set. Thus, summer trawl surveys (and also winter dredge surveys)—which have been undertaken by both Maryland and Virginia since about 1988—should be continued. Such surveys have proven to provide an accurate assessment of young-of-the-year juvenile in-Bay recruitment [104, 33].

Blue Crab Stock Assessment

Adult crab stocks and mortality are assessed in Maryland and Virginia by conducting fishery-independent surveys (as well as by monitoring the commercial fishery) [33]. Recently, tagging [89] has proven to be an effective measure of spawning stock size and mortality.

Although it is possible to assess the spawning stock by using fishery-independent surveys, there are no long-term data available for comparison. The only attempt yet made to directly assess the size of the female spawning stock demonstrated a year-to-year variability of nearly 80% [89]. To guard against recruitment overfishing, more work is necessary to determine the optimum size of the spawning stock. This is especially important for blue crabs owing to the strong impact of physical and environmental factors on recruitment success.

The above problems are not new. They were already identified a decade ago as a major stumbling block to effective Baywide management [49]. In short, then, although Chesapeake Bay agencies can and do effectively assess postlarval and juvenile stages, peeler and adult hard crabs are probably so inaccurately reported as to make meaningless any management efforts based upon landings.

Model-based Analysis

If the blue crab management plan proposes to reduce recruitment overfishing, what models would be appropriate to use and what data could be used for input? Several factors need evaluation. Numerous authors have shown the overwhelming importance of the physical environment in determining fluctuations in year-to-year recruitment success [10, 182, 42, 67, 113, 88], which raises the question of the validity of any spawner/recruit relationship.

Lipcius and van Engel [104], on the other hand, have demonstrated that a Ricker spawner/recruit relationship can explain 80-88% of the interannual variability. This discrepancy between Lipcius and van Engel and the other authors cited above is explained by the fact that Lipcius and van Engel examined postsettlement juvenile crabs assessed in the York River with a 9-m semiballoon trawl whereas the others examined presettlement larval (zoeal and megalopal) stages where strong physical environmental forcing occurs. For spawning stock, Lipcius and van Engel used tagged historical USFWS and commercial VMRC landings data for the winter dredge fishery.

Although Richkus et al. [149] recommended against using yield-per-recruit and surplus-production models for the blue crab, arguing instead for simulation models, the blue crab management plan appears to be based upon just those two approaches. Several surplus-production models [46] suggest that the MSY for blue crabs in the Bay ranges from 69 million to 77 million pounds. Yet, the reported 1988 commercial harvest was 82.7 million pounds, and assuming a modest 35% recreational harvest, total landings in 1988 were 111.6 million pounds. The potential for recruitment overfishing is a clear and present danger.

If MSY for a short-lived (three-year) stock such as the blue crab is 69 million to 77 million pounds, and the actual landings in the Bay during 1988-90 have ranged upward of 111 million pounds, then either the stock has already collapsed (which it has not) or the MSY estimates, set in print in the blue crab management plan, are off by 30%. Is that attributable to the inherent inappropriateness of surplus-production models as suggested by Richkus et al. [149], or was the input (landings and fishing effort) incorrect? Certainly the estuarine environment is nonconstant, and recruitment and natural mortality rates fluctuate widely, which violates the assumptions associated with the surplus-production models [198]. In all likelihood, however, it was the landings data that were seriously underreported. (In fact, as it turns out, the values in estimating MSY are from Tang [182], and the data were for pre-1981 Maryland and Virginia commercial-only landings.)

Conclusion

Unless the stock assessment action strategies proposed in the blue crab management plan are implemented to produce accurate reporting of total landings, unless the survey recommendations of Rothschild et al. [155] are implemented to meet the need for improved population dynamics data, and unless ways are found to restrict harvest to an acceptable level, the blue crab stock, which has long maintained healthy levels of abundance, may suddenly and dramatically decline owing to recruitment overfishing. The probability of such an occurrence is hard to assess, but with such a short life span and such dependence on favorable environmental conditions, the decline of blue crab, like that of the anchovetta in Peru, could wreak havoc on the fisheries segment of the local economy.

Eastern Oyster (Crassotrea virginica)

Introduction

Once named the most valuable American invertebrate [146], the Eastern oyster (*Crassotrea virginica*) has long made a major impact on the social and economic life of the Bay region [94, 36]. As an important source of income for the Chesapeake Bay seafood industry, it has accounted for, on average, 21% of the region's annual commercial catch and 48% of its total dockside landings value. In fact, until the blue crab fishery surpassed it in 1983, the oyster fishery had long been the Bay's most valuable fishery [72, 36].

Studies describe many decades of declining harvests of *C. virginica* and document a nearly 38-fold decline in commercial catch over the last 100 years [85, 94, 36, 158, 43]. After a peak harvest of approximately 15 million bushels in 1884, harvests leveled off in the late 1920s and remained relatively stable at between 2 and 3.5 million bushels a year from about 1925 to 1982 [78, 72]. In the 1980s, however, the Bay's oyster fishery suffered serious effects from the diseases MSX and Dermo, and both Maryland and Virginia have reported record low harvests in recent years. Maryland reported only 395,000 bushels for the 1989-90 harvest, which was under 400,000 bushels for the third year in a row. In Virginia, the 1989-90 production of market and seed oysters was only 355,000 bushels, 39% below the 1988-89 catch and 66% less than the 10-year average [48].

The decline of this famous and once-prolific fishery has led to numerous studies describing the causes of the decline and recommending actions for rehabilitation. The most important factors involved in the decline have been cited as overfishing, disease, and loss of habitat [47, 72, 158].

Given the decline in oyster harvests, researchers and managers alike have a strong interest in measuring the size of oyster stocks and in understanding the factors that control the population. Based on estimates of biomass and processes such as recruitment, growth, and mortality, managers can take actions to control the harvest, optimize shell and seed planting efforts, and set aside sanctuaries or perhaps restore oyster habitat. This case study reviews various approaches to oyster stock assessment; it outlines methods to estimate abundance, reviews data collection and analysis procedures, and explores the factors influencing oyster recruitment and mortality.

Oyster Life Cycle and Growth

Subject to heavy mortalities at all stages, oysters go through a complicated life cycle on their way to three-inch (76-mm) market-sized adults. One estimate suggests that of 40 million eggs produced by a spawning female, only about 30 reach adult size [72]. The oyster life cycle is characterized by wide variation in recruitment success, with successful spat settlement, or strikes, often being years apart.

After fertilization in the water column, oyster larvae normally drift for two to three weeks, traveling a distance of maybe several miles from the broodstock area. Various predators and physicochemical factors take a heavy toll on the larvae, with only about 2% of them surviving to reach the pediveliger stage, during which the larval oyster settles and extends a foot to attach to a substrate. At this point, suitable substrate—also called cultch—is most critical to survival [3, 41, 115, 122, 165]. When pediveliger larvae attach, metamorphosis to the juvenile stage begins immediately, but a variety of predators, physicochemical factors, diseases, and fishing activities act to reduce the number of individuals.

The newly attached larvae are referred to as spat, which grow into juveniles and then spawning adults. Spat provide researchers with an index of recruitment. Each fall, state agencies use average spat counts on numerous oyster bars as a measure of recruitment success during the summer spawning season. In recent years, disease parasites have affected many bars, and the prospects are not good for spat surviving three to five years to grow to market size in such parasite-ridden areas [98].

As a simple growth rate, some researchers generalize oyster growth at about one inch (25 mm) each year [127, 158]. But various studies have described different growth rates [111, 1, 28, 29, 168, 176,147]. Summarizing the results, Stagg [176] described a high variation in growth rates between individuals on the same bar, between different bars, and between different years. Moreover, the sedentary nature of oysters makes them susceptible to many environmental variables, including dissolved oxygen, temperature, salinity, quantity of food, toxins, and turbidity. Oysters grow more slowly in low-salinity areas [1, 82] and do not grow well in high- or low-temperature extremes [66]. Other researchers have identified the availability of food and current velocities as important factors controlling oyster growth [147].

The unique oyster life cycle ensures high variability in recruitment, growth, and mortality and subsequently complicates the application of common fishery models. Moreover, it also helps explain some of the difficulties in gathering good fishery-independent data. Following sections outline important factors affecting oyster recruitment and mortality.

The Oyster Management Plan and Stock Abundance

In response to gubernatorial directive from Maryland and Virginia, CBSAC, along with Bay region state and federal agencies, developed the Chesapeake Bay oyster management plan in 1989 [47]. The goal of the plan is to "increase the Baywide stocks of oysters by initiating short and long-term management actions." To improve oyster harvests, the plan outlines a combination of fishery-dependent and fishery-independent stock assessment programs meant to provide data and other information for management decisions. The overall strategy is to monitor harvest effort and set the annual catch at a level commensurate with some measure of resource status. The initial plan called for an MSY of 2.2 million bushels [47]—a level above the catch for the last few years.

To establish an acceptable rate of fishing mortality and to achieve the goals outlined in the oyster management plan, a stock assessment should be able to determine the size of the adult oyster stock in Chesapeake Bay.

Theoretically, several approaches have been used or suggested, including:

- **Catch and effort analysis:** Regress catch-per-unit (CPUE) against cumulative commercial harvest [22].

Leslie-Delury Method

Catch-per-unit effort (CPUE) is expressed mathematically as:

$$CPUE = C_t/f_t = qN_t,$$

where C_t = catch during interval t
f_t = effort during interval t
q = catchability
N_t = population size (#s)

The original population size at time 0 (N_0) minus the accumulated catch up to time t equals the population size at time t:

$$N_t = N_0 - \sum_{t=0}^{t-1} C_t$$

Substituting A_t for accumulated catch,

$$C_t/f_t = q(N_0 - A_t)$$
$$= qN_0 - qA_t$$

The linear regression, CPUE against accumulated catch, estimates the total population at t=0 (N_0).

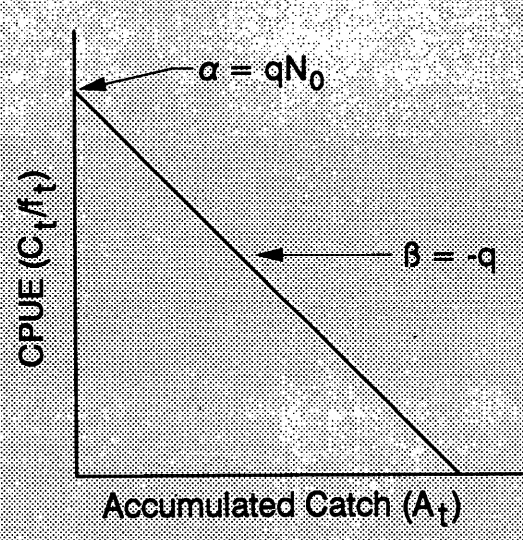

Figure 8. Leslie-Delury method.

- **Fishery-independent sampling surveys:** Sample on-bar oyster densities and multiply by the area of existing oyster bars [125].
- **Analytical yield models:** Use fishery models based on growth, fecundity, and mortality parameters [157, 158].

In practice these approaches require combining fishery-dependent data, such as catch and effort, with fishery-independent data, such as measures of recruitment, growth, and mortality, and—in all cases—the viability of the approach depends on the quality of the data.

Although some useful data are available (owing primarily to the historical importance of the oyster industry), much of the information is of limited value for stock assessment purposes. Some of the data problems can be attributed to the cost and difficulty of quantifying highly variable processes such as recruitment, growth, and mortality. There is clearly a need to collect better fishery-independent data and to compare those measures with historical, fishery-dependent assessments. It is also essential to collect these fishery-independent data now, before the fishery is closed and no more fishery-dependent data can be obtained.

Fishery-Dependent Data and Analysis

Historically, fishery harvest data have been used as an estimate of oyster populations and also for implementing management actions such as restrictions on harvest size, harvesting gear, and fishing season. Maryland has collected harvest data since 1839, Virginia since the 1870s. Several studies provide useful data on such measures as oyster landings and fishing effort [72, 122, 85].

However, data on harvest and fishing effort are often incomplete and/or inaccurate [176]. A decade ago, Krantz and Haven [101] commented that oyster harvest reporting had been more oriented toward tax collection rather than the collection of biological statistics. In fact, Virginia estimated the oyster harvest on the basis of tax receipts rather than the direct measurement of dockside landings [101]. These historical features of fishing data are complicated by repletion programs and diverse types of fishing effort.

The state repletion programs, which involve moving seed oysters and transporting oyster shell (for use as settling substrate, or cultch), complicate the quality of landing statistics. Early landing statistics probably included seed oysters being moved to other areas outside Maryland waters, and that fact limits the value of comparing current harvests with harvests prior to the 1927 cull laws [94].

Several authors [94, 157, 158] have described the evolution of ever more efficient fishing gear in the oyster fishery. This wide variety of fishing practices—based on gear type and on fishing hours, location, and season—still persists in Chesapeake Bay and complicates the accurate measurement of fishing effort. Moreover, harvest limits—restrictions on the amount of oysters caught each day by individual boats—compromise fishing effort data. To be more accurate, harvest data should be collected and organized by individual oyster bars, rather than by regions as currently reported.

Despite data problems, several studies [124, 40, 22] have supported the validity of using the Leslie-DeLury method of regressing CPUE against cumulative commercial harvest to assess adult stock in specific areas such as the Potomac River and James River (see figure 8).

Cabraal [40] applied Leslie-Delury analysis to harvest and fishing effort data to calculate population estimates in various areas of the Bay. Barber and Mann [22] used the same approach for developing population estimates for the James River, and MDNR also has used the Leslie-DeLury method to calculate Potomac River oyster stocks (Homer, pers. comm.).

However, there are problems associated with applying the Leslie-DeLury method to the Bay-wide oyster stock. Accurate estimates require making certain assumptions that may not hold true for the Bay's oyster fishery. For example, the method assumes constant catchability and no natural mortality or recruitment during the time interval covered by the estimate. In addition, accurate estimates depend on measuring all the fishing effort applied to a specific location and catch.

Fishery-Independent Data and Analysis

Taken as part of scientific and statistically designed programs, fishery-independent data include measures of abundance and population characteristics such as recruitment, mortality, and growth [21].

The states of Maryland and Virginia have conducted annual oyster surveys since 1939 and 1946, respectively. Both states use the oyster dredge to sample existing oyster bars and collect data on recruitment and mortality. The Maryland Oyster Spat and Condition Index Program samples 300 to 400 bars each fall. Its objective is to determine recruitment success and oyster condition in the Maryland portion of the Bay [124, 97, 98].

In Virginia, two programs monitor oyster recruitment and survival. The Virginia Spring/Fall Oyster Bar Survey uses the oyster dredge to conduct semiannual counts of spat, juvenile (or yearling), and market oysters at 26 stations. In addition the Virginia Oyster Spat Survey monitors spatfall on suspended shellstrings at 43 stations in the summer.

Based on these and other fishery-independent sampling programs, Maryland and Virginia have generated historical data sets for recruitment indices (spat settlement) and natural mortality.

The Recruitment Issue

Oysters, like other large bivalves, experience intense annual variability in recruitment success, and many years can pass between successful strikes. Pelagic fertilization followed by weeks of planktonic drifting on local currents help explain the random nature of successful spat set. Moreover, it is difficult to identify the broodstock for a successful spat set, in that larvae may drift far from the spawning site, and even with successful sets, many spat do not grow into market-size adults owing to the impact of disease.

Both states count spat, or postsettlement larvae, as an indicator of recruitment success [124, 122, 97]. Although not a precise means of estimating population size, spat monitoring does provide measures of relative abundance and geographic distribution.

Owing to variable mortality rates in postsettlement oysters, traditional spatfall counts do not necessarily serve as a good indicator of recruitment success. Several studies have recommended using a follow-up spring survey as a way to track oyster recruitment through the spat stage and into the juvenile stage [41, 97]. In addition, better correlations between spatfall, juveniles, and market oysters may be able to provide some index of recruitment success [124, 185]. However, such correlations are difficult to ascertain owing to spatial and temporal variations in survival rates.

Factors that affect recruitment. Myriad environmental factors are thought to influence recruitment success in oyster populations. Such factors include temperature, salinity, dissolved oxygen, current regimes, pH, suspended sediments, siltation, pollution, and cultch quality, with each factor affecting the oyster at some point in its complex life cycle [34, 66].

Spawning seasons with high salinities produce high spat settlement, but it is difficult to correlate spat set with adult oyster populations [185]. Nonetheless, spat that survive the metamorphosis from free-swimming larvae to a benthic form have been used as a general measure of recruitment success in both Maryland and Virginia.

Early observers knew the value of good cultch material; as Galtsoff [66] observed, "Clean hard substrate without excess fouling or silt is perhaps the single-most important factor for successful setting." Salinity and available broodstock also have been suggested as important factors. Using multiple regression analysis, Ulanowicz et al. [185] correlated spat set with cumulative salinity during the growing season and inversely correlated spat set with fishing activity during the previous season.

Abbe [2] reviewed the factors that affect recruitment and found the four most critical ones to be (1) adequate broodstock of spawning adults; (2) clean water (because pollution may prevent eggs and embryos from reaching the early larval stage); (3) retention of larvae in suitable settling areas owing to current patterns; and (4) availability of clean, hard substratum . In addition, other authors have commented that the quality of substrate is a factor in determining spat survival, or recruitment success [41, 42, 66, 115, 122, 165, 158].

Spatfall trends. Dredge survey data provide long-term historical data of spat counts in bottom material and can provide the basis for the analysis of long-term trends [124]. Several studies have analyzed dredge survey data to analyze trends in spatfall and oyster recruitment. Since 1931, when regular monitoring of oyster recruitment was initiated in Maryland, there has been a long-term downward trend in spatfall [102, 122, 100, 72]. However, long periods of low recruitment have been punctuated with years of high spatfall, including such years as 1965, 1980, 1981, 1985, 1990, and 1991 [102, 97, 72].

Recently, analysis based on application of autoregressive integrated moving average (ARIMA) models has been used to review 40 years of Maryland spat data [43]. According to the analysis, trends in spatfall were not clearly established and the sampling procedures introduced too much variability.

Some studies attribute the temporal and spatial fluctuations in oyster recruitment to natural variations in mortality rather than to some irreversible ecological change or anthropogenic impact [185, 2, 72]. Other studies put the blame on recruitment overfishing [158] or reduction of broodstock caused by disease [72].

Despite being the second-best spat set since 1939, much of the 1991 Maryland oyster set occurred in high-disease, high-salinity areas of the Bay [98]. By contrast, the record spat set of 1965 produced significant oysters in low-disease areas of the upper Bay—areas that have received little spatfall in recent decades [98].

Recruitment and seed repletion. In addition to natural spat settlement, or strikes, oysters are recruited by either transplanting seed oysters from another area or introducing cultured spat from a hatchery. As part of the repletion programs, states move seed oysters to better grow-out areas and transport shell there for use as a substrate for potential larval setting [40, 72]. Most repletion seed oysters come from productive natural areas and subsequently depend on natural broodstock. In Virginia, the James River represents the primary source of seed oysters; in Maryland, several Bay tributaries provide repletion seed oysters [97, 40].

These repletion efforts are important to the Bay oyster fishery because they boost recruitment and improve the substrate. In fact, shell planting and seed oyster transplanting have been largely responsible for sustaining the oyster fishery in recent years [72, 185, 40].

Rothschild et al. [157] have discussed the repletion effort in detail, outlined some of the problems and described modeling approaches to the repletion process.

Fishery-Independent Sampling Techniques

One of the principal methods of obtaining fishery-independent data for stock assessment of the oyster in Chesapeake Bay is the use of various sampling techniques. Among these techniques are the use of oyster dredges, shellstrings, patent tongs, scuba divers, and also larval monitoring devices.

Oyster dredge. The oyster dredge is commonly used in both Maryland and Virginia to collect spatfall data and other oyster information on a regular basis. In Maryland, for example, 64 representative oyster bars are sampled each fall for recruitment success and oyster conditions. A sample consists of one bushel of dredged oysters that are analyzed for spat counts, meat quality, abundance of fouling organisms, sizes of live and dead oysters, and other measures [124, 98].

Several authors, however, have challenged the efficiency of the oyster dredge [115, 157, 43, 183, 121]. Because the dredge scrapes over an unknown area, it does not provide a standard-unit area sample, but rather a standard-unit volume. The area and depth covered and the efficiency of the dredge in collecting bottom material varies with the location and operator.

On the other hand, the dredge collects data along a towed transect and reflects general trends in oyster populations, and such dredge-based collections are generally taken at the same location each year and may be viewed as being integrative samples. Moreover, in comparison with other sampling techniques, the dredge-based survey is relatively inexpensive and enables more areas to be sampled [124].

Shellstrings. Virginia's oyster spat survey uses shellstrings to monitor spatfall in major tributaries. Each week, observers count spat on a series of 12 oyster shells strung on a wire 20 inches above the bottom. Shellstrings (also called spatfall collectors) are useful because they provide an index of larval abundance and they track the timing of larval settlement. However, they are not useful indices of recruitment because they are ideal surfaces not subject to the competition for space and the mortality problems facing natural spat settling on bottom substrate. Nonetheless, shellstring data are important in helping planters select the most favorable times for moving seed for larval settlement [124].

Patent tongs and scuba divers. Various researchers have noted that although the dredge survey gathers data on the relative abundance of spat, juveniles, and adults, such survey efforts lack consistency in data recording, sampling methods, and sampling locations [183, 43]. In addition, MacKenzie [115] pointed out an instance in which a dredge collected clean shells from areas that he had observed to be covered with silt and mud.

To overcome the monitoring problems inherent in dredge surveys and also in shellstring counts, some authors have suggested using alternative sampling gear and procedures. Most involve statistically based strategies that measure spat, juvenile, and adult densities in standard-unit areas and then apply those sample densities to measures of oyster habitat [124, 125].

Patent tongs have been used to undertake quantitative oyster sampling [43, 183]. The MDNR, along with researchers at the Chesapeake Biological Laboratory (CBL), is currently testing this technique [43].

Another technique, as recommended by MacKenzie [115], involves scuba divers using quadrats, or standardized mapping plots, to accurately count spatfall. One such spatfall monitoring method is based on 0.33 m^2 steel frames as a standard-unit area for counting spatfall [2, 3].

Initial findings show patent tongs to be more accurate sampling gear than either dredges or scuba divers, primarily because of the variability in quantity of shell and bottom type [183]. Tsai and Rothschild also evaluated sampling design to maximize precision based on random, cluster, and stratified sampling approaches. The CBL researchers suggested a comprehensive sampling design for Maryland based on the use of patent tongs and a statistically based sampling survey [43].

Larval monitoring. Several authors have recommended using larval monitoring studies primarily as a way to monitor recruitment processes. For example, a 1990 workshop [124] recommended a fluorescent antibody tagging approach as a simple way to identify larvae caught on a 44-µm screen. Although not a useful index of recruitment, larval monitoring can provide insights into broodstock/larval production relationships and can help explain larval dispersion patterns and survival rates.

But larval sampling based on current plankton monitoring techniques is a labor-intensive effort and it will not provide data on larval survival (to spatfall) on specific oyster bars or in individual tributaries. Moreover, oyster larvae are difficult to distinguish from the larvae of other mulluscan species.

During the 1970s, the National Marine Fisheries Service (NMFS) conducted the Marine Resource Monitoring, Assessment, and Prediction Program (MARMAP). This extensive review concluded that larval sampling was not an effective means of monitoring or predicting recruitment [135]. However, several authors have used traditional plankton studies and larval monitoring to correlate physical processes with larval transport dynamics. The yearly variability in physical processes often explains fluctuations in recruitment [139]. Current flow studies at the mouth of the James River [39, 161, 118], conducted concurrently with larval oyster sampling, have provided valuable insights into the mechanisms of larval retention in the estuary. Andrews [8] has shown that river types can be correlated with patterns of larval transport: open-mouth, high-flow rivers correlate with low oyster set; trap-type, low-flow rivers correlate with high oyster set.

Oyster Mortality

The Chesapeake Bay oyster management plan lists both disease mortality and overfishing as two important reasons for declines in oyster stock abundance [47]. Accurate mortality estimates are important to fishery managers attempting to control harvest or direct repletion programs to low-growth, low-disease areas of the Bay. However, it is difficult to generalize about Baywide oyster survival because of the spatial and temporal variation in mortality rates among individual oyster bars and from year to year [176, 52].

State surveys of oyster bars measure mortality by counting dead oysters in dredged samples [98, 124]. In the 1970s, based on these samples, Choptank River researchers often reported mortality rates of between 0% and 5%, with only occasional mortality rates as high as 20%. In the 1980s, however, disease pushed mortality rates to between 30% and 50% on many bars [52].

In addition to disease and overfishing, other factors affecting oyster mortality rates include changes in physiochemical conditions (salinity, temperature, and dissolved oxygen), sedimentation, natural predation, and loss of habitat [116, 45, 171]. Stagg [176] provides a good overview of oyster mortality studies.

Each of the cited mortality factors is discussed below, starting with disease and overfishing, and then proceeding to physiochemical conditions, natural predation, and loss of habitat.

Disease mortality. Disease has decimated oyster populations. Since 1987, high disease levels have been found in market oysters. The epizootic oyster diseases caused by parasitic protozoans *Haplosporidium nelsoni* (MSX) and *Perkinsus marinus* (Dermo) are currently the most serious sources of natural mortality.

Dermo was first recorded in Chesapeake Bay in the early 1950s [9]. But during the 1960s, MSX killed oysters in high-salinity areas of the lower Bay and replaced Dermo as the major source of oyster mortality [6, 9, 65, 80]. In the mid-1960s, MSX eliminated oyster harvests in Tangier Sound and on many leased oyster bars in Virginia [79].

In the last decade, MSX and Dermo have intensified and expanded their ranges in the Bay. After a brief respite, diseases recurred in Maryland waters in the early 1980s, dwindled in 1984-86, and then reappeared at high levels in 1987, and they remain a severe problem in both Maryland and Virginia today [122, 78, 79, 98]. Currently, dredge surveys report high mortality rates, equivalent to the levels of the 1981-85 epizootic outbreak of MSX [97].

The incidence of these diseases—and the accompanying mortality rates—fluctuate depending upon environmental conditions, primarily salinity. High incidence seems to be associated with reduced rainfall and high salinities [122]. Successive drought years from 1985 through 1988, for example, increased salinity and corresponded with a resurgence of MSX and an intensification and spread of Dermo [38, 9, 80]. MSX in particular seems to be sensitive to salinity variations; it is concentrated in high-salinity (15-25 ppt) regimes of the lower Bay. Dermo reaches areas of lower salinity, and the recent spread of this protozoan to upstream tributaries has extended disease mortality to oysters in previously unaffected areas [98].

Disease can affect population fluctuations in two ways: it can directly kill oysters and it can have significant sublethal effects on important parameters such as growth and fecundity. Moreover, disease infection occurs on different time scales: Dermo kills oysters in two years; MSX can kill oysters in several weeks [122]. During the three years required for an oyster to reach market size, cumulative disease mortality can reach 90% of an infected bar [157, 6]

Several authors have described the sublethal effects of diseases on oyster growth, fecundity, and condition [5, 4, 142]. Researchers have described such effects of MSX in terms of reductions in clearance rates and lowered condition index [133], and changes in other physiological parameters such as fecundity [23, 24, 64]. Other MSX disease studies have examined physiological changes in MSX-resistant oysters, including changes in the amounts and activities of hemocytes and other serum proteins [51, 25]. In addition, reduction in growth rates has been observed for oysters infected with Dermo [141].

Disease monitoring is expensive; researchers detect parasites in body fluids and perform histopathological analysis [98]. After two decades of a low profile program, Virginia cut disease monitoring in 1981 only to begin again after the 1980-81 drought opened up new, up-river regions to infection. Today, Virginia [37] and Maryland [98] collect disease information during the annual spat surveys and publish status reports of oyster disease; these reports estimate the intensity and geographic distribution of disease.

Overfishing. In the last 150 years, fishing activity has had the greatest impact on oyster mortality. According to Hargis and Haven [79], "overfishing is the single-most important factor affecting Virginia oyster grounds." Other studies have estimated growth overfishing, recruitment overfishing, and stock overfishing [158]. According to some authors, the evolution of more efficient gear and the resulting intense fishing effort has reduced stock size, modified oyster habitat, and increased fishing effort on remaining bars [45, 94, 157, 158, 22].

Trends in fishing mortality are difficult to ascertain. Mortality estimates have been made using average length in catch data [158] and CPUE [40]. But without good historical records of oyster harvest and other fishery data, estimates of fishing effort range widely according to various assumptions. For instance, whereas Newell [134] has suggested a fishing mortality rate of 10% in 1890, Rothschild et al. [158] calculated a 90% annual mortality (or instantaneous fishing mortality rate of 2.5) for the same period. Rothschild et al. estimated yield-per-recruit and spawning stock biomass as a function of fishing mortality and calculated the 1990 annual mortality as 80% (instantaneous fishing mortality of 1.6), based on a comparison of average age with age at first capture [158].

Using a fishery-dependent model, Cabraal [40] calculated a 30% annual fishing mortality in the early 1970s. More recently, MDNR (M. Homer, pers. comm.) has estimated annual fishing mortality from harvest data using the Leslie-DeLury method. Mean mortalities were estimated to be about 60% in harvested areas and about 48% overall. These values were similar to the 47-56% mortality estimated from Virginia harvest data by Barber and Mann [22].

Whatever the actual mortality figures, overfishing—together with the effects of diseases and bar destruction—has concentrated what is left of the Bay's oyster fishery on remaining oyster bars. According to Barber and Mann [22], the remaining fishery effort has moved into low-salinity regions and has evolved into isolated, independent fisheries.

Physicochemical conditions. Physical and chemical factors that affect adult mortality include temperature, salinity, dissolved oxygen, wave action, currents, bathymetric gradients, light, suspended sediments, siltation, and pH [2, 176, 7, 116, 157]. Freshets caused by large storms, such as Hurricane Agnes, have caused mass mortalities. Periodic hypoxia also may kill oysters [165]; however, studies on the Choptank River [52] showed little correlation between dissolved oxygen and oyster mortality.

Natural predation. Natural predators can also diminish oyster stocks. The animals that most commonly prey on juvenile and adult oysters include oyster drills (*Urosalpinx cinerea* and *Eupleura caudata*), starfish, flatworms (*Stylochus*), crabs (*Callinectes sapidus and Panopeus herbstii*), fish, birds, and rays. Various studies have documented high mortality caused by these predators [99, 31, 130, 61].

Historically, the oyster drill has been an important oyster predator [172]. In recent years, though, predation by swans and cownose rays (*Rhinoptera bonasus)* has become a serious source of concern, particularly for private planters who have lost an entire season's harvest to foraging rays [83].

Unfortunately, annual mortalities attributable to predators are difficult to quantify because there are few reliable data on predator populations [185]. Nonetheless, both the Maryland Oyster Spat and Condition Index Program and the Virginia Spring/Fall Oyster Bar Survey collect data on important oyster predators, including oyster drills and flatworms.

Habitat Loss. Several studies have estimated the extent and condition of oyster habitat. Rothschild et al. [158] described a 50 percent reduction in Maryland bars since the first Yates survey in the 1900s [197]. Using sounding chains, Yates mapped 215,845 acres, or 21% of Maryland bay bottom, as oyster bar and estimated another 300,000 acres, or 29% of bay bottom to be suitable oyster habitat. More recently, surveys using patent tongs and hydroacoustics documented a 50% decline in Maryland oyster bars by the early 1990s [158].

Other studies have described the areal extent and condition of specific oyster bars. As early as 1881, Winslow [196] delineated oyster areas in Tangier Sound and Pocomoke Sound and classified sediment characteristics. Winslow also compared heavily fished bars with nonfished areas as a way to describe fishing effects on habitat. He found fished bars to be spread and enlarged in area, and changed in terms of the associated worms, size of worms, size of clumps, and amount of broken shells [196]. In Virginia, the Baylor survey of the 1890s [27] defined 243,271 acres of public grounds [86]. Other studies have documented habitat conditions in Pocomoke Sound [192, 84].

Rothschild et al. [158] argued that overfishing and habitat destruction are the major causes of oyster declines in Maryland. They suggested that changes in vertical relief and bathymetric gradients can affect oyster mortality. Questions about the characteristics of successful oyster habitat will require more efficient ways of measuring existing bars; DeAlteris [59] has suggested the use of echosounders and side-scan sonar as a way to provide rapid and cost-effective records.

Analytical models. The differential growth and mortality rates between classes, or locations, or between years, present difficult problems for applying Baywide fishery models to oyster stocks. For example, although recent efforts have been made to model oyster growth on the von Bertalanffy growth equation [158], Stagg [176] describes variations from the von Bertalanffy model in several data sets. In addition, there are few growth data for older oysters or estimates of maximum size [158, 176].

Nonetheless, Rothschild et al. [158] described spawning stock biomass and yield-per-recruit curves expressed as a function of fishing mortality rate and age at first capture. Based on model results, these researchers stated that, while reduction in fishing mortality would not increase oyster stocks, rather substantial gains would accrue from an increase in the size of first capture.

Critics of this approach point out limitations to using yield-per-recruit models on a Baywide basis for oyster stocks. Specifically, the fishery includes oysters with differential growth and mortality rates and a nonhomogenous distribution of fishing mortality. Also, significant by-catch mortality in prerecruitment oysters confuses age-specific mortality rates [149].

In another modeling approach, Malinowski and Whitlatch [117] applied a Leslie population matrix to repleted oyster populations. Based on age-specific fecundity values, their results showed that small oysters had 100 times greater reproduction value than market-size adults. This analysis encourages the design of management strategies to protect seed oysters from by-catch mortality or to move juveniles to areas of low disease and low fishing.

As mentioned earlier, Ulanowicz et al. [184] developed a multiple regression model to predict successful spatfall from environmental conditions and fishing activity. There was a close relationship between predicted and actual spatfall from 1965 to 1985. However, spatfall declined between 1986 and 1988 even though the model predicted heavy spatfalls. This discrepancy led some observers to believe that a major change occurred to affect the relationship between oyster stock and recruitment—specifically, a sharp decline in broodstock associated with the MSX epizootic outbreak [72].

Conclusion

Stock assessment will play an important role in any oyster rehabilitation strategy. Information about the size of adult stocks and the factors affecting population trends can be the foundation for effective management action. In the area of fishery management, estimates of suitable rates of harvest will lead to the variety of actions needed to limit fishing mortality. In other areas, too, rehabilitation management programs depend on stock assessment information. Maximizing repletion programs, setting aside broodstock productive sanctuaries, creating new oyster habitat, or introducing new species—all require accurate data and analysis.

To provide the information needed for these management decisions, more fishery-independent data will be required. We can also make better use of existing historical data and we should compare fishery-dependent data with fishery-independent data to calibrate and verify different data gathering approaches. These recommendations and others are included in a report on a 1990 oyster recruitment workshop [124]. They include:

- **Coordinate sampling programs.** Monitoring programs for Virginia and Maryland should be consistent in terms of sampling proce dure, timing of sampling, and the types of data collected and analyzed.

- **Analyze historical data.** The spat and survey data should be analyzed for trends in abundance, recruitment, and market harvest.

- **Estimate stocks based on fishery data.** Leslie-Delury analysis should be applied to reliable harvest and fishing effort data, especially for the James River and the Potomac River.

- **Estimate stocks with quantitative sampling efforts.** Fishery-dependent stock estimates should be compared with statistically based stock assessments, especially for the Potomac River.

- **Develop an oyster recruitment index.** Data on juvenile oysters should be correlated with those on future market oysters, taking disease mortality into account.

- **Monitor cultch with underwater video.** A pilot program should be implemented to assess cultch quality, especially siltation, in key areas.

- **Implement larval monitoring.** To better correlate broodstock with larval production, traditional plankton monitoring programs should be expanded to cover oyster larvae.

- **Expand the use of off-bottom spat collectors.** Stationary spat collectors should be integrated with planktonic larval monitoring to identify potential rehabilitation areas. In addition, to assess the effects of water quality on larval survival, off-bottom spat sampling should be integrated with the suggested larval monitoring effort.

In theory, these recommendations could certainly improve data collection in specific stock assessment data areas. However, to make any impact on the Bay's oyster stock, management must follow through with action. In recent years, many commissions, blue-ribbon panels, and research teams have offered specific recommendations. For example, Haven et al. [85] outlined 60 pages of detailed steps to restore the oyster resource and fishery; most of their recommendations remain valid today. Since 1990, several other studies have provided updated recommendations to rehabilitate the oyster industry [72, 191]. For the most part, state agencies have been reluctant to limit the oyster fishery or to take the bold regulatory steps needed to protect the oyster resource. Now is the time for change. Faced with the lowest oyster harvest in history, agencies have been called on to close the fishery and/or introduce an exotic oyster species (*C. gigas*) into the Bay as a fishery supplement to *C. virginica*. These are difficult decisions that can be made only with sound stock assessment analyses and bold fisheries management leadership.

Conclusions and Recommendations

In its 1990 report, *Research Recommendations*, the Scientific and Technical Advisory Committee (STAC) to the Chesapeake Bay Program estimated the resources (time and funds) needed to support the next 10 years of research [50]. In the section on "Living Resources," STAC noted the following:

> Two general types of management actions will be required to restore and protect living resources. One is improvement of habitat conditions, such as water quality and access to spawning areas. The other is control of factors that directly affect living-resource populations, including harvest and the introduction of exotic species. Research on living resources should provide the basis for managers to design and implement both types of actions.

The above review of stock assessment and the following case studies of three important Bay fishery stocks illustrate three general points that are applicable to management of the Bay's living resources. These points, which are summarized below, can be identified as (1) fishing effort and recruitment variability, (2) quick response to stock decline, and (3) management priorities.

Fishing Effort and Recruitment Variability

Researchers have demonstrated that the probability of a stock decline is related to the level of fishing intensity on the stock and the degree of recruitment variability exhibited by that stock [169]. These two factors work coactively to destabilize a stock and the likelihood of stock collapse increases as both harvesting level and the degree of recruitment variability increase. However, even a constant level of modestly high fishing intensity can cause the collapse if it occurs over a sequence of poor recruitment years.

The impact of these relationships is evident in various world fisheries (e.g., Peruvian anchoveta, Atlantic menhaden, surf clam, and northern shrimp), as well as in fisheries within Chesapeake Bay (e.g., striped bass, American shad, and Eastern oyster). The literature supports the view that fisheries management science cannot yet construct a reliable point-in-time estimate of recruitment. Yet, to reduce the risk of stock collapse, annual harvest should be linked to annual recruitment. Logically, then, the allowable annual harvests should be established (managed) based on measured (juvenile survey) or calculated (VPA) estimates of recruitment and some estimate of an acceptable fishing mortality rate.

The current quota-based Maryland striped bass management program, which derives from the mathematical model of Rugolo and Jones [160], employs this management approach (i.e., juvenile surveys) and should serve, where appropriate, as a model for management of other Chesapeake Bay species. Constraints on more extensive application of this approach stem from the limited availability of required data on other species [20] and the costs of surveys to collect the required data.

Quick Response to Stock Decline

Although fishing mortality may not be the sole cause of stock collapse, it clearly acts synergistically with other natural and anthropogenic causes of unstable recruitment to increase the risk of collapse. A review of fisheries in the Bay and elsewhere in the world also suggests that the impacts of high fishing mortality are particularly significant during periods of stock decline and poor recruitment, as appears to have been the case with striped bass in the Bay. The review also suggests that once stocks have declined, recovery is slow and limited, even when stringent limitations on harvest are put in place. Such appears to be the case with oysters and shad in the Bay. The Maryland moratorium on shad harvest was established in 1980, and although there is some evidence of an increase in some of the Bay's shad stocks, the major stocks have failed to approach historical population levels [150].

The key point to be drawn from these observations is that management actions taken to reduce or limit the level of fishing mortality experienced by an exploited stock contribute most effectively to maintaining acceptable stock levels if they are implemented prior to or during the early stages of a stock decline. Similar or even more stringent measures taken after significant decline or collapse are often ineffective in stimulating stock recovery.

Reproductive success (i.e., recruitment) serves as a predictive indicator of future stock status, in that low reproduction will be evidenced in a decline in harvestable fish when that particular yearclass reaches a harvestable age and size. More importantly, low recruitment serves as an early warning indicator of potential low spawning stock size in the future, which, if further reduced owing to high exploitation, could result in recruitment failure and stock collapse. Thus, monitoring recruitment and imposing substantial harvest restrictions at the first sign of significant recruitment decline or failure could prevent the collapse and long-term depression of fish and shellfish stocks that are now experiencing high exploitation rates.

Management Priorities

Fish and shellfish stocks can be ranked in order of need for management according to either the degree of variability in their annual recruitment or the intensity of exploitation to which they are exposed. Because the risk of stock collapse in large measure hinges on these two causal factors, stocks that experience highly variable recruitment or high exploitation, or both, are the ones most likely to ultimately collapse. Conversely, stocks known to be experiencing low fishing mortality rates or that exhibit fairly stable levels of recruitment are at low risk of collapse, unless exposed to catastrophic natural events (e.g., Hurricane Agnes) or anthropogenic environmental changes. An allocation of even limited funds to implement management programs in Chesapeake Bay based on recruitment variability or levels of fishing mortality may enhance the cost effectiveness of living resources management.

Decisions on which species to manage and how they should be managed require the application of such primary stock assessment tools as VPA, yield-per-recruit models, specialized simulation models, and a variety of techniques for estimating mortality rates. Use of these tools is predicated on the availability of ample data on such measures as size and age composition of catches, stock-specific harvest and fishing effort levels, growth and mortality rates, and annual recruitment rates.

However, such data still remain unavailable for most of the Bay's species and stocks. And, although CBSAC's stock assessment plan for the Bay [45] established a program and schedule for acquiring these data, fairly lengthy time series of data will be needed to fully implement these management methods, and such time series will not be available for many more years. That suggests that the monitoring of recruitment and the initiation of management measures in response to observed recruitment declines may be the only feasible interim means of protecting heavily fished stocks. Accordingly, it is evident that current fisheries management priorities for the Bay must continue to focus on recruitment-related issues.

References

1. Abbe, G.R. 1982. Growth, mobility and copper accumulation by oysters (*Crassostrea v.*) at the Morgantown Steam Electric Station on the Potomac River. J. Shellfish Res. 2:3-14.
2. Abbe, G.R. 1986. A review of some factors that limit oyster recruitment in Chesapeake Bay. American Malacological Bull., Special Edition No. 3:59-70.
3. Abbe, G.R. 1988. Population structure of the American oyster, *Crassostrea virginica*, on an oyster bar in central Chesapeake Bay: Changes associated with shell planting and increased recruitment. J. Shellfish Res. 7(1):33-40.
4. Abbe, G.R. and J.G. Saunders. 1988. Rapid decline in oyster condition in Patuxent River, MD. J. Shellfish. Res. 7(1):57-59.
5. Andrews, J.D. 1965. Infection experiments in nature with *Dermocystidium marinum* in Chesapeake Bay. Ches. Sci. 6:60-67.
6. Andrews, J.D. 1979. Oyster diseases in Chesapeake Bay. Mar. Fish. Rev. 41:45-53.
7. Andrews, J.D. 1982. Anaerobic mortality of oysters in Virginia caused by low salinities. J. Shellfish Res. 2(2):127-133.
8. Andrews, J.D. 1983. Transport of bivalve larvae in James River, Virginia. J. Shellfish Res. 3(1):29-40.
9. Andrews, J.D. 1988. Epizootiology of the disease caused by the oyster pathogen *Perkinsus marinus* and its effects on the oyster industry. Amer. Fish. Soc. Spec. Publ. 18:47-63.
10. Applegate, A.J. 1983. An environmental model predicting the relative recruitment success of the blue crab, *Callinectes sapidus*, in Chesapeake Bay, Virginia. Gloucester Point, VA: College of William and Mary. Thesis, 73 pp.
11. Atlantic States Marine Fisheries Commission. 1981. Interstate fisheries management plan for the striped bass. Washington, DC. In: National Marine Fisheries Service Cooperative Agreement NA-80-FA-00017, 204 pp.
12. Atlantic States Marine Fisheries Commission. 1986. Supplement to the Atlantic menhaden fishery management plan. Fisheries Management Rep. No. 8, 107 pp.
13. Atlantic States Marine Fisheries Commission. 1989. Amendment 4 to the Atlantic States Marine Fisheries Commission striped bass management plan. 60 pp.
14. Atlantic States Marine Fisheries Commission. 1990. Source document for the supplement to the striped bass fisheries management plan—amendment 4. Columbia: MD: Prepared by Versar Inc., Fishery Management Rep. No. 16, 402 pp.
15. Austin, H.M. 1984. Status of striped bass fisheries in Virginia after implementation of the 1984 emergency regulations. Gloucester Point, VA: Virginia Institute of Marine Science, Virginia Mar. Res. Rep. 84-4, 25 pp.
16. Austin, H.M. 1985. Status of 1984 striped bass fisheries in Virginia after implementation of the 1984 emergency regulations to the 1981 ASMFC interstate management plan for striped bass. Gloucester Point, VA: Virginia Institute of Marine Science, Virginia Mar. Res. Rep. 85-5, 13 pp.
17. Austin, H.M. 1986. Status of 1985 striped bass fisheries in Virginia after implementation of the 1985 amendment 3 to the 1981 ASMFC interstate management plan for striped bass. Gloucester Point, VA: Virginia Institute of Marine Science, Virginia Mar. Res. Rep. 86-3, 15 pp.
18. Austin, H.M. 1988. Contribution of the 1982 and subsequent yearclass females to the Virginia 1987 commercial and recreational harvest. Gloucester Point, VA: Virginia Institute of Marine Science, Virginia Mar. Res. Rep. 88-8, 12 pp.
19. Austin, H.M. and C. Furman. 1987. Status of stocks knowledge: Report of the status of stocks knowledge work group to the CBSAC, December 1987, 96 pp.
20. Austin, H.M., C. Furman, and D.R. Scoles. 1990. Chesapeake Bay Stock Assessment Committee annual report, 1989. Chesapeake Bay Stock Assessment Committee Rep. TRS-90-1, 115 pp.
21. Bacher, C., A.L. Chai, and P. Goulletquer. 1991. Use of the kriging method for oyster stock assessment in the Chesapeake Bay. In: Assessment of the natural and repletion population of American oyster *Crassostrea virginica* in the Chesapeake Bay. Solomons, MD: University of Maryland Center for Environmental and Estuarine Studies, Chesapeake Biological Laboratory, Ref. No. [UMCEES] CBL 091-049, 117-154.
22. Barber, B.J. and R. Mann. 1990. Estimation of standing crop of oysters in the James River, Virginia, using commercial fishing records. CBSAC/NOAA Annual Rep., 1989, 115 pp.
23. Barber, B.J., S.E. Ford, and H.H. Haskin. 1988a. Effects of parasitic MSX (*Minchinia nelsoni*) on oyster energy metabolism. I: Condition index and relative fecundity. J. Shellfish Res. 7(1):25-31.
24. Barber, B.J., S.E. Ford, and H.H. Haskin. 1988b. Effects of parasitic MSX (*Minchinia nelsoni*) on oyster energy metabolism. II: Tissue biochemical composition. Comp. Biochem. Physiol. 91A:603-608.
25. Barber, B.J., S.E. Ford, and D.T.J. Littlewood. 1991. A physiological comparison of resistant and susceptible oysters *Crassostrea virginica* exposed to the endoparasite *Haplosporidium nelsoni*. J. Exp. Mar. Biol. Ecol. 146:101-112.
26. Barth, E. 1991. Report on the 1990 striped bass fishery in Virginia to the ASMFC Striped Bass Technical Committee. Newport News, VA: Virginia Marine Resources Commission, Fisheries Management Division, 10 pp.

27. Baylor, J.B. 1894. Method of defining and locating natural oyster beds, rocks and shoals. Oyster Records Pamphlets, Board of Fisheries in Virginia, 777 pp.
28. Beaven, G.F. 1950. Growth observations of oysters held in trays at Solomons Island, MD. Proc. National Shellfish Assoc. 1949:43-49.
29. Beaven, G.F. 1953. Some observations on rate of growth on oysters in the Maryland area. Proc. National Shellfish Assoc. 43:90-98.
30. Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. United Kingdom Ministry of Agriculture & Fisheries, Fish. Invest. (Ser. 2) 19, 533 pp.
31. Bisker, R. and M. Castagna. 1987. Predation on single spat oyster, *Crassostrea virginica*, by blue crab, *Callinectes sapidus* and mud crab, *Panopeus herbstii*. J. Shellfish Res. 6(1):37-40.
32. Bonzek, C.F. and P.W. Jones. 1984. Assessment of the population dynamics of important commercial and recreational fish in Chesapeake Bay: An atlas of commercial fisheries statistics in Maryland and Virginia, 1929-1980. Maryland Dept. of Natural Resources, Tidewater Admin. Fisheries Division, Technical Memo. No. 5, 379 pp.
33. Bonzek, C.F., P.J. Geer, J.A. Colvocoresses, and R.E. Harris. 1991. Juvenile finfish and blue crab stock assessment program bottom trawl survey. Gloucester Point, VA: Virginia Institute of Marine Science, Annual Rep. Ser., Vol. 1990, VIMS SSR-124, 206 pp.
34. Bradley, B. and M. Roberts. 1987. Effects of contaminants on estuarine zooplankton. In: Majumdar, S., L. Hall, and H. Austin, eds. Contaminant problems and management of living Chesapeake Bay resources. State College, PA: University of Pennsylvania Press, 417-441.
35. Brown, B.E. and G.P. Patil. 1986. Risk analysis in the Georges Bank haddock fishery in a pragmatic example of dealing with uncertainty. North Amer. J. Fish. Mgmt. 6:183-191.
36. Bundy, M. M. 1991. A regional economic evaluation of Maryland's oyster industry. In: Mihursky, J.A. and A. Chaney, eds. New perspectives in the Chesapeake system: A research and management partnership. Proc. of a conference, December 4-6, 1990, Baltimore, MD. Annapolis, MD: Chesapeake Research Consortium Publ. No. 137, 381-390.
37. Burreson, E.M. 1991. Status of the major oyster diseases in Virginia–1990. A summary of the annual monitoring program. Virginia Mar. Res. Rep. 90-1, 17 pp.
38. Burreson, E.M. and J.D. Andrews. 1988. Unusual intensification of Chesapeake Bay oyster diseases during recent drought conditions. Proc. Oceans 88:799-802.
39. Byrne, R. 1987. Newport Island: An evaluation of potential impacts on marine resources of the lower James River and Hampton Roads. Gloucester Point, VA: Virginia Institute of Marine Science, Spec. Sci. Rep. in Applied Mar. Sci. and Ocean Eng. [SRAMSOE] No. 283, 28 pp.
40. Cabraal, R.A. 1978. Systems analysis of the Maryland oyster fishery: Production management and economics. College Park, MD: University of Maryland. Agricultural engineering dissertation, 318 pp.
41. Campbell, D.W. and R.H. Forste. 1978. The biological and economic aspects of oyster propagation in Maryland. Maryland Dept. of Natural Resources, Rep. No. FA-MRR-78-2, 33 pp.
42. Chai, Ai-Ling. 1988. Variability of American oyster recruitment and harvest and blue crab distribution in the Maryland portion of the Chesapeake Bay. College Park, MD: University of Maryland. Thesis.
43. Chai, Ai-Ling, Huaixiang Li, B.J. Rothschild, and D.S. Robson. 1991. A comprehensive sampling design and 1991 sampling program for oyster stock assessment in the Maryland portion of Chesapeake Bay. In: Assessment of the natural and repletion population of American oyster *Crassostrea virginica* in the Chesapeake Bay. University of Maryland, Center for Environmental and Estuarine Studies, final rep. on contract F199-90-008, CEES 07-4-30230, submitted to Maryland Dept. of Natural Resources, Ref. No. [UMCEES] CBL 091-049, 23-116.
44. Chesapeake Bay Commission. 1982. Chesapeake Bay fisheries management primer. Annapolis, MD: Chesapeake Bay Commission Rep., 28 pp.
45. Chesapeake Executive Council. 1988. Chesapeake Bay program: Stock assessment plan, agreement commitment Rep., 66 pp.
46. Chesapeake Executive Council. 1989a. Chesapeake Bay blue crab management plan. Annapolis, MD, agreement commitment rep., 29 pp.
47. Chesapeake Executive Council. 1989b. Chesapeake Bay oyster management plan. Annapolis, MD, agreement commitment rep., 28 pp.
48. Chesapeake Executive Council. 1990. Annual progress report: Chesapeake Bay alosid, blue crab, and oyster fishery management plans. Annapolis, MD: U.S. Environmental Protection Agency, Chesapeake Bay Program, 38 pp.
49. Chesapeake Research Consortium. 1982. Report of workshop on Chesapeake Bay fisheries statistics. Fredericksburg, VA, July 12-13, 1982. Chesapeake Research Consortium Publ. No. 107, 111 pp.
50. Chesapeake Research Consortium. 1990. Research recommendations for the Chesapeake Bay program: A ten-year focus. Scientific and Technical Advisory Committee, Chesapeake Bay Program, Chesapeake Research Consortium Publ. No. 138, 32 pp.
51. Chintala, M.M. and W.S. Fisher. 1991. Disease incidence and potential mechanisms of defense for MSX-resistant and-susceptible Eastern oysters held in Chesapeake Bay. J. Shellfish Res. 10(2):439-443.
52. Christmas, J.F. and S.J. Jordan. 1991. Choptank River oyster mortality study: An analysis of

biological and physicochemical data associated with a study of seven Choptank River oyster bars 1986-1988. Maryland Dept. of Natural Resources, Tidewater Administration, Chesapeake Bay Research and Monitoring Division, Report No. CBRM-HI-91-1, 26 pp.
53. Colvocoresses, J.A. 1988. Intercalibration and refinement of estimates of abundance of Chesapeake Bay juvenile striped bass. Gloucester Point, VA: Virginia Institute of Marine Science, final report, award #NA85-EAH-00026, project 1.2, task 2, 28 pp.
54. Colvocoresses, J.A. and H.M. Austin. 1987. Development of an index of juvenile striped bass abundance for the Chesapeake Bay system: I. An evaluation of present measures and recommendations for future studies. Gloucester Point, VA: Virginia Institute of Marine Science, Special Scientific Rep. No. 120, 108 pp.
55. Cosden, D.T. and R.K. Schaefer. 1990. Maryland striped bass juvenile survey. In: Investigation of striped bass in Chesapeake Bay. U.S. Fish & Wildlife Service, Federal Aid Project F-42-R-2, 1988-1989. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration, 205 pp.
56. Costanza, R. 1987. Social traps and environmental policy. Bio. Sci. 37(6):407-412.
57. Crecco, V. 1988. Equilibrium yield model to assess alternate harvest allocations for striped bass from Chesapeake Bay and along the Atlantic coast. Windsor Locks, CT: Rep. to the ASMFC Striped Bass Scientific Committee, 30 August 1988, 27 pp.
58. Cushing, D.H. 1974. A link between science and management in fisheries. Fish. Bull. 72(4):859-863.
59. DeAlteris, J.T. 1988. Applications of hydroacoustics to mapping of subtidal oyster reefs. J. Shellfish Res. 7(1):41-45.
60. Eberhardt, L.L. 1977. Relationship between two stock-recruitment curves. J. Fish. Res. Bd. Can. 34:425-428.
61. Eggleston, D. 1988. Predator-prey dynamics between blue crab, *Callinectes sapidus*, and juvenile oyster, *Crassostrea virginica*. Williamsburg, VA: College of William and Mary. Thesis, 181 pp.
62. Elser, H. J. 1965. Chesapeake Bay creel census, 1962. University of Maryland Natural Resources Institute Rep. NRI 65-17.
63. Finger, S.E. 1991. Survival of striped bass larvae in Maryland and Virginia tributaries to Chesapeake Bay. NOAA/USFWS, Emergency striped bass study. Norfolk, VA: Annual workshop (abstracts), February 12-13, 1991, pp. 102-110.
64. Ford, S.E. and A.J. Figueras. 1988. Effects of sublethal infection by the parasite *Haplosporidium nelsoni* (MSX) on gametogenesis, spawning, and sex ratios of oysters in Delaware Bay, USA. Diseases of Aquatic Organisms 4:121-133.
65. Ford, S.E. and H.H. Haskin. 1988. Management strategies for MSX (*Haplosporidium nelsoni*) disease in Eastern oysters. Amer. Fish. Soc. Spec. Publ. 18:249-256.
66. Galtsoff, P.S. 1964. The American oyster, *Crassostrea virginica* Gmelin. Fish. Bull. 64:1-480.
67. Goodrich, D.M., J. van Montfrans, and R.J. Orth. 1989. Blue crab megalopal influx to Chesapeake Bay: Evidence for a wind driven mechanism. Estu. Coast. Shelf Sci. 29:247-260.
68. Goodyear, C.P. 1984. Analyses of potential yield per recruit for striped bass produced in Chesapeake Bay. N. Amer. J. Fish. Mgmt. 4(4B):488-496.
69. Goodyear, C.P. 1985. Toxic materials, fishing, and environmental variation: Simulated effects on striped bass population trends. Trans Amer. Fish. Soc. 114:107-113.
70. Goodyear, C.P and S.W. Christensen. 1984. On the ability to detect the influence of spawning stock on recruitment. N. Amer. J. of Fish. Mgmt. 4:186-193.
71. Goodyear, C.P., J.E. Cohen, and S.W. Christensen. 1985. Maryland striped bass: Recruitment declining below replacement. Trans Amer. Fish. Soc. 114:146-151.
72. Governor's Committee. 1990. The role of the State of Maryland in oyster fisheries management. Recommendations of the Governor's Committee to review state policy for funding Maryland's Chesapeake fisheries, 91 pp.
73. Grant, G.C. 1974. The age composition of striped bass catches in Virginia rivers, 1967-1971, and description of the fishery. Fish. Bull. 72:193-199.
74. Gulland, J.A., ed. 1988. Fish population dynamics: The implications of management. 2d ed. New York: John Wiley & Sons, 422 pp.
75. Hall, L.W. 1987. Acidification effects on larval striped bass, *Morone saxatilis*, in Chesapeake Bay tributaries: A review. Water, Air, and Soil Pollution 35:87-96.
76. Hall, L.W. 1988. Studies of striped bass in three Chesapeake Bay spawning habitats. Marine Pollution Bull. 19:478-487.
77. Hall, L.W., S.J. Bushong, M.C. Ziegenfuss, W.S. Hall, and R.L. Herman. 1988. Concurrent mobile on-site and in situ striped bass contaminant and water quality studies in the Choptank River and upper Chesapeake Bay. Environmental Toxicology and Chemistry 7:815-830.
78. Hargis, W.J., Jr. and D.S. Haven. 1988a. Rehabilitation of the troubled oyster industry of the lower Chesapeake Bay. J. Shellfish Res. 7(2):271-279.
79. Hargis, W.J. Jr. and D.S. Haven. 1988b. The imperiled oyster industry of Virginia: A critical analysis with recommendations for restoration. Gloucester, VA: Virginia Institute of Marine Science, Spec. Sci. Rep. in Applied Mar. Sci. and Ocean Eng. [SSRAMSOE] No. 190.
80. Haskin, H.H. and J.D. Andrews. 1988. Uncertainties and speculations about the life cycle of the Eastern oyster pathogen *Haplosporidium nelsoni* (MSX). Amer. Fish. Soc. Spec. Publ. 18:5-22.
81. Hassler, W.W., N.L. Hill, and J.T. Brown. 1981. The

status and abundance of striped bass, *Morone saxatilis*, in the Roanoke River and Albemarle Sound, North Carolina, 1956-1980. North Carolina Dept. of Natural Resources and Community Development, Div. of Marine Fisheries, Special Scientific Rep. No. 38, 156 pp.

82. Haven, D. 1982. The impact of low salinities on James River oyster population 1979-1980. Virginia Institute of Marine Science, Spec. Sci. Rep. in Applied Mar. Sci. and Ocean Eng. [SSRAMSOE] No. 258, 18 pp.
83. Haven, D. 1987. The American oyster, *Crassostrea virginica*, in Chesapeake Bay. In: Majumdar, S., L. Hall, and H. Austin, eds. Contaminant problems and management of living Chesapeake Bay resources. State College, PA: University of Pennsylvania Press, 65-176.
84. Haven, D.S. and J.P. Whitcomb. 1986. The public oyster bottom in Virginia: An overview of their size, location, and productivity. Am. Malacol Bull., Special edition, 3:17-23.
85. Haven, D.S., W.J. Hargis, Jr.; and P. Kendall. 1978. The oyster industry of Virginia: Its status, problems and promise. Gloucester Point, VA: Institute of Marine Science, Spec. Paper in Marine Science No. 4, 1024 pp.
86. Haven, D.S., J.P. Whitcomb, and P. Kendall. 1981. Present and potential productivity of the Baylor grounds in Virginia. Vol. I and Vol. II. Gloucester Point, VA: Virginia Institute of Marine Science Spec. Sci. Rep. in Applied Mar. Sci. and Ocean Eng. [SSRAMSOE] No. 243.
87. Houde, E.D. and E.S. Rutherford. 1992. Egg production, spawning biomass and factors influencing recruitment of striped bass in the Potomac River and Upper Chesapeake Bay. Report to Maryland Dept. of Natural Resources, Contract Number CB89-001-003. UMCEES Report No. CBL92-107.
88. Johnson, D. and K.W. Hess. 1990. Numerical simulations of blue crab larval dispersal and recruitment. Bull. Mar. Sci. 46(1):195-213.
89. Jones, C.M., J.R. McConaugha, P.J. Geer, and M.H. Prager. 1990b. Estimates of spawning stock size of blue crab, *Callinectes sapidus*, in Chesapeake Bay, 1986-1987. Bull. Mar. Sci. 46(1):159-169.
90. Jones, P.W., J.S. Wilson, H.R. Lunsford, and M.A. Cole. 1978. Potomac River Fisheries study: Striped bass spawning stock assessment. Interpretive report for 1977. Solomons, MD: University of Maryland, Chesapeake Biological Laboratory, CEES Ref. No. 78-75 CBL.
91. Jones, P.W., J.S. Wilson, R.P. Morgan, H.R. Lunsford, and J. Lawson. 1977. Potomac River fisheries study: Striped bass spawning stock assessment. Interpretive report for 1974-1976. Solomons, MD: University of Maryland, Chesapeake Biological Laboratory, CEES Ref. No. 77-55 CBL.
92. Jones, P.W., H.J. Speir, N.H. Butowski, R. O'Reilly, L. Gillingham, and E. Smoller. 1990a. Chesapeake Bay fisheries status, trends, priorities, and data needs. Annapolis, MD: Maryland Dept. of Natural Resources/Virginia Marine Resources Commission, Joint MDNR-VMRC Rep., 240 pp.
93. Jones. R. 1961. The assessment of long-term effects of changes in gear selectivity and fishing effort. Mar. Res. (Scotland), 1961(2)1-19.
94. Kennedy, V.S. and L.L. Breisch. 1983. Sixteen decades of political management of the oyster fishery in Maryland's Chesapeake Bay. J. Env. Manage. 16:153-171.
95. Kohlenstein, L.C. 1980. Aspects of the population dynamics of striped bass (*Morone saxatilis*) spawning in Maryland tributaries of the Chesapeake Bay. Baltimore, MD: Johns Hopkins University, JHU/PPSE T-14. Dissertation.
96. Koo, T.S.Y. 1970. The striped bass fishery in the Atlantic states. Ches. Sci. 11(2):73-93.
97. Krantz, G.E. 1991. Maryland oyster population status report: 1990 fall survey. Annapolis, MD: Maryland Dept. of Natural Resources, Chesapeake Bay Research and Monitoring Division Rep. CBRM-OX-91-1.
98. Krantz, G.E. 1992. Maryland oyster population status report: 1991 fall survey. Annapolis, MD: Maryland Dept. of Natural Resources, Chesapeake Bay Research and Monitoring Division Rep. CBRM-OX-92-1.
99. Krantz, G.E. and J.V. Chamberlin. 1978. Blue crab predation on cultchless oyster spat. Proc. Natl. Shellfish Assoc. 68:38-41.
100. Krantz, G.E. and H.H. Davis. 1983. Maryland oyster spat survey: Fall 1982. University of Maryland Sea Grant Program Tech. Rep. UM-SG-TS-83-01.
101. Krantz, G.E. and D. S. Haven. 1982. A study of the present state of oyster statistics in Chesapeake Bay and suggested remedial measures. In: Cronin, L.E., ed. Solomons, MD: CBL-UMCEES, report of a workshop on Chesapeake Bay fisheries statistics. Chesapeake Research Consortium Pub. No. 107, 44-50.
102. Krantz, G.E. and D.W. Meritt. 1977. An analysis of trends in oyster spat set in the Maryland portion of the Chesapeake Bay. Proc. Natl. Shellfish Assoc. 67:53-59.
103. Larkin, P.A. 1988. The future of fisheries management: Managing the fisherman. Fisheries 13(1):3-9.
104. Lipcius, R.N. and W.A. Van Engel. 1990. Blue crab population dynamics in Chesapeake Bay: Variation in abundance (York River, 1972-1989) and stock-recruit functions. Bull. Mar. Sci. 46(1):180-194.
105. Lippson, A.J. and R.L. Lippson. 1984. Life in the Chesapeake Bay. Baltimore, MD: Johns Hopkins University Press, 229 pp.
106. Lippson, A.J., M.S. Haire, A.F. Holland, F. Jacobs, J. Jenson, R. L. Moran-Johnson, T.T. Polgar, and W.A. Richkus. 1979. Environmental atlas of the Potomac estuary. Prepared for Maryland Dept. of

Natural Resources, Power Plant Siting Program. Baltimore, MD: Martin Marietta Corp., Environmental Center, 280 pp.
107. Lipton, D. 1989. The status of Maryland's fishing industry. College Park, MD: University of Maryland Sea Grant Extension, 27 pp.
108. Loesch, J.G. and W.H. Kriete. 1984. Striped bass research, Virginia. Part II: Characterization of Virginia's striped bass commercial fisheries, October 1982-September 1983. Gloucester Point, VA: Virginia Institute of Marine Science Rep. AFC-12-2, 21 pp.
109. Loesch, J.G. and W.H. Kriete. 1985. Striped bass research in Virginia. Part II. Characterization of Virginia's striped bass commercial fisheries, October 1983-September 1984. Gloucester Point, VA: Virginia Institute of Marine Science Rep. AFC-16-1, 27 pp.
110. Loesch, J.G., B.W. Hill, and P.W. Sadler. 1991. A mark-recapture study of striped bass in the Rappahannock River, Virginia. Annual report 1989/1990. Gloucester Point, VA: Virginia Institute of Marine Science Sport Fish Restoration Project F77-R, 31 pp.
111. Loosanoff, V.L. and C.A. Nomejko. 1949. Growth of oysters *C. virginica* during different months of the year. Biol. Bull. 47:82-84.
112. Logan, P.T. 1985. Environmental variation and striped bass population dynamics: A size dependent mortality model. Estuaries 8:28-38.
113. McConaugha, J.R. 1988. Export and reinvasion of larvae as regulators of estuarine decapod populations. Am. Fish. Soc. Symp. 3:90-103.
114. McHugh, J.L. 1972. Marine fisheries of New York State. Fish. Bull. 70:585-610.
115. MacKenzie, C.L., Jr. 1983. To increase oyster production in the northeastern United States. Mar. Fish. Rev. 45(3):1-23.
116. Mackin, J.G. 1961. Mortalities of oysters. Proc. Natl. Shellfish. Assoc. 50:21-40.
117. Malinowski, S. and R.B. Whitlatch. 1988. A theoretical evaluation of shellfish resource management. J. Shellfish Res. 7(1):95-100.
118. Mann, R. 1988. Distribution of bivalve larvae at a frontal system in the James River, Virginia. Mar. Ecol. Prog. Serv. 50:29-44.
119. Mansueti, R.J. 1961. Effects of civilization on striped bass and other estuarine biota in Chesapeake Bay and tributaries. In: Proc. Gulf and Caribbean Fisheries Institute, 14th Annual Session. Solomons, MD: Chesapeake Biological Laboratory, 110-136.
120. Marshall, A. and J. Lucy. 1981. Virginia's charter and head boat fishery: Analysis of catch and socioeconomic impacts. Gloucester Point, VA: Virginia Institute of Marine Science, Spec. Sci. Rep. in Applied Mar. Sci. and Ocean Eng. [SSRAMSOE] No. 253, 90 pp.
121. Maryland Department of Natural Resources. 1985 to 1990. Annual status report on striped bass. Annapolis, MD: MDNR, Tidewater Administration, Fisheries Division.
122. Maryland Department of Natural Resources. 1987. Status & Trends 1987: Maryland's oyster resources Report. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration, Fisheries Divison, 63 pp.
123. Maryland Department of Natural Resources. 1990a. Investigation of striped bass in Chesapeake Bay. Annapolis, MD: U.S. Fish & Wildlife Service Federal Aid Project F-42-R-2, 1988-1989, 209 pp.
124. Maryland Department of Natural Resources. 1990b. Summary and recommendations of the oyster recruitment and standing stock monitoring workshop. Horn Point Laboratory, November 6-7, 1990. 32 pp.
125. Maryland Department of Natural Resources. 1991. Initiation of patent tong-based oyster stock assessment in Maryland Chesapeake Bay. Data summary, 1991. Maryland Tidewater Administration, Fishery Division, Spec. Rep. No. 6.
126. Merriman, D. 1952. Striped bass, fact or fiction? New York State Conservationist 6(6):2-4.
127. Meritt, D.W. 1977. Oyster spat set on natural cultch in the Maryland portion of the Chesapeake Bay (1939-1975). University of Maryland, Center for Environmental and Estuarine Studies, CEES Spec. Rep. No. 7, 30 pp.
128. Middle Atlantic Fishery Management Council (MAFMC). 1988. Amendment #8 to the fishery management plan for the Atlantic surf clam and ocean quahog fishery. NOAA, National Marine Fisheries Service, 144 pp.
129. Miller, R.J. 1990. Properties of a well-managed nearshore fishery. Fisheries 15(5):7-13.
130. Morales-Almo, R., C. Cox, K. McCarthy, and R. Mann. 1988. Seasonal abundance of oyster spat and four animals associated on an oyster reef in the James River, Virginia. J. Shellfish Res. 7(3):401-406.
131. Murphy, G. 1965. A solution of the catch equation. J. Fish. Res. Board Can. 22:191-202.
132. Neville, W.C. 1942. The striped bass problem. Proc. Atlantic States Marine Fisheries Commission first annual meeting, September 18, 1942.
133. Newell, R.I.E. 1985. Physiological effects of the MSX parasite *Haplosporidium nelsoni* (Haskin, Stanber and Mackin) on the American oyster *Crassostrea virginica* (Gmelin). J. Shellfish Res. 5:91-95.
134. Newell, R.I.E. 1988. Ecological changes in Chesapeake Bay: Are they the result of overharvesting the American oyster, *Crassostrea virginica?* In: Lynch, M.P. and E.C. Krome, eds. Understanding the estuary: Advances in Chesapeake Bay research. Proc. of a conference, March 29-31, 1988, Baltimore, MD. Annapolis, MD: Chesapeake Research Consortium Publ. No.129, 536-546.
135. National Marine Fisheries Service. 1972. Program Development Plan (PDP) for MARMAP.

MARMAP Program Office, NMFS/NOAA.
136. National Oceanic and Atmospheric Administration. 1990a. Status of the fisheries resources off the northeastern United States for 1990. Washington, DC: National Marine Fisheries Service, NOAA Tech. Memo. NMFS-F/NEC-81, 130 pp.
137. National Oceanic and Atmospheric Administration. 1990b. Chesapeake Bay Stock Assessment Committee annual report 1989. Joint NOAA/CBSAC Rep., 115 pp.
138. Nicholson, L., ed. 1986. Striped bass fishery management plan (Gulf of Mexico). Ocean Springs, MS: Gulf States Marine Fisheries Commission, Publ. No. 16, 119 pp.
139. Norcross, B. and R. Shaw. 1984. Oceanic and estuarine transport of fish eggs and larvae: A review. Trans. Amer. Fish. Soc. 113:153-165.
140. Pauly, D. 1987. Managing the Peruvian upwelling ecosystem: A synthesis. In: Pauly, D. and I. Tsukayama, eds. The Peruvian anchoveta and its upwelling ecosystem: Three decades of change. International Center for Living Aquatic Resources Management (ICLARM), ICLARM Studies and Reviews 15, 351 pp.
141. Paynter, K.T. and E.M. Burreson. 1991. Effects of *Perkinsus marinus* infection in the Eastern oyster, *Crassostrea virginica*: II. Disease development and impact on growth rate at different salinities. J. Shellfish. Res. 10:425-431.
142. Paynter, K.T and M.E. Mallonee. 1991. Site-specific growth rates of oysters in Chesapeake Bay and impact of disease. In: Mihursky, J.A. and A. Chaney, eds. New perspectives in the Chesapeake system: A research and management partnership. Proc. of a conference, December 4-6, 1990, Baltimore, MD. Annapolis, MD: Chesapeake Research Consortium Publ. No. 137, 391-399.
143. Polgar, T.T. 1977. Striped bass ichthyoplankton abundance, mortality and production estimation for the Potomac River population. In: Van Winkle, W., ed. Proc. of a conference on assessing the effects of power plant-induced mortality on fish populations. New York: Pergamon Press, 110-126.
144. Polgar, T.T. 1980. Is striped bass a manageable resource? In: Clepper, H., ed. Fifth Annual Marine Recreational Fisheries Symposium. Washington, DC: Sport Fishing Institute.
145. Prager, M.H. and A.D. MacCall. 1990. Assessing effects of aging errors on fishery yield models. In: Chesapeake Bay Stock Assessment Committee annual report, 1989. Joint NOAA/CBSAC Report, 61-64.
146. Pratt, H. S. 1935 (1951 ed.). A manual of the common invertebrate animals. Philadelphia, PA: The Blakiston Co., 854 pp.
147. Prou, J., P. Goulletquer, and C. Bacher. 1991. Modeling of oyster shell growth. In: Assessment of the natural and repletion population of American oyster *Crassostrea virginica* in the Chesapeake Bay. Solomons, MD: University of Maryland, Center for Environmental and Estuarine Studies. Final rep. submitted to Maryland Dept. of Natural Resources, Ref. No. (UMCEES)CBL091-049, 204-219.
148. Rago, P.J., R.M. Dorazio, R.A. Richards, and D.G. Deuel. 1991. Emergency striped bass research study report for 1990. U.S. Dept of the Interior, U.S. Fish & Wildlife Service, Washington, DC: Dept. of Commerce, National Marine Fisheries Service.
149. Richkus, W.A., J.K. Summers, T.T. Polgar, and A.F. Holland. 1980. A review and evaluation of fisheries stock management models, Part I—Text. Prepared for Maryland Dept. of Natural Resources, Coastal Resources Div., Tidewater Admin., Baltimore, MD, by Martin Marietta Corp., 63 pp.
150. Richkus, W.A., P. Jacobson, A. Ranasinghe, A. Shaughnessy, J. Chaillou, P. Kazyak, C. DeLisle, R. Batiuk, and D. Packer. 1991. Characterization of the current status of key resource species in the basins of the Chesapeake Bay. Columbia, MD: Prepared for U.S. Environmental Protection Agency Chesapeake Bay Program by Versar Inc., 402 pp.
151. Ricker, W.E. 1940. Relation of catch per unit effort to abundance and rate of exploitation. J. Fish. Res. Bd. Can. 5:43-70.
152. Roedel, P. M., ed. 1975. Optimum sustainable yield as a concept in fisheries management. Proc. symposium of the American Fisheries Society, September 9, 1974, Honolulu, HI. Washington, DC: American Fisheries Society, Spec. Publ. No. 9, 89 pp.
153. Rothschild, B.J. 1986. Dynamics of marine fish populations. Cambridge, MA: Harvard Univerity Press, 277 pp.
154. Rothschild, B.J., P.W. Jones, and J.S. Wilson. 1981. Trends in Chesapeake Bay fisheries. Transactions of the 46th North American Wildlife and Natural Resources Conference. Washington, DC: Wildlife Management Institute, 3-17.
155. Rothschild, B.J., C.M. Stagg, K.S. Knott, G.T. Dinardo, and A. Chai. 1988. Blue crab stock dynamics in Chesapeake Bay. Solomons, MD: University of Maryland, Center for Environmental and Estuarine Studies, Chesapeake Biological Laboratory, UMCEES(CBL)88-51, 163 pp.
156. Rothschild, B.J., B. Golden, P. Goulletquer, J.S. Ault, A.L. Chai, Q. Wang, M. Heral, C. Bacher, and J. Prou. 1990. Rehabilitation of the Maryland oyster industry: Assessment of the natural and repletion population of oyster in Chesapeake Bay. Solomons, MD: Report of the Chesapeake Biological Laboratory to Maryland Dept. of Natural Resources. University of Maryland CMCEES(CBL)90-131.
157. Rothschild, B. J., J. S. Ault, P. Goulletquer, C. F. Tsai, M. Homer, A. L. Chai, H. Li, B. Golden, Q. Wang, M. Heral, C. Bacher, and J. Prou. 1991a. Assessment of the natural and repletion popula-

tion of American oyster, *Crassostrea virginica*, in the Chesapeake Bay. Solomons, MD: University of Maryland, Center for Environmental and Estuarine Studies. Final rep. submitted to Maryland Dept. of Natural Resources, Ref. No. (UMCEES) CBL 091-049, 239 pp.

158. Rothschild, B.J., J.A. Ault, P. Goulletquer, W.P. Jensen, and M. Heral. 1991b. The decline of Chesapeake Bay oyster populations: A century of habitat destruction and overfishing. In: Assessment of the natural and repletion population of American oyster *Crassostrea virginica* in the Chesapeake Bay. Solomons, MD: University of Maryland, Center for Environmental and Estuarine Studies. Final rep. submitted to Maryland Dept. of Natural Resources, Ref. No. (UMCEES)CBL091-049, 1-18.
159. Rounsefell, A.H. 1975. Ecology, utilization and management of fisheries. St. Louis, MO: C. V. Mosby Co., 516 pp.
160. Rugolo, L. and P. Jones. 1989. A recruitment-based interseason harvest model for Chesapeake Bay striped bass. Annapolis, MD, Maryland Dept. of Natural Resources, Chesapeake Bay Research and Monitoring Division. Unpub. ms, 31 pp.
161. Ruzecki, E.P. and W.J. Hargis, Jr. 1989. Interaction between circulation of the estuary of the James River and transport of oyster larvae. In: B.J. Nelson, J. Brubaker, and A. Kuo, eds. Estuarine circulation. The Humana Press. Inc.
162. Schaefer, R.K., R.H. Bradford, J.L. Markham, and H.T. Hornick. 1990. Characterization of striped bass stocks in Maryland. In: Investigation of striped bass in Chesapeake Bay. U.S. Fish & Wildlife Service, Federal Aid Project F-42-R-3, 1989-1990. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration Rep., 1-74.
163. Schaefer, M.B. 1954. Some aspects of the dynamics of populations important in the management of the commercial marine fisheries. Inter-Amer. Trop. Tuna Comm. Bull. 1(2):26-56.
164. Schaefer, M.B. 1957. A study of the dynamics of the fishery for yellowfin tuna in the Eastern Tropical Pacific Ocean. Inter-Amer. Trop. Tuna Comm. Bull. 2(6):247-285.
165. Seliger, H.H. and J.A. Boggs. 1988. Evidence for loss of suitable benthic habitats for oysters in tributaries of the Chesapeake Bay. In: Lynch, M.P. and E.C. Krome, eds. Understanding the estuary: Advances in Chesapeake Bay research. Proc. of a conference, March 29-31, 1988, Baltimore, MD. Annapolis, MD: Chesapeake Research Consortium, Publ. No. 129, 111-127.
166. Setzler, E.M., W.R. Boynton, K.V. Wood, H.H. Zion, L. Lubbers, N. K. Mountford, P. Frere, L. Tucker, and J.A. Mihursky. 1980. Synopsis of biological data on striped bass, *Morone saxatilis* (Walbaum). NOAA Tech. Rep., NMFS Circular 433, 69 pp.
167. Setzler-Hamilton, E.M. 1991. Habitat requirements for striped bass *Morone saxatilis* (Walbaum). Solomons, MD: University of Maryland System, Center for Environmental and Estuarine Studies, Chesapeake Biological Laboratory, 105 pp.
168. Shaw, W.N. 1966. The growth and mortality of seed oysters, *C. virginica* from Broad Creek, Chesapeake Bay Maryland in high- and low-salinity waters. Proc. Natl. Shellfish Assoc. 56:59-63.
169. Sissenwine, M.P., M.J. Fogarty, and W.J. Overholtz. 1988. Some fisheries management implications of recruitment variability. In: Gulland, J.A., ed. Fish population dynamics: Implications for management. New York: John Wiley & Sons, 129-152.
170. Smith, T. D. 1988. Stock assessment methods: The first fifty years. In: Gulland, J.A., ed. Fish Population Dynamics: Implications for Management. New York: John Wiley & Sons, 1-34.
171. Snyder, E. 1988. Distribution and taxonomy of endolithic algae occurrence in the shells of *Crassostrea virginica* throughout the lower James River, VA. Williamsburg, VA: College of William and Mary. Thesis, 130 pp.
172. Soniat, T.M. and M.S. Brody. 1988. Field validation of a habitat suitability index model for the American oyster. Estuaries 11(2):87-95.
173. Speir, H.J., D.R. Weinrich, and R.S. Early. 1977. 1976 Maryland Chesapeake Bay sport fishing survey. Annapolis, MD: Maryland Dept. of Natural Resources Rep., 23 pp.
174. Speir, H.J., W.R. Carter, S. Early, R. Lunsford, and M. Burch. 1983a. Population structure of striped bass in commercial landings in Maryland Chesapeake Bay, 1981-1982. National Marine Fisheries Service, Federal Aid Rep., Project No. AFC-11, Job 4. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration, Fisheries Division.
175. Speir, H.J., W.R. Carter, S. Early, R. Lunsford, M. Burch, and J. Foster. 1984. Population structure of striped bass in commercial landings in Maryland Chesapeake Bay, 1982-1983. National Marine Fisheries Service, Federal Aid Rep., Project No. AFC-11, Job 4. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration, Fisheries Division.
176. Stagg, C. 1986. An evaluation of the information available for managing Chesapeake Bay fisheries: Preliminary stock assessments, volumes I and II. The American oyster. Solomons, MD: University of Maryland, Center for Environmental and Estuarine Studies, Chesapeake Biological Laboratory. Dissertation, 11-43.
177. Stagg, C. and K. Knotts. 1991. Survey of the Maryland 1987-1989 and Virginia 1988 commercial blue crab (*Callinectes sapidus*) pot fisheries. Unpub. rep., July, 1991, 99 pp.
178. Stevens, E.E., D.W. Kohlhorst, L.W. Miller, and D.W. Kelly. 1985. The decline of striped bass in the

Sacramento-San Joaquin Estuary, California. Trans. Amer. Fish. Soc. 114:12-30.

179. Summers, J.K., H.W. Hoffman, and W.A. Richkus. 1983a. Randomized sample survey designs to estimate annual blue crab harvest in a multi-gear fishery in the Maryland waters of Chesapeake Bay. N. Amer. J. Fish. Mgmt. 3:9-21.
180. Summers, J.K., W.A. Richkus, H.W. Hoffman, C. Bonzek, H.H. King, and M. Burch. 1983b. Application of random sample survey designs to estimate the commercial blue crab harvest in Maryland. N. Amer. J. Fish. Mgmt. 3:21-25.
181. Summers, J.K. and K.A. Rose. 1987. The role of interactions among environmental conditions in controlling historical fisheries variability. Estuaries 10:255-266.
182. Tang, Q. 1985. Modification of the Ricker stock recruitment model to account for environmentally induced variation in recruitment with particular reference to the blue crab fishery in Chesapeake Bay. Fish. Res. 3:13-21.
183. Tsai, Chu-fa and B.J. Rothschild. 1990. Assessment of the natural and "repletion" population of oysters in the Chesapeake Bay. In: Chesapeake Bay Stock Assessment Committee annual report 1989. NOAA/CBSAC, 115 pp.
184. Ulanowicz, R.E. and T.T. Polgar. 1980. Influence of anadromous spawning behavior and optimal environmental conditions upon striped bass (*Morone saxatilis*) year-class success. Can. J. Fish. Aquat. Sci. 37:143-154.
185. Ulanowicz, R.E., W.C. Caplins, and E.A. Dunnington. 1980. The forecasting of oyster harvest in central Chesapeake Bay. Estua. and Coast. Mar. Sci. 11:101-106.
186. Uphoff, J.H. 1989. Environmental effects on survival of eggs, larvae, and juveniles of striped bass in the Choptank River, Maryland. Trans. Amer. Fish. Soc. 118:251-263.
187. Uphoff, J.H. 1992. Striped bass egg and larval survival in the Choptank River. Maryland Dept. of Natural Resources, Tidwater Administration, Chesapeake Bay Research and Monitoring Division CBRM-HI-92-1, 28 pp.
188. U.S. Environmental Protection Agency. 1983. Chesapeake Bay: A profile of environmental change, Chapt. 2, Living Resources: A history of biological change, 83-186. In: Environmental Protection Agency (EPA). Chesapeake Bay: A framework for action. Philadelphia PA, 186 pp.
189. Van Engel, W.A. 1987. Factors affecting the distribution and abundance of the blue crab in Chesapeake Bay. In: Majumdar, S.K., L. W. Hall and H. M. Austin, eds. Contaminant Problems and Management of living Chesapeake Bay resources, ch. 10, pp. 117-209. Penn. Acad. Sci., 573 pages.
190. van Montfrans, J., C.A. Peery, and R.J. Orth. 1990. Daily, monthly and annual settlement patterns by *Callinectes sapidus* and *Neopanope sayi* megalopae on artificial collectors deployed in the York River, Virginia, 1985-1988. Bull. Mar. Sci. 46(1):214-229.
191. Virginia Sea Grant Program. 1990. A plan addressing the restoration of the American oyster industry. Charlottesville, VA: University of Virginia, Sea Grant College Program, Sea Grant Publ. VSG-90-02, 64 pp.
192. Whitcomb, J.P. and D.S. Haven. 1987. The physiography and extent of public oyster grounds in Pocomoke Sound, Virginia. J. Shellfish Res. 6:55-65.
193. Williams, J.B., T.P. Smith, H.J. Speir, and R.S. Early. 1983. 1980 Maryland saltwater sport fishing survey. Annapolis, MD: Maryland Dept. of Natural Resources, Tidewater Administration Rep. No. TA-CRD-83-1,
194. Wilson, J.S., R.P. Morgan, G.B. Grey, F.W. Jones, J. Lawson, and R. Lunsford. 1974. Potomac River fisheries study: Striped bass spawning stock assessment. Final rep. Solomons, MD: Chesapeake Biological Laboratory Ref. No. 75-91,
195. Wilson, J.S., R.P. Morgan, P.W. Jones, J. Lawson, R. Lunsford, and S. Murphy. 1975. Potomac River fisheries study: Striped bass spawning stock assessment. Final rep. Solomons, MD: Chesapeake Biological Laboratory Ref. No. 76-14,
196. Winslow, F. 1881. Deterioration of American oyster beds. Popular Science Monthly. 20:45-156.
197. Yates, C.C. 1913. Summary of survey of oyster bars in Maryland, 1906-1912. Washington, DC: U.S. Dept. of Commerce, U.S. Coast and Geodetic Survey, 80 pp.
198. Zuboy, J.R. and A.C. Jones. 1980. Everything you always wanted to know about MSY and OY (but were afraid to ask). National Oceanic & Atmospheric Administration, Technical Memorandum NMFS F/SEC-17, 19 pp.