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BLUE CRAB TARGET SETTING

FINAL REPORT

Prepared For

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EXECUTIVE SUMMARY

The fishery for blue crab (*Callinectes sapidus*) is the most valuable commercial fishery in Chesapeake Bay. In 1997, 69 million lbs. were landed with dockside value of \$73 million. A large, but unquantified amount, is taken by recreational crabbers. Ecologically, blue crab is an important benthic predator. In turn, it is prey for several predatory fish. Sound management of this resource to insure a sustainable population is critical. It is important to establish targets to protect the resource and judge the efficacy of management actions.

We have developed a hierarchy of target levels, designated to address sustainability, efficiency, and recovery scenarios. Targets were derived from 1) reported catches and effort in the commercial fishery, 2) statistics from fishery-independent surveys, and 3) knowledge of the biology of blue crab. Targets that are recommended include population sizes, catches, and effort levels, as well as reference fishing mortality rates. They are intended to be conservative and risk-averse. Proposed targets will promote a sustainable and economically viable fishery, while protecting the ecological value of the blue crab in Chesapeake Bay. In the hierarchy, the first targeting level is one that designates population abundances and fishing mortality rates to insure sustainability of the resource. A second level of targeting insures that the maximum reproductive potential per crab is obtained over the long term. The final targeting level is one that recommends a population abundance and fishing mortality rate to insure a growing crab population.

The assessment and analyses included in this report bear many similarities to those presented by the CBSAC Technical Committee in their stock assessment of blue crab. Our report differs, however, by concluding that the change initiated in 1981 in Maryland's statistical reporting of commercial blue crab landings had a major effect on the landings time series. The net effect is that our adjusted statistics and analyses indicate that the blue crab has been fished more heavily, and that stock abundance has declined recently and is lower than the CBSAC Committee believed. The CBSAC Committee had concluded that stock abundance had increased in the 1980s and then returned to average levels in the 1990s.

A major difficulty in analyzing blue crab stock dynamics is the uncertainty associated with aging crabs and its potential effects on determining growth and mortality rates. Like the CBSAC Committee, we explored various scenarios of maximum age to derive estimates of a range of probable mortality and exploitation rates. We reconstructed a commercial landings time series based upon the adjusted landings, after 'correcting' the Maryland statistics from 1945 to 1980. From the time series and from fishery-independent surveys, we estimated population abundances, biomasses, maximum sustainable yields (MSY), fishing effort to obtain MSY, fishing mortality rates, exploitation rates, yield per recruit, spawning potential per recruit, and relationships between spawning stock and recruitment. In a novel assessment of blue crab population dynamics, we developed a life-stage-based model in both aggregated and spatially-explicit forms to determine what life stages are most critical for future population growth and stability of blue crab in Chesapeake Bay.

Tier 1: Sustainability Limit

We analyzed fishery-independent, fishery-dependent and life history information on blue crab in Chesapeake Bay. The spatial and temporal coverage of the data varied considerably. The winter dredge survey, supported by NOAA's Chesapeake Bay Stock Assessment Committee (CBSAC), is the only Bay-wide index of crab abundance that has been consistently collected. Unfortunately, this survey has been conducted for only 9 years and is not of sufficient duration to reach conclusions about the dynamics of blue crab in the Bay. Consequently, conclusions on the relationship between population abundance and exploitation must stem from analyses that combine data of differing resolutions to make Bay-wide inferences.

A time-series intervention analysis and other lines of evidence supported our decision to adjust Maryland landings statistics for 1945-1980. Estimated baywide landings in those years were increased substantially as a consequence of the adjustment. The adjusted mean annual landings from 1945-1996 were 84.6 million lbs in contrast to 69.7 million lbs based upon the unadjusted landings. We believe that the long-term potential yield of the blue crab commercial fishery in Chesapeake Bay lies in the range 80-100 million lbs. Based upon the adjusted landings data, there is little evidence that overall commercial landings of blue crab have changed much during the >50 years included in the landings time series. The upper bound of the long-term potential yield 'target' level is a risky choice, especially since information on possible trends in recreational fishery catches are lacking. A preferable commercial fishery target is near 80 million lbs.

Effort in the commercial fishery has increased progressively over the years. Recent landings have only been maintained by a substantial increase in effort. Based upon our adjusted landings statistics, catch-per-unit-effort continued to decline, at least through the mid-1980s. This observation indicates that stock abundance probably has been declining throughout the time series and supports our risk-averse recommendation of a target, long-term potential yield near 80 million lbs rather than 100 million lbs.

Our estimate of MSY (99 million lbs), based upon the adjusted landings time series, also indicates that increases in commercial landings above levels in recent years may not be sustainable, especially when viewed with respect to present levels of effort and the declining catch-per-unit-effort. Effort in the fishery during the past 15 years has been greater than that required to obtain MSY. In fact, effort to obtain MSY ($\sim 450,000 \text{ pot} \cdot \text{hrs} \cdot \text{month}^{-1}$) has been exceeded by $\sim 100,000 \text{ pot} \cdot \text{hrs} \cdot \text{month}^{-1}$ in recent years. MSY and its respective effort level should not be targets in a risk-averse blue crab fishery, but rather should be considered upper 'limits,' above which the stock is likely to decline.

A target fishing mortality rate of approximately $F \# 0.9$ may maintain blue crabs at the stock level believed capable of supporting the long-term potential yield from the commercial fishery. Our estimates of baywide abundance of potentially catchable crabs that can support that level of yield is ~ 1 billion crabs with a biomass of ~ 300 million lbs. Blue crab numbers have declined in the 1990s and exploitation rate from fishing has increased. Fishing mortality rates

>1.0, now being observed, may not allow catches to be maintained at high and sustainable levels.

Estimates of fishing mortality rate in the fishery indicate that F has ranged from 0.6 - 1.3, with sharp increases and highest levels in the most recent years. This supports our conclusion that increased effort has maintained landings at near-constant levels. The evidence points to a need to reduce effort to insure the sustainability of high yields in the fishery. An effort level and fishing mortality rate that would leave 10% of the virgin spawning potential in the population is often used to manage productive crustacean fisheries. Basing our sustainability target on this reference point, $F_{10\%}$ is ~ 0.9 . This level of exploitation may insure that the stock will not collapse due to reproductive or recruitment failure, but it is too high to allow the fishery to be most productive in either a biological or economic sense.

Tier 2: Efficiency Target

Our analysis of the yield to the fishery for every blue crab that recruits to it, strongly suggests that the productivity of the fishery would improve if fishing effort decreased. The fishery is technically “growth overfished,” meaning that the present fishing mortality rates are too high to obtain the maximum yield per recruit from the fishery. Although there is no evidence at present of a declining trend in recruitment, reducing effort would increase abundance and average size of crabs in the stock, in addition to increasing profitability in the fishery. Our analyses suggest that F should be reduced to ~ 0.6 to maximize yield per recruit and lower still to maximize profitability. That level may be viewed as an ‘efficiency’ target.

If F declined to ~ 0.6 , the spawning potential of blue crab would increase to $\sim 20\%$ of that in the virgin, unfished population from a level that is $<10\%$ in the most recent years. Although blue crab is resilient to reductions in adult stock and no trend in recruitments is apparent, we found evidence in our stock-recruitment analysis that low adult stocks only infrequently were associated with high recruitments. In this sense, reducing present F from ~ 1.0 to ~ 0.6 or lower may increase average recruitment levels and contribute to the stability of the fishery.

There also may be ecological advantages derived from implementing a reduction in F . There is clear evidence of a decreasing trend in the average size of crabs collected in the fishery-independent Calvert Cliffs pot survey. Reducing F would cause the size structure of the current population to shift to favor larger crabs. This would produce a population more closely resembling the historical size structure and is likely to have two benefits. Increases in average size of adult crabs will increase reproductive potential because there is an allometric relationship between fecundity and female size, and some evidence of an allometric relationship between male size and sperm production. Larger crabs may also be more capable of multiple matings. Additionally, increases in average size would increase the predation pressure that blue crab exerts in the benthic community. If blue crab is a keystone predator that controls benthic community structure, allowing its historical size-distribution to redevelop may have important community-wide effects.

Tier 3: Recovery Target

The third targeting level in our hierarchy is useful in the context of possible future needs to manage for population recovery in the event of precipitous, unexpected declines of blue crab. The stage based model results indicated that abundance of mature females, proportion of age 1 crabs recruiting into the fall fishery, and overwinter mortality on pre-recruit crabs were likely to exercise the most control on potential growth of the blue crab population. Management actions directed at reducing mortality of those life stages are likely to have positive results with respect to population growth rates of blue crab. Though preliminary, modeling results indicated that F would have to be reduced substantially from present levels to insure increase in population growth rate. The stage based model indicated that $F < 0.5$ would be required to insure a positive rate of population increase. This target F may not represent the ideal long-term level of exploitation, since the population clearly has withstood higher rates of exploitation. However, it is a level of F that guarantees high probability of positive population growth and can be regarded as a contingency level to foster recovery should the blue crab stock require such management action in the future.

Management Options and Monitoring Needs

Management options that may be effective to attain goals and targets, determined in part from stage based-modeling of blue crab, to reduce the fraction of age-1 crabs that reach recruitable size and become vulnerable to the fishery include increases in size limits during the fall fishery, or reducing effort in late-summer and fall peeler pot fishery. Reductions in fishing effort in the winter dredge fishery also may be beneficial to stabilize long-term abundance in the population, although this approach alone would not be sufficient to achieve such stability. In our analysis, an overall reduction in fishing mortality of approximately 30% from present levels would benefit the fishery and would be protective of the long-term ecological benefits that accrue from a healthy and resilient blue crab population in Chesapeake Bay.

Continuous monitoring of the blue crab stock is essential to know its status and to develop effective management actions. The fishery has been essentially healthy, although productivity of the stock and quality of the fishery may be improved by reducing fishing mortality. The temporal and spatial variability in elements of the fishery and the spatially-explicit nature of the crab population must be understood better to improve modeling of the stock and its management. Programs to determine trends and variability in the recreational fishery need to be instituted, and the recreational landings eventually must be considered in stock assessments of blue crab in Chesapeake Bay.

TABLE OF CONTENTS

f f f f f f f f f f

1. INTRODUCTION	1
1.1 STOCK ASSESSMENT AND FISHERY MANAGEMENT PLAN	2
1.2 DATA, ANALYSIS, AND MODELS	3
1.3 OBJECTIVES	4

f f f f

2. STOCK ASSESSMENT PARAMETER ESTIMATION	7
2.1 ANALYSIS OF BLUE CRAB ABUNDANCE	7
2.1.1. Fishery-dependent Survey Time Series	8
2.1.1. a. Smith Island Scrape Survey	8
2.1.2 Fishery-independent Survey Time Series	8
2.1.2.a. VIMS Trawl Survey	9
2.1.2.b. Calvert Cliffs Pot Survey	10
2.1.2.c. MD DNR Trawl Survey	11
2.1.2.d. CBSAC Winter Dredge Survey	13
2.1.2.e. Coherence in Combined Fishery Independent Survey Time Series.	.14
2.1.3. Commercial Data	14
2.1.3.a Analysis of Commercial Landings Time Series.	14
2.2. LIFE HISTORY PARAMETERS	18
2.2.1. Spawning Season and Early Development	18
2.2.2. Age and Growth	18
2.2.2.a. Maximum Age	19
2.2.2.b. Growth	19
2.2.3. Maturity	20
2.2.4. Fecundity	21
2.3 PARTIAL RECRUITMENT	21
2.3.1 Estimation of Partial Recruitment Vector.	21

f f f f

3. SURPLUS PRODUCTION MODELING	65
3.1 EQUILIBRIUM SURPLUS PRODUCTION MODELS	65
3.2. NON-EQUILIBRIUM SURPLUS PRODUCTION MODELING	66

f f f f

4. EXPLOITATION RATES AND STOCK SIZE ESTIMATION	75
4.1 EXPLOITATION RATES	75
4.1.1. Mortality rates	75
4.1.2. Exploitation Rates	76
4.2 STOCK SIZE ESTIMATES	77

f f f f

5. YIELD PER RECRUIT MODELING	97
-------------------------------------	----

f f f f

6. STOCK AND RECRUITMENT MODELING	103
6.1 CLASSICAL S-R MODELS OF BLUE CRAB	103
6.2 NON-PARAMETRIC S-R MODELS OF BLUE CRAB	105
6.2.1. Markov Models	105
6.2.2. Non-Parametric Density Function Approach	107
6.3 SUMMARY	108

f f f f

7. STAGE-BASED MODELING	115
7.1. MODEL FORMAT	115
7.2. PARAMETER ESTIMATION	117
7.2.1. Proportion of megalopae surviving	118
7.2.2. Proportion of 1 yr olds vulnerable to the pot fishery.	118
7.2.3. Overwinter survival rate.	118
7.2.4. Fecundity.	118
7.2.5. Spatially-explicit model parameters	119
7.3. MATRIX FORMULATION	119
7.4. MODEL RESULTS	120
7.4.1. Aggregate Model	120
7.4.2. Spatially-explicit model	121
7.4.2.a Regulation of the dredge fishery	122
7.4.2.b Protection of migrating females	122

f f f f

8. DEVELOPMENT OF POPULATION TARGETS	137
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8.1. TIER 1 TARGET–SUSTAINABLE POPULATION ABUNDANCE 137
8.2. TIER 2 TARGET–ABUNDANCE WITH HIGHEST PRODUCTIVITY 139
8.3. MANAGEMENT APPROACHES TO ACHIEVE TARGETS 139
8.4. MONITORING AND RESEARCH NEEDS 140
 8.4.1. Resolution of landings and effort data 140
 8.4.2. Fishery-independent data 140
 8.4.3. Growth trajectories 140
 8.4.4. Spatially-explicit management 140
8.5 CONCLUDING STATEMENTS 141

f f f f

REFERENCES 144

f f f f

APPENDIX A. BLUE CRAB YPR 149

f f f f

APPENDIX B. RESPONSE TO REVIEWERS 157

f f f f

LIST OF TABLES



Table 1. Smith Island Scrape survey CPUEs	24
Table 2. Results of Smith Island scrape survey conducted in 1987 (Rothschild et al. 1988) ...	25
Table 3. VIMS juvenile finfish and blue crab trawl survey CPUEs.	26
Table 4. Results of time series analysis of CPUE of age-0 crabs from VIMS juvenile finfish and blue crab trawl survey data utilizing a mean term	27
Table 5. Results of time series analysis of CPUE of age-0 crabs VIMS juvenile finfish and blue crab trawl survey data utilizing mean and 1 st order autoregressive terms	28
Table 6. Results of time series analysis of CPUE of age -1 +crabs from VIMS juvenile finfish and blue crab trawl survey utilizing a mean term	29
Table 7. Results of time series analysis of CPUE of age-1 crabs from VIMS juvenile finfish and blue crab trawl survey data utilizing a mean and 1 st order autoregressive terms	30
Table 8. Calvert Cliffs pot survey CPUEs	31
Table 9. Results of time series analysis of total CPUE for Calvert Cliffs pot survey data utilizing mean and 1 st order autoregressive terms	32
Table 10. Results of time series analysis of CPUE of age-0 crabs for Calvert Cliffs pot survey data utilizing mean and 1 st order autoregressive terms	33
Table 11. MD DNR Trawl Survey CPUEs	34
Table 12. Results of time series analysis of CPUE of age-0 crabs in MD DNR trawl survey utilizing a mean term	35
Table 13. Results of time series analysis of CPUE of age-0 crabs in MD DNR trawl survey utilizing mean and 1 st order autoregressive terms	36
Table 14. Results of time series analysis of CPUE of age-1+ crabs in MD DNR trawl survey utilizing mean term and 1 st order autoregressive terms	37
Table 15. Results of time series analysis of CPUE of age-1+ crabs in MD DNR trawl survey	

utilizing mean term and 1 st order autoregressive terms	38
Table 16. CBSAC winter dredge survey CPUEs	39
Table 17. Commercial landings (lbs x 10 ³) of blue crab landed by category and state for 1945 - 1997	40
Table 18. Average annual commercial landings (lbs x 10 ³) of blue crab by decade from Chesapeake Bay	42
Table 19. Results of time series analysis of Maryland commercial landings (1945-1997) utilizing mean and 1 st order autoregressive terms	43
Table 20. Results of time series analysis of Maryland commercial landings (1945-1996) utilizing mean and intervention terms	44
Table 21. Results of time series analysis of Maryland commercial landings (1945-1996) utilizing mean, 1 st order autoregressive and intervention (pre- and post-1981) terms	45
Table 22. Results of time series analysis of Virginia commercial landings utilizing mean and 1 st order autoregressive terms	46
Table 23. Comparison of unadjusted and adjusted time series of commercial landings	47
Table 24. Published estimates of expected maximum age, \bar{a} , and age at maturity, a_m , for blue crab	48
Table 25. Estimated values for the partial recruitment of age-1 crabs, PR_1 , given variable levels of under-reporting	49
Table 26. Schaefer model fits for blue crab fishery in Chesapeake Bay (1945 - 1996)	68
Table 27. Difference equation surplus production model fits for blue crab fishery in Chesapeake Bay (1945 - 1996)	69
Table 28. Parameter estimated used in developing length-based estimates of Z	79
Table 29. Length-based estimates of Z and F for A) VIMS trawl survey, B) Calvert Cliffs pot survey, C) MD NDR trawl survey and D) CBSAC winter dredge survey	80
Table 30. Mean annual exploitation rates as a function of maximum expected age, \bar{a} and the partial recruitment of age-1 crabs, PR_1 , for 1956 - 1997	86
Table 31. Estimates of blue crab stock sizes (biomass and abundance)	87

Table 32. Yield per recruit reference points for Chesapeake Bay blue crab	100
Table 33. Distribution of observed stock and recruitment indices categorized with reference to their median levels	109
Table 34. Distribution of transitions between the four stages in the stock-recruitment plane .	110
Table 35. Predicted expected probabilities of occurrence of Chesapeake Bay blue crab in each stage of the stock-recruitment plane	111
Table 36. Expected first passage times for Chesapeake Bay blue crab S-R data	112
Table 37. Definitions of Chesapeake Bay regions used in estimating model parameters	124
Table 38. Average abundance estimates for each region of Chesapeake Bay	125
Table 39. Parameter estimates for aggregate model	126
Table 40. Parameter estimates for spatially-explicit model	127
Table 41. Recommended targets for Chesapeake Bay blue crab	143

LIST OF FIGURES



Figure 1. Flow chart indicating the integration of data into the modeling and assessment framework adopted to develop targets for blue crab	6
Figure 2. Time series of CPUE for components of the populations from the Smith Island scrape survey (1948 - 1972)	50
Figure 3. Time series of CPUE from the experimental Smith Island scrape survey conducted in 1987	51
Figure 4. Mean carapace width (CW) of crabs collected in experimental Smith Island scrape survey	52
Figure 5. Maps showing the spatial coverage of the principle fishery independent surveys. A) Calvert Cliffs pot survey, B) CBSAC winter dredge survey, C) MD DNR trawl survey, and D) VIMS juvenile fish and blue crab survey	53
Figure 6. Time series of CPUE for components of the population from the VIMS juvenile fish and blue crab trawl survey indices (1968 - 1998)	54
Figure 7. Time series of total CPUE for the Calvert Cliffs pot survey (1968 - 1997)	55
Figure 8. Time series of CPUE for components of the population for the Calvert Cliffs pot survey (1968 - 1998). Components plotted are A) total age-1 crabs, B) total age-2 crabs, C) legal female crabs, and D) legal male crabs	56
Figure 9. Time series of CPUE for components of the population for the MD DNR trawl survey (1988 - 1997). Components are A) age-2+ crabs, B) age-1 crabs, and C) age-0 crabs ..	57
Figure 10. Time series of CPUE for components of the population for the CBSAC winter dredge survey (1989-1998). Components are A) mature female crabs, B) age-1+ crabs, and C) age-0	58
Figure 11. Cross-correlation analysis of CPUE of age-1+ crabs from the VIMS trawl survey with the CPUE of legal crabs in the Calvert Cliffs pot survey	59
Figure 12. Cross-correlation analysis of CPUE of age-0 crabs from the VIMS trawl survey with the CPUE of legal crabs in the Calvert Cliffs pot survey	60
Figure 13. Commercial landings of blue crab (Lbs x10 ³) landed by category and state for the	

period 1945-1996. Categories plotted are hard shell, soft shell and combined landings for A) Maryland, B) Virginia, and C) Bay wide	61
Figure 14. Mean percent deviations of landings from time series mean by decade for A) Maryland, B) Virginia , and C) Bay wide	62
Figure 15. Adjusted time series of commercial landings (Lbs x 10 ³) for A) Maryland, B) Virginia, and C) Baywide for the period 1945-1996	63
Figure 16. Comparison of continuous and discontinuous descriptions of crab growth dynamics (after Smith 1997)	64
Figure 17. Time series of estimated Bay wide CPUE (lbs @pot ⁻¹) for 1945-1996	70
Figure 18. Unadjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996)	71
Figure 19. Adjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996)	72
Figure 20. Time series of unadjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996)	73
Figure 21. Time series of adjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996)	74
Figure 22. Carapace width-based estimates of total mortality derived from an analysis of the catches in the VIMS juvenile finfish and blue crab survey	88
Figure 23. Carapace width-based estimates of fishing mortality rates derived from an analysis of the catches in the VIMS juvenile finfish and blue crab survey	89
Figure 24. Mean annual exploitation rates as a function of the partial recruitment of age-1 crabs for three different growth models for the soft and peeler component of the fishery based upon fishery-independent estimates of F derived from A) Calvert Cliffs and B) VIMS	90
Figure 25. Time series of annual exploitation rates derived from time series of two fishery-independent estimates of F. For all panels the partial recruitment of age-1 crabs was set = 0.67. Expected maximum age = 6. Time series shown are A) Calvert Cliffs-based estimates, and B) VIMS-based estimates	91
Figure 26. Time series of annual exploitation rates derived from time series of two fishery-independent estimates of F	92

Figure 27. Time series of estimated total population biomass of blue crab in Chesapeake Bay based upon exploitation rates derived from the VIMS trawl survey	93
Figure 28. Time series of estimated total population biomass of blue crab in Chesapeake Bay based upon exploitation rates derived from the Calvert Cliffs pot survey	94
Figure 29. Time series of estimated total population abundance of blue crab in Chesapeake Bay based upon exploitation rates derived from the VIMS trawl survey	95
Figure 30. Time series of estimated total population abundance of blue crab in Chesapeake Bay based upon exploitation rates derived from the Calvert Cliffs pot survey	96
Figure 31. Relationship between yield per recruit (YPR -- heavy line - left ordinate), % spawning per recruit (SPR -- light line, right ordinate) and reference points $F_{0.1}$, F_{max} , $F_{20\%}$, $F_{10\%}$ and $F_{5\%}$	101
Figure 32. YPR and SPR curves for blue crab in Chesapeake Bay	102
Figure 33. Stock-recruitment curve for blue crab	113
Figure 34. Cumulative recruitment probability distributions for three stock sizes	114
Figure 35. Life cycle graph for blue crab	128
Figure 36. A spatially-explicit life cycle diagram for blue crab	129
Figure 37. Relationship between the intrinsic rate of natural increase of the population, r and the fishing mortality rate, F , as a function of the partial recruitment of age-1 crabs	130
Figure 38. Reproductive values of each stage in the aggregate model	131
Figure 39. Growth elasticity of each life history stage in the aggregate model	132
Figure 40. Reproductive values of each stage in the spatially-explicit model model	133
Figure 41. Growth elasticity of each life history stage in the spatially-explicit model	134
Figure 42. Migration elasticity of each life history stage in the spatially-explicit model	135
Figure 43. Relationship between the intrinsic rate of natural increase of the population, r and the fishing mortality rate, F , for two different management options	136

1. INTRODUCTION

An important measure of our success of our stewardship of Chesapeake Bay will be the ability to maintain, restore, and enhance its living resources. One method to focus attention and activities on goals is to establish targets for key living resources. Targets can be envisaged in many forms and may serve different purposes. Restoration targets may be established, as they have for submerged aquatic vegetation or anadromous alosids in the Chesapeake Bay Program (Chesapeake Executive Council, Directive 93-3 and 93-4). These abundance targets, whether measured in terms of aerial coverage (seagrasses), or tributary-specific abundances (aloids) provide goals to focus tasks in conservation efforts. For commercially and recreationally exploited species, targets can help to define the status of stocks and probable status under alternative management strategies. In some cases, habitat-related targets, such as SAV acreage, may seem little related to fisheries targets, such as threshold or optimum fishing mortality rates for striped bass. But, the ecology of Chesapeake Bay species is often intricately linked because they rely on the same habitat at some point in their life histories, or they respond similarly to environmental forcing, or they interact in trophic relationships that are habitat-specific (Houde et al. 1998). Target-setting is an important step toward defining and understanding the implications of managing living resources for a “healthy” Chesapeake Bay.

Blue crab (*Callinectes sapidus*) is a widely recognized symbol of the Chesapeake Bay region. Important coastal and estuarine fisheries for blue crab occur from the Gulf of Mexico, along the Atlantic coast of the United States, and as far north as New England. In 1996, 31% of the US blue crab catch came from Chesapeake Bay, with a dockside value of \$73 million (NMFS 1997). Beside its economic importance, blue crab plays a central role in the ecology of Chesapeake Bay. Thus, for both ecological and economic reasons, it is important that blue crab is assessed and monitored to ensure that a healthy population is maintained in Chesapeake Bay. A wealth of information has been published on Chesapeake Bay blue crab over the past century. Much of it is reviewed in the recently revised Blue Crab Fishery Management Plan (CBP 1997) and in the first Baywide stock assessment of blue crab (Rugolo et al. 1997). We have not undertaken yet another review, except where specific issues require it to support our analyzes on population and fisheries data. However, we briefly summarize important aspects of the life history below.

Blue crab is an estuarine-dependent species. Typically, adult females release larval crabs, termed zoea, from high salinity areas of coastal estuaries in July and August. Historical records provide evidence of release of larvae throughout the late spring - early summer period in addition. The zoea are advected offshore, eventually transforming into megalopae, which re-enter coastal estuaries and bays (Johnson and Hess 1990; Olmi 1995; Johnson 1995). Megalopae settle into favorable habitats, such as submerged aquatic vegetation and oyster reefs, eventually taking on the juvenile form which disperses widely, while continuing to mature (Orth and van Montfrans 1987; Rothschild et al. *in press*). Mature males compete for pre-pubertal females. Successful males cradle the female until she molts at which time insemination occurs. The adult crabs then separate. The female likely does not mate again, but may store sperm to be used in subsequent periods of reproduction (A. Hines, Smithsonian Environmental Research

Center, pers. comm.). Brooding females carry the eggs externally as a sponge on their pleiopods. As the eggs develop, the females return to the high salinity areas where the eggs undergo the final maturation and the zoea are released. The entire life cycle following the late megalopal stage is spent within the estuary.

In general crabs are opportunistic predators. Their diets may include a wide range of taxa including bivalves, crustacea and fish (Hines et al. 1990; Mansour and Lipcius 1991). It is a dominant benthic predator and scavenger (Eggleston et al. 1992; Mansour and Lipcius 1993). Diets vary with crab size. Small crabs exploit thin-shelled bivalves and other invertebrates that are buried relatively shallowly in the sediments. Larger crabs can exploit thicker shelled bivalves and cannibalism is not uncommon (Hines and Ruiz 1995). Thus, crabs may be keystone predators in the estuary, *sensu* Paine, possibly playing a dominant role in structuring benthic communities throughout its range (Hines et al. 1990). In turn, crabs may fall victim to several fish species including sciaenids and moronids. For example, recent concern has been expressed over the interaction between striped bass and Chesapeake Bay blue crabs. Thus, blue crab may provide a link between the benthic and pelagic food webs. If true, the status of blue crab stocks within an individual system, may yield important insights into ecosystem health and function.

1.1 Stock Assessment and Fishery Management Plan

Maryland, Virginia and the Potomac River Fisheries Commission are the management jurisdictions for blue crab in Chesapeake Bay. The management actions of the three jurisdictions are coordinated since all are signatories to the Chesapeake Bay Blue Crab Fishery Management Plan (FMP) (CBP 1997). The FMP provides management guidance and regulations for commercial and recreational fishing of blue crab in the Bay. Its goal is “to manage blue crabs in the Chesapeake Bay to conserve the baywide stock, protect its ecological value, and optimize the long-term utilization of the resource.” Regulations and management actions are uniform or complementary across the jurisdictions, recognizing age-specific and sex-specific differences in utilization of the estuary by blue crab, and recognizing historical fishing patterns. The objectives and recommendations of the FMP focus on stabilizing the fishery, limiting access to the fishery, preventing increases in exploitation rates, monitoring the blue crab resource, improving enforcement, and developing better socioeconomic data bases. Moreover, this FMP is the first of Chesapeake Bay FMPs to explicitly recommend habitat and water quality restoration and protection as insurance for the blue crab resource. The FMP is a flexible document that will be amended regularly (CBP 1997). It adheres to the principles proposed for Chesapeake Bay FMPs that were developed by the Living Resources Subcommittee (LRSC 1997), in which precautionary management and protection of critical habitats are highlighted.

A Baywide stock assessment of blue crab had been lacking until NOAA’s Chesapeake Bay Stock Assessment Committee undertook the task. In 1997, the Technical Subcommittee (TSC) of the Chesapeake Stock Assessment Committee (CBSAC) produced the first comprehensive stock assessment of blue crab in Chesapeake Bay (Rugolo et al. 1997). This is an important achievement that provided a starting point for our targeting efforts and a reference against which to compare our conclusions. The CBSAC assessment focused primarily on

developing risk-averse fishery reference points. In so doing, the TSC fulfilled its mandate, but did not fully address potential ecological concerns that should be considered in developing population targets. The CBSAC effort was the template and springboard from which our project was initiated. Many of our conclusions regarding reference points and targets resemble those reached by the CBSAC Committee, but in other cases our conclusions differ.

The CBSAC Assessment (Rugolo et al. 1997) indicated that stock abundance had been high in the 1980s and had returned to average abundance during recent years. The stock assessment also found that recruitments of young crabs had been above average since the 1970s. The stock was characterized as moderately to fully utilized at present exploitation levels. CBSAC recommended that a fishing mortality rate which insured escapement of at least 10% of the spawning stock that would be present in the absence of fishing be maintained. Although finding no cause for alarm, the stock assessment and the FMP recognized the need for caution in the fishery and recommended no further increases in fishing effort or fishing mortality. The CBSAC assessment noted a decrease in catch-per-unit-effort (CPUE) in the blue crab fishery since 1945 but no apparent declines in CPUE or fishing mortality rate since 1970. The TSC attributed these counter-intuitive results to gear saturation effects as the amount of commercial gear proliferated in recent years.

1.2 Data, Analysis, and Models

There is a rich database on blue crabs from which to develop targets. We have outlined schematically how the available databases and analytical tools can be related (Figure 1). The figure also identifies the relationship between the various analytical approaches that we have utilized in developing targets. Some are similar to those utilized by the CBSAC TSC in their stock assessment (Rugolo et al. 1997). The commercial fishery provides fishery-dependent data directly with respect to landings and fishing effort. Based upon Maryland and Virginia statistics, there are four separate fishery-dependent databases available for analysis: Maryland landings, Maryland effort, Virginia landings, Virginia effort (Figure 1). In addition, several fishery-independent survey time series exist (Figure 1). Correlation analysis of fishery-dependent and fishery-independent data provides a mechanism to determine trends in underlying patterns of abundance. However, to relate the trends in landings directly to abundance it is necessary to consider data on the life history of blue crabs (Figure 1). Combining fishery-dependent, fishery-independent and life history information provides four principal stock assessment approaches to develop targets: 1) stock size estimation, 2) surplus production modeling, 3) yield-per-recruit modeling and 4) stock-recruitment modeling.

Given an understanding of life-history parameters, it is possible to develop fundamental population dynamics models for blue crab in Chesapeake Bay. Such models lend insight into the potential of the population to respond to changes induced not only by fishing mortality but also by the environment and to recover from changes in abundance. We adopted a stage based modeling framework (Caswell 1989) in which to explore basic ecological questions relating to population targets for blue crab (Figure 1).

Blue crab stocks, like those of most marine organisms, vary in abundance, largely due to interannual differences in levels of recruitment which are believed to be mostly the consequence of variability in the environment experienced by young crabs. This inherent variability must be considered in assessments and in development of reference points or targets. Values assigned to targets also are dependent upon assumptions and variability in the quality of data used in calculations. Importantly, the values of many parameters that must be estimated in calculating targets or reference points have associated uncertainty. It is unrealistic to promote a single target value, whether it be an abundance estimate, a fishing mortality rate, or a specified yield without considering the effects of parameter uncertainty on target estimates.

1.3 Objectives

At the outset, we had three objectives, each of which had specific tasks. Our success in meeting objectives varied. Some tasks did not lead to effective delineation of targets.

Objective 1: Review existing knowledge of the blue crab resource and factors that may regulate its abundance in Chesapeake Bay.

Objective 2: Undertake technical analysis and modeling of blue crab abundance and factors which control its population dynamics.

Task 2.1. Review and extend, where possible, existing stock assessment models. Explore how varying some assumptions of biological and exploitation parameters in the current stock assessment will affect population targets. Evaluate the reliability of resulting biological reference points, considering the sensitivity of predicted reference points to variability in input parameters.

Task 2.2. Undertake stock-recruitment modeling. Apply a range of methodologies to determine the functional form of the stock-recruitment relationship for blue crab.

Task 2.3. Assess and consider the probable impact of environmental covariates on the relationship between stock and recruitment.

Task 2.4. Develop a stage-based model of blue crab to quantify spatially-explicit dynamics in the blue crab population in Chesapeake Bay.

Task 2.5. Consider multiple potential indices to explore whether a reliable composite index can be produced.

Objective 3: Recommend targets and levels, including a tiered approach if feasible.

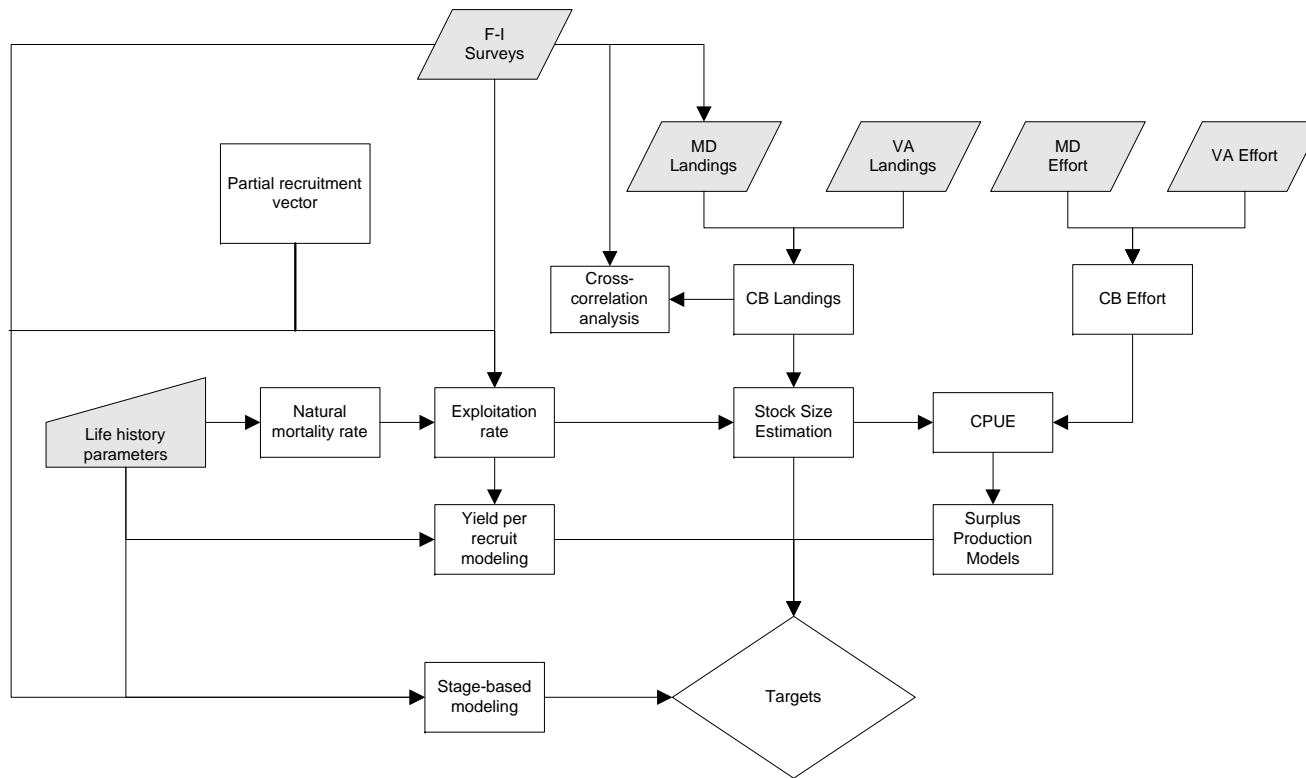
Task 3.1. Identify specific population targets that will insure sustainable population levels of blue crab in Chesapeake Bay.

Task 3.2. Identify modifications to existing sampling programs or recommend new sampling programs that must be developed to insure that population abundances and recommended targets are monitored adequately.

We have completed the principle objectives and tasks. We focused on Tasks 2.1, 2.2, 2.4 and 2.5. The analyzes under our work on tasks under Objective 2 provide the framework on which to develop the specific targets required in Objective 3.

In the sections that follow, we present the results of our analyses. In Chapter 2, we present the analysis of both fishery-independent and fishery-dependent time series. It also contains a review of the fundamental life history information for blue crabs. In Chapter 3, we present the surplus production model which leads to an estimate of the maximum sustainable yield for the population. In Chapter 4, we present the estimation of mortality rates and stock sizes. In Chapter 5, we present the results of our yield per recruit modeling which is used to develop a range of fishing mortality reference points. In Chapter 6, we review existing stock and recruitment models and develop estimates of the variability in recruitment. A general stage-based, spatially-explicit population model is presented in Chapter 7 which is used to establish reference points that would lead to stock rebuilding. Finally, in Chapter 8, we develop specific targets and make recommendations for improvement in monitoring and assessment. The report is organized such that tables and figures specific to each chapter follow immediately after each chapter.

Figure 1. Flow chart indicating the integration of data into the modeling and assessment framework adopted to develop targets for blue crab



2. STOCK ASSESSMENT PARAMETER ESTIMATION

In this chapter, we explore variability and uncertainty in three important categories of data that are used in the targeting process. Specifically, we quantify the uncertainty in 1) abundance and landings time series, 2) life history parameters and 3) partial recruitment.

2.1 Analysis of blue crab abundance

Abundance data clearly are critical to developing targets. We conducted a detailed, quantitative exploration of fishery independent and fishery dependent data and undertook analyses of commercial landings, effort, and fishery-independent data time series to identify trends and shifts in abundance.

We identified and examined several fishery-dependent and fishery-independent data sets. In sections that follow we describe each time series and summarize time-series trends. In the final section we conduct analyses to identify similarities and differences in the responses of each time series. Unless otherwise noted, we adopted the size-age standard used in the CBSAC stock assessment (Rugolo et al. 1997). The assumed ages for ranges of carapace widths (cw) are:

Assumed Age Class	Size Range (mm)	Month Range
0	< 60	Aug - Nov
1	60 < cw < 120	Sept - Nov
1+	> 60	Sept - Nov
2+	\$ 120	June - Nov
Spawner	\$ 130	May - Sept

There is considerable uncertainty over the accuracy of estimated sizes-at-age in blue crabs. Kahn et al. (1998) present evidence that the criteria above underestimate growth rates of crabs in Delaware Bay. Until accurate ageing of crabs is feasible, or until more substantial evidence of the appropriate size-at-age matrix for Chesapeake Bay blue crabs is available we decided to continue to adopt the above matrix. The advantage of retaining this categorization is that it enables direct comparison with the results of Rugolo et al. (1997), and it requires no adjustment of the winter dredge survey data (see below) which is reported using the above criteria.

Where the length of a time series permitted (i.e., more than 30 data points) we conducted formal time-series analysis of the data. For this application, time-series analysis has two phases: identification and estimation (Chatfield 1989). The identification step identifies a set of probable model structures that explains the pattern. In this phase one also can identify whether there are

significant correlations with other time series. For example, it is possible to determine whether abundance of age-1 crabs is significantly correlated with abundance of age-0 crabs in the previous year. The second step in a time-series analysis is the estimation step, which provides parameter estimates for the model judged most appropriate.

2.1.1. Fishery-dependent Survey Time Series

2.1.1.a. Smith Island Scrape Survey

From 1948 - 1972, researchers at the Chesapeake Biological Laboratory compiled a fishery-dependent time series in collaboration with commercial crabbers on Smith Island. The crabbers reported their daily catch and effort (number of scrapes) for each week of the season. One crabber recorded the size and sex of the first 200 crabs collected each week. The time series is complete, except for three years; 1955, 1956 and 1959. These data on relative abundances were analyzed to provide mean annual CPUEs (Table 1).

Subsequently, researchers at the Chesapeake Biological Laboratory repeated this survey in 1987 (Rothschild et al. 1988). The research survey comprised 1,113 scrapes on 31 days during the 1987 commercial season, and collected 10,837 crabs (Table 2).

The mean CPUE for the 1948-1972 commercial scrape time series for all sizes of crabs was 415.6 ± 152.1 crabs @person⁻¹ @day⁻¹ (mean \pm SD - Figure 2). The CPUE values were at or above the mean for 1948 - 1953 and 1969 - 1972 and at or below the mean during 1953-1967, most notably from 1960 - 1965. The increases in abundance in 1966 and 1967 are a result of the large 1965 year class. Trends in apparent abundance were similar for both presumed age-0 and age-1 crabs (Figure 2.B and C). Why these series begin to lose coherence after 1968 is unclear. The time series for age-2 crabs appears qualitatively different to the other series (Figure 2.D), being relatively less variable, and was notably >1 SD above the mean only in 1969.

The mean CPUE for the 1987 research series was 56.28 ± 34.9 crabs @scrape⁻¹. This value is not directly comparable to CPUE's calculated for the longer time series. However, the short experimental survey does provide information on the seasonality of the catch. In general, catches as measured by CPUE were at or below average for the first half of the season (Figure 3). CPUE increased to above average levels during the second half of the season. However, the size of the crabs later in the season were typically smaller (Figure 4). As can be seen in Figure 4, the decline in mean size reflects the recruitment of a new year class to the gear and vicinity. This pattern reflects the underlying life history of blue crabs (see Chapter 1).

2.1.2 Fishery-independent Survey Time Series

Data were analyzed from five fishery-independent surveys that differ in duration and geographical coverage. The VIMS trawl survey, conducted for the past 43 years, is the longest-standing fishery-independent survey. It samples the southern portion of the Bay (Figure 5). The

Calvert Cliffs pot survey is the second longest time series, covering 29 years. It is the most geographically restricted, sampling at one location in the mid-Bay (Figure 5). The MD trawl survey, which is restricted to eastern shore sites and tributaries in Maryland waters of the Bay, has been conducted for the last 19 years (Figure 5). The winter dredge survey (WDS) has been conducted for 9 years and is the only Baywide survey (Figure 5). Other research surveys that have been conducted typically have covered only single years and may document the seasonal pattern within the survey year. Examples of such surveys include the CBL Smith Island scrape survey in 1987, and CBL pot and trotline surveys. We have analyzed data from the four multi-year surveys.

2.1.2.a. VIMS Juvenile Fish and Blue Crab Trawl Survey

Since 1955, VIMS has conducted a trawl survey to monitor abundance trends in selected finfish and shellfish in the southern portion of Chesapeake Bay. Originally, the survey sampled only the York River, but it has expanded steadily. Currently, seven strata are recognized that cover an area from the mouth of the Bay to the VA/MD border, and up to the freshwater interfaces of the York, James and Rappahannock Rivers. Samples are collected monthly from about 60 stations within the strata. Both fixed and random station assignments have been employed. The trawl gear has changed over the survey time series. The most important changes were the addition of a tickler chain and a net liner in 1973 and 1979, respectively. Although calibration factors between the different gear types remain to be finally determined, provisional corrections have been published, which we have adopted in our analysis (Hata 1996).

Blue crabs collected in the VIMS survey are enumerated, sexed and measured. Three age classes of crabs are recognized; age-0, age-1, and age-1+ (Table 3; Figure 6). However, the age-at-size matrix used in calculating the VIMS Survey Index is different from that used elsewhere. The size cut off for age-0 crab varies seasonally from 50 mm cw in September to 90 mm cw in the following July. Similar variation is included in the index for age-1 (<125 mm cw in January, #135 mm cw in July). The time-series mean CPUEs (crabs @ow⁻¹) for the three age classes are 5.90 ± 4.39 (age-0), 3.89 ± 2.75 (age-1) and 7.00 ± 4.6 (age-1+). The indices of abundance for all ages are low from the early to mid 1970s. Conversely, all indices appear high during the early to mid 1980s, and again for 1989-1991.

Time-series analysis of the corrected abundance of age-0 crabs suggested that the time series was stationary (i.e. varying around a mean value). However, a model that included only a mean value exhibited significant autocorrelations among the residual values at all lags, indicating that the residuals were not randomly distributed about the mean (Table 4). Inclusion of a 1st order autoregressive term improved the model fit, as indicated by Akaike's information criteria statistic (Table 5). Moreover, there was no significant autocorrelation among model residuals. There remained some evidence of higher order processes at a five-year lag, but inclusion of this term did not improve model performance significantly. We judged that a 1st order autoregressive model fit the time series adequately. We also conducted a time-series analysis of the age-1 crab data. Time series analysis of age-1 and age 1+ crabs did not indicate a need to include an autoregressive term in the model. This implies that the annual deviations

around these means are, or cannot be distinguished from, completely random (white noise) fluctuations (Table 6 and 7). These analyses imply that the abundance of crabs as indexed by the VIMS survey, shows a pattern by which the abundance this year are best predicted by the abundance last year and the time series mean.

If a survey accurately reflects trends in population abundance, then abundances of age-0 individuals might be expected to be correlated with abundances of age-1 crabs in the subsequent year, and with age-2 crabs two years later. To explore whether the VIMS survey data display this internal consistency we conducted a cross-correlation analysis. There was a significant cross-correlation with both a 0 and 1 yr lag between the abundance of age-0 crabs and the abundance of age-1+ crabs (0 yr lag $r = 0.639$, $p < 0.05$; 1 yr lag $r = 0.329$, $p < 0.05$). However, there also were significant autocorrelations at 4 and 5 yr periods. This suggests that there is some internal consistency within the time series. However, one would expect the abundance of age-1 crabs this year to be more highly correlated with the abundance of age-0 crabs in the previous year (1 yr lag), than with the abundance of age-0 crabs this year (0 yr lag). This was not observed. This pattern may reflect errors in assignment of ages resulting from misspecification of the size-at-age matrix. Alternatively, the pattern may imply the presence of density-independent mortality in the population.

2.1.2.b. Calvert Cliffs Pot Survey

A standardized pot survey of blue crabs in waters near Calvert Cliffs has been conducted since 1968 (Abbe and Stagg 1996). The survey originally was initiated to determine the potential environmental impact of a nuclear power plant. Accordingly, sampling was specified at three stations: one adjacent to the power plant, and two at 4 - 8 km distances from the plant. Sampling is conducted using standard commercial crab pots, with 25 mm mesh, but without cull rings. Approximately 20 pots are fished at biweekly intervals at each site. Upon retrieval, crabs in each pot are measured (point to point), weighed and sexed. Data on catches from June - November are included in analyses. The smallest crab collected during the time series was 38 mm CW. However, >70% of the crabs collected were of legal size or greater. This indicates that the abundances of sub-legal crabs in this time series may be seriously biased. Thus sub-legal crabs were not analyzed.

From 1968-1997 more than 120,000 crabs were collected. The CPUE data (crabs @pot⁻¹) are tabulated (Table 8) and illustrated (Figure 7). Presumed ages were determined from carapace width measurements using the CBSAC Assessment criteria given above. The mean CPUE for the total time series is 6.00 ± 3.55 crabs @pot⁻¹. It is clear that the CPUE in 1981 was significantly higher than for the other years in the time series (Figure 7). CPUEs in 1984 and 1985 also were more than 1 SD above the mean, while CPUEs in 1968 and 1987 were more than 1 SD below the mean. However, except for these peaks, the time series appears stationary (i.e. no trend). When partitioned into size and sex categories, broadly similar trends are apparent (Figure 8). There is some evidence of increased abundance during the period 1981-1985 of age 2+ crabs and legal females. Their abundances during this five-year period are at or above the time-series mean and more than 1 SD above the mean for three out of the five years. However, these two groups

depend upon the same underlying data and, thus, are not independent.

There may be a trend towards decreased mean abundance of legal males during the 28-yr series (Figure 8). Except for 1993, all CPUEs for legal males after 1985 fell below the time-series mean. Abundance of legal females in this period was variable, but showed no apparent decline. The CPUEs of legal males and legal females were similar in years at the beginning of the survey, but females were dominant during the last decade.

Time-series analysis was applied to the Calvert Cliffs survey data. A simple 1st order autoregressive model was fit (Table 9). The constant term was highly significant, whereas the autoregressive terms was insignificant. This suggests that the variation around the time-series mean is uncorrelated variation (noise). An intervention model also was fit (Table 10). This acts to separate a time series into two periods: a pre- and a post-intervention series. Interventions we applied in all years sequentially. Only the intervention in 1981 was significant. However, residuals in this model are consistently negative after 1986 (with one exception) suggesting model inadequacies. A combined autoregressive, intervention model provided a poorer fit to the data than the simple intervention model and was not considered further. Thus, the evidence for a domain shift in 1981 is not compelling. It appears more accurately to be simply a case of an unusually large CPUE in a single year, 1981.

We conducted an autocorrelation analysis on the presumed age-1 CPUE abundance and presumed age-2 CPUE abundance data. There were no significant autocorrelations at 1 year lags, suggesting that the survey may not be tracking year classes adequately, i.e. it is not internally consistent. It is likely that errors in size at age matrix used in our analyses and in the CBSAC stock assessment further restrict our ability to detect progression of year classes within this and other surveys. This issue requires further attention.

Abbe and Stagg (1996) found compelling evidence that the mean size of crabs caught in the Calvert Cliffs survey had declined over the survey period. The percentage of legal-sized males had declined from >50% of the catch in 1968 to <20% in 1995. The decline is evident even if calculated on absolute numbers. Correspondingly, the mean size of males had declined from >150 mm cw in 1968 to <125 mm in 1995. The decline in mean male size was well described by a linear regression with slope $-0.663 \text{ mm @yr}^{-1}$. In their paper, Abbe and Stagg (1996) suggest that mean size of females had not declined over the same period. However, close inspection of the data suggests that a decline in mean female size began in the 1990s. Recent data indicates that this trend is continuing, and at a steeper rate than the decline in size of males (G. Abbe, Academy of Natural Sciences-Estuarine Research Laboratory, pers. comm.).

2.1.2.c MD DNR Trawl Survey

Beginning in 1977, Maryland DNR instituted a trawl survey of Eastern Shore sites and tributaries, and the Patuxent River. The survey is conducted from May - November. However, coverage is inconsistent temporally and spatially from year to year. In our analysis, we followed the approach of the CBSAC stock assessment and focused only on the Choptank River, Eastern

Bay, and Pocomoke and Tangier Sounds. To reduce the impact of missing strata on the overall index, we again followed the CBSAC approach and calculated monthly average CPUEs (number @tow⁻¹) for all regions combined, which were subsequently averaged to yield annual mean CPUE estimates for age-0, age-1 and age-2 male and female crabs (Table 11 and Figure 9).

The time series includes periods of above- and below-average abundances (Figure 9). However, the periods differ among the presumed age classes and between the sexes. The time series mean abundances of age-2 males (2.28 crabs @tow⁻¹) and females (2.59 crabs @tow⁻¹) do not differ (paired t-test, $t = 0.58$, $p = 0.56$). The time series suggests that a period of above average abundance of age-2+ crabs occurred between 1983-1987, particularly for females. In contrast, the period from 1977-1980 was associated with below average catches of males and females. Furthermore, the catches of age-2+ females were below average from 1988 onwards. Abundances of age-1 males and females did differ over the time series. Age-1 males were more abundant than age-1 females on average (male mean CPUE = 6.15, female mean CPUE = 4.50, paired t-test $t = 5.67$, $p < 0.0001$). The general trend in the age-1 male and female time series was broadly similar. Age-1 males and females were caught at above average abundances from 1983 - 1986, and at below average abundances from 1978 - 1980, while abundances in all other years were nearer to the mean. Age-0 crabs showed two distinct peaks in abundance in the Maryland trawl survey, one in 1985 and the other in the period 1990-1993. Both sexes of age-0 crabs were below average abundance from 1977 - 1980. The abundance of age-0 males was higher than females over the entire survey period (mean male CPUE = 3.44, mean female CPUE = 2.84; paired t-test, $t = 3.69$, $p < 0.01$). The recent trend in age-0 abundances from 1994-1997 has been down.

Time-series analysis was applied to both the combined-sex age-0 and age-1+ time series. There was no evidence of non-stationarity in the age-0 time series. A constant model provided a reasonable fit to the data (Table 12). The model residuals did not exhibit significant autocorrelations, but subjectively, the model did not provide a convincing fit to the data. Inclusion of a simple autoregressive term greatly improved model fit, as judged by reduced residual variance and a reduced Akaike's information criteria statistic (Table 13). There was no autocorrelation among model residuals. Thus, higher order models were not justified. We judged a 1st order autoregressive model to provide an adequate fit to the data. Analysis results for the age-1+ crabs were very similar. The survey time series appeared stationary. A simple constant model fit the data, but model residuals were high (Table 14). Inclusion of a 1st order autoregressive term improved model fit (Table 15) and was judged adequate.

We conducted cross-correlation analysis on both the aggregated abundance data and that for each sex separately. Only the cross-correlation between the abundance of age-0 females and age-2 females was significant at other than a zero lag. Even for this correlation, the significant lag was 1 yr rather than the expected 2 yr. These analyses indicate that the survey does not track year classes adequately and therefore is not internally consistent.

2.1.2.d. CBSAC Winter Dredge Survey

Crabs overwinter in bottom sediments of Chesapeake Bay and can be sampled effectively by dredge. In 1989 CBSAC initiated a sampling program that took advantage of this life history trait and instituted a Baywide survey to estimate crab abundance. The winter dredge survey employs a stratified random design to estimate abundance by presumed age and sex. Except in 1989, the strata have been consistent during the nine years of the survey. The survey samples >1,200 randomly selected stations throughout the Bay from December - March. At each site a single 100 m tow of a 6' standard Virginia dredge (15 mm mesh bag) is made. All crabs in each tow are counted, measured and sexed. The gear samples crabs as small as 15 mm cw. CWs are converted to presumed ages, and abundance is expressed as crabs 1,000 m⁻² (Table 16 and Figure 10).

As the only Baywide abundance index, the winter dredge survey provides a unique view of the crab population. The time-series mean abundance for mature females is 1.69 ± 0.92 crabs @1,000 m⁻². Abundance estimates of mature females in 1991 and 1992 were >1 SD above the time-series mean (Figure 10 A), but values for remaining years are within 1 SD of the mean. It is important to note that the precision of annual abundance estimates in this survey is unusually high (SD ~ 5-10% - M. J. Fogarty, Chesapeake Biological Laboratory, pers. comm.). Thus, the SD for the time series reflects true inter-annual variability rather than parameter uncertainty. Consequently, declines in mature females from the high abundances in 1991 and 1992 may be significant.

The time-series mean abundance for age-1+ crabs is 5.08 ± 1.66 crabs 1,000 m⁻². The estimated abundance of this age-class has declined significantly since the time series peak abundance in 1991 (Figure 10 B). A simple regression of the 1991-1998 abundance of age-1+ crabs on year yielded a significant negative relationship (Age-1+ abundance = $829.9 - 0.413 * \text{year}$, $r^2 = 0.46$, $p < 0.05$). Age-1+ abundances prior to 1994 were above the time-series mean; all age-1+ abundance estimates since 1994 have been below the mean. Despite this significant decline, abundances in the most recent years are still within 1 SD of the time-series mean.

The estimated abundance of age-0 crabs has been more variable than for the other two presumed age classes (Figure 10 C). The time-series mean is 6.15 ± 3.63 crabs 1,000 m⁻². The age-0 time-series abundance was lowest in 1992, but recovered to its highest observed value in 1997. In 1998, age-0 abundance declined again, emphasizing the naturally high variability in recruitment that can occur. However, the abundance in 1998 is similar to abundances in earlier years, with the exception of 1996 and 1997. This may suggest that an index of 2-6 crabs @tow⁻¹ is more typical than the higher values observed in 1996-97.

The winter dredge survey includes only nine years of data, and is presently too short for formal time-series or cross-correlation analysis. However, qualitative analysis of lagged data suggests that, like the other surveys, the winter dredge survey is not internally consistent.

2.1.2.e. Coherence in Combined Fishery-Independent Survey Time Series

We analyzed the fishery-independent time series to determine if there were correlations

in abundance indices among the different time series. The primary tool for this evaluation was time-series analysis. This tool is restricted to relatively long time series (>30 observations) with extensive periods of overlap. Thus, we were only able to explore the potential cross-correlations for time periods in the VIMS trawl survey and the Calvert Cliffs pot survey indices.

Our first analysis explored the relationship between the abundance of age-1+ crabs in the VIMS trawl survey and the abundance of legal crabs in the Calvert Cliffs pot survey. The two surveys were significantly cross-correlated at 0 and 1 year lags (Figure 11). This result may reflect the expected lifespan of mature crabs in the exploited population in Chesapeake Bay. Higher order cross-correlations at 6-9 years also were significant but are difficult to interpret. We also calculated the cross-correlation between the abundance of age-0 crabs in the VIMS trawl survey and the abundance of legal crabs in the Calvert Cliffs survey. There was a significant correlation at 1 yr lag (Figure 12), indicating that abundance of legal crabs as measured at Calvert Cliffs is significantly related to abundance of age-0 crabs measured in the VIMS trawl survey one year earlier. Higher order interactions at between 6-11 years also were present but not interpretable.

2.1.3. Commercial Data

2.1.3.a Analysis of Commercial Landings Time Series

The first landing records for blue crab in Chesapeake Bay can be found in Rathburn (1886). Landings data for Maryland and Virginia were maintained sporadically until 1929, and consistently thereafter. In 1981, Maryland instituted a more detailed reporting system. This system was based upon a monthly, random sample of catch and effort reported by individual fishers, stratified by gear, location and degree of involvement. More recently, both Virginia (1993) and Maryland (1994) have adopted mandatory reporting systems.

We first analyzed aggregate annual (1945-1996) landings by combining catches from all reporting authorities and for all gear. Landings data are summarized in Table 17 and Figure 13. We calculated simple summary statistics for the each time series, and then for specific periods within the time series to look for potential changes and trends (Table 18). Baywide, the mean landings of blue crab over the entire time series were 69.828 ± 17.543 million lbs. In Maryland, the mean was 31.902 ± 11.556 million lbs. Mean landings in Virginia over the time series were 37.925 ± 9.693 million lbs. Of the Baywide and individual state totals, more than 95% of the reported landings were hard shell crabs. The two states have shared the landings about equally over the entire time series (VA - 54%, MD - 46%), although Maryland landings have been highest in the past 15 years (Table 17). There is considerable variability in the landings time series (Figure 13). Landings time series may not accurately reflect trends in underlying abundance. They also may reflect changes in effort and possible changes in reporting.

We believe that the reporting changes that occurred in Virginia in 1992-1994 and particularly in Maryland in 1981 have impacted estimates of landings. For example, it has been suggested that the abrupt increase in landings in Virginia in 1992, apparent in the time series,

results from a reporting change. However, these changes are too close to the end of the time series to permit quantitative adjustments (Chatfield 1989).

The change in reporting method in Maryland that was instituted in 1981 is particularly important in the analysis and interpretation of landings statistics of blue crab, and in the overall interpretation of the status of the fishery in Chesapeake Bay. It is clear from Figure 13 that the landings time series shifted dramatically in Maryland in 1981. The Maryland time series does not vary equally about the mean over the course of the time series. All except one annual landing estimate before 1981 are below the mean, and all except one annual landing estimate after 1981 are above the mean (Figure 13 A). In contrast, the Virginia time series shows that annual landings vary equally around the time-series mean (Figure 13 B). While there are periods of low (1955-1960) and high (1962-1968) landings in Virginia, the overall time series is stationary. Moreover, the Maryland and Virginia time series do not appear to be in phase - i.e., a peak in landings in one state does not always appear as a peak in the other state. It is believed that crabs in Chesapeake Bay are a unit stock. Thus, if the time series for the two states are not in phase, it is necessary to hypothesize that effort in the fishery, or the spatial distribution of crabs within the Bay, varies annually between the two states.

A robust interpretation of the time-series data is dependent upon an accurate understanding of the cause of the abrupt increase in landings observed in the Maryland statistics. It is important to distinguish whether there was a real change in landings, or if the shift was primarily due to the change in reporting procedures.

We confirmed the non-stationary pattern of the Maryland landings statistics by several analyses. First, we simply divided each time series into decade-long blocks and examined the deviations from the time-series mean (Table 18 and Figure 14). The relative deviations in the Maryland landings are clearly seen. The data indicate that the shift in 1981, whether resulting from reporting or a real change in level of landings, has persisted since that time, i.e. both decadal bars since 1981 show strong positive deviations from the time-series mean (Figure 14). All other decades show negative deviations from the time-series mean. In contrast, the decadal deviations are smaller and without trend in Virginia (Figure 14).

A formal time-series analysis of the Maryland and Virginia landings was applied to the patterns in the time series for the two states. The raw Maryland landings time series was judged to be stationary based on inspection of the autocorrelation function, which declined steadily towards zero with increasing lags, and the partial autocorrelation function, which showed a single significant peak at lag = 1. The first model fit was a simple 1st order autoregressive model. Model parameters are given in Table 19. Both the constant and the 1st order autoregressive terms were significant. However, an autocorrelation test for model residuals indicated that there remained a significant lack of fit (Table 19). We conducted a random intervention analysis in which interventions were applied in sequential years. The model for 1981 was most significant. We fit a simple intervention model, that separated the time series into pre- and post-1981 periods. Model parameters are given in Table 20. Both the constant and intervention terms are highly significant. Moreover, the intervention model is significantly

better than the simple autoregressive model as judged by Akaike's information criteria statistic. There was no significant autocorrelation among model residuals for the intervention model. Finally, we fit a combined autoregressive-intervention model. Parameter estimates are provided in Table 21. The constant and intervention terms in this model were highly significant, whereas the autoregressive term was not significant. However, the overall fit of the combined model was poorer than the simple intervention fit, as judged by Akaike's information criteria statistics.

The raw landings time series for Virginia showed some evidence of non-stationarity. The autocorrelation function declined to non-significant values by a lag of two, reached a minimum at a lag of four and then increased up to a second peak at a lag of eight. First differencing was sufficient to produce a stationary time series. Inspection of the autocorrelation and inverse correlation functions showed evidence of the presence of a 8-yr cycle. Model parameters are presented in Table 22. There was no significant autocorrelation in model residuals. A 1st order autoregressive model was deemed adequate to fit the data. We also fit higher order autoregressive models (order 1 and 8). These more complicated models did not yield a substantial improvement in model fit, even though the 8th order parameter was significant.

Summarizing, the time-series analysis of Maryland landings data has identified two significantly different periods in the landings time series; a pre-1981 period and a 1981- present period. In contrast, time-series analysis of the Virginia landings could not identify different periods.

Having confirmed the presence of a pattern, we explored possible alternative explanations. First, we assumed that the Maryland reporting change was the sole factor responsible for the observed shift in the time series. We calculated the mean landings of the 1945-1980 and 1981-1997 time periods. These values were 25.385 and 46.984 million lbs., respectively. We then adjusted landings in the 1945-1980 period upward:

$$L_{adj,i} = \overline{L}_{81-97} + \frac{(L_i - \overline{L}_{45-80})}{\overline{L}_{45-80}} \cdot \overline{L}_{81-97}$$

where $L_{adj,i}$ is the adjusted landing in year i , \overline{L}_{x-y} is the mean landings for the time period x to y , and L_i is the unadjusted landings in year i . This adjustment procedure assumes that the deviation of the landings for a single year from the time-series mean is constant. The time series for the adjusted landings is illustrated in Figure 15.

The adjustments to the 1945-1980 Maryland landings (Figure 15) show two clear differences when compared with the unadjusted data (Figure 13). First, the time series for Maryland landings is now stationary - there is an equal chance of landings in any one year being above or below the mean. Second, there now appears to be a stronger correlation between the landings time series for Virginia and Maryland.

The algorithm we used for adjustment was not the only one available. One possibility would be to use the same algorithm, but adjust the more recent landings downward. However, this implies that reporting changes were made that lessened the quality of the data. This is highly unlikely. The algorithm adopted assumes that all of the change was due solely to the reporting change. Perhaps the jump in landings did reflect a change in underlying abundance. We examined possible evidence for this suggestion.

Did the shift in landings subsequent to 1980 in the Maryland time series result not from the reporting change, but from a real increase in abundance in Maryland? If such a change in abundance occurred, we would expect to see evidence of it in the fishery-independent surveys. We examined two surveys to evaluate this possibility: the Calvert Cliffs survey and the Maryland trawl survey. The Calvert Cliffs time series does lend some support to the increased abundance hypothesis (Figure 7). Time series modeling did suggest the possibility of a change in 1981. There was a sharp increase in the Calvert Cliffs index in 1981. The index for this year is the highest in the time series, and is almost double the next highest value. The index also is well above the mean in 1984 and 1985. However, the increased index levels were not maintained in the Calvert Cliffs index during subsequent years, as would be expected if the higher landings in Maryland were resulting from a sustained increase in abundance.

There are too few years in the Maryland trawl survey to undertake a formal time series analysis. Moreover, the potential abundance shift in 1981 occurred early in the time series. Even if the time series were longer, fitting an intervention model would be problematical under this circumstance because intervention analysis is most reliable when the presumed change occurs during mid-time series rather than at the beginning. However, in a qualitative sense the Maryland trawl survey does not support a change in the underlying abundance of crabs in 1981 (Figure 9). The time series shows a gradual increase in abundance from 1980 to 1985, but no sharp increase in 1981. Thus, overall the Maryland trawl survey indicates increased abundances between 1980 and 1985, but does not indicate a sudden shift in 1981.

Can we conclude that the change in landings documented in 1981 resulted from a change in reporting or in underlying crab abundance? There is evidence to support both explanations, although we suggest that the evidence based upon reporting change is more compelling. The implications are important. If we believe that the increase in Maryland landings in 1981 resulted from a reporting change, we conclude that overall landings essentially have been stable since 1945 and that there is little reason to expect increased landings at higher levels of exploitation. Alternatively, if we accept the increased abundance explanation, then the crab population may be able to sustain higher catches at a higher level of exploitation. If we opt for the first explanation (reporting change) and are wrong, then we will have underestimated the level of exploitation. In contrast, if we accept the second explanation (increased abundance) and are wrong, we may well have tacitly recommended a level of exploitation higher than justified. Thus, accepting the first explanation is a more risk-averse policy. In the remainder of the report we present analyses based upon both options to evaluate implications for management. It is important to note that an independent assessment of the effects of the reporting change is not possible, thus it is important

to carry through analyses based on both the adjusted and unadjusted values. It is also important to note that potential effects of reporting changes on estimates of effort have not been assessed. Thus, the commercial landings time series should be viewed with caution, regardless of which form of adjustment is applied.

Our algorithm does not preclude expression of the above average abundances that were present in the early 1980's (particularly 1981, 1983 - 1985). For example, the a majority of the adjusted landings for 1981- 1985 are above the average. Our adjustment simply diminishes the degree to which the landings in these years were above the long term average.

A comparison of the Baywide landings, based upon the two different scenarios is presented in Table 23. The mean Baywide landings for the 1945-1996 period, unadjusted for possible reporting change, are 68.38×10^6 lbs, while the mean landings, after adjustment for the reporting change, are 84.6×10^6 million lbs.

2.2. Life History Parameters

2.2.1. Spawning season and early development

The spawning season for crabs in Chesapeake Bay has been fairly well documented. The height of spawning occurs between May - August in waters near the Bay mouth. Some spawning may occur as early as April, but spawning of consequence does not occur until June (Prager et al. 1990).

Early larval development occurs in coastal waters. Post-larval stages then re-enter the Bay and settle in high salinity waters in southern portions of the Bay. Settlement can occur as early as August and may continue until November (Olimi 1995).

2.2.2. Age and Growth

Knowledge of schedules of age and growth are at the heart of understanding and predicting the dynamics of exploited populations. The majority of population dynamics models, whether used for assessment or basic ecological research, are aged-based. Moreover, age information is important because it provides a means estimate natural mortality rate. Maximum age in a population is inversely related to the rate of natural mortality. Put simply, animals with short life expectancies die at a faster rate than do animals with longer life expectancies. Yet, many ecological and fishery-dependent processes are size-based and a knowledge of growth trajectories of animals is important.

2.2.2.a. Maximum Age

Defining the maximum age of blue crab has proved controversial. The controversy, in part, involves confusion arising from different definitions. The maximum expected age of an animal may be defined, but only rare individuals actually attain this age. Average life

expectancy is considerably shorter. Furthermore, when a population is exploited the expected life expectancy declines further as a result of fishing mortality even though the maximum expected age remains constant. Individuals in heavily exploited populations will have shorter life expectancies than those in populations less heavily exploited. Thus, estimating maximum expected age is problematical.

To estimate the rate of natural mortality, we require an estimate of the maximum expected age in the absence of exploitation. We designate ω to represent this parameter. Table 24 summarizes all of the age data published for blue crab in either peer-reviewed journals or grey literature. Crabs have been documented to live as long as 8 years. Rathburn (1886) quoted a Mr. Mitchell who documented a maximum age of 7 years, presumably at a time when fishing pressure was lower than currently. The results of a molt-process model (Smith 1997) suggest an ω of 5½ years, independent of fishing mortality. Given the current fishery, crabs may survive only one winter, and possibly two (CBP 1997). In sum, information available indicates that the range of possible maximum ages is 3-8 years. Accordingly, we selected $\omega = 4, 6, \text{ and } 8$ years in our analyses to explore the sensitivity and range of population responses of blue crab to fishing and to help select targets for the stock.

2.2.2.b. Growth

Growth in Chesapeake Bay blue crabs is discontinuous in two respects. First, as in all crustaceans, crabs increase in size only by molting. In general, the smallest crabs molt every 3-5 days (Smith 1997). As crabs grow, the intermolt period increases, reaching up to 50 days in the largest individuals (Intermolt period = $5.1 + 4.95 * \text{carapace width (cm)}$, $r^2 = 0.22$, $n = 32$, $p < 0.05$ - Brylawski and Miller, *in prep*). Carapace width increases an average of 22% on each molt (Brylawski and Miller, *in prep*). A similar figure of 26% was given by Newcombe et al. (1949) in their study of crab growth. Second, growth of blue crab is temperature-dependent and occurs only above a threshold of approximately 9°C. Thus, in Chesapeake Bay growth ceases in November and does not begin again until the following April. Consequently, whereas in the Gulf of Mexico, individuals may reach maximum size within the first year, in Chesapeake Bay crabs reach their maximum size in their second summer (Smith 1997).

There have been several attempts to model the growth process in blue crabs. Due to the difficulty in ageing crabs many descriptions of “growth” are only allometric relationships between carapace width and weight. The majority of attempts to model growth itself have assumed continuous growth (Figure 16). In contrast, Smith (1997) modeled crab growth discontinuously (Figure 16). Figure 16 effectively illustrates the differences in estimated sizes-at-ages generated by the two techniques. If we assume the discontinuous model provides an accurate, unbiased estimate, it is clear that the continuous growth function will over-estimate size-at-age for age-0 and age-1 crabs, and under-estimate size-at-age for age-2 and age-3 crabs.

Two continuous von Bertalanffy-type growth models have been published. They are based upon different assumptions. Rothschild et al. (1991) modified the continuous von Bertalanffy growth function to account for molting. They used a maximum carapace width of

178 mm and $t = 6$ years using information in Churchill (1919). These parameter estimates yielded a von Bertalanffy $K = 0.5056$ and $CW_4 = 187$ mm. Rugolo et al. (1997) used a more standard von Bertalanffy growth model, with an assumed maximum carapace width of 260 mm and an $t = 8$ years. The resulting model parameters were: $K = 0.587$ and $CW_4 = 262.5$ mm. Rugolo et al. (1997) also reported von Bertalanffy parameters for assumed $t = 4$ and 6 years, for which the estimates of K and CW_4 are 0.714, 231.5 mm and 0.335, 285.0 mm, respectively.

In his dissertation, Smith (1997) developed a complete, discontinuous model of crab growth. At the heart of his model are temperature- and size-dependent functions for the intermolt period and the growth per molt. Together these can be combined to describe the entire growth trajectory. When applied to Chesapeake Bay, Smith's model incorporates the discontinuities that result both from the growth process itself and from seasonal temperature variability (Figure 16). In Smith's model, young crabs settle in the Bay in August and grow to reach approximately 10 mm, on average, by the beginning of the first winter. They emerge in the following spring, and grow throughout the summer and early autumn, reaching about 80 mm, on average, by the beginning of their second winter. Crabs re-emerge in spring in their second spring and grow to maximum size by mid-summer.

Allometric relationships between carapace width and weight are needed for subsequent modeling exercises. Newcombe et al. (1949) reported that for males: $W = 0.00026 * CW^{2.67}$, and for females $W = 0.00034 * CW^{2.57}$, where weight is in g and carapace width (CW) is in mm. An alternative parameterization for both sexes combined, based upon the Newcombe et al. data, was reported by Rothschild et al. (1991) as $W = 0.001089 * CW^{2.363}$. The CBSAC stock assessment used a different, female-specific allometric function given by $W = 0.003486 * CW^{2.1165}$. Based upon a narrower range of adult sizes, Abbe and Stagg (1996) used linear relationships ($W = 2.73 CW - 211.15$ and $W = 2.47 CW - 210.83$) to describe the weight-carapace width relationship.

2.2.3. Maturity

Long ago, Paulmier (1901) suggested that it required at least three years for blue crabs to attain maturity. More recently, Rothschild et al. (1991) produced maturity ogives for blue crab based on 10-mm increments for crabs from 60 - 180 mm CW. This range spans sizes of both presumed age-1 and presumed age-2 crabs. Rugolo et al. (1997) weighted the maturity ogives by estimates of the percentage of the population within each length class to give a maturity proportion for each age: age-1 = 0.11, age-2 = 0.92. All crabs >age-2 were assumed to be mature.

There is insufficient knowledge to define the maturity schedule for crabs of all ages, mainly due to difficulties in assigning ages. Rugolo et al. (1997) explored the implications of applying three models that differed in the pattern of maturity for ages >3 years. One scenario, termed flat-topped, assumed that maturity remained at 100% at all ages >3 years. Three other scenarios allowed the probability of being mature to decline for ages >3 years. In the "Dome -1" scenario, maturity probability declined in a mirror image to the development of maturity (i.e.

probability of maturity-at-age, $p_4 = 1$, $p_5 = 0.92$, $p_6 = 0.5$, $p_7 = 0.11$, $p_8 = 0$). In "Dome-2" maturity probability declined more precipitously (i.e. $p_4 = 0.5$, $p_5 = 0.11$, $p_6 = 0$). In a final scenario, "Dome -3", maturity was set to 0 for all ages >3 years.

2.2.4. Fecundity

Prager et al. (1990) conducted an extensive study of fecundity patterns in Chesapeake Bay blue crab. They found that fecundity level varied seasonally. Fecundity was low early in the season, peaked in mid season and declined at the end of the season (Prager et al. 1990). They concluded that fecundity was an increasing linear function of female carapace width, given by $\text{Fecundity (millions)} = -2.248 + 0.377 * \text{CW (cm)}$, $r^2 = 0.24$. The low r^2 value was partly due to a striking variability within a season, or may have arisen because of errors in estimation of carapace width.

2.3 Partial Recruitment

The abundance of an exploited population reflects a balance between recruitment, which adds individuals to the population, and mortality from natural and fisheries sources, which removes individuals from the population. Most fishery models assume that both natural mortality and fishing mortality rates remain constant after individuals recruit to the population. Fishery models often assume that mortality due to fishing is experienced equally by all individuals greater than some critical size or age threshold. This is termed knife-edge selection, with the threshold size or age governing when individuals recruit to the fishery. However, application of this assumption is unrealistic in many fisheries, including that for blue crab. In such fisheries, parts of the population are allowed to experience partial recruitment. This is achieved by assigning a probability of experiencing levels of fishery mortality to age or size groups. The individual probabilities are expressed in a partial recruitment vector. The magnitude of elements of the partial recruitment vector may have considerable impact on the dynamics of an exploited population. We examine the variation in the elements of the recruitment vector.

2.3.1 Estimation of Partial Recruitment Vector

The presence of fisheries that focus on different components of the blue crab population in Chesapeake Bay complicates calculation of the partial recruitment vector. Blue crabs are harvested as hard shell crabs, peeler crabs and soft shell crabs. Each category is harvested by potentially different gear, and is managed with different size limits. The legal size for male and immature female hard shell crabs in Chesapeake Bay is 5" cw (CBP 1997). There is no legal size limit for mature female crabs. Peeler crabs are legal at 3" cw in Maryland and Potomac River Fishery Commission jurisdictions. Virginia has no legal size limit on peeler crabs. All jurisdictions have a 3½" cw limit for soft shell crabs. Estimation of a partial recruitment vector must consider impacts of the different fisheries and size limits.

The growth and reproductive patterns of crabs (see Sections 2.2.1 and 2.2.4) allow a first

approximation of the partial recruitment vector. Settlement of blue crab postlarvae in Chesapeake Bay occurs between July and mid-November. A small fraction of the early settling age-0 crabs may become vulnerable to the peeler fishery in the year that they settle. The crabs then over-winter and emerge as age-1 crabs the following spring. The newly emerged age-1 crabs remain vulnerable to the peeler/soft shell fishery throughout the summer. By August, some age-1 crabs have grown sufficiently to become vulnerable to the hard shell fishery. More age-1 crabs recruit to the fishery as the season progresses. Finally, the crabs overwinter and emerge as age-2 crabs the following spring. These crabs are fully vulnerable to the hard shell fishery from this point onwards. From this basic knowledge of life history, the partial recruitment vector must increase with crab age, and saturate at $PR_2 = 1$ (PR_2 is the partial recruitment for age-2 crabs). We would expect PR_0 to be very small since age-0 crabs are only vulnerable to the peeler fishery, and only for a maximum period of perhaps 3 months.

Calculation of PR_1 is difficult. The partial recruitment vector used in the stock assessment was derived from the ratio of total Baywide harvest to the harvest of peeler and soft shell crabs. These calculations require several parameters to be estimated prior to the final calculations. The methodology is developed in the stock assessment (Rugolo et al. 1997) and is reviewed here. The calculations are based upon converting the catch reported (lbs) into a harvest (numbers) by accounting for the mean weight per crab in each harvest category, the proportion vulnerable to the hard crab fishery, the potential under-reporting in the soft and peeler fishery, and the different harvest regulations in Maryland and Virginia. No account is taken of the recreational harvest. The resulting harvest (numbers) in any year can be calculated as:

$$H_{ps} = \sum \left(\frac{Catch_{st,ps}}{\bar{W}_{st,ps}} \cdot \frac{N_H}{N_{PS}} \cdot \frac{1}{UR} \right) + \left(\frac{Catch_{st,h}}{\bar{W}_{st,h}} \right)$$

The first term in the equation estimates the harvest of soft and peeler crabs, where $Catch_{st,ps}$ refers to the soft/peeler landings in a single state, $\bar{W}_{st,ps}$ refers to the mean weight of soft and peelers in that state, N_H/N_{PS} refers to the expected ratio of abundances in the Bay of crabs in the hard shell (N_H) and soft/peeler (N_{PS}) categories, and UR is the fraction of the harvest that is reported as landings. The second term estimates the harvest of hard shell crabs. The estimates for each market category in each state are then summed to give a Baywide figure. The partial recruitment of age-1 crabs is calculated as:

$$PR_1 = 0.82 * \left(\frac{H_{ps}}{H_{Total}} \right)$$

where H_{ps} is the Baywide harvest of soft and peeler crabs, H_{total} is the total Baywide harvest and 0.82 is a factor that accounts for the different soft and peeler size limits in Maryland and Virginia.

We calculated PR_1 values for several different scenarios. We based estimates on the average H_{ps}/H_{Total} for two time periods: 1946-1996, and 1981-1996. We also calculated estimates based upon the unadjusted and adjusted landings time series (see Section 2.1.3.). PR_1 values were calculated for several different levels of possible under-reporting. We calculated PR_1 values under assumptions that the catch of age-1 crabs could be 20, 15, 10, 5, or 1% of the total catch. PR_1 values for the different scenarios varied from 0.44 - 0.89. Table 25 gives the estimated PR_1 values for all scenarios. A higher PR_1 implies a larger proportion of the year class will be removed at age-1 and thus will not be available to support the hard shell fishery later on. In general, PR_1 estimates based upon the entire time series were higher than those for the most recent period (Table 25), indicating a possible increase in recruitment probability of age-1 crabs in recent years. The landings did not have a significant impact on the PR_1 estimates.

Table 1. Smith Island Scrape survey. Catches are reported as the mean weekly mean number of crabs caught per man per day for the entire crabbing season.

Year	Age-0	Age-1	Age-2+	Age-1+	Total
1948	116	232	37	269	385
1949	184	305	37	342	526
1950	227	311	40	351	578
1951	162	379	38	417	579
1952	193	261	25	296	479
1953	112	278	31	309	421
1954	102	271	27	298	400
1955					
1956					
1957	92	239	22	261	353
1958	88	307	29	336	424
1959					
1960	60	210	26	236	296
1961	52	222	30	252	304
1962	40	162	18	180	220
1963	32	124	14	138	170
1964	53	208	33	241	294
1965	48	199	22	221	269
1966	104	254	28	282	386
1967	70	319	53	372	442
1968	22	125	28	153	175
1969	107	551	79	630	737
1970	123	318	36	354	477
1971	132	489	39	529	660
1972	147	416	6	422	569
Mean	103.0	280.91	31.72	313.13	415.64
SD	55.18	106.48	14.50	115.71	152.11

Table 2. Results of Smith Island Scrape survey conducted in 1987 (Rothschild et al. 1988).

Date	CPUE (# · scrape ⁻¹)	Mean Male Carapace-Width (mm)	Mean Female Carapace-Width (mm)	Sex Ratio (male:female)
6/09/87	30.6	87	86	1
6/10/87	22.6	66	64	1.1
6/16/87	29.1	80	76	1.48
6/17/87	33.5	88	76	1.34
6/18/87	84.6	75	65	0.94
6/24/87	59.4	79	67	1.55
6/30/87	29.6	77	67	1.09
7/01/87	53.2	85	78	0.82
7/02/87	82.8	71	64	0.88
7/09/87	23.4	97	85	1.43
7/13/87	22.2	97	84	1.35
7/14/87	38.9	86	80	0.73
7/16/87	49.6	80	76	0.63
7/21/87	26.1	84	81	0.74
7/22/87	56	81	85	0.95
7/28/87	23.4	86	89	1.47
7/29/87	125.6	81	82	0.75
7/30/87	60	81	82	1.02
8/04/87	69.6			
8/05/87	63.8	70	76	1.23
8/10/87	51.7	85	90	1.08
8/14/87	35.9	84	91	0.87
8/15/87	83.9	73	81	1.54
8/17/87	38.5	77	88	1.74
8/18/87	40	81	79	1.42
8/19/87	47.5	79	89	1.41
8/25/87	97.5	46	41	1.13
8/26/87	25.4	79	73	1.62
9/03/87	82.1	66	68	1.39
9/11/87	74.8	26	31	1.67
9/19/87	183.4	34	32	1.31
Mean	56.28	76.03	74.2	1.19
SD	34.93	15.79	15.66	0.31

Table 3. VIMS juvenile finfish and blue crab trawl survey. Index values are the stratified mean catch per trawl based upon catches in the Bay and main tributaries expressed as number.tow⁻¹. See text for definition of the age-size matrix used.

Year	Uncorrected (#.tow ⁻¹)			Corrected (#.tow ⁻¹)		
	Age-0	Age-1	Age-1+	Age-0	Age-1	Age-1+
1968	1.64	0.55	0.71	3.29	1.32	1.56
1969	1.22	2.36	4.04	2.29	6.42	11.95
1970	4.81	2.71	4.45	12.47	6.43	11.55
1971	2.87	3.43	5.18	6.70	8.61	12.98
1972	1.75	0.98	1.29	3.15	1.49	1.92
1973	2.11	1.93	2.76	3.22	2.74	3.89
1974	0.41	0.59	0.97	0.54	0.95	1.54
1975	0.35	0.25	0.31	0.55	0.32	0.38
1976	1.76	1.15	1.68	2.56	1.68	2.40
1977	2.49	2.07	4.93	3.87	2.84	7.34
1978	4.55	4.56	7.49	6.92	6.25	10.35
1979	0.66	1.85	3.84	0.94	2.52	5.27
1980	5.48	3.63	10.62	9.31	4.98	12.70
1981	6.37	5.57	13.27	10.80	7.57	16.26
1982	2.77	2.69	5.45	4.52	3.50	6.46
1983	6.30	4.53	10.98	10.67	6.06	13.30
1984	3.24	3.66	6.09	5.38	4.87	7.68
1985	3.55	4.94	8.57	5.74	6.66	10.68
1986	1.48	0.72	3.17	2.27	0.91	3.52
1987	2.04	1.14	3.46	3.05	1.46	3.89
1988	1.99	2.47	6.82	2.89	3.13	7.84
1989	8.39	1.75	4.46	14.27	2.32	5.19
1990	13.43	7.53	17.82	18.12	7.81	17.62
1991	6.46	2.92	6.31	6.46	2.92	6.31
1992	4.34	2.82	5.99	4.34	2.82	5.99
1993	4.17	1.36	2.91	4.17	1.36	2.91
1994	2.92	1.26	2.20	2.92	1.26	2.20
1995	4.48	2.70	5.55	4.48	2.70	5.55
1996				3.18		5.35
1997				3.09		5.5
Mean	3.64	2.58	5.40	5.41	3.64	7.00
SD	2.79	1.71	3.99	4.2	2.43	4.60

Table 4. Time series analyses of CPUE of age-0 crabs from VIMS juvenile finfish and blue crab trawl survey data. The model fit only a constant, time series mean. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	5.41	0.76	7.705	0

Variance	17.64
S.E. Estimate	4.20
Akaike's	172.2

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	7.44	6	0.282	
12	8.84	12	0.717	
18	18.59	18	0.418	
24	26.78	24	0.315	

Table 5. Time series analyses of CPUE of age-0 crabs VIMS juvenile finfish and blue crab trawl survey data. Fitted time series model included a mean and 1st order autoregressive function. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	5.32	1.06	4.98	0
AR1	0.32	0.18	1.78	1

Const. Estimate	3.61
Variance Estimate	16.41
S.E. Estimate	4.05
Akaike	171.01

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	2.64	6	0.755	
12	3.78	12	0.976	
18	8.47	18	0.956	
24	16.61	22	0.828	

Table 6. Time series analysis of CPUE of age -1 +crabs from VIMS juvenile finfish and blue crab trawl survey. Fitted time series model included only a constant, mean term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate

Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	7.00	0.84	8.33	0

Const. Estimate	7.00
Variance Estimate	21.18
S.E. Estimate	4.6
Akaike	177.71

Autocorrelation Test of Residuals

To Lag	P	df	P
6	9.26	6	0.16
12	11.16	12	0.516
18	16.75	18	0.541
24	28.31	24	0.247

Table 7. Time series analysis of CPUE of age-1 crabs from VIMS juvenile finfish and blue crab trawl survey data. Fitted time series model included a mean and 1st order autoregressive terms. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate

Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	6.92	1.05	6.58	0
AR1	0.21	0.18	1.16	1

Const. Estimate	5.44
Variance Estimate	20.94
S.E. Estimate	4.57
Akaike	178.3

Autocorrelation Test of Residuals

To Lag	P	df	P
6	6.42	6	0.268
12	10.57	12	0.48
18	15.57	18	0.55
24	25.34	24	0.33

Table 8. Calvert Cliffs Pot Survey. Index values are annual average CPUE's (crabs@pot⁻¹) for the year indicated.

Year	Total	Legal	Legal Males	Legal Females	Age-1 Total	Age 2+ Total	Females
1968	0.85	0.73	0.47	0.26	0.09	0.76	0.27
1969	6.00	4.25	3.07	1.18	1.32	4.72	1.26
1970	2.62	2.01	1.22	0.79	0.42	1.95	0.83
1971	7.56	5.84	3.07	2.77	1.05	5.83	2.88
1972	3.91	2.99	1.68	1.31	0.68	3.46	1.25
1973	3.99	3.15	1.74	1.41	0.69	3.69	1.42
1974	5.81	4.37	2.59	1.78	1.10	4.63	1.85
1975	5.95	5.00	2.28	2.72	0.69	5.26	2.79
1976	3.73	2.57	1.01	1.56	0.92	2.80	1.67
1977	3.17	2.70	1.40	1.30	0.35	2.70	1.36
1978	4.51	3.39	1.56	1.83	0.85	3.85	1.91
1979	7.71	6.06	3.02	3.05	1.18	6.53	3.18
1980	4.33	3.70	1.47	2.23	0.45	3.87	2.29
1981	20.01	13.57	4.57	9.00	4.51	14.48	9.30
1982	5.78	4.42	1.49	2.92	1.04	4.73	3.04
1983	7.92	6.20	2.61	3.59	1.14	6.78	3.68
1984	11.25	7.54	2.66	4.89	2.69	8.56	5.06
1985	12.03	8.99	2.44	6.55	1.95	10.20	6.74
1986	6.17	4.99	1.62	3.37	0.73	5.46	3.42
1987	2.29	1.63	0.83	0.80	0.51	1.78	0.83
1988	5.16	3.69	1.50	2.19	1.09	4.07	2.27
1989	6.27	4.02	1.11	2.91	1.68	4.59	3.06
1990	5.25	4.39	1.63	2.76	0.54	4.72	2.83
1991	6.01	5.01	1.14	3.87	0.67	5.33	3.92
1992	4.53	2.55	0.87	1.91	1.41	3.12	1.79
1993	8.30	5.75	1.99	3.76	1.66	6.64	3.92
1994	5.75	2.67	0.76	1.91	2.39	3.37	2.11
1995	3.54	1.91	0.69	1.23	1.22	2.31	1.26
1996	4.35	1.73	0.61	1.12			1.67
1997	5.24	2.59	0.56	2.03			2.85
Mean	6.00	4.28	1.72	2.57	1.18	4.86	2.69
SD	3.55	2.54	0.95	1.79	0.887	2.77	1.83

Table 9. Time series analysis of total CPUE for Calvert Cliffs pot survey data. Fitted time series model included a mean and 1st order autoregressive terms. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	5.98	0.68	8.57	0
AR1	0.58	0.18	0.31	1

Const. Estimate	5.63
Variance Estimate	13.02
S.E. Estimate	3.61
Akaike	166.86

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	3.06	5	0.69	
12	9.23	11	0.60	
18	15.26	17	0.57	
24	16.36	23	0.84	

Table 10. Time series analyses of CPUE of age-0 crabs Calvert Cliffs pot survey data. Fitted time series model included a mean and 1st order autoregressive function. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	4.62	0.94	4.91	0
Intervention	2.42	1.25	1.94	0

Const. Estimate	4.62
Variance Estimate	11.52
S.E. Estimate	3.39
Akaike	160.39

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	3.00	6	0.09	
12	9.12	12	6.93	
18	16.25	18	5.75	
24	17.03	24	0.47	

Table 11. MD DNR Trawl Survey. Index CPUE's are calculated as the unweighted mean of mean monthly CPUE's (# crabs @tow⁻¹) from four areas (Choptank River, Eastern Bay, Pocomoke Sound and Tangier Sound). The areas were sampled from May - September. The CBSAC CW-at-age matrix was used to determine presumed ages.

Year	Age-0		Age-1		Age-2+		Totals		
	Fem	Male	Fem	Male	Fem	Male	Fem 1+	Male 1+	
1977	2.10	2.66	8.70	10.99	5.81	2.93	14.51	13.92	4
1978	0.39	0.38	1.70	1.49	0.78	0.50	2.48	1.99	0
1979	0.79	0.75	1.40	1.40	1.19	0.64	2.58	2.04	1
1980	0.20	0.34	0.32	0.52	0.49	0.26	0.81	0.78	0
1981	2.30	3.27	4.44	6.36	2.40	1.80	6.84	8.21	5
1982	0.89	1.36	2.09	2.71	2.26	0.62	4.34	3.32	2
1983	3.30	3.82	6.53	8.09	4.59	2.27	11.12	10.37	7
1984	2.15	3.09	6.80	11.25	6.21	4.65	13.01	15.90	5
1985	6.66	7.46	8.27	11.45	4.21	2.73	12.48	14.19	14
1986	4.12	5.59	5.53	9.45	5.66	1.97	11.19	11.42	9
1987	0.98	1.34	4.41	6.08	4.73	2.10	9.14	8.19	2
1988	3.01	2.40	5.06	7.00	1.00	3.77	6.06	10.77	5
1989	3.41	5.15	4.58	7.33	0.63	3.44	5.21	10.78	8
1990	5.69	7.57	3.25	4.95	1.39	3.03	4.64	7.98	13
1991	4.07	4.23	3.95	5.77	1.00	3.03	4.95	8.81	8
1992	5.97	6.18	4.55	5.70	0.78	1.56	5.33	7.26	12
1993	4.82	6.41	5.35	6.76	2.28	4.22	7.63	10.99	11
1994	2.50	2.90	6.72	7.13	1.13	2.45	7.85	9.59	5
1995	0.53	0.54	1.93	2.38	1.74	1.34	3.67	3.73	1
1996	—	—	—	—	3.58	—	—	—	—
1997	—	—	—	—	2.58	—	—	—	—
Mean	2.84	3.44	4.50	6.15	2.54	2.28	7.04	8.43	6
SD	1.99	2.39	2.32	3.32	1.97	1.27	3.91	4.35	4

Table 12. Time series analyses of CPUE of age-0 crabs in MD DNR trawl survey. Fitted time series model included a mean term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	6.28	0.99	6.29	0
<hr/>				
Const. Estimate		6.28		
Variance Estimate		18.94		
S.E. Estimate		4.35		
Akaike		110.78		
<hr/>				
Autocorrelation Test of Residuals				
To Lag	P	df		P
6	5.31	6		0.505
12	16.20	12		0.182
18	22.08	18		0.229

Table 13. Time series analyses of CPUE of age-0 crabs in MD DNR trawl survey. Fitted time series model included a mean and autoregressive term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	5.96	1.62	3.68	0
AR1	0.457	0.227	2.01	0

Const. Estimate	3.23
Variance Estimate	16.23
S.E. Estimate	4.03
Akaike	108.7

Autocorrelation Test of Residuals				
To Lag	P	df	P	P
6	3.54	5	0.617	
12	9.77	11	0.551	
18	13.21	17	0.722	

Table 14. Time series analyses of CPUE of age-1+ crabs in MD DNR trawl survey. Fitted time series model included a mean term and 1st order autoregressive term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate

Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	15.47	1.83	8.42	0

Const. Estimate	15.47
Variance Estimate	64.21
S.E. Estimate	8.01
Akaike	133.97

Autocorrelation Test of Residuals

To Lag	P	df	P
6	13.12	6	0.041
12	13.72	12	0.319
18	20.29	18	0.317

Table 15. Time series analyses of CPUE of age-1+ crabs in MD DNR trawl survey. Fitted time series model included a mean term and 1st order autoregressive term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	15.84	2.71	5.83	0
AR1	0.37	0.23	1.62	1

Const. Estimate	9.87
Variance Estimate	59.04
S.E. Estimate	7.68
Akaike	133.29

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	5.75	5	0.332	
12	6.43	11	0.843	
18	17.81	17	0.401	

Table 16. CBSAC winter dredge survey. Index CPUE's are calculated as the weighted mean CPUE (crabs @tow⁻¹) for the entire season (December - March). The CW-at-age used in the CBSAC stock assessment is used to determine presumed ages. Index CPUE's and their associated standard errors are shown for each age class within sex category.

Year	Female						Male						Total									
	0	SE	1	SE	2	SE	0	SE	1	SE	2	SE	0	SE	1	SE	2	SE	1+	SE	All Ages	SE
1990	2.65	0.22	0.89	0.10	1.28	0.18	3.32	0.25	1.78	0.16	1.43	0.17	5.98	0.43	2.68	0.23	2.72	0.28	5.39	0.42	11.37	0.73
1991	2.72	0.18	1.04	0.13	3.21	0.46	2.79	0.18	2.43	0.41	2.11	0.26	5.51	0.32	3.47	0.52	5.32	0.57	8.79	0.89	14.30	0.97
1992	0.79	0.07	0.47	0.04	3.26	0.67	0.71	0.06	0.73	0.06	0.77	0.07	1.50	0.11	1.20	0.08	4.03	0.69	5.23	0.71	6.73	0.72
1993	2.37	0.29	1.54	0.29	1.21	0.14	2.31	0.31	1.97	0.31	1.56	0.32	4.68	0.55	3.51	0.53	2.77	0.38	6.28	0.82	10.95	1.03
1994	2.88	0.26	0.66	0.08	1.26	0.11	2.67	0.24	1.29	0.14	0.79	0.14	5.55	0.47	1.95	0.19	2.04	0.19	3.99	0.31	9.53	0.61
1995	2.63	0.31	0.84	0.11	0.60	0.07	2.15	0.26	1.46	0.18	0.79	0.08	4.78	0.54	2.30	0.27	1.39	0.12	3.69	0.32	8.47	0.69
1996	6.22	0.40	0.61	0.07	1.72	0.24	5.90	0.45	1.27	0.12	1.28	0.12	11.97	0.82	1.88	0.16	3.00	0.31	4.88	0.48	16.85	0.96
1997	6.55	---	0.53	---	1.28	---	5.57	---	0.91	---	0.81	---	12.2	---	3.52	---	2.09	---	3.52	---	15.56	---
1998	1.84	---	0.62	---	1.39	---	1.54	---	0.96	---	0.98	---	3.38	---	5.57	---	2.37	---	3.96	---	7.34	---
Mean	3.18	---	0.80	---	1.69	---	3.00	---	1.42	---	1.17	---	6.15	---	2.90	---	---	---	5.08	---	11.24	---
SD	1.93	---	0.33	---	0.92	---	1.73	---	0.55	---	0.47	---	3.63	---	1.3	---	---	---	1.66	---	3.65	---

Table 17. Commercial landings (lbs x 10³) of blue crab landed by category and state for 1945 - 1997. Note data for 1997 are provisional.

Year	Maryland			Virginia			Total		
	Hard	Soft	Total	Hard	Soft	Total	Hard	Soft	Total
1945	18019	1695	19714	17406	1797	19203	35425	3492	38917
1946	24837	2577	27414	24847	1611	26458	49684	4188	53872
1947	24944	3002	27946	31755	2396	34151	56699	5398	62097
1948	20117	1857	21974	39486	2717	42203	59603	4574	64177
1949	21592	2325	23917	37599	2462	40061	59191	4787	62978
1950	26851	2890	29741	42911	3168	46079	69762	6058	75820
1951	26513	2016	28529	34758	3921	38679	61271	5937	67208
1952	25931	1571	27502	30988	2174	33162	56919	3745	60664
1953	26366	1906	28274	30212	2563	32775	56580	4469	61049
1954	17973	1105	19078	30145	2060	32205	48118	3165	51283
1955	15232	1201	16433	25208	1772	26980	40440	2973	43413
1956	21208	1829	23037	22982	1733	24715	44190	3562	47752
1957	27384	3426	30810	22168	1578	23746	49552	5004	54556
1958	25515	3172	28687	15936	1240	17176	41451	4412	45863
1959	20738	1962	22701	17861	1066	18927	38600	3028	41628
1960	26557	2786	29343	35392	1376	36768	61949	4162	66111
1961	26464	2691	29155	39053	1365	40418	65517	4056	69573
1962	27446	3887	31333	48310	1210	49520	75756	5097	80853
1963	16732	2105	18837	42120	830	42950	58852	2935	61787
1964	22298	3492	25790	45920	800	46720	68218	4292	72510
1965	31244	2605	33849	44666	953	45619	75910	3558	79468
1966	36227	1883	38110	61987	974	62961	98214	2857	101071
1967	24380	2176	26556	54823	1217	56040	79203	3393	82596
1968	9226	1002	10228	44841	806	45647	54067	1808	55875
1969	22834	2237	25071	33694	1971	35665	56528	4208	60736
1970	24616	1576	26192	40534	838	41372	65150	2414	67564
1971	25792	1492	27284	46643	643	47286	72435	2135	74570

Table 17. (Continued)

1972	23043	1526	24569	46046	749	46795	69089	2275	71364
1973	19183	1470	20653	34222	863	35085	53405	2333	55738
1974	22852	1798	24650	37641	748	38389	60493	2546	63039
1975	23260	1561	24821	31280	708	31988	54540	2269	56809
1976	18734	1382	20116	25289	747	26036	44023	2129	46152
1977	19973	1157	21130	35418	683	36101	55391	1840	57231
1978	16035	858	16893	35031	774	35805	51066	1632	52698
1979	23750	9167	32917	37351	1079	38430	61101	10246	71347
1980	23865	1079	24944	33492	575	34067	57357	1654	59011
1981	56804	2154	58958	45860	720	46580	102664	2874	105538
1982	45895	2693	48588	48036	934	48970	93931	3627	97558
1983	52346	3977	56323	46876	784	47660	99222	4761	103983
1984	43916	1935	45851	49111	881	49992	93027	2816	95843
1985	52750	2776	55526	38001	1009	39010	90751	3785	94536
1986	44935	1478	46413	34105	567	34672	79040	2045	81085
1987	40858	1789	42647	29663	398	30061	70521	2187	72708
1988	40566	1107	41673	33330	972	34302	73896	2079	75975
1989	41128	1224	42352	40352	1326	41671	81473	2550	84023
1990	43678	1416	45094	44872	951	45823	88550	2367	90917
1991	45750	1740	47490	42076	1331	43407	87826	3071	90897
1992	29654	1203	30857	23309	499	23808	52963	1702	54665
1993	55428	1845	57273	54234	1866	56100	109662	3711	113373
1994	41897	1646	43543	34182	1450	35632	76079	3096	79175
1995	40479	1702	42181	29859	1732	31591	70338	3434	73772
1996	35918	1781	37700	32518	1698	34216	68436	3480	71916
1997	38019	2140	40159	34861	1528	36389	72881	3668	76549
Mean	29769	2133	31902	36589	1336	37925	66358	3469	69828
SD	11423	1230	11556	9783	725	9693	17511	1465	17543

Table 18. Average annual commercial landings (lbs x 10³) of blue crab by decade from Chesapeake Bay.

Years		Maryland		Virginia		Baywide	
From	To	Mean	SD	Mean	SD	Mean	SD
1944	1950	25117.67	3877.41	34692.50	10226.49	59810.17	12407.83
1951	1960	25439.40	4845.57	28513.30	7339.54	53952.70	9388.49
1961	1970	26512.10	7784.24	46691.20	7927.24	73203.30	13308.70
1971	1980	23797.70	4437.64	36998.20	6373.15	60795.90	9160.06
1981	1990	48342.50	6336.23	41874.10	7027.47	90216.60	11353.32
1991	1997	43174.00	8946.56	37459.11	11113.05	80633.11	19883.50

Table 19. Time series analyses of Maryland commercial landings (1945-1996). Fitted time series model included a mean and 1st order autoregressive function. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	30764.1	3396.8	9.06	0
AR1	0.663	0.106	6.21	1

Const. Estimate	10,358.3
Variance Estimate	77,975,910.3
S.E. Estimate	8,830.39
Akaike	1,094.46

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	12.67	5	0.027	
12	26.14	11	0.006	
18	33.86	17	0.009	
24	37.16	23	0.031	

Table 20. Time series analyses of Maryland commercial landings (1945-1996). Fitted time series model included a mean and intervention terms. The intervention term separated the time series into pre- and post-1981 periods. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	25227.7	1029.6	24.50	0
Intervention	21176.6	1856.2	11.41	0

Const. Estimate	25,227.7
Variance Estimate	38,164,966.5
S.E. Estimate	6,177.7
Akaike	1,057.31

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	5.62	6	0.467	
12	17.05	12	0.148	
18	22.76	18	0.20	
24	31.10	24	0.151	

Table 21. Time series analyses of Maryland commercial landings (1945-1996). Fitted time series model included mean, 1st order autoregressive and intervention (pre- and post-1981) terms. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	25,205.5	1,081.6	23.3	0
AR1	0.040	0.145	0.28	1
Intervention	21,210.9	1,947.6	10.89	0

Const. Estimate	24,190.6
Variance Estimate	38,883,644.8
S.E. Estimate	6,235.67
Akaike	1,059.23

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	5.75	5	0.331	
12	17.10	11	0.105	
18	23.18	17	0.143	
24	31.28	23	0.116	

Table 22. Time series analyses of Virginia commercial landings. Fitted time series included a mean and 1st order autoregressive term. Parameter estimates are given in the upper portion. Akaike's statistic provides a goodness of fit test. Autocorrelation patterns are shown in the lower portion. The autocorrelation tests provide information on whether additional non-random covariation remains in the residuals to the fitted model. Non-significant **P** indicate no significant covariation exists.

Conditional Least Squares Estimate				
Parameter	Estimate	S.E.	T-Ratio	Lag
Mean	262.28	986.8	0.27	0
AR1	-0.26	0.13	-1.89	1

Const. Estimate	330.75
Variance Estimate	78,394,524
S.E. Estimate	8,854.0
Akaike	1,073.73

Autocorrelation Test of Residuals				
To Lag	P	df	P	
6	1.03	5	0.96	
12	8.73	11	0.64	
18	13.35	17	0.71	
24	16.49	23	0.83	

Table 23. Comparison of unadjusted and adjusted time series of commercial landings. The adjustment, which increased landings prior to 1981 so that the mean 1945-1980 value was equal to the mean 1981-1996 value was applied to the Maryland values only. Empty cells in the adjusted portion of the table signify that these values are the same as the equivalent unadjusted values.

		Unadjusted (lbs x 10 ³)						
		Mean 1945-1980	Mean 1981-1997	Mean 1945-1997	SD	min	max	Geometric Mean
MD	Hard	23135	44500	29610	11475	9226	56804	27581
	Soft	2251	1904	2133	1242	858	9167	1926
	Total	25385	46404	31744	11611	10228	58958	29762
VA	Hard	36017	39149	36623	9876	15936	61987	35206
	Soft	1439	1070	1332	732	398	3921	1170
	Total	37457	40218	37955	9786	17176	62961	36617
Baywide	Hard	59152	83649	66233	17658	35425	109662	63990
	Soft	3690	2974	3466	1480	1632	10246	3216
	Total	62842	86623	69699	17689	38917	113373	67552

		Adjusted (lbs x 10 ³)						
		Mean 1945-1980	Mean 1981-1997	Mean 1945-1997	SD	min	max	Geometric Mean
MD	Hard	44500		44311	8670	17746	69684	43381
	Soft	1904		1895	1064	726	7756	1716
	Total	46404		46206	9099	18594	71277	45220
VA	Hard			36623	9876	15936	61987	35206
	Soft			1332	732	398	3921	1170
	Total			37955	9786	17176	62961	36617
Baywide	Hard	80517		80934	15530	52066	131671	79498
	Soft	3343		3228	1307	1488	8835	3007
	Total	8261		84161	15852	54665	134238	82712

Table 24. Published estimates of expected maximum age, \bar{a} , and age at maturity, \bar{a}_m , for blue crab.

Reference	Age Parameter		Comment
	\bar{a}	\bar{a}_m	
Havens and McConaugha (1990)	2 - 4		Inferred from life history
Van Engel (1958)	3 - 3½	1 - 1½	Inferred from life history pattern
Fishler (1965)	5	1	Tagging of mature females in NC
Smith (1997)	5½		Inferred from molt-process model
Churchill (1919)	6		Presumed from anecdotal evidence
Mitchill in Rathburn (1886)	7	3	Presumed ages from anecdotal evidence
McConaugha pers. comm.	8		Tag return

Table 25. Estimated values for the partial recruitment of age-1 crabs, PR_1 , given variable levels of under-reporting.

Under-reporting Level	Unadjusted		Adjusted	
	1946 - 1996	1981 - 1996	1946 - 1996	1981 - 1996
20	0.53	0.44	0.54	0.44
15	0.59	0.50	0.60	0.50
10	0.67	0.58	0.68	0.58
5	0.77	0.71	0.78	0.71
1	0.89	0.87	0.89	0.87

fig2

Figure 3. Time series of CPUE from the experimental Smith Island scrape survey conducted in 1987

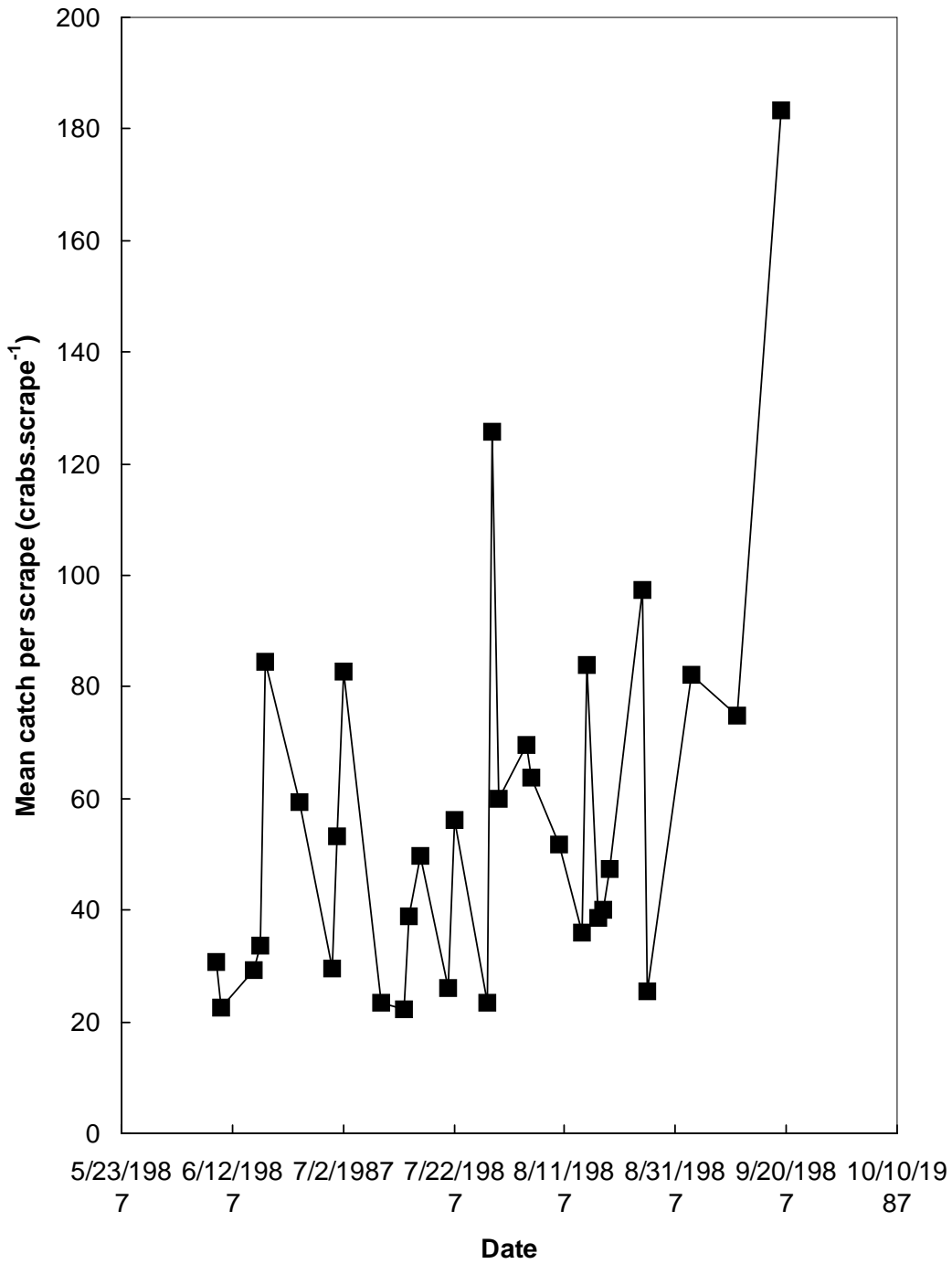


Figure 4. Mean carapace width (CW) of crabs collected in experimental Smith Island scrape survey

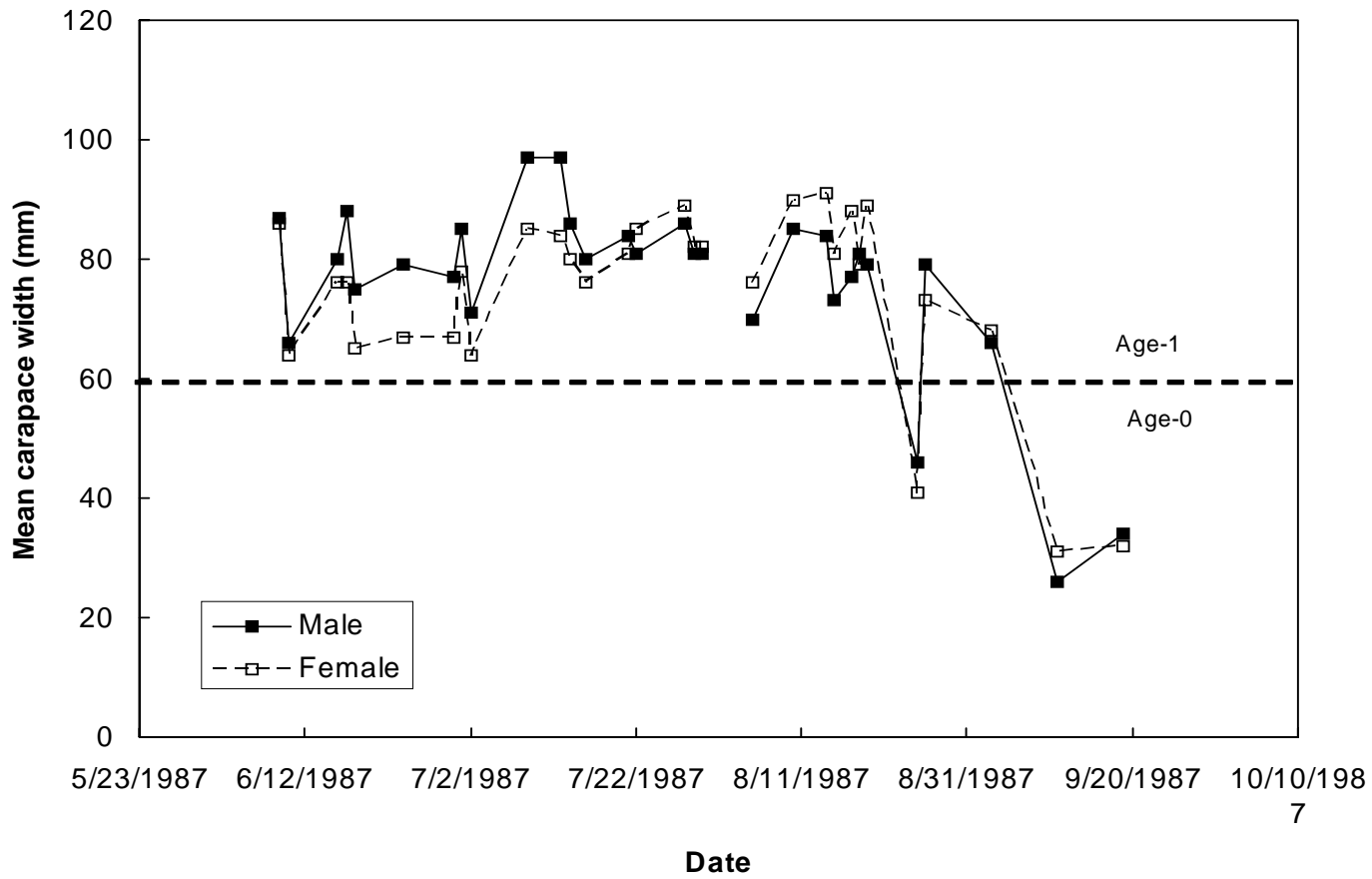


fig5

Figure 6. Time series of CPUE for components of the population from the VIMS juvenile fish and blue crab trawl survey indices (1968 - 1998)

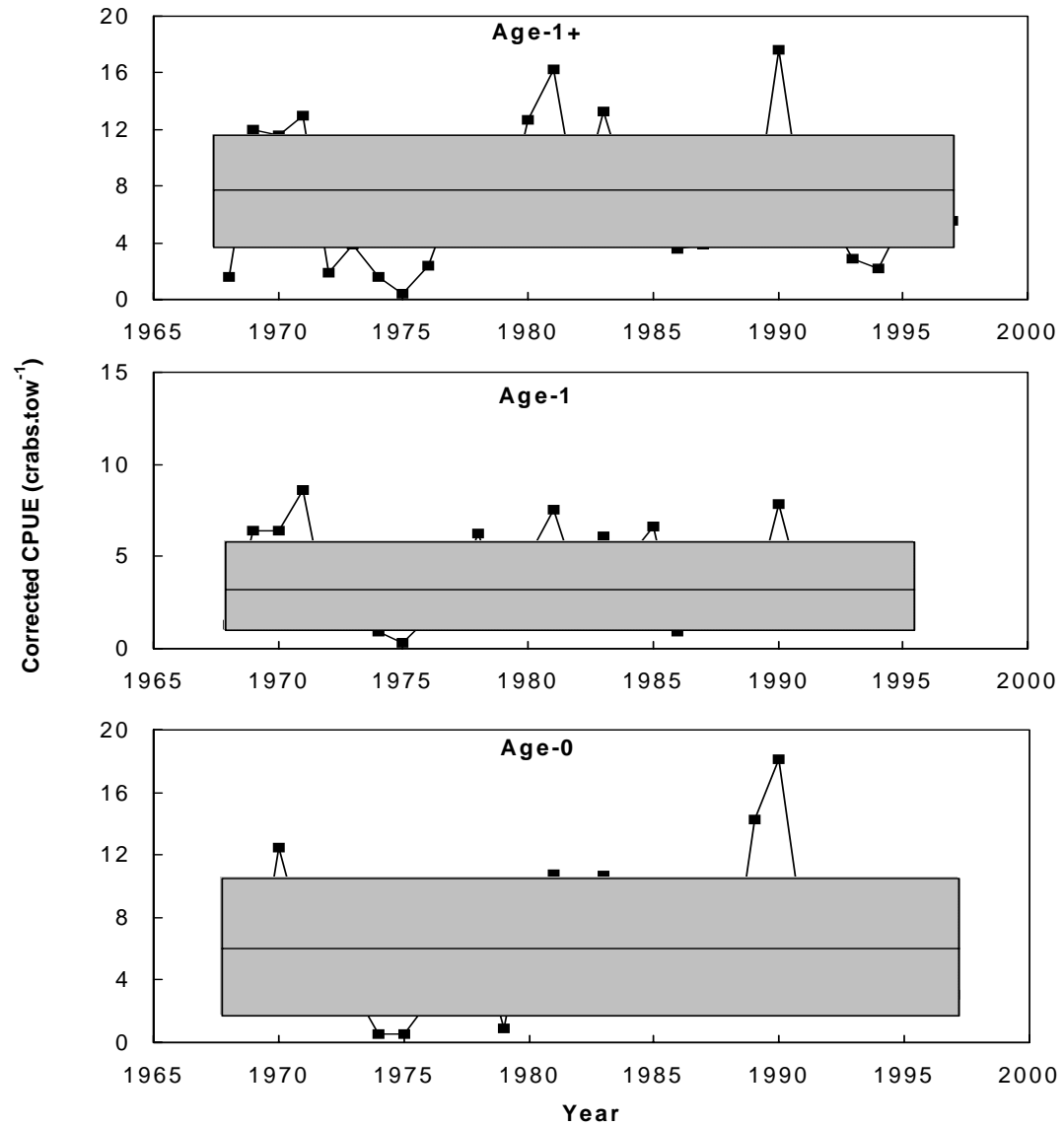


Figure 7. Time series of total CPUE for the Calvert Cliffs pot survey (1968 - 1997)

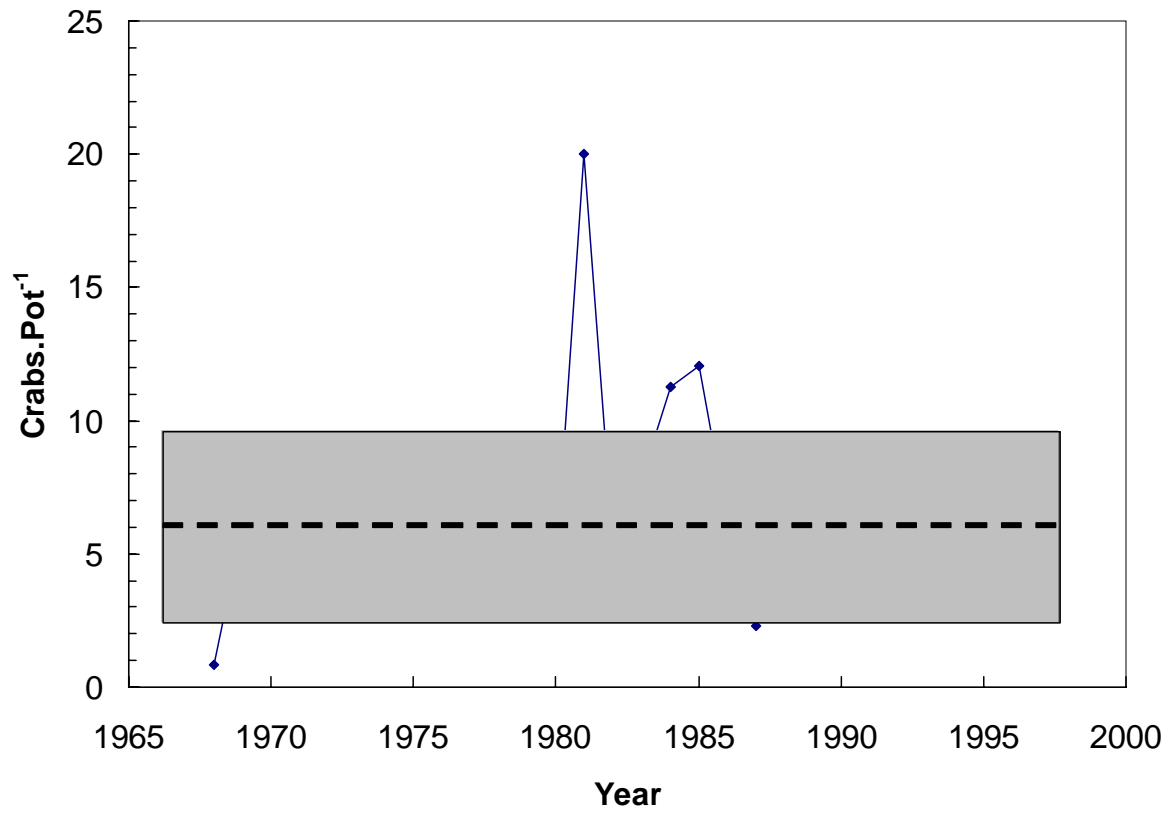


Figure 8. Time series of CPUE for components of the population for the Calvert Cliffs pot survey (1968 - 1998). Components plotted are A) total age-1 crabs, B) total age-2 crabs, C) legal female crabs, and D) legal male crabs

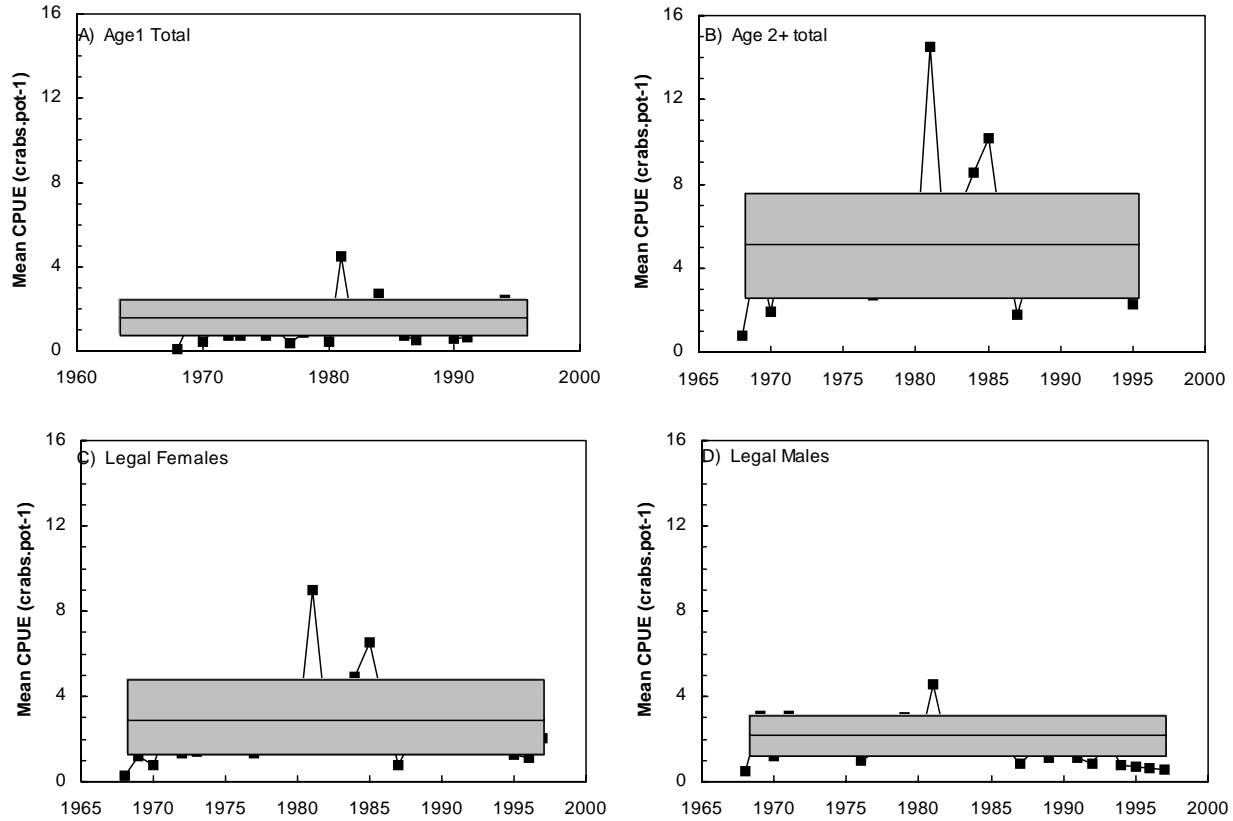


Figure 9. Time series of CPUE for components of the population for the MD DNR trawl survey (1988 - 1997). Components are A) age-2+ crabs, B) age-1 crabs, and C) age-0 crabs

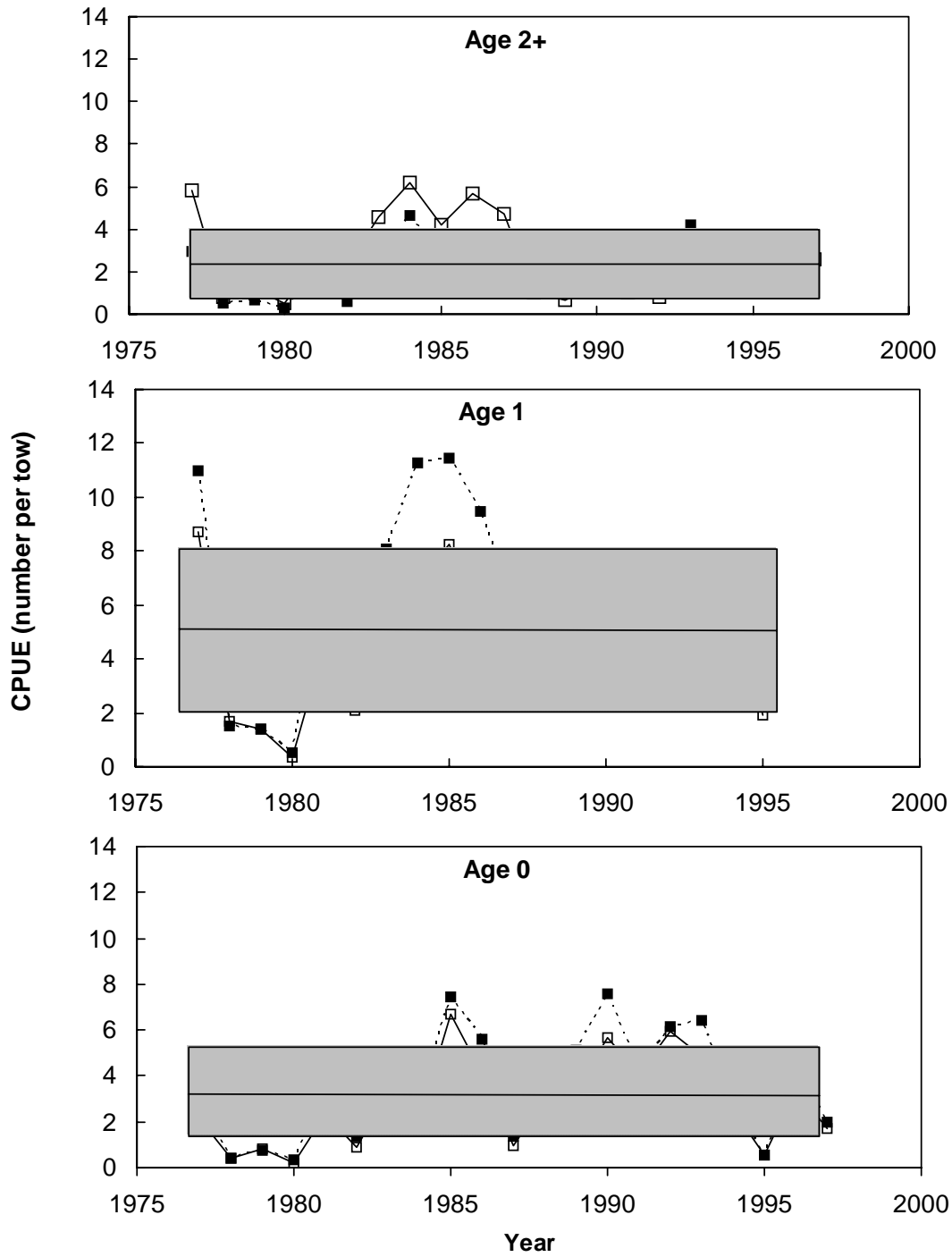


Figure 10. Time series of CPUE for components of the population for the CBSAC winter dredge survey (1989-1998). Components are A) mature female crabs, B) age-1+ crabs, and C) age-0

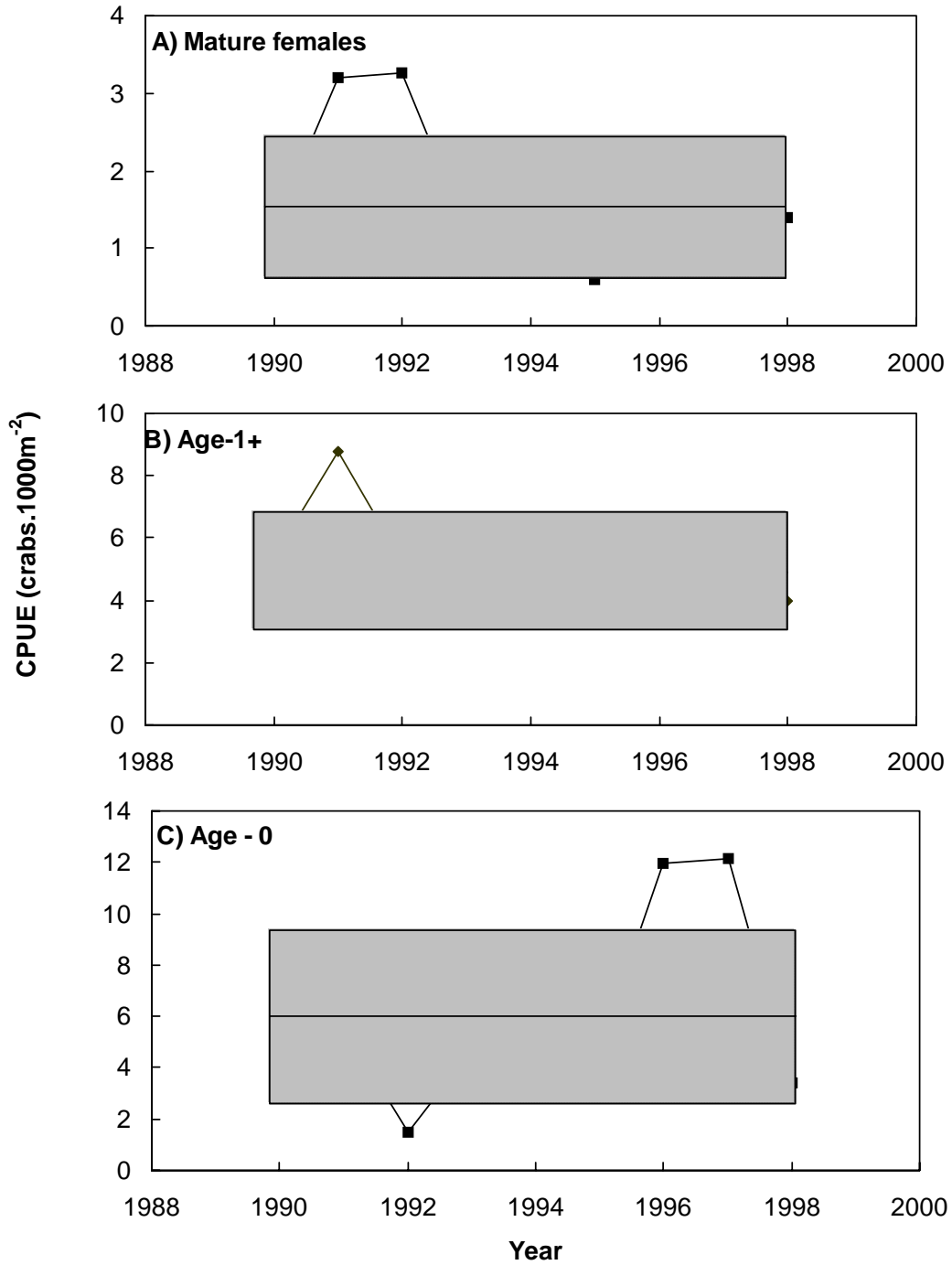


Figure 11. Cross-correlation analysis of CPUE of age-1+ crabs from the VIMS trawl survey with the CPUE of legal crabs in the Calvert Cliffs pot survey

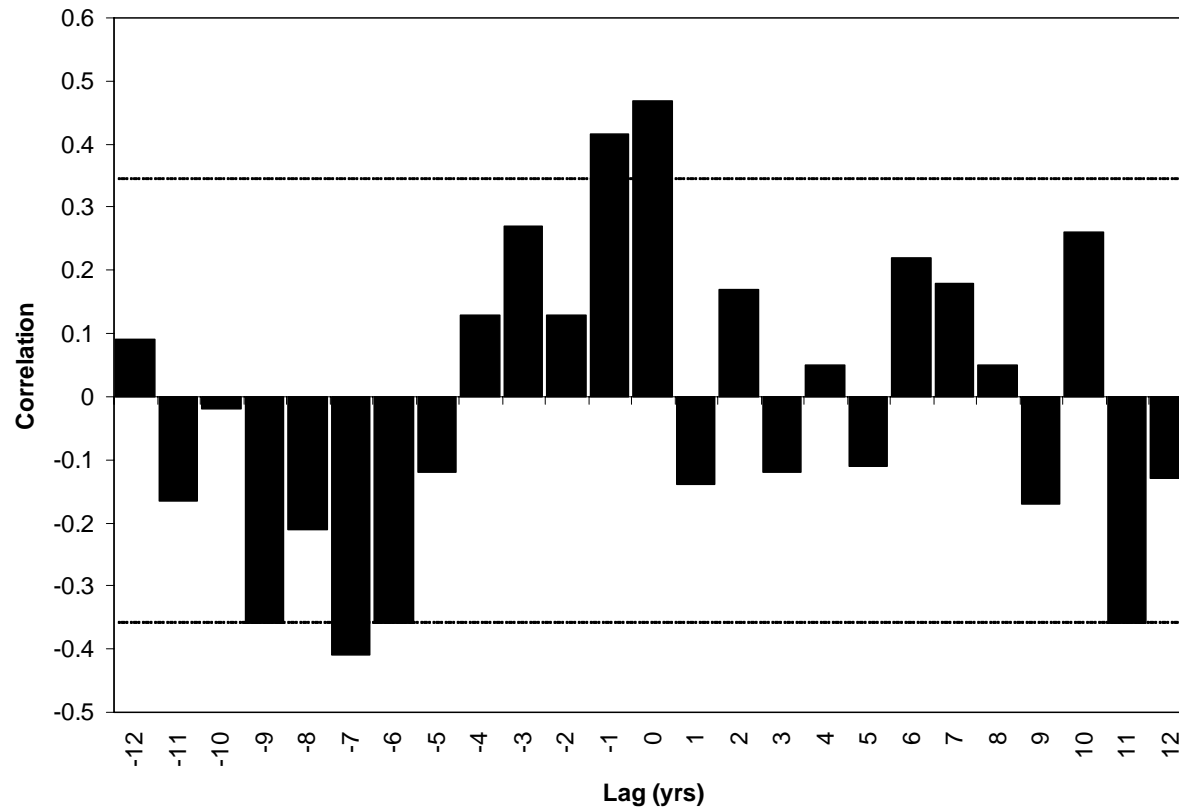


Figure 12. Cross-correlation analysis of CPUE of age-0 crabs from the VIMS trawl survey with the CPUE of legal crabs in the Calvert Cliffs pot survey

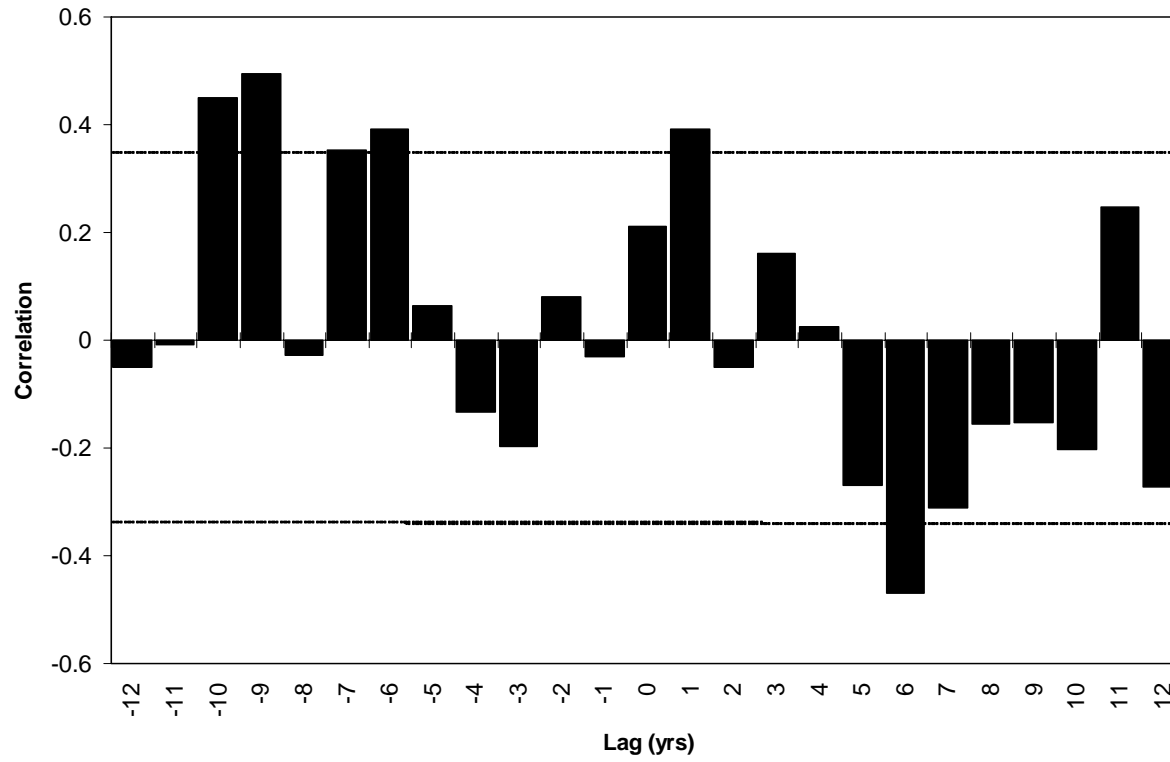
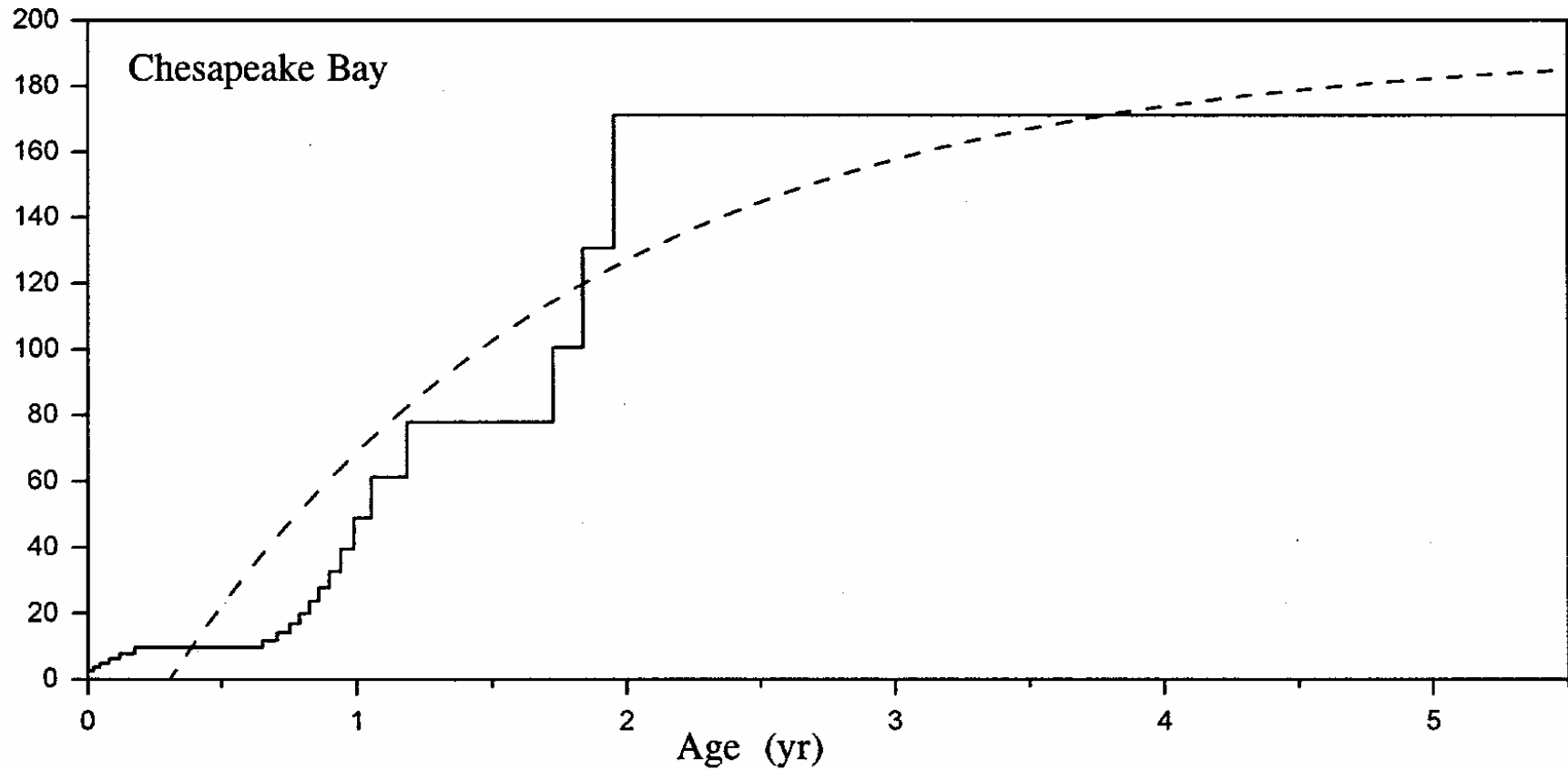


fig13

fig14

fig15

Figure 16. Comparisons of continuous and discontinuous descriptions of crab growth dynamics after Smith (1997). Fitted responses show a von Bertalanffy size at age curve ($C_{winf} = 187$ mm, $k=0.5056$ yr⁻¹, dashed line) and a molt process model



3. SURPLUS PRODUCTION MODELING

The biomass of any population in the next time period is equal to its current biomass plus increases from growth and recruitment, minus decreases from natural and fishery mortality in the present time period. It is usual to combine the growth and recruitment terms as production. When production exceeds mortality the population grows; when production is less than mortality the population declines. Surplus production is the amount that can be removed from the population as catch without reducing the population biomass. When populations are small, surplus production is small because there are few individuals to grow or reproduce. When populations are very large, density-dependent processes reduce surplus production to low levels. At population levels in between these extremes surplus production generally is a dome-shaped function of biomass, with production (and sustainable catch) potentially highest at intermediate stock levels. The objective of surplus production modeling is to describe the functional form of the relationship between production and stock biomass, and to estimate the rate of exploitation which adjusts population biomass to a level that allows maximum sustainable yield.

Several surplus production models have been developed and potentially could be fit to data on blue crab catch and effort. We have fit two models to blue crab data. The simplest model assumes that there is no age- or spatial-structure within the population, and that the population is in equilibrium. The second model also assumes limited stock structure but, importantly, relaxes the equilibrium constraint. Both types of stock assessment require CPUE data as input. We used two CPUE time series as inputs to the production models; the unadjusted CPUE time series, which included no adjustment for the 1981 Maryland reporting change, and an adjusted CPUE time series which applied an adjustment (see section 2.1.3.a).

3.1 Equilibrium Surplus Production Models

We generated two alternative CPUE time series, based upon standardizing the total catch to the effort in the pot fishery as described in the CBSAC stock assessment (Rugolo 1997). Briefly, we calculated the CPUE in the pot fishery and then divided the total catch by the pot CPUE to get the nominal effort. The overall CPUE was then expressed as the total landings divided by the nominal effort. The two CPUE time series show declines since 1946 (Figure 17). Adjustment for the Maryland change in reporting and in landings affected CPUE prior to 1981. Thus, the CPUE time series differ only for years prior to 1981. The adjustment to the landing time series increased the estimates of CPUE. An exponential decay function was fit to both time series. The exponential function explained 71% of the variation in the unadjusted time series and 87% of the variation in the adjusted time series. The adjusted time series shows a continuously decreasing CPUE, at least until the 1980s, while the unadjusted series indicates a leveling of CPUE after 1970 (Figure 17). However, although the patterns are broadly similar, the models differ to the extent that they predict recent CPUE's. The adjusted model suggests CPUE's are still declining. In the unadjusted model, CPUE's appear constant in recent years. In the adjusted scenario, there is no need to invoke gear saturation to explain the trend in CPUE's.

We fit standard Schaefer surplus production models to both nominal effort time series

(Ricker 1975). The model is given by:

$$Y_e = B_\infty \cdot q \cdot f - \frac{B_\infty \cdot q^2}{K} \cdot f^2 \quad (3.1.1.)$$

where Y_e is the harvest, B_4 is the equilibrium biomass under no exploitation, q is the catchability and K is the biomass growth rate assuming logistic population growth. The model parameters for the unadjusted and adjusted time series are given in Table 26. The model predicted a maximum sustainable yield of 86,995,620 lbs. at a nominal effort 572,830 pot-hrs @month⁻¹ (Figure 18.) The comparable surplus production model for the adjusted time series predicted a higher maximum sustainable yield of 99,675,320 lbs, but this yield is achieved at a greatly reduced effort of 449,190 pot-hrs @month⁻¹ (Figure 19). Recent catches, based upon the unadjusted data, indicate that landings were above nominal MSY (averaging >90 million lbs.) in the 1980s but declined, averaging only 81 million lbs in the 1990s (Figure 13). For the adjusted data, landings varied about the long-term mean of 84.6 million lbs in the 1980s, with average landings below nominal MSY; landings declined in the 1990s, on average, and, except for 1993, were well below the MSY level (Figure 15).

Surplus production models, especially equilibrium versions, are frequently criticized. Hilborn and Walters (1992) strongly caution against their use on theoretical grounds. Additionally, they criticize the technique because of characteristics of the data set to be modeled, particularly in fisheries which have experienced continuously increasing effort and simultaneously declining CPUE, as with blue crab. They term this pattern a one-way walk. When a stock is perturbed in this way, estimates derived from surplus production models are unreliable. It is instructive to identify the years for each data point on Figures 18 and 19 from this viewpoint. For both the unadjusted and adjusted time series the landings and associated effort for individual years are grouped around the predicted surplus production function (Figures 20-21). Both figures show clear increasing trends in effort, indicating that nominal effort generally continued to increase throughout the 1945-1980 period. Landings increased during this period as well but less dramatically than effort. In neither case is there a period of decreasing nominal effort. Thus, we have little empirical evidence from these poorly fit models that the estimates of MSY are either reliable or sustainable. Nevertheless, it is notable that effort levels predicted to produce MSY were exceeded in 15 years for the adjusted time series (Figure 21) but in only 5 years for the unadjusted time series (Figure 20). In this sense, the model based upon the adjusted landings data offers more precautionary and risk-averse advice.

3.2. Non-equilibrium Surplus Production Modeling

A second class of surplus production models does not require the restrictive assumption of equilibrium conditions, but may be difficult to fit with existing data. These non-equilibrium models recognize the dynamics of the population. Two approaches are commonly used: regression techniques and time-series analysis. For the blue crab population we applied regression models. We fit a difference equation model of Hilborn and Walters (1992) given by:

$$\frac{U_{t+1}}{U_t} - 1 = r - \frac{r}{K \cdot q} \cdot U_t - q \cdot f_t \quad (3.1.2.)$$

where U_t is the catch per unit effort in year t , f_t is the effort in year t , K , and q are as before.

We fit the difference equation model to both unadjusted and adjusted time series. The model fits for both time series were poor. The r^2 for the unadjusted time series was 0.05 (Table 27). The estimate of the intrinsic rate of natural increase (r) was 0.2. The estimate of q was small, not significantly different from zero and had wide confidence limits. The model for the corrected time series also had a low r^2 value (Table 27). For this data series, the estimate of the intrinsic rate of natural increase (r) was 0.3. Once again, the estimate of q was small, and not significantly different from zero.

The difference equation form of the surplus production model provided no useful information additional to that provided by the Schaefer model. However, the results do emphasize the unreliability of applying the general surplus production formulation to the blue crab dataset.

In summary, production models can be fit to the blue crab data, but the results of such exercises should be interpreted with caution. The CBSAC assessments indicates an MSY of 82-85 x 10⁶ lbs. Our production models indicate that the MSY of the blue crab fishery lies in the rather broad range of 80-100 x 10⁶ lbs at levels of nominal effort in the range 450,000 - 575,000 pot-hrs @month⁻¹, while effort in recent years has exceeded 600,000 pot-hrs @month⁻¹. However, given the probable unreliability of the MSY estimates, particularly under the circumstance of the unidirectional nature of catch-effort time series for blue crab, we believe that the lower effort estimate level to attain MSY may be more appropriate and risk-averse. This recommendation is further warranted given the observation that effort in the fishery may have exceeded f_{MSY} for much of the last 20 years.

Table 26. Schaefer model fits for blue crab fishery in Chesapeake Bay (1945 - 1996). Model fits were derived from standard least squares estimation of eq. 3.1.1, fitted as $Y_e = af + bf^2$.

Series	MSY (lbs x 10 ³)	f_{MSY} (Pot C hours C month ⁻¹)	Linear Term	Quadratic Term	r^2
Unadjusted	86955	572,830	0.3036	-2.65 x 10 ⁻⁷	0.02
Adjusted	99675	449,190	0.4438	-4.94 x 10 ⁻³	0.09

Table 27. Difference equation surplus production model fits for blue crab fishery in Chesapeake Bay (1945 - 1996). Model fits were derived from standard least squares estimation of eq. 3.1.2. Parameter (\pm SD) estimates are given for r , K , and q .

Series	MSY	f_{MSY}	r	K	q	r^2
Unadjusted			0.196 (0.190)	1.906×10^{-6}	1.8×10^{-7} (2.9×10^{-7})	0.05
Adjusted			0.297 (0.22)	1.41×10^{-6}	3.8×10^{-7} (3.5×10^{-7})	0.05

Fig 17

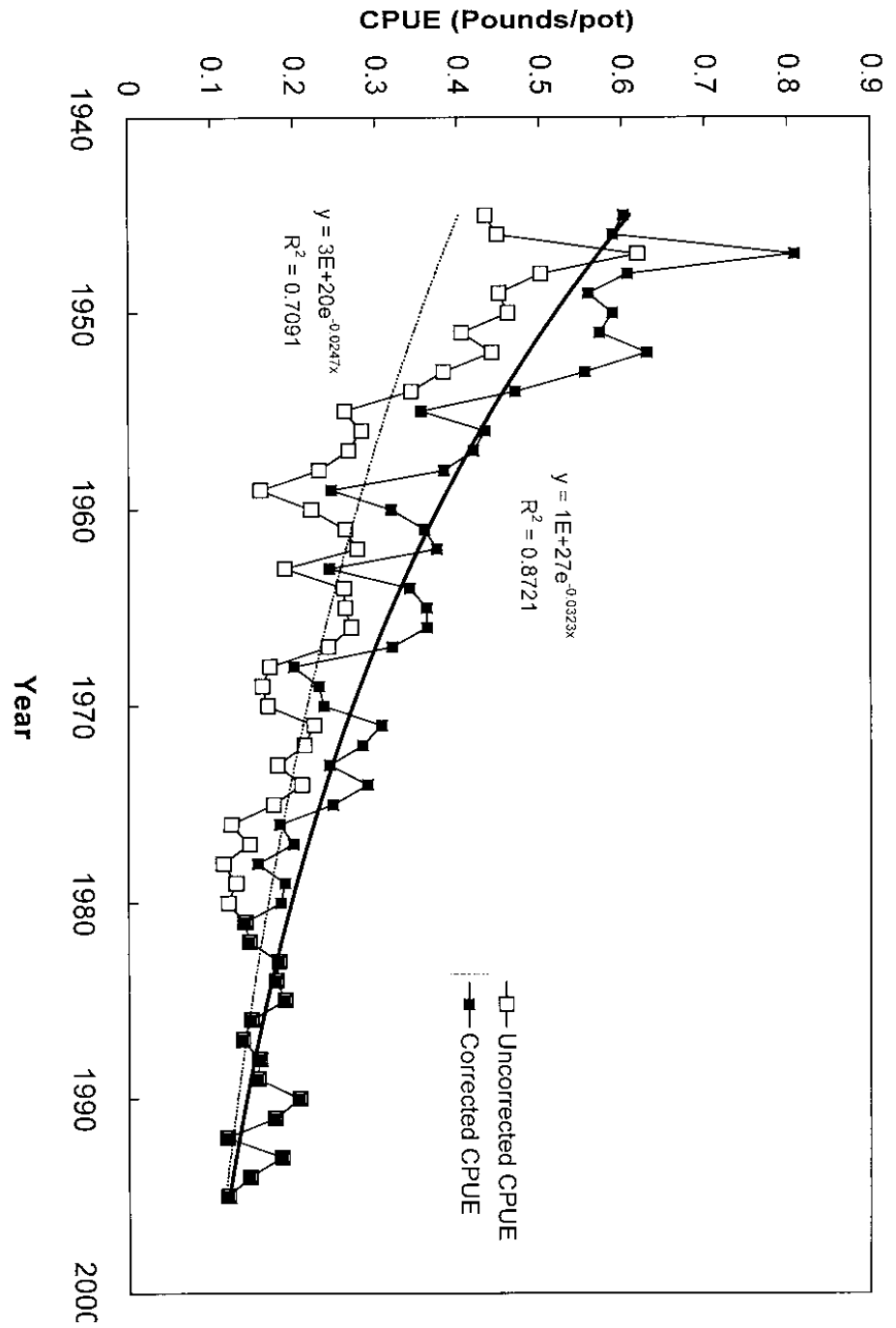


Figure 17. Time series of estimated Bay wide CPUE (lbs · pot⁻¹) for 1945-1996. Plotted in the figure are time series developed from the unadjusted and adjusted landings (see Section 2.1.3 for details of the adjustment algorithm).

fig1
8

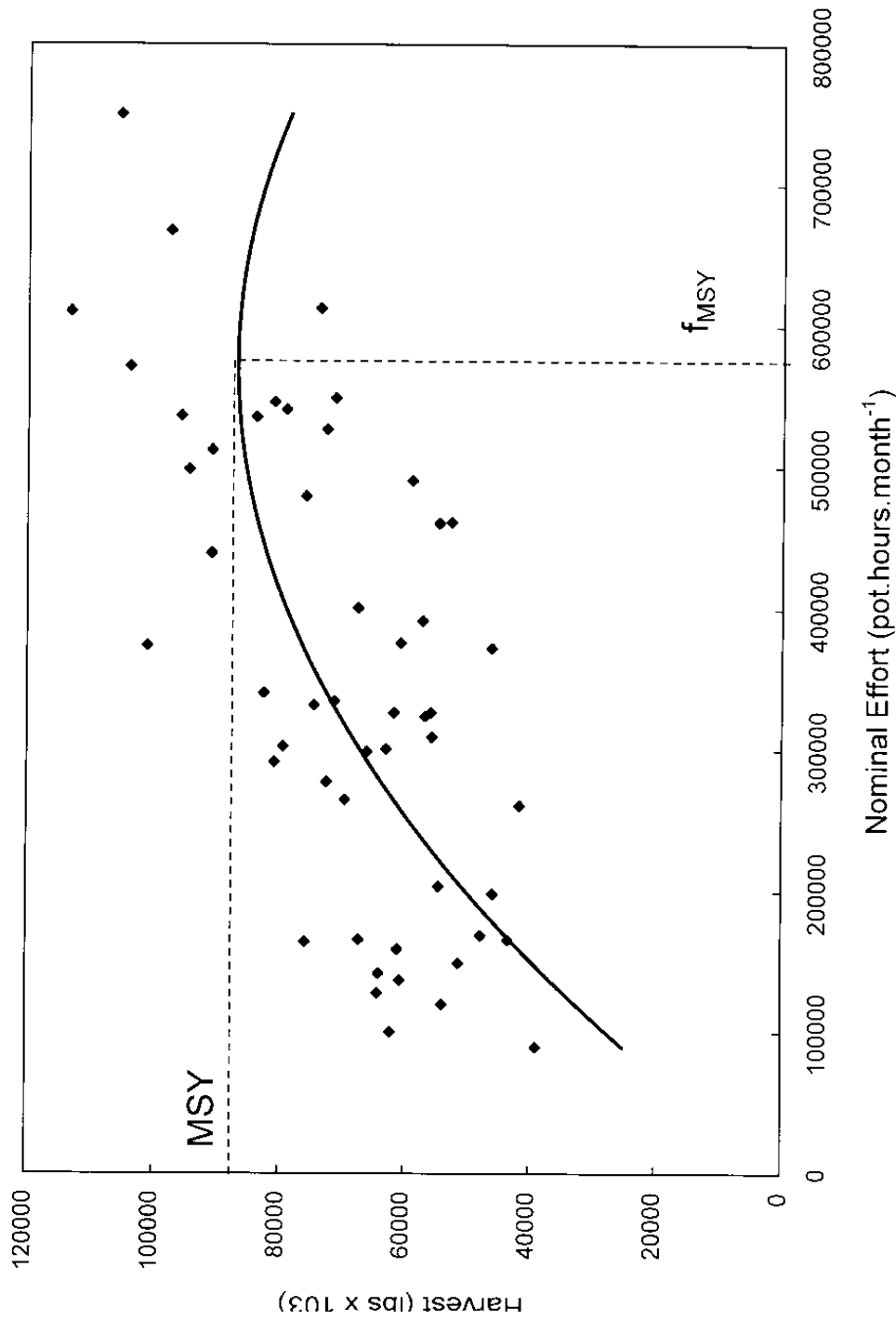


Figure 18. Unadjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996). Also shown on the figure is the fit of the Schaefer surplus production model to the data. The Schaefer model predicts the MSY harvest to be 86,955,623 lbs. at a nominal effort of 572,830 pot-hours · month⁻¹. See text for details of calculation of nominal effort.

fig1

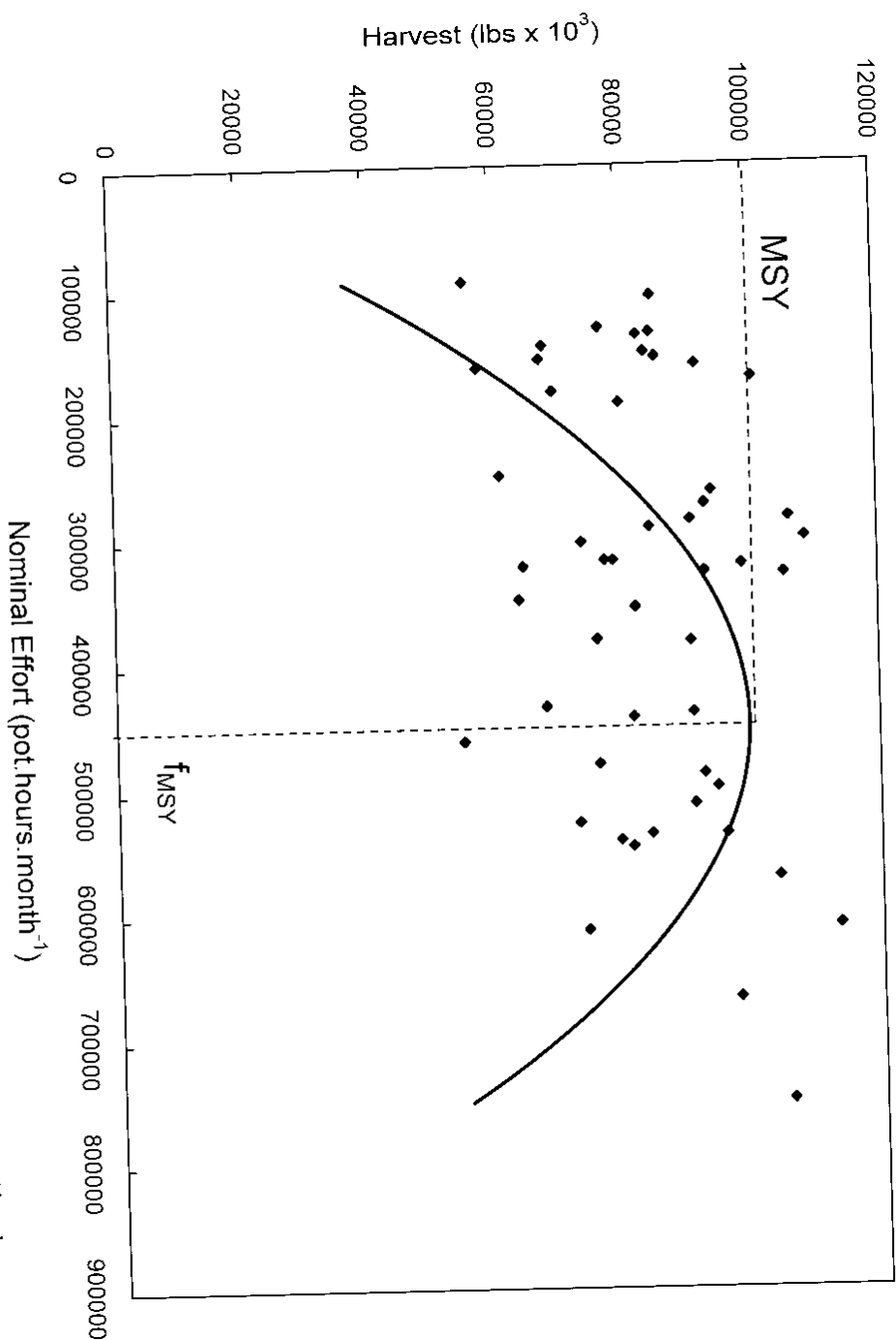


Figure 19. Adjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996). Also shown on the figure is the fit of the Schaefer surplus production model to the data. The Schaefer model predicts the MSY harvest to be 99,675,324 lbs. at a nominal effort of 449,190 pot-hours month⁻¹. See text for details of calculation of nominal effort.

Figure 20. Time series of unadjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996). Also shown on the figure is the fit of the Schaffer surplus production model to the data. See text for details of calculation of nominal effort.

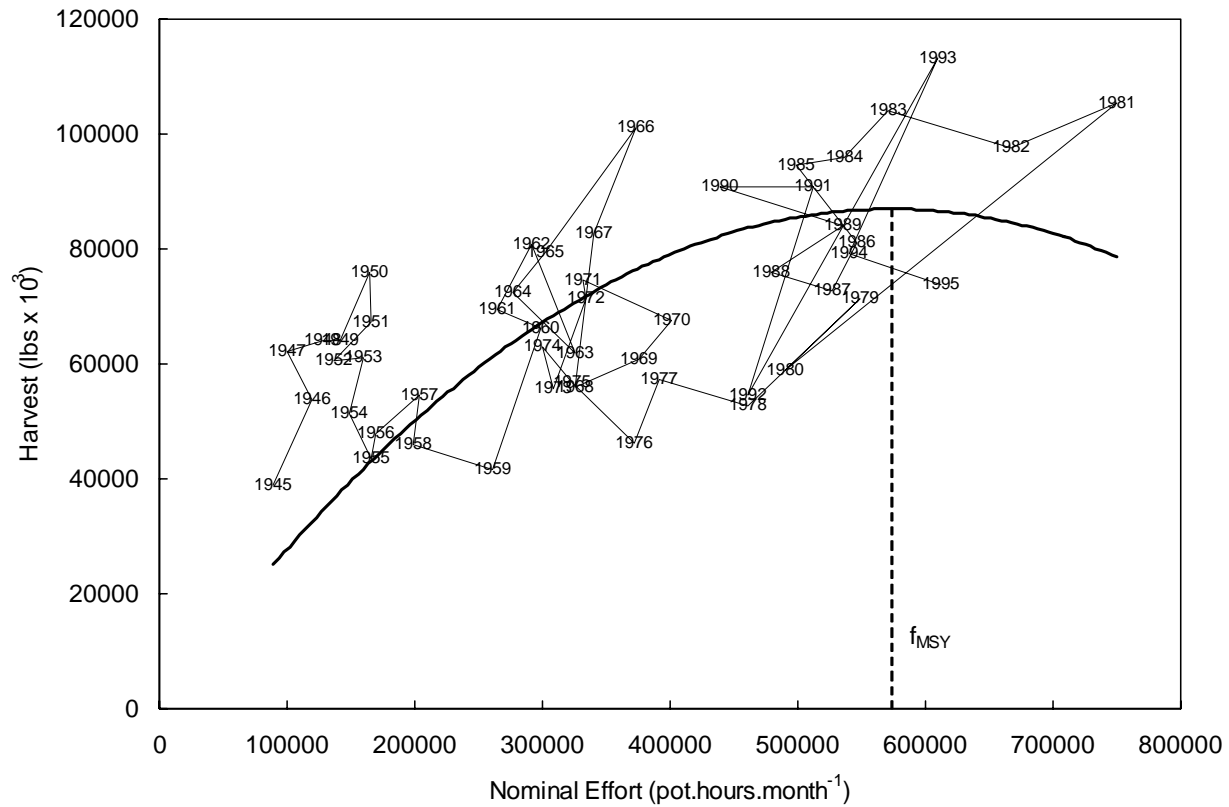
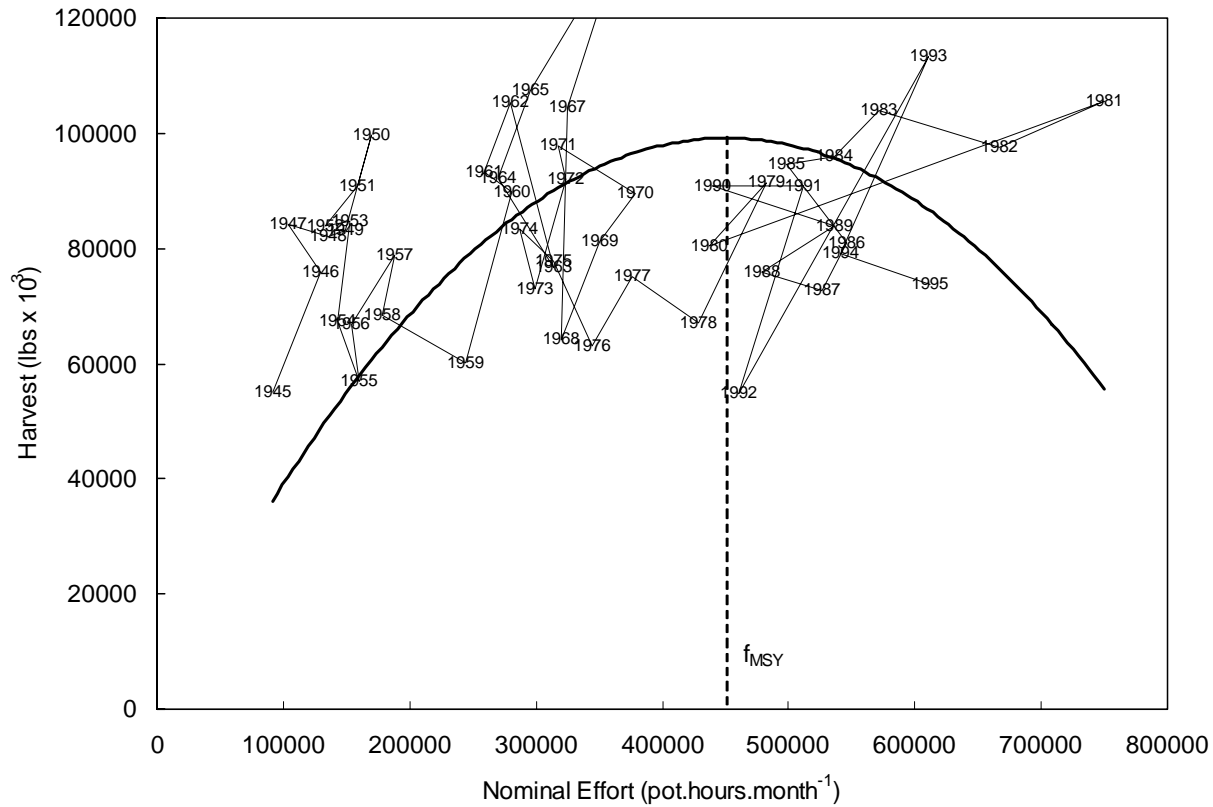


Figure 21. Time series of adjusted harvest as a function of nominal effort in the Chesapeake Bay blue crab fishery (1945-1996). Also shown on the figure is the fit of the Schaefer surplus production model to the data. See text for details of calculation of nominal effort.



4. EXPLOITATION RATES AND STOCK SIZE ESTIMATION

In Figure 1, we outlined how fishery-independent data can be used to estimate the rate of exploitation in the fishery. Subsequently, the estimates of exploitation rate can be combined with fishery-dependent estimates of landings and effort to develop estimates of the total stock size. In this section we present these calculations for a range of different assumptions. The objective is to calculate time series of exploitation rates and stock size to determine potential target levels.

4.1. Exploitation Rates

4.1.1. Mortality rates

Our initial step to estimate rates of exploitation was to combine fishery-independent abundance time series with the partial recruitment vector to produce a time series of estimated total mortality rates. The Calvert Cliffs pot-, VIMS trawl-, MD trawl and CBSAC winter dredge survey are sufficient to allow calculation of the total mortality rates.

The time series of fishery-independent abundances were analyzed using Hoenig's (1987) method. This approach allows estimation of total mortality rate $Z (= F + M)$, where F and M are the fishing and natural mortality rates, respectively, from estimates of the size of animals in the catch, and K and CW_4 derived from the von Bertalanffy growth model. Specifically,

$$Z = \ln \left(\frac{(e^{-k \cdot (\overline{CW} - CW_\infty)}) + CW_\infty - CW_t}{(\overline{CW} - CW_t)} \right)$$

CW_4 is the carapace width at full recruitment (~120 mm), and \overline{CW} is the mean carapace width of fully recruited crabs.

As discussed in section 2.2.2.b, estimates of growth parameters are uncertain for blue crab. To reflect this uncertainty we explored the sensitivity of estimating Z over a range of estimates of K and CW_4 (by varying estimates of μ , the maximum age). We also calculated Z values for Rothschild et al. (1991) von Bertalanffy parameter estimates. The parameter estimates used and resulting estimates of Z are given in Table 28. For illustration, we plotted the VIMS-based estimates (Figure 22). It is clear from this figure that the different von Bertalanffy estimates shifted the magnitude of estimated Z values, but did not affect the pattern in the time series. However, while the different estimates of μ had minor effects on the total mortality estimates, selection of Rothschild et al. (1991) von Bertalanffy parameter estimates yields substantially different estimates of Z . In fact, the Rothschild et al.'s-based estimates are approximately 50% of those derived from the von Bertalanffy estimates used in the CBSAC stock assessment (Table 29 and Figure 22). This difference emphasizes the importance of having an accurate growth model for blue crab. It also is clear from Figure 22 that the growth

parameters based upon selection of $\tau = 8$ yrs yield consistently highest estimates of Z . In this sense, given the uncertainty of maximum age in blue crab, the assumption of $\tau = 8$ years is the most precautionary.

Estimates of F can be generated from estimates of Z , given a value of M . For our calculations, M was estimated as $3/\tau$, the method adopted for stock assessments by the International Council for the Exploration of the Seas and also used in the CBSAC stock assessment of blue crab. We have not explored the effects of possible variation in M during ontogeny, or either temporally or spatially. The presence of such variation would lead to biases in our estimated values of F . However, ontogenetic and spatial variation would not lead to errors in the estimates of deviation of F 's relative to a reference limit of target. However, ontogenetic and spatial variability in M would change the absolute magnitude of estimated limits and targets calculated from the estimated time series of F . In contrast, temporal variation in M would change both the absolute and the relative estimates of F . The estimated limit and target values would be underestimated if M had increased over time, and be overestimated if M had decreased over time. We have no basis on which to determine whether there is any trend in M .

The time series of estimates of F are plotted in Figure 23 and are presented in Table 29. The effect of variation in M , resulting from different τ , is striking, especially when the spread of values for Z (Figure 22) and F (Figure 23) are compared. Estimates of F , based upon the Z calculated from the Rothschild et al. (1991) growth model parameters, seem unrealistic in this analysis. The general trends in the time series of F are the same for all scenarios. Levels of F increased in the 1990s, but were not substantially higher than they were previously. Similarly high estimates of F occurred in the early 1970s and mid 1980s. However, estimates of F for the last two years are time series highs and may be cause for concern. Estimates of F are highest for $\tau = 8$ years. For that scenario, the time-series mean $F = 0.87 \pm 0.14$. As with total mortality, selection of $\tau = 8$ years, is a risk-averse strategy, given the uncertainty of maximum age and associated natural mortality rate.

Similar patterns are evident for carapace width-based F 's derived from the other fishery-independent time series (Table 29). For example, regardless of survey, all F time series appear to vary without trend. There is some evidence of increases in F in the most recent years. In all cases, estimates of F are highest for $\tau = 8$ and lowest for the Rothschild et al.'s (1991) formulation. Estimates of F based on MD DNR survey data are most sensitive to growth parameter estimates, whereas estimates of F based on Calvert Cliffs pot surveys are least sensitive.

4.1.2. Exploitation Rates

We calculated annual exploitation rates for the soft/peeler and the hard shell crab fishery. We used the same type II fishery model as used in the CBSAC stock assessment (Rugolo et al. 1997). Exploitation rate is:

$$\mu_i = \frac{(PR_i \cdot F \cdot (1 - e^{-(M + PR_i \cdot F)}))}{(M + PR_i \cdot F)} \quad (4.1.1.)$$

where μ_i is the exploitation rate on a component (stage or age) of the stock, and PR_i is the partial recruitment value for component i calculated from the commercial fishery. We calculated exploitation rates for the soft/peeler and hard crab fisheries. We used PR_1 values that ranged from 0.53 - 0.89, covering the range of potential variability from underreporting in the soft/peeler fishery (See section 2.3.1, Table 25). Estimates of exploitation rates in the hard shell fishery varied only with M and F because $PR_2 = 1$. We also allowed M to vary to simulate effects of uncertainty in $\mu = 4, 6, \text{ or } 8$ years. Accordingly, values of M were 0.75, 0.50, and 0.375 (i.e. $3/\mu$). The carapace width-based F values were from the mortality analysis (See Section 4.1.1). To obtain time series of exploitation rates, we used the two longest series, the VIMS trawl and Calvert Cliffs pot surveys, as the sources of estimates of F (Table 29).

Across all possible combinations of PR_1 , M and F , mean exploitation rates ranged from 0.106 - 0.482 (Table 30). Exploitation rates based upon estimates of F from the Calvert Cliffs pot survey were slightly higher than those based upon the VIMS trawl survey. Exploitation rates for soft and peeler crabs were lower than those for the hard shell fishery. Exploitation rates increased as PR_1 increased (Figure 24). The relationship between μ and M was linear. Moreover, the slope of the mean annual exploitation rate -- PR_1 relationship increased as M decreased. Thus, accurate estimation of PR_1 is more important at lower values of M than at higher values.

We also examined the time series of annual estimates of μ to determine if rates of exploitation may have increased in the fishery. The time series of μ (Figure 25) were derived from VIMS- and Calvert Cliffs-based values of F at $\mu = 6$ (Figure 25) and 8 years (Figure 26), with PR_1 set at 0.67. There is variability in all of the estimated exploitation-rate time series. In general, the VIMS-based time series varies without trend. However, the VIMS-based series does exhibit periods of above average exploitation rates in the early to mid 1970s and mid 1980s. The time series maximum occurred in 1994. In contrast, the Calvert Cliffs-based time series does exhibit a trend, in which μ has increased since 1987. This trend was apparent whether estimates were based upon a maximum age of 6 or 8 years. The time-series peak occurred in 1994 and estimates of μ in the hard shell fishery were more than 1 SD above the mean during the last 4 years of the series.

4.2. Stock Size Estimates

The abundance or biomass of crabs in the population can be estimated from the total commercial and recreational harvest and the exploitation rate. The estimated stock size is

$$N_t = \frac{C_t}{\mu_t}$$

where N_t is the estimated abundance in year t , μ_t is the exploitation rate, and C_t is reported landings. Estimates of N_t depend upon assumptions regarding landings and exploitation rates. We examined two exploitation-rate scenarios. We developed stock size estimates based upon Calvert Cliffs and VIMS derived exploitation rates. We also compared the effects of assuming a maximum expected life expectancy of 6 and 8 years. We also compared effects on stock size estimates of using either the unadjusted or the adjusted Baywide commercial landings data (See Section 2.1.3). To account for landings of the recreational fishery, which have been estimated to be between 25-75% of commercial landings we arbitrarily chose a value of 0.25. While this might lead to an underestimate of stock size, trends in the time series will not differ. However, if the recreational harvest has varied significantly over time, then the relative trends in stock size will also be biased.

Estimates of mean stock abundance for the period 1956-1997 varied depending upon the assumptions made regarding maximum age and whether or not the commercial landings were adjusted (Table 31).

In general, VIMS-based estimates were lower both for biomass (Figures 27 and 28) and abundances (Figures 29 and 30) than were estimates derived using Calvert Cliffs exploitation rates. This reflects the higher exploitation estimates in the VIMS time series. Estimates suggest that there have been 300 - 400 x 10⁶ lbs. of harvestable crabs, equivalent to 1.2 x 10⁹ harvestable crabs, in the bay annually over the past 30 years.

There was a substantial effect of the landings adjustment on the estimated time series of stock sizes (Figures 27 - 30). Based upon the unadjusted time series, the most recent abundances appear to be slightly higher than abundances in the 1970s, but considerably lower than abundances in the 1980s. However, if the reporting change in Maryland was the primary cause of the shift in landings in 1981, then adjusting for it produces a dramatically different pattern in the abundance time series. Using the adjusted time series of landings, stock sizes in the 1970s were estimated to be higher. It is also important to compare the recent estimates of stock size with respect to the long term mean. Estimates based upon the Calvert Cliffs survey are highly variable. Moreover, 4 of the last 5 years are time series lows. Recent estimates are below the time series mean, and are approaching a level that may cause concern. Concern is heightened by knowledge that reporting changes occurred in Virginia in 1992 that may account for the dramatic and abrupt change in the time series for that year. If the 1992 estimates are artificially inflated, then it may be that estimates for the last six years have been below average, indicating a need to reexamine management guidelines.

The abundance estimates based on VIMS-derived exploitations show less dramatic declines in recent years. For this time series, 4 of the last 5 annual abundance estimates are below the mean.

Table 28. Parameter estimated used in developing carapce width-based estimates of Z . Three

different estimates of maximum expected age, ω , were employed together with a separate formulation from Rothschild et al. (1991).

Parameter	Expected Maximum Age, ω			Rothschild et al. 1991
	4	6	8	
K	0.714	0.335	0.582	0.505
CW	231.5	285.0	258.1	178

Table 29. Carapace width-based estimates of Z and F derived from analyses of fishery independent time series and differing assumptions regarding growth. Shown in subsequent panels are estimates of Z and F for each time series for A) VIMS juvenile finfish and blue crab survey; B) Calvert Cliffs pot survey; C) MD DNR trawl survey; and D) CBSAC winter dredge survey.

A) VIMS

Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1956	1.21	1.06	1.14	0.51	0.84	0.56	0.39	0.01
1957	1.34	1.17	1.26	0.61	0.97	0.67	0.51	0.11
1958	1.30	1.13	1.22	0.57	0.92	0.63	0.47	0.07
1959	1.29	1.13	1.22	0.57	0.92	0.63	0.47	0.07
1960	1.28	1.11	1.20	0.56	0.90	0.61	0.45	0.06
1961	1.28	1.12	1.20	0.56	0.91	0.62	0.45	0.06
1962	1.30	1.14	1.22	0.57	0.93	0.64	0.47	0.07
1963	1.29	1.12	1.21	0.56	0.91	0.62	0.46	0.06
1964	1.28	1.11	1.20	0.56	0.90	0.61	0.45	0.06
1965	1.28	1.12	1.20	0.56	0.90	0.62	0.45	0.06
1966	1.28	1.12	1.20	0.56	0.91	0.62	0.45	0.06
1967	1.29	1.12	1.21	0.56	0.91	0.62	0.46	0.06
1968	1.28	1.11	1.20	0.56	0.90	0.61	0.45	0.06
1969	1.26	1.10	1.18	0.54	0.89	0.60	0.43	0.04
1970	1.12	0.98	1.04	0.44	0.75	0.48	0.29	-0.05
1971	1.35	1.18	1.27	0.61	0.97	0.68	0.52	0.11
1972	1.30	1.14	1.23	0.58	0.93	0.64	0.48	0.08
1973	1.49	1.31	1.42	0.73	1.12	0.81	0.67	0.23
1974	1.32	1.15	1.24	0.59	0.94	0.65	0.49	0.09
1975	1.40	1.23	1.33	0.66	1.03	0.73	0.58	0.16
1976	1.15	1.00	1.07	0.46	0.78	0.50	0.32	-0.03
1977	1.10	0.96	1.02	0.42	0.73	0.46	0.27	-0.07

Table 29. (Continued).

A) VIMS (Continued)								
Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1978	1.15	1.00	1.07	0.46	0.78	0.50	0.32	-0.03
1979	1.14	0.99	1.06	0.45	0.77	0.49	0.31	-0.04
1980	1.00	0.87	0.92	0.35	0.62	0.37	0.17	-0.14
1981	1.20	1.05	1.12	0.50	0.83	0.55	0.37	0.00
1982	1.17	1.02	1.09	0.47	0.80	0.52	0.34	-0.02
1983	1.20	1.04	1.12	0.49	0.82	0.54	0.37	-0.00
1984	1.38	1.21	1.30	0.64	1.00	0.71	0.55	0.14
1985	1.40	1.23	1.32	0.65	1.03	0.73	0.57	0.15
1986	1.10	0.96	1.02	0.42	0.73	0.46	0.27	-0.07
1987	1.07	0.93	0.99	0.40	0.70	0.43	0.24	-0.09
1988	1.08	0.94	1.00	0.41	0.71	0.44	0.25	-0.08
1989	1.08	0.94	1.00	0.41	0.71	0.44	0.25	-0.08
1990	1.11	0.97	1.03	0.43	0.74	0.47	0.28	-0.06
1991	1.04	0.90	0.96	0.37	0.66	0.40	0.21	-0.12
1992	1.06	0.92	0.98	0.40	0.69	0.42	0.23	-0.09
1993	1.22	1.06	1.14	0.51	0.85	0.56	0.39	0.01
1994	1.44	1.26	1.36	0.69	1.07	0.76	0.61	0.19
1995	1.21	1.05	1.13	0.509	0.83	0.55	0.38	0.00
1996	1.63	1.44	1.56	0.85	1.26	0.95	0.81	0.34
1997	1.59	1.41	1.52	0.81	1.22	0.91	0.77	0.31
Mean	1.25	1.09	1.17	0.54	0.87	0.59	0.42	0.04
SD	1.00	0.13	0.14	0.11	0.14	0.12	0.14	0.11
Min	1.33	0.87	0.92	0.35	0.62	0.37	0.17	-0.14
Max	1.63	1.44	1.56	0.84	1.26	0.95	0.81	0.34

Table 29. (Continued).

B) Calvert Cliffs

Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1968	0.86	0.74	0.78	0.25	0.48	0.24	0.03	-0.24
1969	1.32	1.15	1.24	0.59	0.95	0.65	0.49	0.09
1970	1.14	0.99	1.06	0.45	0.76	0.49	0.31	-0.04
1971	1.29	1.12	1.21	0.56	0.91	0.62	0.46	0.06
1972	1.21	1.05	1.13	0.50	0.83	0.55	0.38	0.00
1973	1.02	0.88	0.94	0.36	0.64	0.38	0.19	-0.13
1974	1.04	0.90	0.96	0.38	0.66	0.40	0.21	-0.11
1975	1.05	0.91	0.97	0.39	0.68	0.41	0.22	-0.10
1976	1.08	0.93	1.00	0.40	0.70	0.43	0.25	-0.09
1977	0.90	0.78	0.82	0.28	0.52	0.28	0.07	-0.21
1978	1.01	0.88	0.93	0.36	0.64	0.38	0.18	-0.13
1979	1.08	0.94	1.00	0.41	0.71	0.44	0.25	-0.08
1980	0.92	0.80	0.84	0.29	0.55	0.30	0.09	-0.20
1981	1.30	1.13	1.22	0.57	0.92	0.63	0.47	0.07
1982	1.04	0.90	0.96	0.38	0.66	0.40	0.21	-0.11
1983	1.09	0.95	1.01	0.41	0.72	0.45	0.26	-0.08
1984	1.28	1.12	1.21	0.56	0.91	0.62	0.46	0.06
1985	1.27	1.11	1.19	0.55	0.90	0.61	0.44	0.05
1986	1.17	1.01	1.09	0.47	0.79	0.51	0.34	-0.02
1987	1.02	0.88	0.94	0.36	0.64	0.38	0.19	-0.13
1988	1.04	0.90	0.96	0.38	0.66	0.40	0.21	-0.11
1989	1.10	0.96	1.02	0.42	0.73	0.46	0.27	-0.07
1990	1.08	0.93	1.00	0.41	0.70	0.43	0.25	-0.08
1991	1.11	0.96	1.03	0.43	0.74	0.46	0.28	-0.06
1992	1.31	1.15	1.23	0.58	0.94	0.65	0.48	0.08
1993	1.28	1.12	1.21	0.56	0.91	0.62	0.46	0.06

Table 29. (Continued).

B) Calvert Cliffs (Continued)

Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1994	1.44	1.27	1.37	0.69	1.07	0.77	0.62	0.19
1995	1.33	1.17	1.26	0.60	0.96	0.67	0.51	0.10
1996	1.66	1.44	1.58	0.86	1.28	0.96	0.83	0.36
1997	1.46	1.41	1.38	0.70	1.08	0.78	0.63	0.20
Mean	1.16	1.09	1.08	0.47	0.79	0.52	0.33	-0.02
SD	0.18	0.13	0.18	0.14	0.17	0.16	0.18	0.14
Min	0.90	0.78	0.82	0.28	0.48	0.24	0.03	-0.24
Max	1.66	1.44	1.58	0.86	1.28	0.96	0.83	0.36

Table 29. (Continued).

C) MD DNR

Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1977	1.20	1.04	1.12	0.49	0.82	0.54	0.37	-0.00
1978	1.33	0.60	1.25	0.60	0.95	0.10	0.50	0.10
1979	1.26	0.55	1.19	0.55	0.89	0.05	0.44	0.05
1980	1.22	0.51	1.14	0.51	0.84	0.01	0.39	0.01
1981	1.29	0.57	1.21	0.57	0.92	0.07	0.46	0.07
1982	1.23	0.52	1.15	0.52	0.85	0.02	0.40	0.02
1983	1.23	0.52	1.15	0.52	0.85	0.02	0.40	0.02
1984	1.20	0.50	1.13	0.50	0.83	0.00	0.38	0.00
1985	1.29	0.57	1.21	0.57	0.91	0.07	0.46	0.07
1986	1.21	0.50	1.13	0.50	0.83	0.00	0.38	0.00
1987	1.00	0.35	0.92	0.35	0.62	-0.14	0.17	-0.14
1988	1.24	0.53	1.16	0.53	0.87	0.03	0.41	0.03
1989	1.17	0.48	1.10	0.48	0.80	-0.01	0.35	-0.01
1990	1.59	0.46	1.08	0.46	0.78	-0.03	0.33	-0.03
1991	1.15	0.46	1.07	0.46	0.78	-0.03	0.32	-0.03
1992	1.23	0.52	1.15	0.52	0.86	0.02	0.40	0.02
1993	1.08	0.41	1.00	0.41	0.71	-0.08	0.25	-0.08
1994	1.26	0.54	1.18	0.54	0.88	0.04	0.43	0.04
1995	1.17	0.48	1.09	0.48	0.80	-0.01	0.34	-0.01
1996	1.57	0.79	1.50	0.79	1.20	0.29	0.75	0.29
1997	1.31	0.58	1.23	0.58	0.94	0.08	0.48	0.08
Mean	1.23	0.55	1.15	0.53	0.86	0.05	0.40	0.02
SD	0.11	0.14	0.11	0.09	0.11	0.14	0.11	0.08
Min	1.00	0.35	0.92	0.35	0.62	-0.14	0.17	-0.14
Max	1.57	1.04	1.50	0.79	1.20	0.54	0.75	0.29

Table 29. (Continued).

D) CBSAC Winter Dredge

Year	Z				F			
	" = 8	" = 6	" = 4	Rothschild	" = 8	" = 6	" = 4	Rothschild
1990	1.18	1.02	1.10	0.48	0.80	0.52	0.35	-0.01
1991	1.04	0.91	0.96	0.38	0.67	0.41	0.21	-0.11
1992	1.07	0.93	0.99	0.40	0.69	0.43	0.24	-0.09
1993	1.29	1.13	1.21	0.57	0.92	0.63	0.46	0.73
1994	1.37	1.20	1.30	0.63	1.00	0.70	0.55	0.13
1995	1.21	1.05	1.13	0.50	0.83	0.55	0.38	0.00
1996	1.23	1.07	1.15	0.52	0.86	0.58	0.41	0.03
1997	1.25	1.09	1.17	0.54	0.88	0.59	0.42	0.04
Mean	1.21	1.05	1.13	0.51	0.83	0.55	0.38	0.01
SD	0.11	0.09	0.11	0.08	0.10	0.09	0.18	0.08
Min	1.04	0.91	0.96	0.38	0.67	0.41	0.21	-0.11
Max	1.37	1.20	1.30	0.63	1.00	0.70	0.55	0.13

Table 30. Mean annual exploitation rates as a function of maximum expected age, ω and the partial recruitment of age-1 crabs, PR_1 , for 1956 - 1997. Exploitation rates were calculated using equation 4.1.1. for each year and then averaged over all years.

Average Exploitation Rate							
CC Peeler				CC Hard			
PR_1	$\omega = 4$	$\omega = 6$	$\omega = 8$	PR_1	$\omega = 4$	$\omega = 6$	$\omega = 8$
0.53	0.106	0.180	0.279	0.53	0.278	0.206	0.452
0.59	0.117	0.199	0.305	0.59	0.278	0.206	0.452
0.67	0.131	0.222	0.337	0.67	0.278	0.206	0.452
0.77	0.148	0.249	0.375	0.77	0.278	0.206	0.452
0.89	0.168	0.187	0.417	0.89	0.278	0.206	0.452

Average Exploitation Rate							
VIMS Peeler				VIMS Hard			
PR_1	$\omega = 4$	$\omega = 6$	$\omega = 8$	PR_1	$\omega = 4$	$\omega = 6$	$\omega = 8$
0.53	0.130	0.203	0.302	0.53	0.226	0.341	0.482
0.59	0.143	0.222	0.329	0.59	0.226	0.341	0.482
0.67	0.160	0.247	0.363	0.67	0.226	0.341	0.482
0.77	0.181	0.277	0.406	0.77	0.226	0.341	0.482
0.89	0.205	0.312	0.446	0.89	0.226	0.341	0.482

Table 31. Estimates of mean blue crab stock sizes (biomass and abundance). Estimates are reported for time series of exploitation rates derived from the Calvert Cliffs pot survey and from the VIMS trawl survey. For each survey estimates are provided for two different estimates of maximum expected age, and are based on either adjusted or unadjusted commercial landings. Standard deviations are given in parentheses.

Exploitation Series Max. Exp. Age, "	Calvert Cliffs				VIMS			
Commercial Series	" = 6		" = 8		" = 6		" = 8	
	Unadju sted	Adjuste d	Unadju sted	Adjuste d	Unadju sted	Adjuste d	Unadju sted	Adjus ted
Biomass (lbs x 10 ⁻³)	313704	355293	209175	235197	282947	316062	197032	21973 7
	(74418)	(76231)	(45296)	(38435)	(78964)	(64841)	(50594)	(3889 9)
Abundance (number x 10 ⁻⁶)	1270	1328	9748	10957	1143	1189	790	821
	(426)	(405)	(2109)	(1791)	(407)	(372)	(260)	(235)

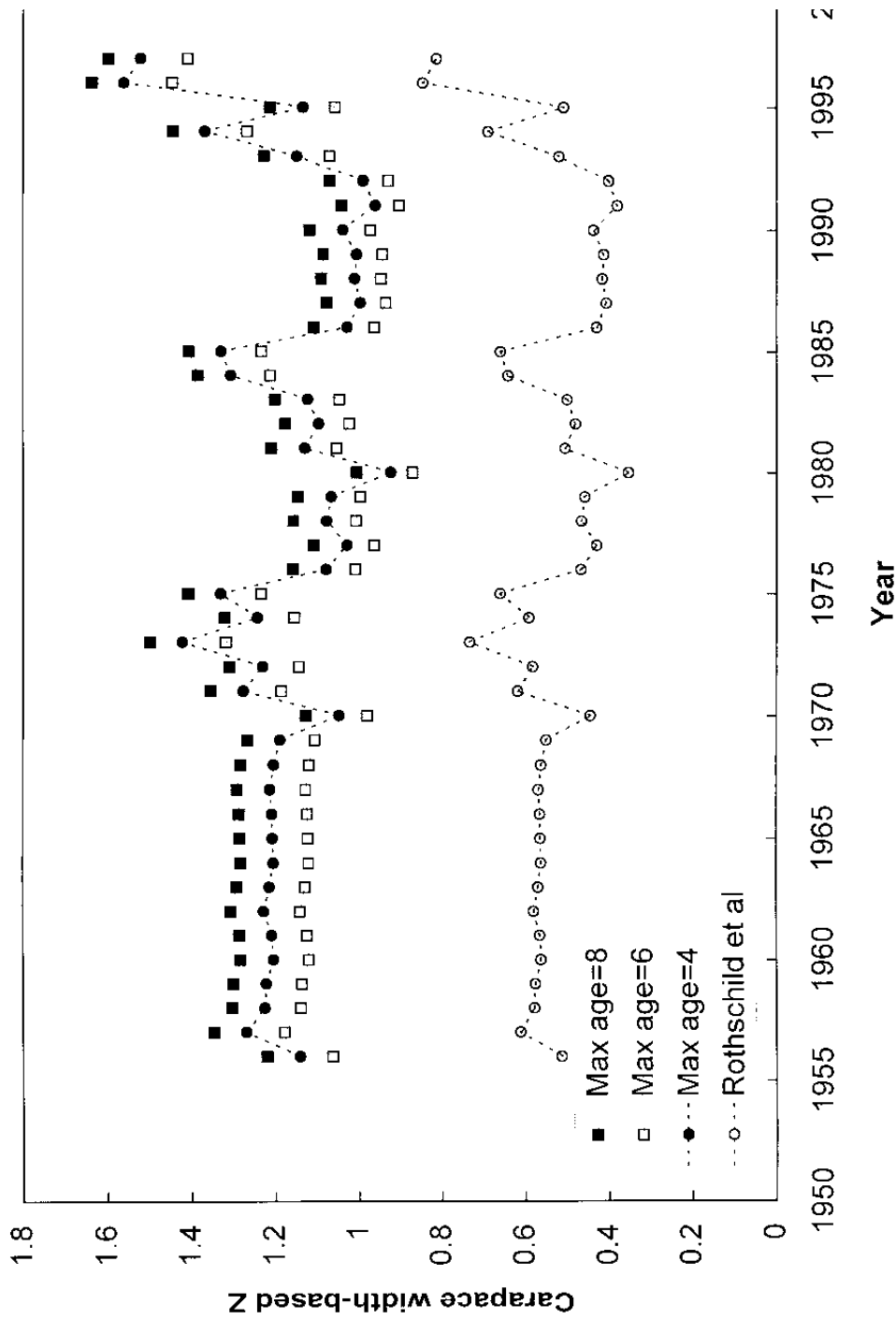


Figure 22. Carapace width-based estimates of total mortality derived from an analysis of the catches in the VIMS juvenile finfish and blue crab survey.

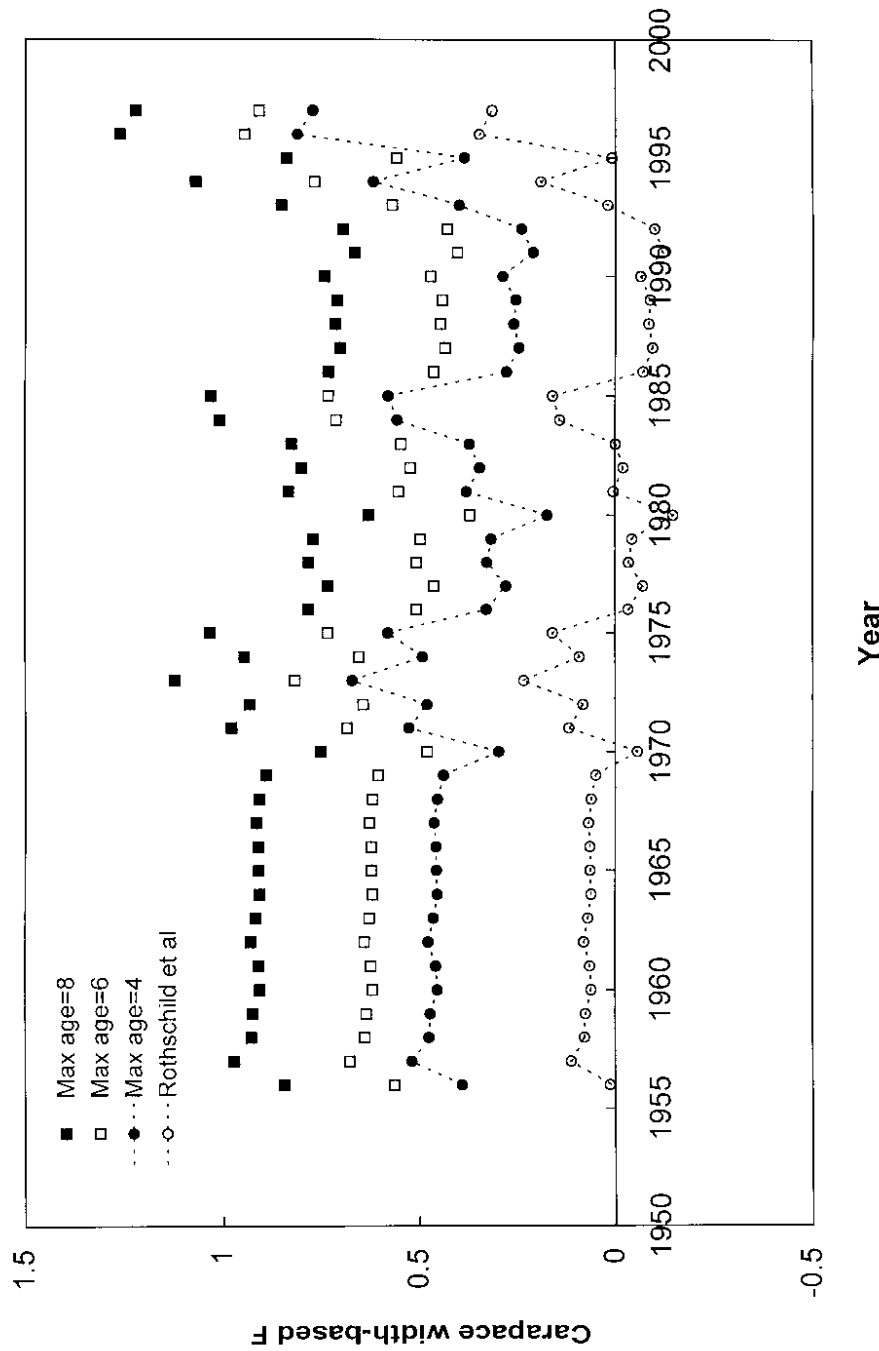


Figure 23. Carapace width-based estimates of fishing mortality rates derived from an analysis of the catches in the VIMS juvenile finfish and blue crab survey.

fig2
4

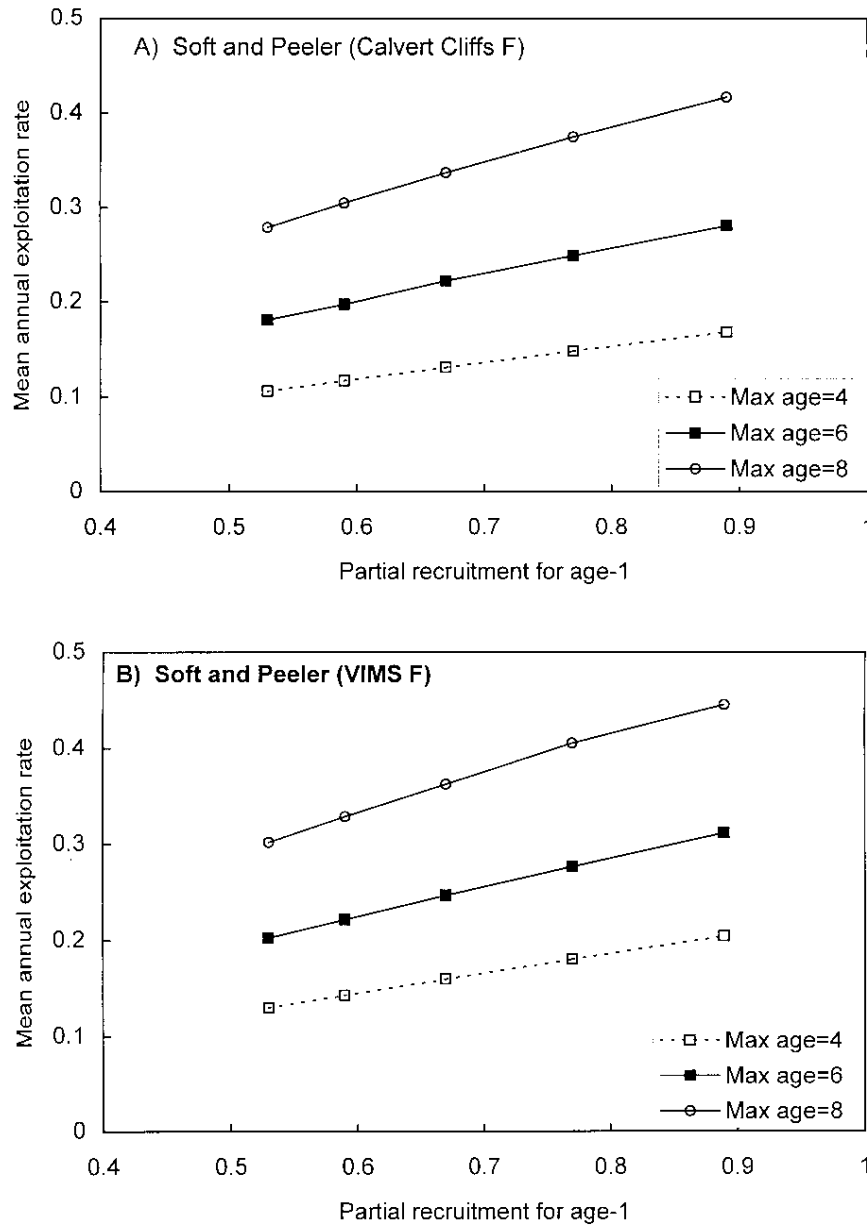


Figure 24. Mean annual exploitation rates as a function of the partial recruitment of age-1 crabs for three different growth models for the soft and peeler component of the fishery based upon fishery-independent estimates of F derived from A) Calvert Cliffs and B) VIMS

fig25

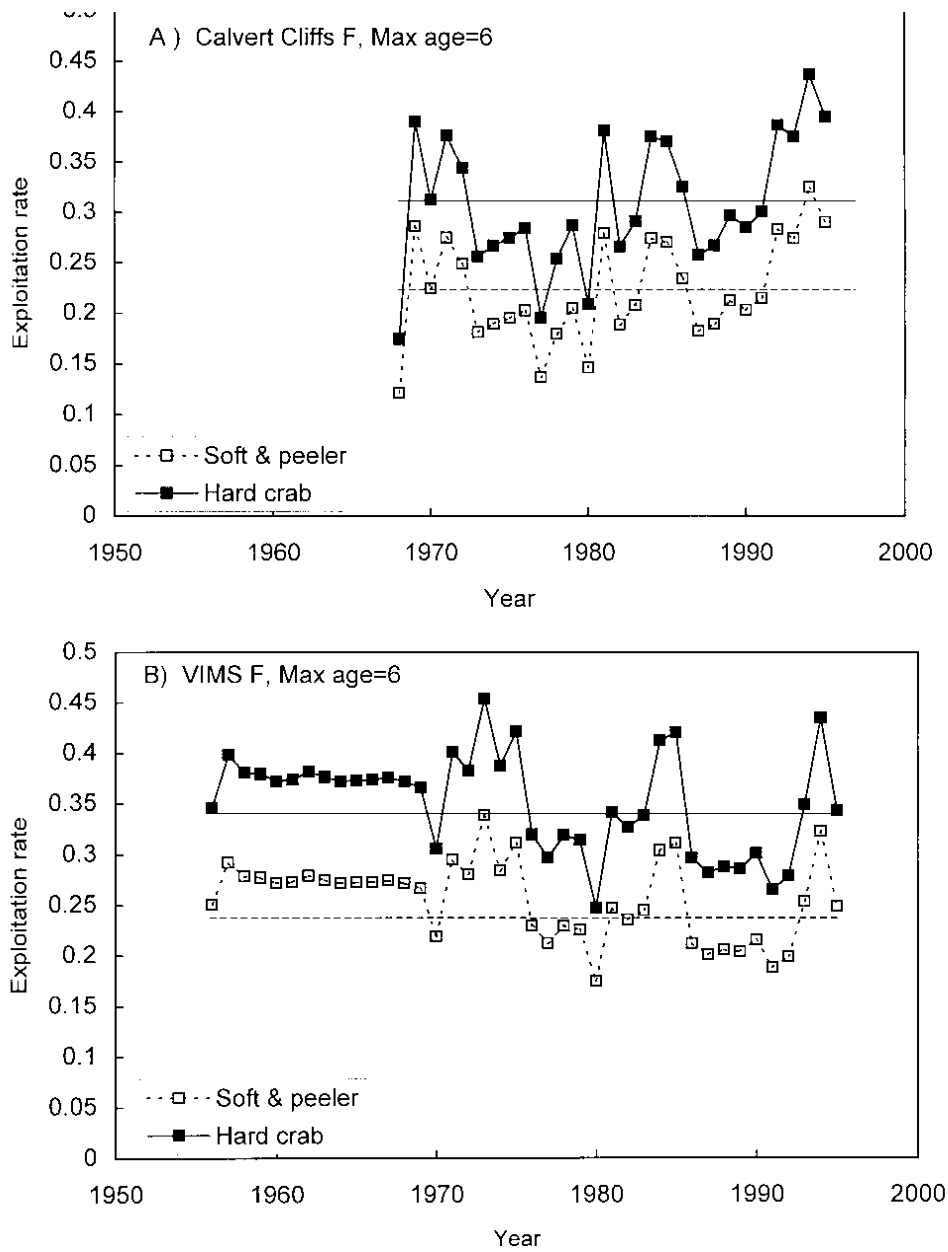


Figure 25. Time series of annual exploitation rates derived from time series of two fishery-independent estimates of F . For all panels the partial recruitment of age-1 crabs was set = 0.67. Expected maximum age = 6. Time series shown are A) Calvert Cliffs-based estimates, and B) VIMS-based estimates.

fig2

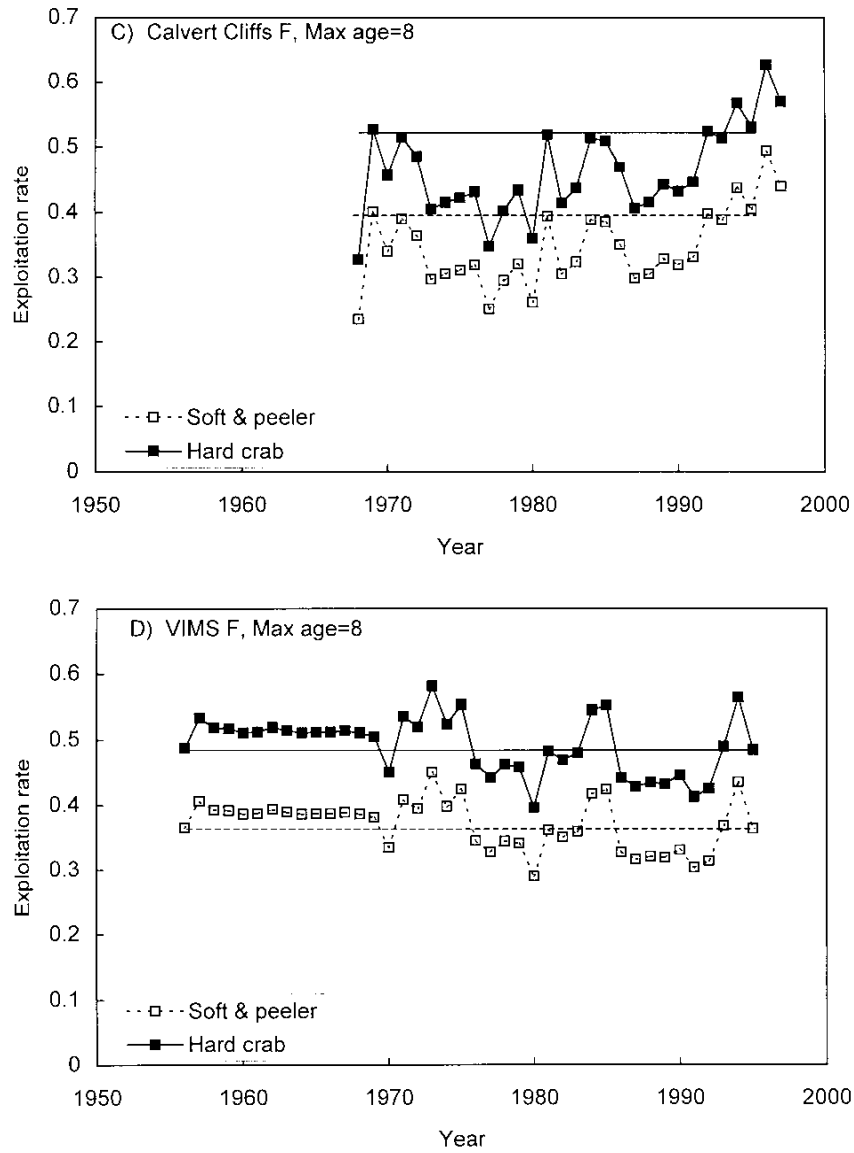


Figure 26. Time series of annual exploitation rates derived from time series of two fishery-independent estimates of F . For all panels the partial recruitment of age-1 crabs was set ± 0.67 . Expected maximum age = 8. Time series shown are A) Calvert Cliffs-based estimates, and B) VIMS-based estimates.

fig2

7

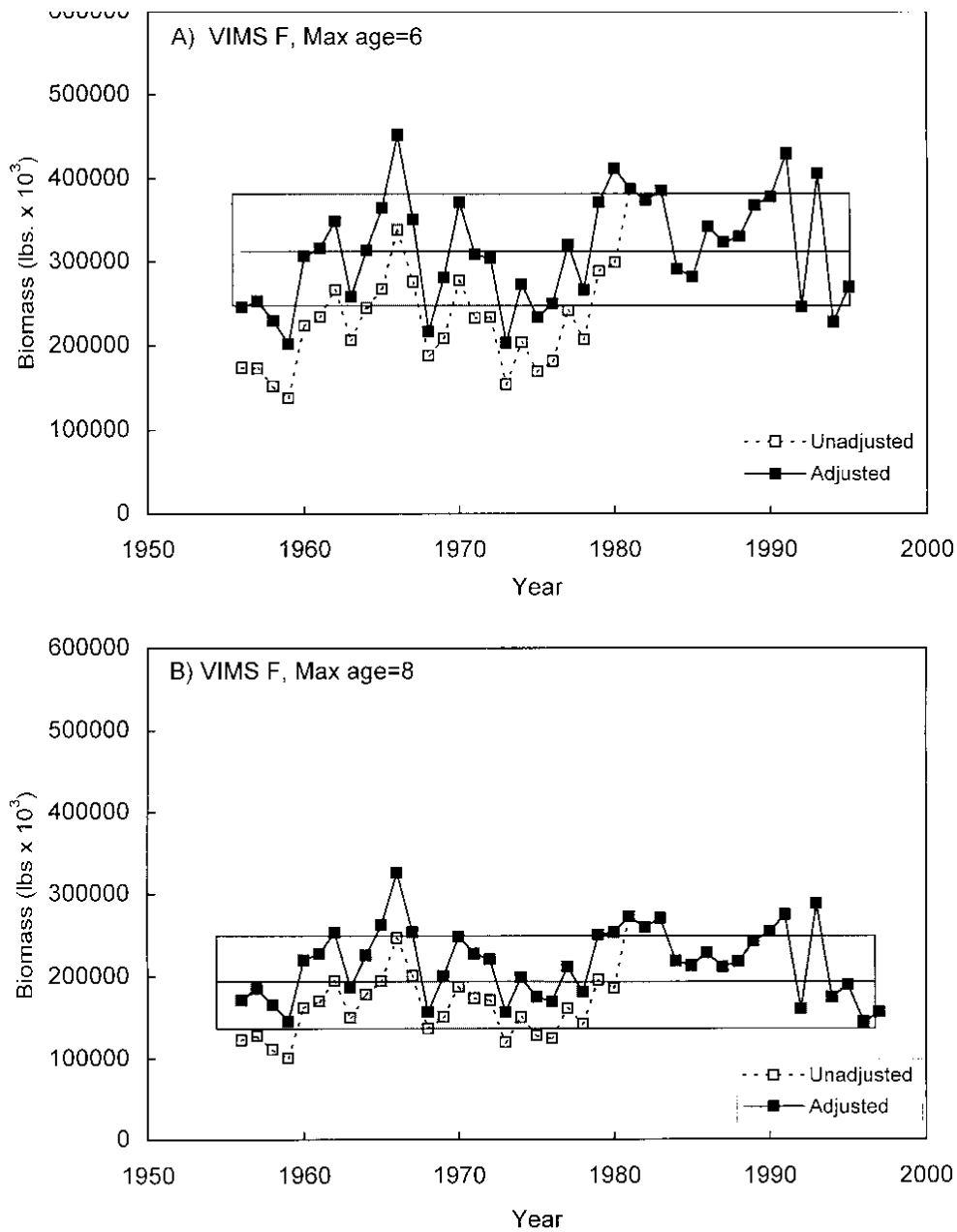


Figure 27. Time series of estimated total population biomass of blue crab in Chesapeake Bay based upon exploitation rates derived from the VIMS trawl survey. Biomass were estimated for two separate expected maximum ages of A) $\alpha = 6$ and B) $\alpha = 8$. Shown are estimates based upon unadjusted (open symbols) and adjusted (solid symbols) commercial landings in Maryland. The shaded areas on each panel enclose the mean + 1 SD for each time series.

fig2

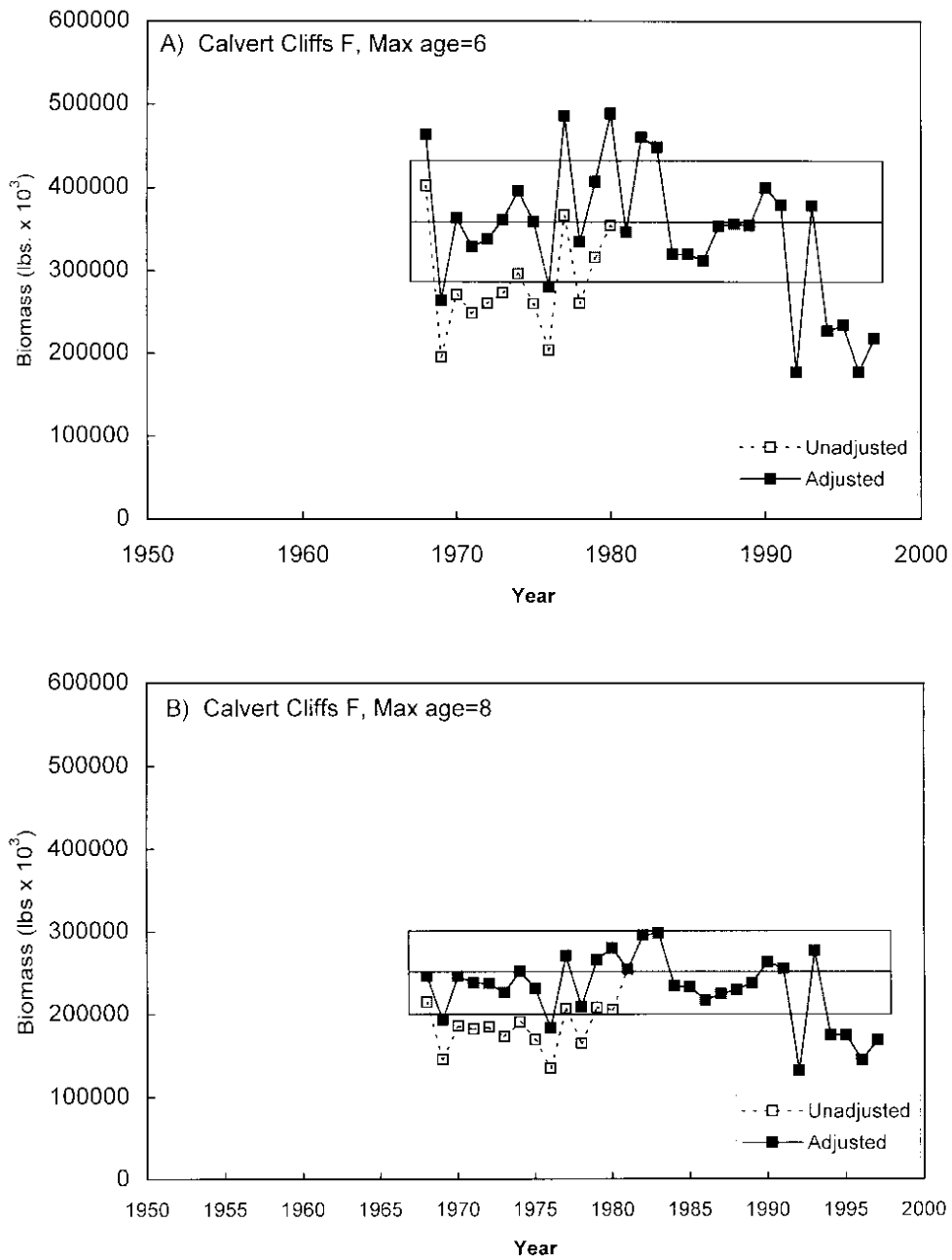


Figure 28. Time series of estimated total population biomass of blue crab in Chesapeake Bay based upon exploitation rates derived from the Calvert Cliffs pot survey. Biomass were estimated for two separate expected maximum ages of A) $\alpha = 6$ and B) $\alpha = 8$. Shown are estimates based upon unadjusted (open symbols) and adjusted (solid symbols) commercial landings in Maryland. The shaded areas on each panel enclose the mean \pm 1 SD for each time series.

fig2

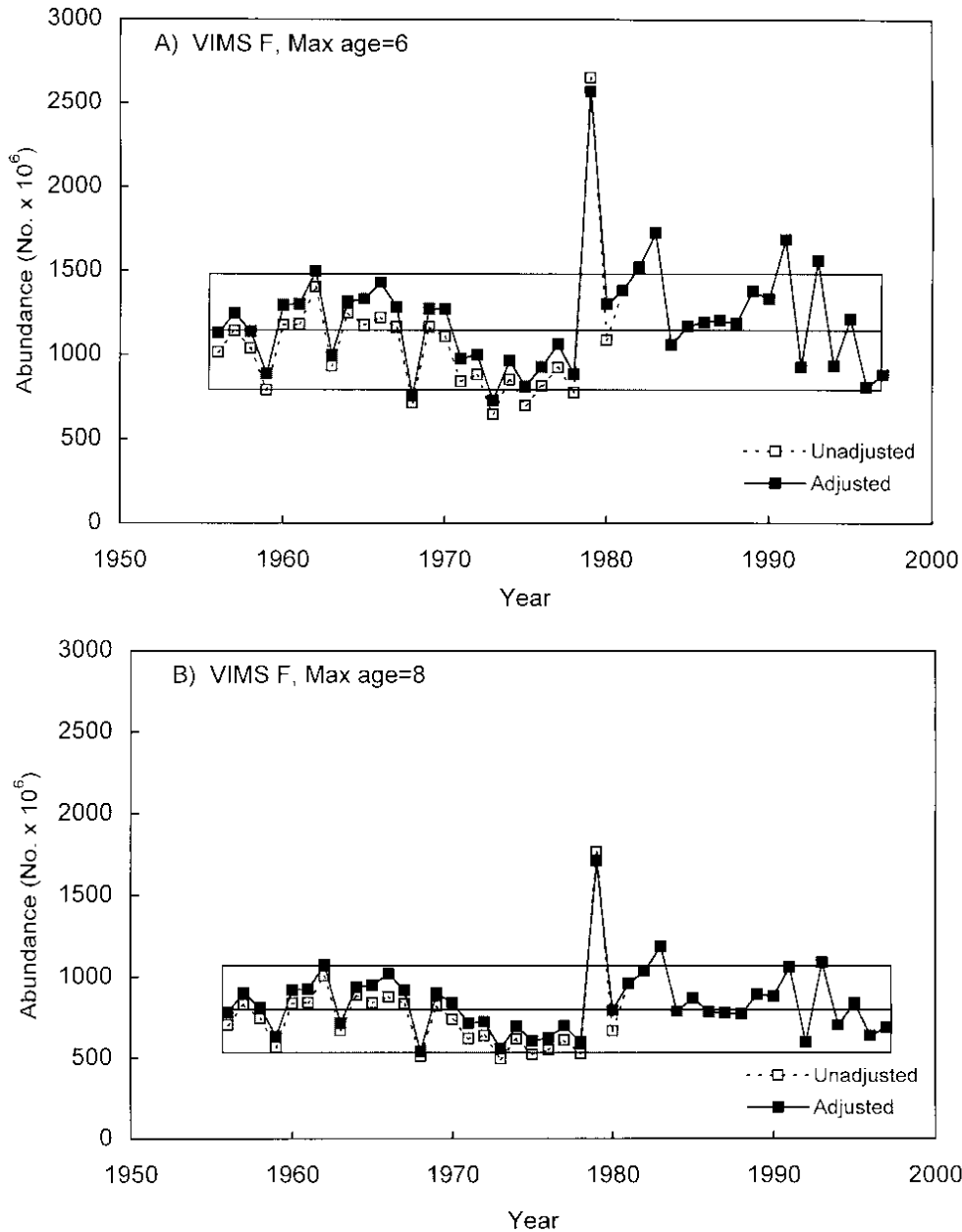


Figure 29. Time series of estimated total population abundance of blue crab in Chesapeake Bay based upon exploitation rates derived from the VIMS trawl survey. Abundances were estimated for two separate expected maximum ages of A) $\alpha = 6$ and B) $\alpha = 8$. Shown are estimates based upon unadjusted (open symbols) and adjusted (solid symbols) commercial landings in Maryland. The shaded areas on each panel enclose the mean + 1 SD for each time series.

fig3

0

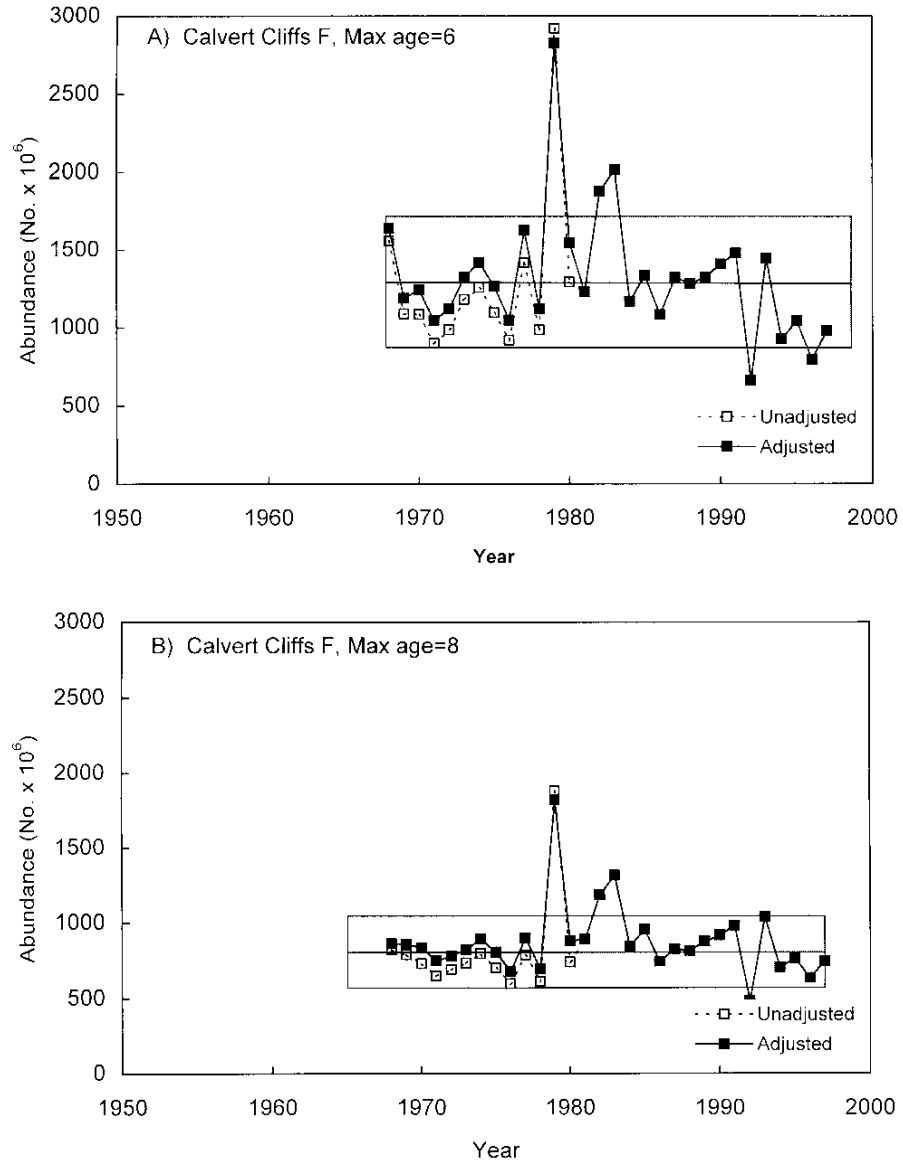


Figure 30. Time series of estimated total population abundance of blue crab in Chesapeake Bay based upon exploitation rates derived from the Calvert Cliffs pot survey. Abundances were estimated for two separate expected maximum ages of A) $\alpha = 6$ and B) $\alpha = 8$. Shown are estimates based upon unadjusted (open symbols) and adjusted (solid symbols) commercial landings in Maryland. The shaded areas on each panel enclose the mean \pm 1 SD for each time series.

5. YIELD-PER-RECRUIT MODELING

Another approach to analyze the dynamics and potential yields of fished populations is yield-per-recruit (YPR) modeling. In this analytical approach, an age class is followed through the fishery to estimate the total yield (catch) expected for every individual (recruit) that enters the fishery. Thus, YPR models include age-specific functions for natural and fishing mortality, and for growth. YPR models allow examination of probable consequences to yield of varying fishing mortality and age (size) at recruitment. Our analysis builds upon the YPR modeling done by Rugolo et al. (1997) in the CBSAC stock assessment.

Several biological reference points are products of a YPR analysis. For a fixed age at recruitment, YPR is a non-linear convex function of fishing mortality (Figure 31). A primary objective is to define the value of F that yields the maximum YPR - i.e., the peak on the YPR curve, a value designated F_{\max} . In a management framework, F_{\max} generally is an unsuitable reference point. Fishing at the relatively high F_{\max} level is economically inefficient and may expose the stock to threat of recruitment failure as spawning stock abundance is reduced to low levels. Managers frequently opt for the lower $F_{0.1}$ reference level, the fishing mortality rate at which the slope of the YPR curve is 1/10 that of its slope at the origin (Deriso 1987 -- Figure 31). This F -level will be substantially less than F_{\max} , more economically efficient and will not reduce spawning stock to dangerously low levels. Fishing at $F_{0.1}$ usually causes only a small loss in YPR. It is a conservative and more cautious reference point.

When combined with estimates of fecundity and individual weights, the YPR modeling framework permits calculation of the spawning potential per recruit (SPR) or spawning stock biomass per recruit (SSBR) in relation to fishing mortality. Expressed in relative terms, SPR or SSBR is maximized at $F = 0$, where values are 1.0. The SPR or SSBR declines non-linearly towards 0 as F increases (Figure 31). Additional reference points can be defined that relate to proportional egg production of the unexploited stock or stock biomass in the population at defined F levels. For example, $F_{50\%}$ is the fishing mortality rate that reduces spawning potential per recruit to 50% of the virgin, unfished stock level. Typically, species with short lifespans, high natural mortality rates, and high fecundities can be exploited to stock levels that are a smaller percentage of the original spawning stock size with less risk of stock collapse or recruitment failure than longer-lived, less fecund species. In short-lived crustacean species (e.g. shrimp, crabs and lobsters) $F_{10\%}$ and $F_{5\%}$ are not uncommon reference points. For example, $F_{10\%}$ is the overfishing definition used by NEFSC of NMFS for three American lobster populations in the northeast.

We explored YPR and SPR responses to F for Chesapeake Bay blue crab over a range of simulated life-history parameter values (Table 32). We used standard von Bertalanffy growth models for initial analyses. In these instances, we used maximum expected life expectancies in a virgin stock of 6 or 8 years. For each age we used the corresponding parameter estimates for K and CW_4 from the von Bertalanffy growth model. We also explored the effect of alternative allometric relationships between weight of crabs and carapace width on the YPR and SPR reference points. An illustration of model output is provided (Figure 32) and reference points for

other model runs are listed (Table 32).

Several conclusions can be reached from the YPR analysis results presented in Table 32. Differences in maturity schedules (rows in Table 32) did not affect estimates of F_{\max} and $F_{0.1}$. The reference points were strongly affected by the choice of growth and allometry models. Estimated $F_{0.1}$ values varied by 46% considering all plausible growth and allometry models. $F_{0.1}$ estimates ranged from 0.35 - 0.47 with a mean value of 0.40 ± 0.04 (mean \pm SD). Within any one growth model, estimated $F_{0.1}$ values varied by approximately 20% depending upon the form of the allometry model adopted. Within an individual allometry, models estimated $F_{0.1}$ values varied by approximately 10% depending upon the form of the growth model adopted.

These results highlight the importance of both growth and allometry models to the reference points estimated. The importance of allometry was not considered in the CBSAC stock assessment.

Whereas the choice of maturity schedule did not affect estimates of F_{\max} and $F_{0.1}$, it did impact reference points based upon spawning potential per recruit. In contrast, the allometry model did not affect SPR reference points, and the different growth models only had marginal effects. Using $F_{10\%}$ as an example, overall the reference point varied from 0.88 - 1.22 with a mean 1.08 (\pm 0.11 SD). This represents a 38% variation over all possible values. However, most of this variation stems from variability between maturity schedules. Within any single maturity estimated SPR reference levels varied by <10%.

Given this pattern of variability, what factors influence the selection of reference points? If we choose to manage blue crab populations by YPR reference points such as $F_{0.1}$, we must strive to determine growth and allometry patterns more accurately. If, however, we seek to employ SPR reference levels, then we must focus more attention on patterns of maturity.

Regardless of the particular parameterization, several general conclusions can be drawn from the YPR modeling. Size-based F , estimated in the fishery for $\tau = 6$ or 8 years (Figure 25), are always higher than $F_{0.1}$ and were often higher than F_{\max} derived from YPR models. This outcome suggests that it is highly probable that blue crab in Chesapeake Bay is growth overfished. This does not imply that the population is in a continuous decline in abundance. It does imply that the fishery is inefficient, and that yield-per-recruit and overall yield could be increased through appropriate management actions. If F were reduced to levels near F_{\max} , the yield from each crab that recruits would be higher. In addition, the size-based estimates of F in the fishery (0.6 - 1.3) are now close to the modeled $F_{20\%}$ and $F_{10\%}$ SPR and SSB reference levels (0.56 - 1.24) that are typically used to manage crustacean fisheries. There is no indication that recruitment has failed or will fail under present effort levels, but the productivity of the blue crab stock is diminished at such high levels of fishing mortality.

All of the YPR modeling discussed above was based upon application of von Bertalanffy growth models. As discussed in Section 2.2.2.b, the assumption of continuous growth does not

fully describe crustacean growth processes. Recently, Smith (1997) completed an exhaustive study of crustacean growth models. And, he developed a non-continuous, stochastic YPR model which incorporates a more realistic model of crustacean growth. Smith compares the output of his saltatory growth model with that of a more traditional YPR model. He presents estimates of $F_{20\%}$ for a variety of scenarios. For example, his continuous growth YPR predicts an $F_{20\%} \sim 1.4$. In contrast, his stochastic, non-continuous growth model predicts an $F_{20\%} \sim 2$. The conclusion we draw from Smith's modeling efforts is that the population may withstand a higher level of exploitation. Additionally, however, Smith's work points to the need for more work on crab growth. A central conclusion from Smith's work, based upon the demonstrated sensitivity of the continuous growth YPR model to parameters associated with crab growth, is its reiteration of the fundamental importance of accurate growth models to reliable stock assessments. Most modeling to date has applied growth models developed for fish, which may not be fully adequate in assessment of blue crab.

Overall, our analysis is in qualitative agreement with the conclusions of the CBSAC assessment. The crab population is being exploited at levels broadly consistent with an $F_{10\%}$ strategy. However, levels are as high or higher than F_{\max} , suggesting the presence of growth over-fishing.

Table 32. Yield per recruit reference points for Chesapeake Bay blue crab. Reference points were calculated for a variety of plausible age, growth, and fecundity estimates. Each cell of the table provides estimates of F_{max} , $F_{0.1}$, $F_{20\%}$, $F_{10\%}$, and $F_{5\%}$ reading from top to bottom. YPR reference points were estimated using an algorithm written for MathCad (Appendix A).

Max Age		" = 6					" = 8			
Growth Model	K = 0.335 CW ₄ = 285 Stock Assessment			K = 0.5056 CW ₄ = 187 Rothschild and Ault			K = 0.335 CW ₄ = 262.5 Stock Assessment			
Allometry model	w = 0003486 CW ^{2.116} Stock Assessment	w = 001089 CW ^{2.363} Rothschild et al.	w% = 0.00026 CW ^{2.67} w & = 0.00034 CW ^{2.57} Newcombe et al.	w = 0003486 CW ^{2.116} Stock Assessment	w = 001089 CW ^{2.363} Rothschild et al.	w% = 0.00026 CW ^{2.67} w & = 0.00034 CW ^{2.57} Newcombe et al.	w = 0003486 CW ^{2.116} Stock Assessment	w = 001089 CW ^{2.363} Rothschild et al.	w% = 0.00026 CW ^{2.67} w & = 0.00034 CW ^{2.57} Newcombe et al.	
Flat Top	0.65	0.59	0.54	0.79	0.71	0.65	0.65	0.60	0.55	
	0.41	0.39	0.36	0.47	0.44	0.42	0.39	0.36	0.35	
	0.63	0.63	0.63	0.65	0.65	0.65	0.56	0.56	0.56	
	0.97	0.97	0.97	1.00	1.00	1.00	0.88	0.88	0.88	
	1.35	1.35	1.35	1.40	1.40	1.40	1.25	1.25	1.25	
Dome 1	0.65	0.59	0.54	0.79	0.71	0.65	0.65	0.60	0.55	
	0.41	0.39	0.36	0.47	0.44	0.42	0.39	0.36	0.35	
	0.67	0.67	0.67	0.70	0.70	0.70	0.62	0.62	0.62	
	1.04	1.04	1.04	1.07	1.07	1.07	0.96	0.96	0.96	
	1.44	1.44	1.44	1.48	1.48	1.48	1.34	1.34	1.34	
Dome 2	0.65	0.59	0.54	0.79	0.71	0.65	0.65	0.60	0.55	
	0.41	0.39	0.36	0.47	0.44	0.42	0.39	0.36	0.35	
	0.76	0.76	0.76	0.77	0.77	0.77	0.75	0.75	0.75	
	1.13	1.13	1.14	1.16	1.16	1.16	1.10	1.10	1.10	
	1.56	1.56	1.56	1.59	1.59	1.59	1.46	1.46	1.46	
Dome 3	0.65	0.59	0.54	0.79	0.71	0.65	0.65	0.60	0.55	
	0.41	0.39	0.36	0.47	0.44	0.42	0.39	0.36	0.35	
	0.82	0.82	0.82	0.83	0.83	0.82	0.82	0.82	0.82	
	1.22	1.22	1.22	1.24	1.24	1.21	1.21	1.21	1.21	
	1.66	1.66	1.66	1.68	1.68	1.65	1.66	1.65	1.65	

Fig31

fig32

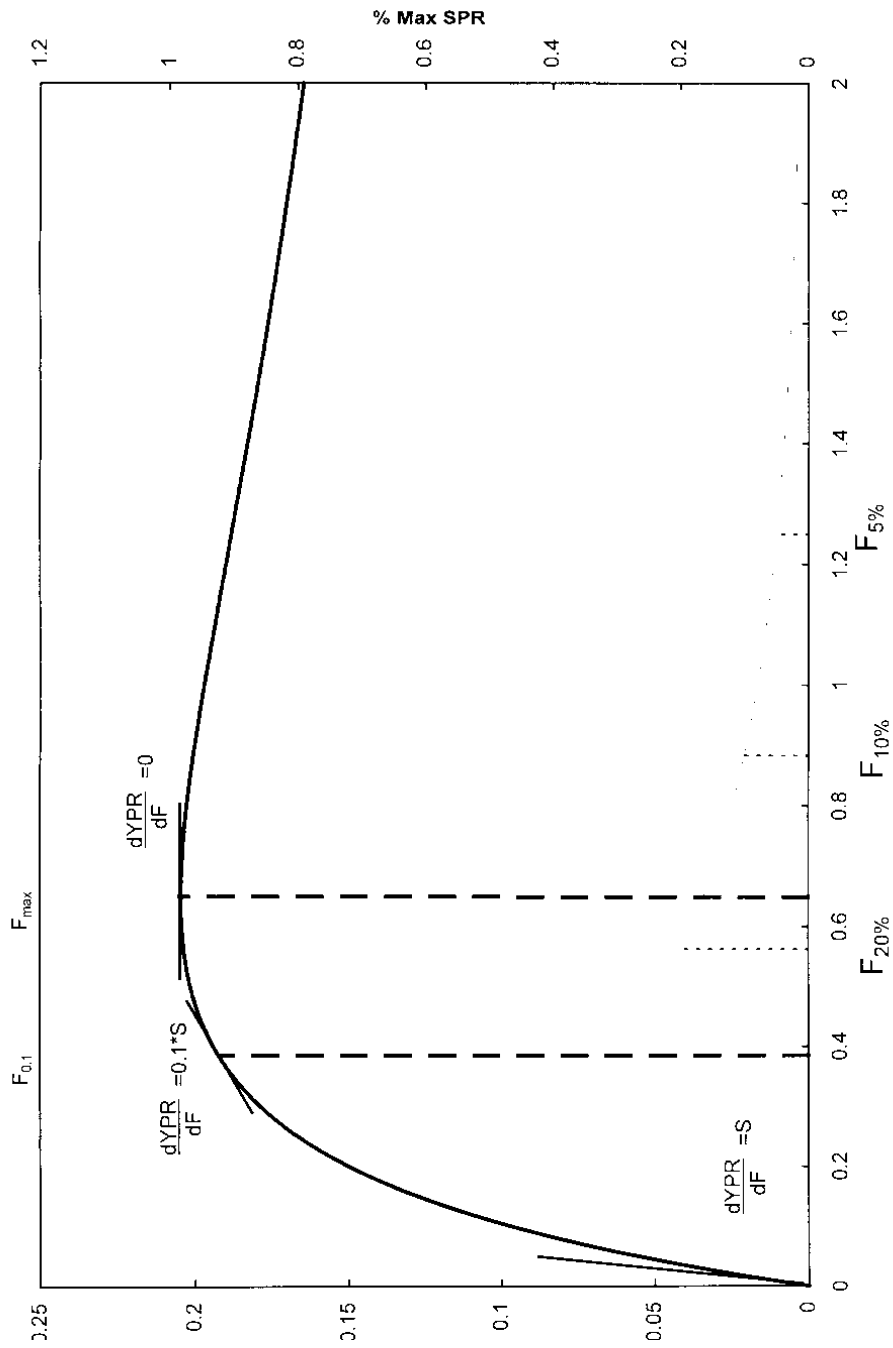


Figure 31. Relationship between yield per recruit (YPR -- heavy line - left ordinate), % spawning per recruit (SPR -- light line, right ordinate) and reference points $F_{0.1}$, F_{max} , $F_{20\%}$, $F_{10\%}$, and $F_{5\%}$.

6. STOCK AND RECRUITMENT MODELING

Hilborn and Walters (1992) consider the quantification of the relationship between the abundance of a stock and the number of recruits it produces to be the most important and generally the most difficult problem in fisheries. From both theoretical and empirical points of view, the form of the stock - recruitment (S-R) relationship is not well understood. Clearly, one can not have recruitment in the absence of a mating pair of animals, and thus the relationship must cross the stock axis close to the origin. However, defining the relationship at stock levels above 0 is difficult. It is particularly difficult from an empirical point of view as one would need estimates of recruitment at very low stock sizes to be able to accurately describe the S-R relationship. Yet low stock sizes are clearly not desirable. Thus, in one sense, we only have good stock recruitment relationships in fisheries that have collapsed. Moreover, the problem of defining a S-R is not restricted to fisheries. Chambers and Trippel (1997) provide clear examples of equally poor S-R fits for two species of amphibians.

There are two important goals in S-R modeling. The first is to understand what the expected level of recruitment should be at a given stock size. In this approach one attempts to define empirically the relationship between stock and recruitment. Typically the data are fit to a theoretical model. Common models are the Ricker (1954), Beverton and Holt (1957), or a generalized model that combines both classical models (Deriso 1980). To date, this has been the approach to estimates the S-R for blue crab (Tang 1985; Lipcius and Van Engel 1990; Watkins 1995; Rugolo et al. 1997). The goal of these analyzes is to estimate the parameters that describe the best theoretical relationship for the specific data set (Figure 33). The relationship thus described estimates the expected level of recruitment given the stock sizes. However, these analyses do not directly speak to the level of variation in the data, and thus may not be predictive for the level of recruitment realized in a particular year at a given stock size (Fogarty et al. 1991).

A second approach to modeling recruitment considers the variability in the S-R relationship directly (Evans and Rice 1988). One seeks to estimates the likelihood of a specific level of recruitment occurring, given a particular stock size. The intent is to describe the probabilities associated with a range of recruitments for each stock level (Fogarty et al. 1991). This information is of direct use to managers because it indicates the likelihood of recruitments of a specified level. Thus, these analyses provide insight into the probabilities of strong and weak year classes at any stock size.

6.1. Classical S-R Models of Blue Crab

Several authors have quantified the S-R relationship for blue crab. We review them here to provide a framework for our own analyses.

Tang (1985) undertook one of the first attempts to model the S-R relationship in blue crab. He found a significant Ricker-type relationship between stock size (as indexed by the

catch in the commercial dredge fishery) and recruitment (as indexed by commercial harvest subsequently). However, the fit was unsatisfactory. Tang extended the relationship by including five additional environmental variables: monthly radiant energy, annual stream flow, average salinity, minimum water temperature, and average annual water temperature, in a stepwise regression. These variables considerably improved model fit ($r^2 = 0.691$). Using this framework, Tang recommended a management target stock size of that would be expected to produce the highest predicted recruitment levels.

Lipcius and Van Engel (1990) used data specific to the York River, VA to derive an S-R relationship for blue crab. They attempted to partition the commercial data to account for the overlap of year classes and so derive estimates of stock size and appropriately lagged recruitment. They applied Ricker-type, Beverton and Holt-type and a generalized S-R model to the data they compiled. The Ricker-type model provided the best fit. A derived model that included the stock size and the ratio of recruitments 1 and 2 years subsequently provided the best fit of all and explained 82% of the variation in the data. The quality of the fit of their model, led Lipcius and Van Engel to suggest that it was more important to disaggregate the abundance estimates to more correctly reflect the life history, than it was to include environmental variables.

Watkins (1995) attempted to similarly disaggregate her data. She indirectly explored the S-R relationship by correlating Baywide commercial harvest with the wind speed at the Bay mouth lagged to reflect the likely time of larval ingress. However, she found no relationship between harvest and wind speed. She did however, find a significant correlation between harvest and appropriately lagged Susquehanna River discharge. Thus, her findings support the idea that environmental parameters may be important in determining S-R relationships.

As a part of the CBSAC stock assessment Rugolo et al. (1997) fit 42 different combinations of stock and recruitment estimates derived from different fishery-independent and fishery-dependent time series. In all cases they fit Ricker-type relationships. Only three provided sufficient explanatory power to warrant further examination. These were the relationship between VIMS spawners (>130 mm cw in year t) and VIMS age-0 recruits (<60 mm cw in year $t+1$), VIMS spawners (>130 mm cw in year t) and MDNR age-0 recruits (in year $t+1$) and between the number of crabs caught in the commercial winter dredge fishery (in year t) and the subsequent commercial harvest in Virginia in August -March (combining $t+1$ and $t+2$). The coefficients of determination for these relationships were 0.27, 0.21 and 0.19, respectively.

There are clear patterns in the S-R data. From 1968- 1994, recruitments indexed by the VIMS trawl survey were above the long-term mean (9.11) and median (7.30). This suggests that F levels were not high enough to have had any notable effect on recruitments. Mace (1994) and Myers et al. (1994) suggest that a safe level for stock size is associated with an F value (termed F_{med}) such that half of the observed recruitments occur below the associated F value. For the VIMS 0+ on spawner relationship (Figure 33), this would suggest a spawning stock abundance index just under 1.0, which gives the approximate 50% theoretical recruitment level (near the median level). The spawner abundance index has been at 1.0 or higher in only 13 years in the 1956-1994 period. So, it seems for blue crab that an F level higher than what is the F_{med} level

may be well within the “safe” range for this stock, which is not inconsistent with the crab’s life history characteristics.

Other trends are evident in the S-R data. Relatively small recruitments appear more frequent than middling or large recruitments. In the VIMS series, 2/3 of recruitments are less than the long-term mean (See Section 6.2.1). Good and bad recruitment years tend to come in series, so that positive or negative deviations from the mean or median persist for a few years. The VIMS series for <60 mm crabs shows below average recruitment in the 1950s and 1960s, a blip of good recruitments in the late 1960s and then generally low recruitments throughout the 1970s, followed by very high recruitments in the 1980s, with a fall towards the mean or median in the mid-1990s. Finally, there is a propensity for the lowest recruitments to be associated with the lowest spawner densities in the VIMS trawl survey and also for the relationship between Maryland trawl survey young crabs and VIMS spawners.

Rugolo et al. (1997) explored the management implications of their best fitting model in a spawning stock vs. recruitment analysis. They calculated F values that would encompass the upper 25, 50 and 75% of the observed recruitment levels. The value associated with the 50% level, i.e. F_{med} , has been suggested as a management target (Mace 1994). For the blue crab data, $F_{med} = 1.17$.

6.2 Non-Parametric S-R Models of Blue Crab

Classical S-R models constrain the data to fit pre-conceived notions of an underlying recruitment pattern. It has been suggested that it may be preferred to use non-parametric methods, thereby allowing a wider variety of forms (Getz and Swartzman 1981; Rothschild and Mullen 1986; Evans and Rice 1988; Hilborn and Walters 1992). These approaches can be useful in management practices. For example, a distribution-free method has been used to project recruitment of some New England groundfish (Overholtz et al. 1986). Here, we apply two approaches to Chesapeake Bay blue crab to quantify the variation in recruitment expected in any given year at individual stock sizes.

6.2.1. Markov Models

Getz and Swartzman (1981) and Rothschild and Mullen (1986) used Markov matrix models to describe recruitment. Conceptually, both methods would be applicable to blue crab. However, the Rothschild and Mullen approach has the advantage of requiring less data. Accordingly we focus here on the application of the Rothschild and Mullen (1986) model.

As a basis for our analyses we used the relationship between the abundance of spawning females in the VIMS finfish and blue crab trawl survey (stock) and the abundance of recruiting crabs in the following year, also from the VIMS trawl survey (recruits). These data were fit to a Ricker-type recruitment function by Rugolo et al (1997 - See section 6.1). We adopted a 2 x 2 classification which divides the data into groups of above- and below-median stock size and above- and below-median recruitment level (Figure 33). The potential combinations (Stages)

are:

Stock		Recruitment	
		Below median	Above median
	Below Median	Stage 1	Stage 2
	Above Median	Stage 4	Stage 3

From this classification we calculated the number of occurrences of data in each stage. We tested the null hypothesis of an equal distribution of occurrences in all stages using a χ^2 test (Table 33). We conclude that the data are not distributed at random. Specifically, data are more common than would be expected by chance in stages 1 and 3. This pattern suggests that compensatory control is not strong in blue crabs in Chesapeake Bay. Rothschild and Mullen (1986) describe such a pattern as characteristic of a type II stock.

We then calculated the transition probabilities for each stage. These estimate the probability that, for example, a population that is in stage 1 this year will be characterized as stage 2 next year (Table 34). The probabilities are defined as the number of transitions from stage i (where $i = 1, 2, 3$ or 4) to stage j (where $j = 1, 2, 3$, or 4) divided by the total number of transitions from stage i that were observed. We tested whether the probabilities are uniformly distributed among cells using a χ^2 test (Table 34). We conclude that the distribution is not significantly different from random. However, once in stage 1, the population is more likely to remain in stage 1 ($p = 0.58$) than transition to any other stage ($p = 0.42$). In contrast, if the population were in stage 2 it would be more likely to move to a different stage ($p = 0.57$) than remain in stage 2 ($p = 0.43$). Similar to years when the population is in stage 1, years when the population is in stage 3 are more likely to be followed by additional years in stage 3 than by any transitions.

The transition estimates can then be used to estimate the long-term, expected distribution of stages (Table 35). Our calculations suggest that in 36% of all years, we would expect to find the population in stage 3, in 30% of all years we would expect the population to be in stage 1, and in approximately 16% of all years the population would be in either stage 2 or stage 4. These calculations imply that above-median recruitments are less likely than below-median recruitments from weak stock sizes. Nevertheless, above-median recruitments may occur fully 1 year in 3 when stock size is below median.

The probabilities of the expected stage distribution can be used to estimate the number of years that can be expected to elapse between two consecutive occurrences of any individual state. These estimates are termed first passage times. We estimated these values for blue crab (Table 36). These estimates suggest that the most likely stages for the population are repeated sequences of stage 1 and 3. One can expect repeated sequences of low stock and low recruitments to occur on average every decade (Table 36 - First passage time (1,1) = 10.6).

Repeated sequences of high stock and high recruitment should occur every seven years (Table 36 - First passage time (3,3) = 7.7).

6.2.2. Non-Parametric Probability Density Function Approach

The objective of these approaches is to describe the probability of a given level of recruitment in a given year for a stock of given size. Fogarty et al. (1991) provide an approach to develop recruitment probability density functions for the classical recruitment models. However, non-parametric methods have also been developed that do not presume an underlying S-R relationship (Evans and Rice 1988). Here, we apply a non-parametric estimation approach (Evans and Rice 1988) to quantify the cumulative probability distribution of recruitment at three different stock sizes.

The non-parametric method assumes that only recruitments from past observed stock sizes are possible. Evans and Rice (1988) suggest two non-parametric approaches: a constant interval approach in which all observed recruitments are equally likely, and a Cauchy algorithm in which the likelihood of each recruitment varies. In this latter approach, the likelihood of each recruitment level is weighted by the difference between the stock level at which that recruitment was observed and the current stock level. This approach implies that recruitments observed at stock sizes similar to the current stock size are more likely to occur than recruitments observed at stock sizes dissimilar to the current stock size. Simply put, observations from similar stock sizes tell us more than observations under different conditions. We present the results of application of the Cauchy algorithm to blue crab S-R patterns.

Again, we used the relationship between the abundance of spawning females in the VIMS finfish and blue crab trawl survey (stock) and the abundance of recruiting crabs in the following year in the VIMS trawl survey (recruits) as the basis for our calculations (see Rugolo et al. 1997 and Section 6.1). We estimated the cumulative probability distribution of recruitment for three hypothetical indices of stock sizes 0.2, 1, and 3 x 10³ spawners in the VIMS trawl survey. The first step in the procedure was to sort the S-R data by stock size. We next estimated the step size, which is given by:

$$\text{Step } \alpha = \frac{1}{1 + \left[\frac{x}{D^2} \right]}$$

where x is the absolute difference between the stock size at the observed recruitment level and the target stock size (i.e., 0.2, 1 or 3), and D is a characteristic width. Rice and Evans (1988) show that the cumulative probability functions derived from use of this approach are generally insensitive to the value of D used. In our calculations we set D = 2. Higher values of D tend to underestimate differences among the cumulative recruitment probability functions, while low values of D emphasize the differences. Values of the step are calculated for all observed stock sizes, and summed. The cumulative recruitment probability distribution can then be calculated

iteratively as:

$$PDF_{s+1} = PDF_s + \frac{Step_s}{\sum Step}$$

where s refers to a specific stock size observed in the S-R data, and $s+1$ refers to the next biggest observed stock size.

We estimated cumulative recruitment probability distribution for low (0.2×10^3 spawners), medium (1×10^3 spawners) and high (3×10^3 spawners) stock indices (Figure 34). In general, the cumulative probability functions are similar. We estimated the expected (50%) recruitment indices level for each stock size. These were 5.23, 5.57 and 6.45 for low, medium and high stock indices, respectively. These cumulative distributions also serve to indicate how rare large recruitments are for Chesapeake Bay blue crabs. For example, the highest observed recruitment is almost 8-fold greater than the median recruitment level.

6.3. Summary

The S-R relationship for blue crab remains ill-defined. There is general consensus that compensatory processes are important in blue crabs, and thus a Ricker-type model is most appropriate (Tang 1985; Lipcius and van Engel 1990; Watkins 1995; Rugolo et al. 1997). However, there remains considerable unexplained variation in these models, even when attempts to account for environmental variability are made (Tang 1985; Watkins 1995; Rugolo et al. 1997).

In part, the variability should be expected because the time series that are available for S-R estimation are crude and often short. Both life history of blue crab and our inability to age individuals complicate providing accurate data at appropriate time lags. While several fisheries-independent data sets have been collected for a sufficient period of time, they only sample a portion of the population, and thus may provide biased results. Ultimately, the winter dredge survey should provide the best stock and recruitment relationships. Yet, today the survey only provides 9 years of data, which is woefully inadequate for S-R purposes. However, as the length of the survey increases it may become an invaluable tool.

Mace (1994) and Myers et al. (1994) suggest that a safe level for stock size is the stock size that supports 50% of the observed recruitment level in a theoretical S-R model. From Figure 34, it can be seen that the almost 95% of all recruitments are less than 50% of the maximum. Thus our non-parametric estimation suggest that this level of recruitment is likely to occur less than 5% of the time. (Figure 34). When based upon the VIMS 0+ on spawner relationship, management to maintain the median level of recruitment would suggest a spawning stock abundance index just under 1.0. The spawner abundance index has been at 1.0 or higher in only 13 years during the 1956-1994 period.

Table 33. Distribution of observed stock and recruitment indices categorized with reference to their median levels. Included in the table is the Chi-square test of an equal distribution in all

cells.

		Recruitment	
		Below Median	Above Median
Stock Size	Below Median	12	7
	Above Median	7	13

$$\mathbf{P}_{(3)}^2 = 3.15, p = 0.3$$

Table 34. Distribution of transitions between the four stages in the stock-recruitment plane (see text for definitions).

		Initial Stage			
		1	2	3	4
Final Stage	1	7	3	0	2
	2	3	1	3	0
	3	1	1	8	2
	4	1	2	2	2

$$P_{(9)}^2 = 17.528, p < 0.05$$

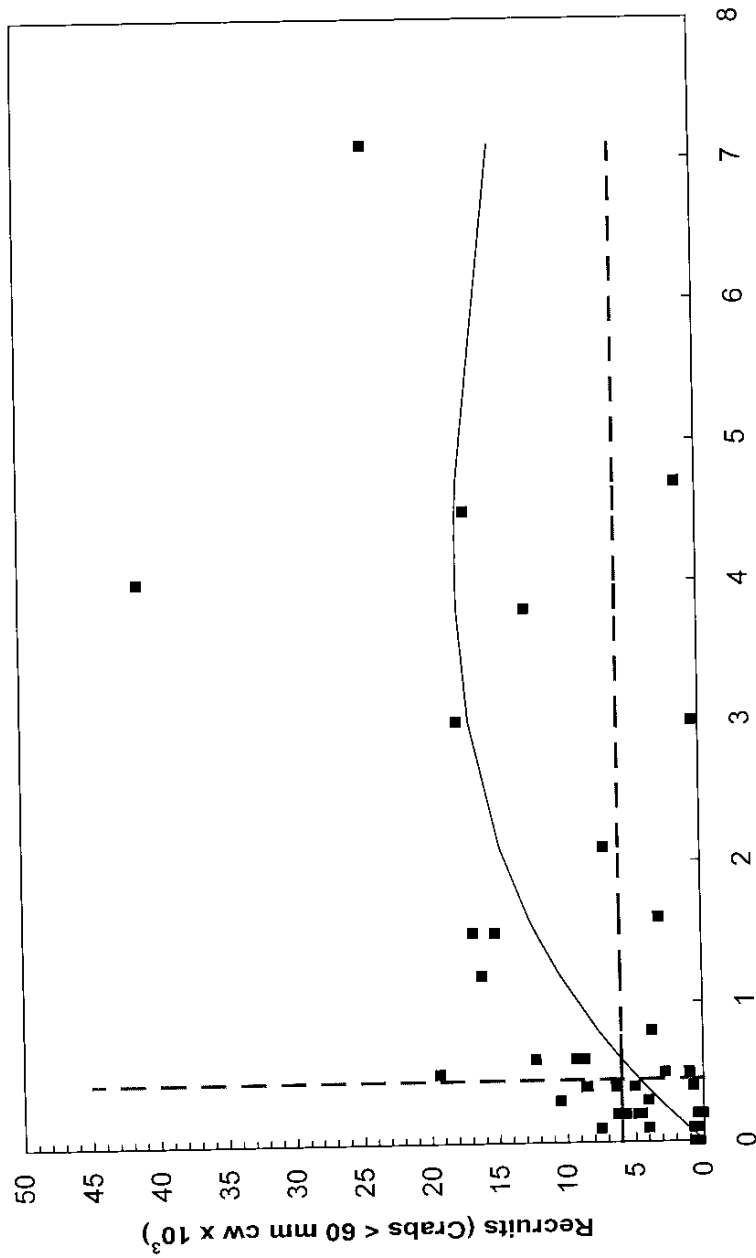
Table 35. Predicted expected probabilities of occurrence of Chesapeake Bay blue crab in each stage of the stock-recruitment plane.

		Recruitment	
		Below Median	Above Median
Stock Size	Below Median	0.307	0.177
	Above Median	0.156	0.361

Table 36. Expected first passage times for Chesapeake Bay Blue Crab. First passage times estimate the number of years between periods when stages repeat. Thus the first passage time for stages (1,1) gives the number of years between periods when two years of below median stock and below median recruitment will be followed by another similar period.

		Initial Stage			
		1	2	3	4
Final Stage	1	10.6	18.4	9.07	20.8
	2	18.4	31.9	15.7	36.2
	3	9.0	15.6	7.7	17.8
	4	20.1	36.2	17.7	41.1

figure 33



Stock (Spawners > 130 mm c.w. x 10³)
 Figure 33. Stock-recruitment curve for blue crab. The stock index is based on the abundance of egg-bearing females in the VIMS trawl survey. The recruitment index is based upon the number of crabs <60 mm in the VIMS trawl survey in the following year. The solid line is the predicted Ricker-type S-R function for the data. The two dashed lines represent the median stock and median recruitment levels.

figure
34

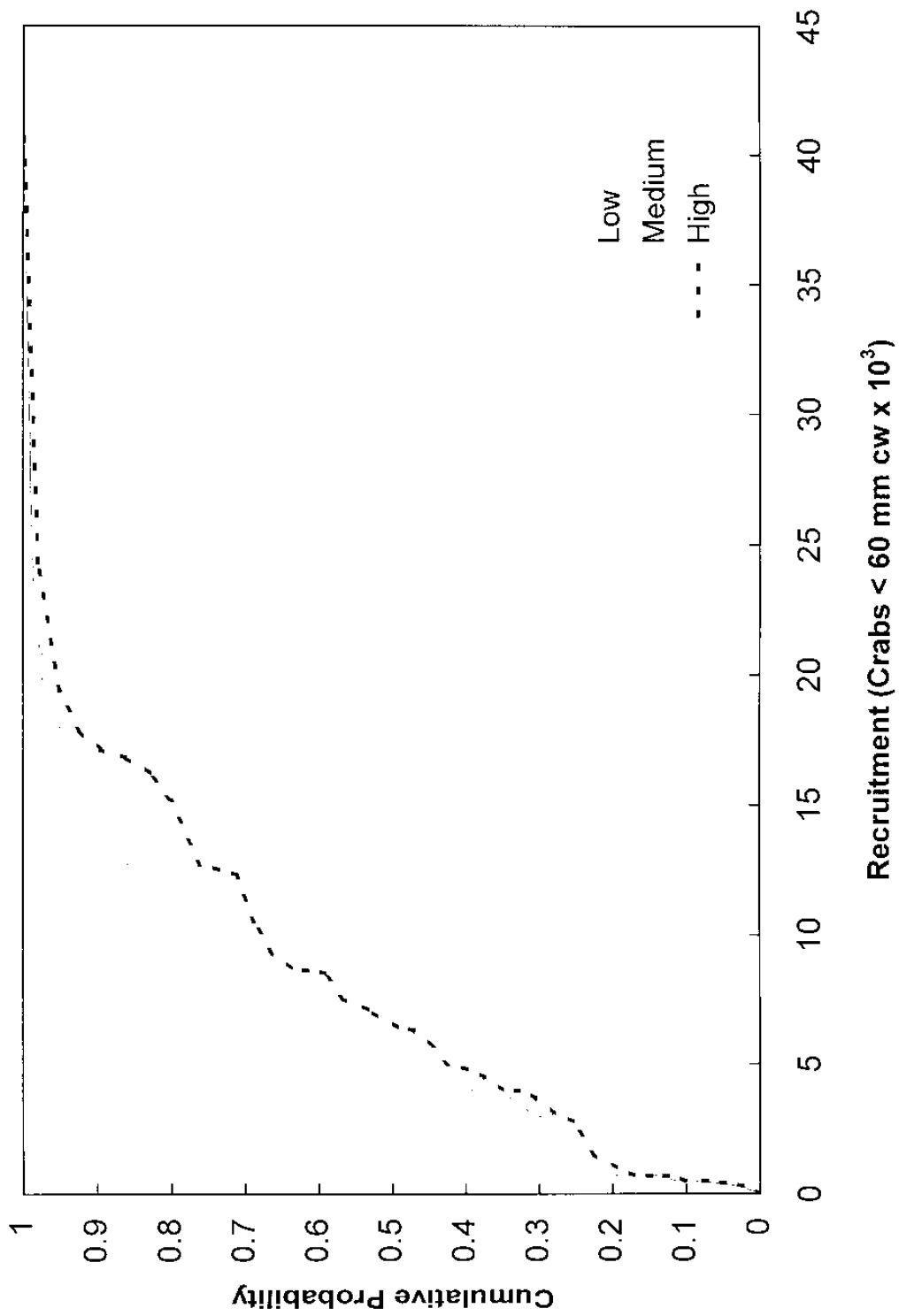


Figure 34. Cumulative recruitment probability distributions for three stock sizes. Cumulative probabilities were estimated using a non-linear Cauchy procedure to low, medium and high spawner indices. The step length used to calculate the distribution was 2.

7. STAGE-BASED MODELING

Mathematical models have often been employed to understand the dynamics of populations. A variety of model structures has been employed in such efforts, but they can be broadly separated into categories. Models may be in continuous or discrete time. Continuous time models allow vital processes such as birth, death and growth rates to occur constantly. Such models are appropriate, for example, to represent species that have prolonged or continuous breeding seasons. In contrast, discrete time models limit the action of these vital processes to limited number of times. Thus, the model views the population as stepping through time. Consequently, this approach is suitable for species that show distinct breeding seasons or exhibit pulses in mortality and growth. The other broad distinction between model categories is that of deterministic and stochastic models. In deterministic models the predicted outcome is independent of the initial conditions or completely described by external factors. These models do not allow the expression of variable environments or individual variability between organisms. If such processes are thought to regulate the dynamics of the species under consideration, stochastic models are more appropriate.

We developed a discrete-time model of the Chesapeake Bay blue crab population. Moreover, as our intention was to provide targets based upon expected rates of growth, survival and fecundity, the model was deterministic and time invariant. These criteria narrow the choice of model structure considerably. Furthermore, we wished to explore the impact of spatial patterns on vital rates. These constraints effectively limited our choice to one model format - stage-based projection models (Caswell 1989). Accordingly we have developed two stage-based models. The first considers blue crab in Chesapeake Bay as a single well mixed population. We term this model the aggregate model. We also developed a spatially-explicit model that divides Chesapeake Bay into two areas; nominally a lower Bay in which spawning occurs and an upper Bay into which newly settled crabs must migrate.

7.1. Model Format

Stage-based models are highly flexible, heuristic tools that have been used extensively in the ecological literature. They are discrete, time invariant, probabilistic matrix models that resemble life-table analysis (Caswell 1989). Life tables use age as a state variable and generally have a yearly time step. Thus, individuals remain in each age class for a single time step. Models of this structure, often referred to as Leslie matrix models, are widely used in demographic studies of humans and other organisms, including some fish, for which age is a good predictor of an organism's biological capability and fate. However, for many species age is not a good predictor of capability. For such species, using size or life-history stage as the state variable is better. Stage-based models still function with a discrete time step. However, the stage duration is often longer than the model time step and, consequently, individual organisms may remain in a single stage for multiple time steps.

The fundamental relationship underlying matrix projection models is:

$$N(t) = A^t \cdot N(0)$$

where $N(0)$ is the vector of abundances in the population initially, A is the population projection matrix, t is the number of time steps to project the model forward and $N(t)$ is the vector of abundances in the population at time t . The population projection matrix is a matrix that contains all of the individual transition probabilities (defined below), such that when multiplied by the population vector, will project the population forward one time step.

An important assumption in most stage-based models is that the elements of A are constant. More specifically, none of the elements of A are functions of population size. Thus populations modeled in this fashion can not demonstrate any density-dependent regulation. Evidence for density-dependence in Chesapeake Bay blue crabs exists for juvenile mortality rates (Dittel et al. 1995). Dittel et al. (1995) reported that rates of cannibalism of large crabs on smaller juvenile crabs was density-dependent and had a potential to destabilize the predator-prey interaction. There have been no studies to assess the potential for density dependent regulation in other stages of the life cycle. These concerns suggest that stage-based modeling may not be a suitable approach to setting targets when population abundances are high. However, when populations reach low levels, density dependence is likely to be less important. Thus, stage-based modeling is a suitable framework on which to base recovery targets. This is the principle use to which stage-based models are put here.

The first step in formulating a stage-based model is to construct a life-cycle graph at the time scale over which the model will operate (Caswell 1989). A life-cycle graph represents different stages of the life cycle as nodes in the graph, and growth, survival and movement between stages are represented by connections between each node. The connections between the nodes represent all possible transitions in the life cycle. The model censuses crabs on the day that animals enter each stage and all reproduction occurs on the last day of the mature overwintering stages. Our model runs in six-month time steps. At this temporal scale, we have chosen to represent the crab life cycle as being composed of seven stages (Figure 35). The first stage in the models considers zoea that are released on June 1 in year 0. This stage includes the zoea, megalopae and newly settled crab stages. The stage lasts until November 30 when all individuals enter the overwintering juvenile stage. The survival probability of individuals in this stage is expressed as a_{21} . Juveniles overwinter from December (year 0) to May of the following year (year 1). During this period only natural mortality acts upon the crabs, governed by the transition probability a_{32} . Upon emergence from the sediment on June 1 individuals enter one of two pathways in the model. One pathway in the model considers slower growing individuals in this cohort that do not grow to legal size in the May to November period (Node 4). These individuals experience only natural mortality during the summer, governed by transition probability a_{43} . These individuals overwinter as pre-pubertal crabs. However, some crabs grow and reach sufficient size during the June 1 to November 30 period to become vulnerable to the pot fishery before a second overwinter period (Node 5). Thus these crabs experience both natural and fishing mortalities, governed by transition probability a_{53} . These large individuals mature during the growth season (June 1 - November 30) and overwinter as mature age-1 crabs.

On the very last day of this stage the females release zoea. The proportion that enter each pathway can be varied in the model. Crabs overwinter in either node 4 or 5 from December 1 (year 1) - May 30 (year 2). After emergence on June 1 (year 2), all age-2 crabs are vulnerable to fishing (Node 6). Individuals in Node 6 continue to grow and that fraction that did not mature in year 1, mature at this stage. All adults overwinter as mature adults (Node 7) from December 1 (year 2) to May 30 (year 3). These mature females release zoea on the last day of the overwinter period and re-emerge as adults (Node 6). The model includes a difference in fecundity between the Node 5 and Node 7 females to reflect the size-dependent pattern in fecundity reported by Prager et al. (1990).

For the spatially-explicit model, we recognize that each of the stages of the life cycle discussed above may occur in either the upper Bay region or the lower Bay region (Figure 36; Table 37). The regions approximate, but do not coincide exactly with Maryland and Virginia's territorial waters. Nodes 1-7 refer to crab life-history stages in the upper Bay and nodes 8-14 refer to crab life-history stages in the lower Bay. The basic life history depicted in Figure 36 is identical to that in the aggregate model. However, spawning is only permitted to occur in the lower Bay (F_{12} , F_{14}). Newly settled crabs occur in both upper and lower Bay areas. The proportions that occur in the two areas are governed by a_{28} and a_{98} . The newly settled crabs overwinter and emerge the following spring. These crabs experience only natural mortality. As growing juveniles crabs may remain in the region of the Bay in which they emerged or migrate to the other region ($a_{3,9}$ and $a_{10,2}$). The transition frequencies are based on the relative areas of the Upper and Lower Bay. Age-1 crabs that have matured in the Upper Bay migrate to the Lower Bay ($a_{12,3}$). Crabs overwinter as prepubertal age-1 in the Upper Bay or as mature or prepubertal age-1 in the Lower Bay. All experience rates of natural mortality. In addition, those adult age-1 crabs in the Lower Bay are vulnerable to the dredge fishery. All crabs then overwinter and emerge as mature adults (age-1+). Crabs may migrate to the other area of the Bay at this time. Mature crabs in the lower Bay spawn and then overwinter, where they are exposed to the dredge fishery (age-2+). Mature crabs in the upper Bay do not spawn before overwintering. Overwintering crabs in the upper Bay are not exposed to the dredge fishery, but may re-emerge (age-2+) to once again enter the pot fishery.

7.2. Parameter Estimation

Transition probabilities were calculated by combining data from the fishery-independent winter dredge survey and estimates of fishing mortality (F) and natural mortality (M) from the stock assessment. We allowed F to vary from 0.6 - 1.2 to cover the range observed in the estimates (Figure 23). We set M to either 0.50 or 0.375 to reflect estimates of the maximum expected life span, ω , of 6 and 8 years, respectively. To generate the parameter estimates we made the several assumptions. The assumptions apply to both the aggregate and the spatially-explicit model unless stated otherwise. The assumptions were:

- Assumption 1. No size effect on natural mortality during the overwintering period (i.e., all overwintering mortality was the same and = M).

- Assumption 2. Fishing mortality on 1-year-old crabs is not applied to all individuals in the stage, but is weighted by the partial recruitment vector PR_1 . Fishing mortality on age 2+ crabs occurs on all individuals throughout the stage.
- Assumption 3. The winter dredge fishery in Virginia is an additional source of overwintering mortality in excess of natural rates only for crabs overwintering in the lower Bay area (i.e. $a_{13,14} = a_{6,7} + F_{\text{dredge}}$).

We derived many of the estimates of the model parameters from an analyses of data from the winter dredge survey from 1991-1995. Analysis of the winter dredge survey data was conducted by Jon Volstad (then at Versar Corp.). We developed abundance estimates for four regions based upon winter dredge survey data (Table 37). Abundance estimates included a correction for gear efficiency (11%). Average abundance estimates for each region are provided in Table 38.

All parameters estimated in the aggregate model are defined in Table 39. Below we detail how each estimate was derived.

7.2.1. Proportion of Megalopae Surviving

We require an estimate of the proportion of megalopae surviving to return to the Bay. No such estimates have been published. Accordingly, we arbitrarily set this parameter = 0.000016. This value exactly balances the fecundity term. Thus, we have assumed that the fecundity rate of females would have evolved such that the population is capable of replacement.

7.2.2. Proportion of 1-yr-olds Vulnerable to the Pot Fishery

We estimated the proportion of age-1 crabs vulnerable to the fishery from successive length frequency plots provided by Rothschild et al. (1988). Assuming a 5" (127 mm) legal size, we calculated the fraction of crabs within the average size frequency of crabs that would become >120 mm in the summer following their first overwintering to be ~ 0.15.

7.2.3. Overwinter Survival Rate, a_2

We set the overwintering survival rate to be equal to the natural mortality rate (individuals.individual⁻¹.year⁻¹) divided by 2 to reflect the six month time step in the model.

7.2.4. Fecundity

Prager et al. (1990) give mean fecundity as 3.2×10^6 for all adult females. Our model includes only females, and thus, assuming a sex ratio of 50:50, estimated fecundity is 1.6×10^6 . To account for the size-dependent nature of fecundity, we assumed the fecundity of age-1 females was 66% of average female fecundity. This estimate was based on the size-dependent

slopes reported by Prager et al. (1990)

All other parameters can be estimated from combinations of f , F , and M . The final set of parameters for the aggregate model is given in Table 39.

7.2.5. Spatially-explicit Model Parameters

To calculate model parameters, we have assumed all areas of the Bay are equally capable of supporting crabs. We divided the Bay into an upper and lower region (Figure 36; Table 37). Eggs and megalopae only exist in the lower region (Node 8). Subsequently, newly settled crabs distribute themselves into both regions (Nodes 2 and 9). Currently, the proportion moving is calculated from the average abundances of newly-settled crabs in the winter dredge survey in the upper and lower regions of the Bay. Using values in Table 38, this is given by:

$$\begin{aligned} a_{28} &= \frac{1.132 \times 10^7 + 4.21 \times 10^7}{2.68 \times 10^6 + 7.43 \times 10^7} \\ &= 0.695 \end{aligned}$$

For all other migrations in the bay we assumed that the fraction that moves is directly proportional to the relative areas of the two regions. Thus, the migration probability to the upper bay is given by:

$$\begin{aligned} r &= \frac{\textit{Area of Upper Bay}}{\textit{Area of Total Bay}} \\ &= \frac{1.865 \times 10^6}{1.865 \times 10^6 + 6.065 \times 10^6} \\ &= 0.235 \end{aligned}$$

Similarly, the probability of migrations to the lower bay is $1-r$.

The complete set of parameters for the spatially-explicit model is given in Table 40.

7.3. Matrix Formulation

In their most elementary applications, matrix projection models can be used to estimate the intrinsic rate of natural increase in a population, r . When $r > 0$, a population increases in abundance, and when $r < 0$, a population declines in abundance. In this particular application we are more interested in the relationship between r and F , given assumptions about M . Specifically, we want to estimate the value of F at which $r = 0$. This threshold F is the fishing mortality rate at which, if increased, the crab population will begin to decline.

One can also examine two additional characteristic features of the population. All populations, when left undisturbed, eventually reach a level at which relative abundances of the different stages remain constant. This is termed the stable stage distribution. It is important to realize that a population, having reached a stable stage distribution, may continue to experience changes in abundance. Related to the stable stage distribution is the reproductive value. Reproductive values estimate the expected number of offspring an individual would produce were it to survive. By convention, reproductive values are reported as a relative number, standardized so that the reproductive value of the first stage is 1. Protection of stages with high reproductive values is important to conserve a population.

Importantly, for this application, we have conducted formal sensitivity analyses of the transition probabilities in the projection matrix A . These are termed elasticities. They can be interpreted in several different ways. When comparing two transition probabilities within the same projection matrix, variability in the transition probability with the higher elasticity will have greater impact on the population. Thus, we did analyses to give the elasticity of the model which indicates at what stages the population is most sensitive to variability. When identified, these stages and transitional probabilities should be sensitive indicators of future trends in the population. An alternative possibility is that transition probabilities associated with the highest elasticity will be at those stages in which natural environmental variability and forcing will have the most impact.

7.4. Model Results

7.4.1. Aggregate Model

We used an initial vector of abundances given by the average abundances from the winter dredge survey. However, model projections are not particularly sensitive to initial conditions. Matrix projection models can be used to examine several features of a population. The initial parameter set, with annual $F = 1.0$, and annual $M = 0.375$ (equivalent to $\tau = 8$ years), and $PR1 = 0.9$ yielded an estimate of population intrinsic growth rate of $r = -0.105$. This value indicates that, under the modeled scenario, the population abundance is slowly declining. It suggests that at current rates of exploitation the crab population may be declining at a very slow rate. We examined the relationship between r and F (Figure 37). It is important to recognize any strong non-linearities because they would suggest potential breakpoints in the benefits of management action to control F . The slope of the relationship between r and F is an indication of the sensitivity of the population to changes in F . We were also interested in the threshold values of F at which $r = 0$.

For the range of $PR1$ values examined, the relationship between r and F was weakly non-linear. This suggests that there may not be a strong relationship between management action to reduce F and population growth rate until F is reduced substantially. Thus, effort control in the crab fishery may be little more than a blunt management tool.

The model can also be used to estimate values of F to ensure population growth. If the

maximum expected lifespan = 8, our model suggests that F should be between 0.54 - 0.55 depending upon the pattern in partial recruitment (Figure 37). Estimates based on $n = 6$ suggest high values of $F \sim 0.32 - 0.39$.

The estimated reproductive value vector indicated that mature crabs have the highest reproductive values (Nodes 5 and 7). The stage with the highest reproductive value is mature overwintering crabs that will release zoea at the beginning of the next summer (Node 7). The stage with the second highest reproductive value is overwintering mature age-1 crab (Node 5). These represent those individuals that grow sufficiently fast in their first year to mature and reproduce. In combination these two stages reflect directly, or are influenced by the hardshell fishery. This suggests that regulation of the hardshell fishery, particularly as it relates to the harvest of crabs in their first year will be an effective conservation measure.

More specifically, we can estimate the relative biological value of small and large age-1 crabs. Figure 38 indicates that the reproductive values of small and large age-1 crabs are 6.68 and 9.95, respectively. This means that large age-1 crabs are $\sim 1.5x$ as valuable biologically as small age-1 crabs because of the increased likelihood of them contributing reproductively to the population. Furthermore, overwintering mature age-1 crabs are 1.4 x as valuable biologically as mature hard shell crabs in the following summer growth period, suggesting that efforts to limit the harvest of age-1 crabs will be particularly effective as a conservation measure.

We calculated the transition elasticities for all of the transitions in the life cycle (Figure 39). The highest elasticities are associated with the adult stage, with fecundity and with early-life survival. This can be interpreted in two distinct ways. First the pattern in elasticity indicates the stages at which natural environmental stochasticity in survival would have maximum effects. For example, natural variability in early life survival and survival of adults is likely to have a substantial impact on population growth rates. However, variability in overwinter survival is likely to have less impact. A second interpretation of these data are to indicate where research efforts should be focused. The findings suggest that research to understand early life and adult survival will be particularly effective in removing the uncertainty around predictions of future population status for blue crab.

7.4.2. Spatially-explicit model

Assigning the same underlying dynamics as in the aggregate model (i.e. annual $F = 1.0$, $M = 0.375$), the spatially-explicit model predicts a faster rate of decline in population abundance ($r = -0.111$). This implies that at current levels of exploitation we may expect declines in the abundance of crabs. Overall, F must be reduced to ~ 0.5 in this model for r to become positive. We conducted an eigen-analysis of the model results to examine the stable stage distribution and the reproductive values of each stage. It is most instructive to examine the reproductive values plot (Figure 40). The estimated values reinforce our earlier comments regarding the importance of the proportion of age-1 crabs that become vulnerable to the commercial fishery. However, the central feature of Figure 40 is the importance of mature females in the lower Bay. The reproductive value of this stage is 1.3x that of any other stage.

We also examined the elasticities of the model. We consider first the elasticities for transitions within each region (Figure 41). Sensitivities to two transitions dominate the model: the transition from overwintering adult to adult in the lower Bay, and the transition from overwintering pre-pubertal age 1 to adult in the lower Bay. The high sensitivity of these stages suggests that these stages should receive attention in assessing population trends. Moreover, management action to reduce mortality in these stages is likely to be particularly effective.

We now consider the sensitivity of the model to transitions involving migrations between the regions (Figure 42). Two migration routes are of importance. The migration of crabs that settle in lower Bay habitats into the upper Bay is the sole source of crabs for the upper Bay. The two important migration is of overwintering juveniles in the upper Bay to juveniles in the lower Bay. The model is almost as sensitive to these transitions as it is to the overwinter mortality of adults in the lower Bay (Figure 41).

Overall, the model suggests that management action to curtail or limit overwinter mortality would be most effective, particularly of egg-bearing females.

An additional application of the spatially-explicit model is to examine a broader range of potential management options than could be examined in the aggregate model. In our tests, we examined the modeled response of the crab population in terms of r to management actions. We considered two proposed actions.

7.4.2.a. Regulation of the Dredge Fishery

We sought to compare the effect of regulating effort in the dredge fishery compared with regulation of overall effort. We assumed only the larger, mature age-1+ crabs in the lower Bay were potentially vulnerable to the fishery. We estimated the change in r of similar reductions in F by applying different proportions of the current F (Figure 43). While obviously there is greater impact of reductions in overall F , a significant proportion of the reductions can be achieved by reducing effort in the winter dredge fishery. However, by itself even complete elimination of the dredge fishery in Virginia only just brings the blue crab population into a zone of net increase of population size. This suggests that reduction in F needs to be more broad-based if it is to be most effective.

7.4.2.b. Protection of Migrating Females

We examined this option by simply setting the transition values to 1.0 for crabs moving from Node 6 to Node 14, and from Node 3 and 12. These transitions represent the movement of mature, egg-bearing females from the upper Bay to the lower Bay. This implies a perfect protective corridor, that is all migrating, egg-bearing females successfully arrive in the spawning areas. This action increased the intrinsic rate of natural increase of the population; r increased from -0.111 to -0.013. For comparison this increase could also be achieved by a reduction in overall F from 1 to 0.52. We concluded that, by itself, this approach is insufficient to protect the resource. However, it may be a useful adjunct to broad-based reductions in F .

In summary, the stage-based model suggests that F should be reduced to ~ 0.5 to ensure a positive rate of population growth. The model has highlighted 1) the sensitivity of the population to the proportion of crabs that recruit to the fishery in their first summer after settlement, and 2) the high biological value of these stages. Finally, the spatially explicit version of the model has suggested the importance of protecting ensuring the adequate survival of newly settled crabs migrating toward the upper Bay and the return movement of age-1 mature crabs to the lower Bay spawning area.

Table 37. Definitions of Chesapeake Bay regions used in estimating model parameters.

	Region	Spatial Coverage
Upper Bay	A	Upper Bay (N of Bay Bridge); Black, Chester, Elk and Sassafrass Rivers
	B	Mainstem Bay from Bridge to Cove Point; Eastern Bay including Wye and Miles Rivers Choptank River Little Choptank River
Lower Bay	C	Mainstem Bay from Cove Point to Wolftrap Light Fishing Bay Tangier Sound including Wicomico, Manokin, Big Annemessex and Little Annemessex Rivers
	D	Pocomoke Sound and River Honga, Nanticoke, Patuxent and Potomac Rivers Lower Mainstem Bay south of Wolftrap Light James, Rappahannock and York Rivers Chesconessex, Ohancock, Pungoteague, Nandue, Occohannock Creeks.

Table 38. Average abundance estimates for each region of Chesapeake Bay.

	Uncorrected Abundance crabs @1000 m ⁻²				Corrected Abundance crabs @1000 m ⁻²				Total x 10 ⁶				All Regions
	A	B	C	D	A	B	C	D	A	B	C	D	
Newly settled N ₂	2.03	3.71	7.48	3.8	18.4	33.7	68.1	34.8	11.32	42.19	26.8	74.3	395.7
Age-1 N ₅	2.43	3.04	3.18	2.02	22.15	27.65	28.96	18.37	13.59	34.61	11.4	39.15	201.3
Age-2+ N ₇	1.88	4.32	1.95	2.58	17.16	39.3	17.86	23.5	10.53	49.2	70.2	50.1	180.1
Area Km ²	613.9	1251.5	3934.7	2130.5									

Table 39. Parameter estimates for aggregate model.

Parameter	Symbol	Value	Comment
Rate of natural mortality	M	0.1875, 0.25	Equivalent to annual M = 0.375, and 0.5 for $\Delta t = 8$ and $\Delta t = 6$ years
Rate of fishing mortality	F	0, 0.1, . . . 1.0	Equivalent to annual F = 0, 0.2, . . . 2.0 for six-month time step
Rate of fishing mortality in dredge fishing	F _{dredge}	F	Assumed equal to summer exploitation
Proportion of age-1 crabs vulnerable to pot fishery	f	0.15	
Partial recruitment of age-1 crabs	PR ₁	0.5, 0.7, 0.9	See Section 2.3.1.
Transition probabilities			
Probability of survival of eggs to overwintering	a ₂₁	1.6 x 10 ⁻⁶	Arbitrary
Overwintering juveniles	a ₃₂		e ^{-M}
Slow growing juveniles	a ₄₃		e ^{-M}
Fast growing juveniles	a ₅₃		e ^{-(PR₁*F+M)}
Overwintering pre-pubertals	a ₆₄		e ^{-M}
Overwintering age-1 adults	a ₆₅		e ^{-(M+F_{dredge})}
Adults	a ₇₆		e ^{-(M+F)}
Overwintering adults	a ₆₇		e ^{-(M+F_{dredge})}
Fecundity	F		F5 = 0.66*F7, F7 = 1.6 x 10 ⁶

Table 40. Parameter estimates for spatially-explicit model.

Parameter	Symbol	Value	Comment
Rate of natural mortality	M	0.1875, 0.25	Equivalent to annual M = 0.375, and 0.5 for " = 8 and " = 6 years
Rate of fishing mortality	F	0, 0.1, . . . 1.0	Equivalent to annual F = 0, 0.2, . . . 2.0 for six-month time step
Rate of fishing mortality in dredge fishing	F _{dredge}	F	Assumed equal to summer exploitation
Proportion of age-1 crabs vulnerable to pot fishery	f	0.15	
Partial recruitment of age-1 crabs	PR ₁	0.5, 0.7, 0.9	See Section 2.3.1.
Probability of survival of eggs to overwinter	elhsurv	1 x 10 ⁻⁶	Arbitrary
Transition probabilities			
<u>Upper Bay</u>	a _{3,2} a _{4,3} a _{5,3} a _{6,4} a _{6,5} a _{7,6} a _{6,7}		$r C a_2$ $(1-f) C a_2$ 0 $r C a_2$ a_2 $r C e^{-(M+F)}$ a_2
<u>Lower Bay</u>	a _{9,8} a _{10,9} a _{11,10} a _{12,10} a _{13,11} a _{13,12} a _{14,13} a _{13,14}		$(1-q) C e l h s u r v$ $(1-r) C a_2$ $(1-r) C (1-f) C a_2$ $f C e^{-M+PRF}$ $(1-r) C a_2$ $a_2 C e^{-F d r e d g e}$ $e^{-(M+F)}$ $a_2 C e^{-F d r e d g e}$
Migration Transitions	a _{2,8} a _{3,9} a _{4,10} a _{6,11} a _{10,2} a _{12,3} a _{13,4} a _{14,6}		$q C e l h s u r v$ $r C a_2$ $(1-r) C (1-f) C e^{-(F+M)}$ $r C a_2$ $(1-r) C a_2$ $f C e^{-M+PRF}$ $(1-r) C a_2$ $t C e^{-(M+F)}$

figure
35

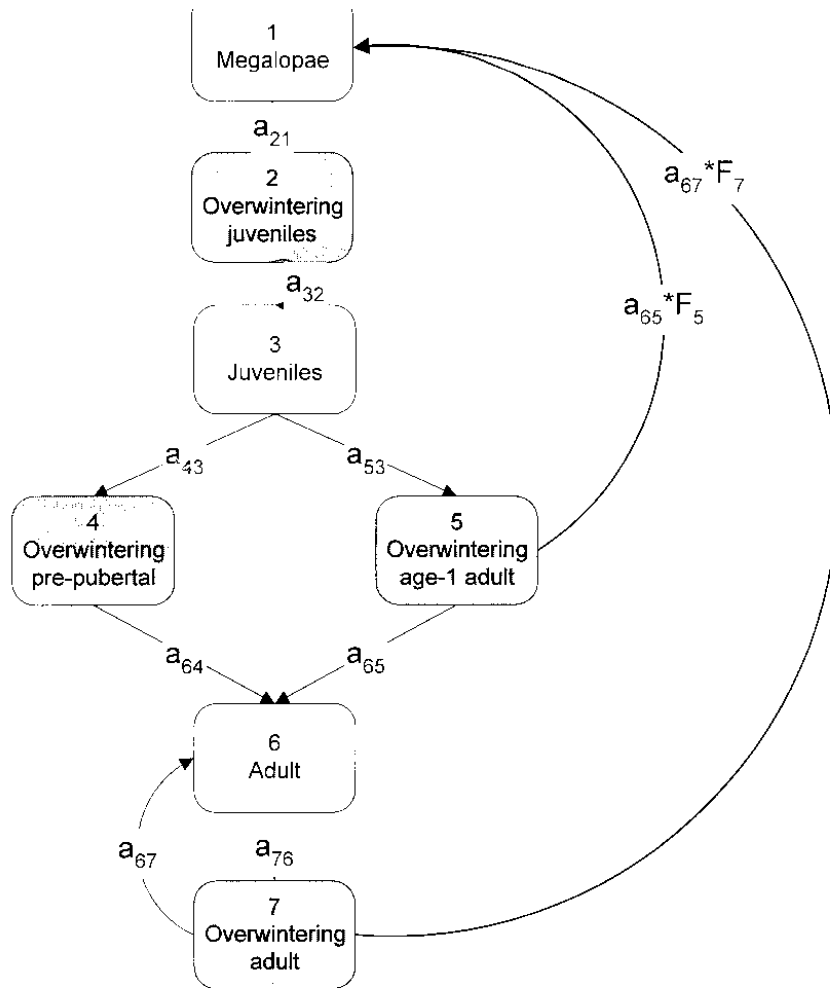


Figure 35. Life cycle graph for blue crab. The diagram considers the life cycle to be divided into 7 stages, each represented by a node in the diagram. Arrows connecting nodes represent possible transitions in the life cycle. Arrows labeled a_{ij} represent growth and survival probabilities. The arrow labeled F_i represents a fecundity term.

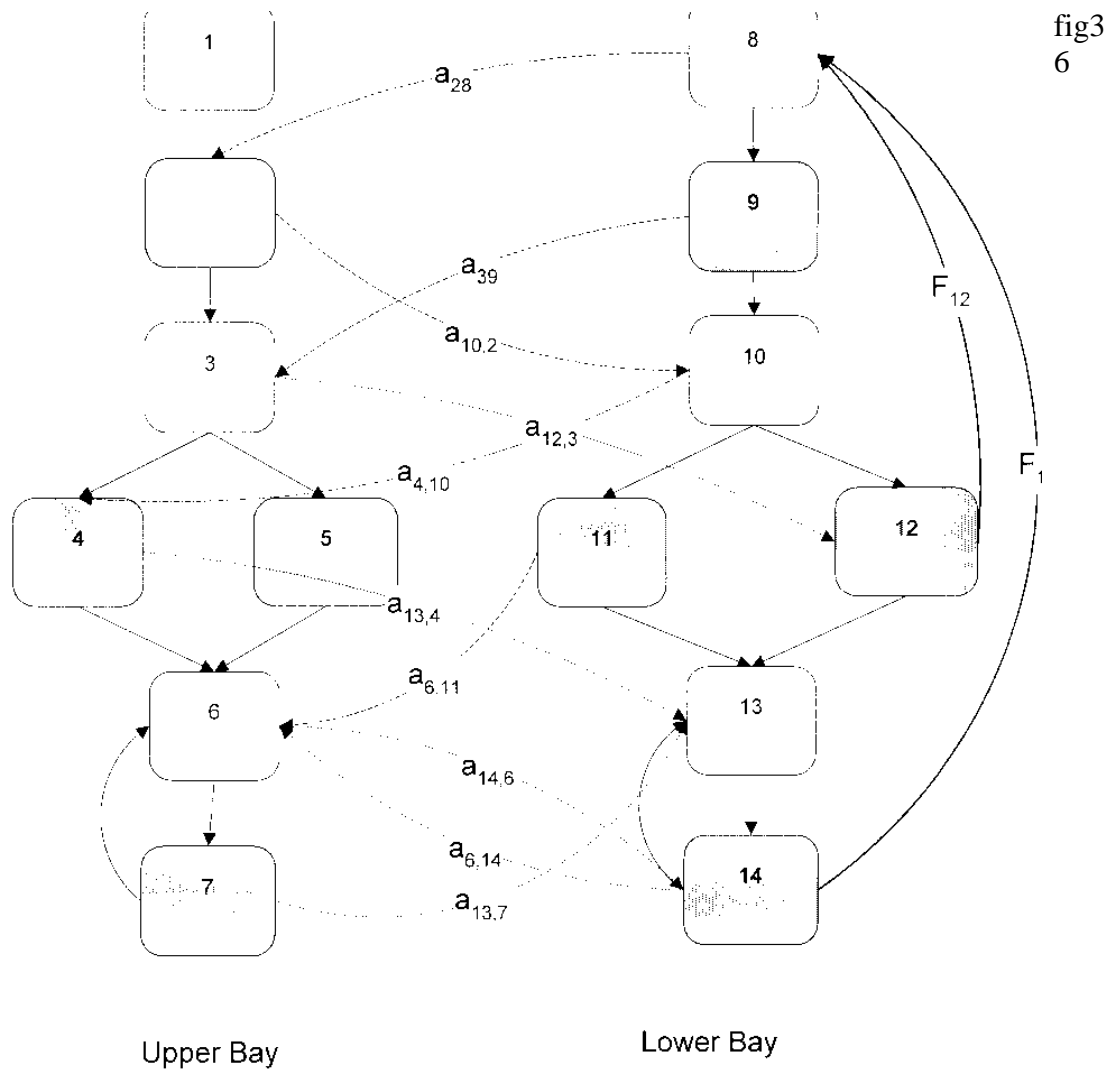


Figure 36. A spatially-explicit life cycle diagram for blue crab. The life cycle is depicted occurring over two spatial domains. The Upper Bay domain is represented on the left hand side of the diagram (Nodes 1-7); the Lower Bay domain is represented on the right hand side of the diagram (Nodes 8-14). Arrows indicate possible growth, migration, and fecundity transitions.

fig37 Blue Crab Target Setting Miller and Houde

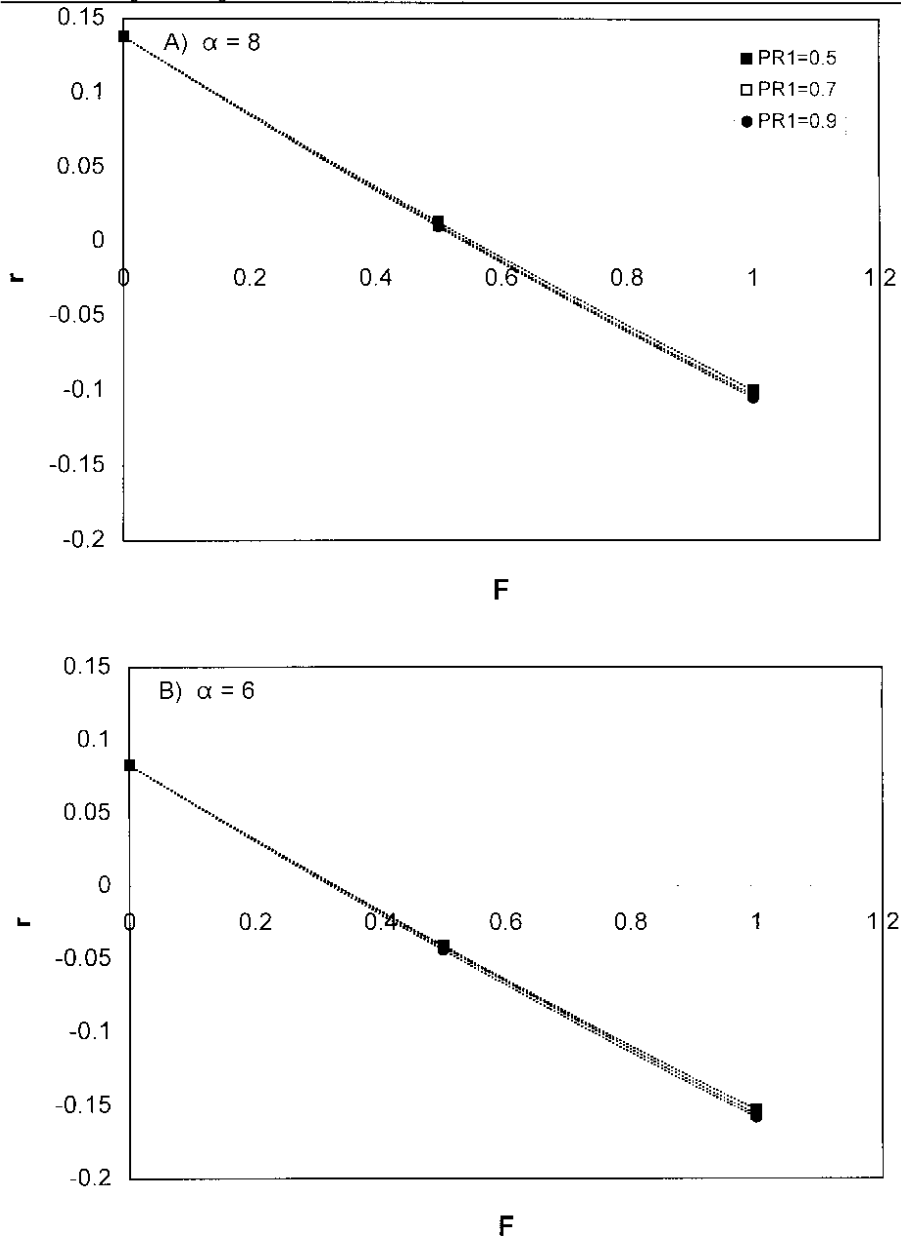


Figure 37. Relationship between the intrinsic rate of natural increase of the population, r and the fishing mortality rate, F , as a function of the partial recruitment of age-1 crabs. Shown are estimated relationships for two different maximum expected ages of A) $\alpha = 8$, and B) $\alpha = 6$.

fig38 Blue Crab Target Setting

Miller and Houde

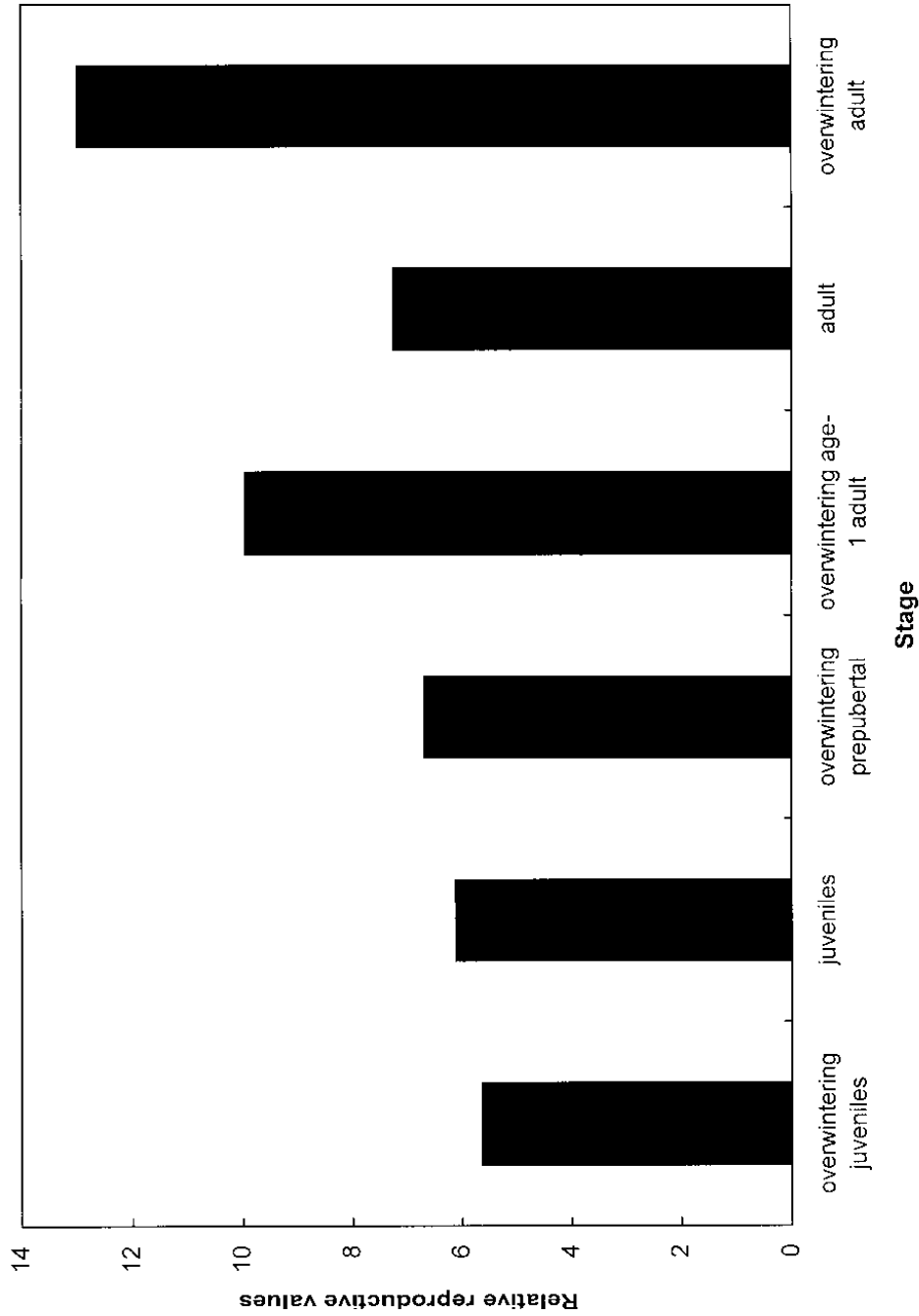


Figure 38. Reproductive values of each stage in the aggregate model. Reproductive values are expressed relative to the reproductive value of megalopae x 10⁵.

fig39

Blue Crab Target Setting

Miller and Houde

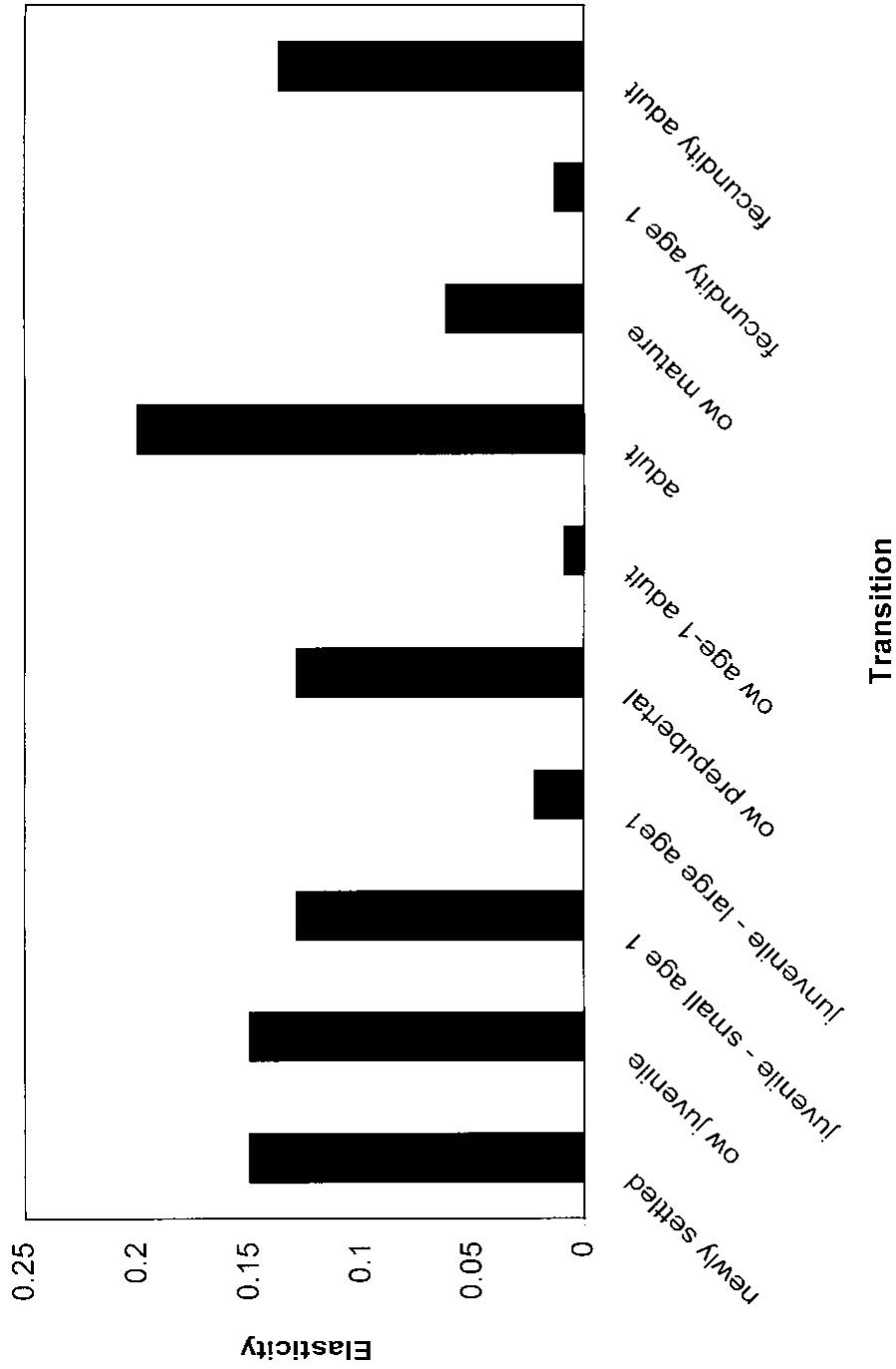


Figure 39. Growth elasticity of each life history stage in the aggregate model.

fig40

fig41

fig42*

fig43

8. DEVELOPMENT OF POPULATION TARGETS

Establishing overall goals, targets and reference points represents a strategic approach to management of valuable fisheries and other resources. Globally and nationally, such goal-setting is being adopted to insure the long-term sustainability of exploited resources. There also is a notable trend towards adoption of precautionary and risk-averse approaches as insurance against declines in quality of fisheries and, too frequently, collapses of stocks under exploitation (FAO 1995; NAS *in press*; NMFS *in press*). The Living Resources Subcommittee of the Chesapeake Bay Program has developed guidelines that support such principles (LRSC 1997). As the Bay's most valuable fishery, it is appropriate that targets for blue crab be established to insure the long-term productivity of the stock and also, where possible, to maintain or improve quality of the fishery. The CBSAC stock assessment (Rugolo et al. 1997) made positive steps in this direction. We build upon their work.

Target-setting as a minimum measure should provide a target-level of population abundance (or index) that must be maintained to insure a sustainable, exploited population. This population level and fishing mortality rates associated with it should be viewed as limit thresholds, rather than targets that one hopes to achieve. Given the negative biological and economic consequences of exceeding this level, targets should ideally build in a protection buffer to insure that the population remains above the threshold level and fishing mortality rates do not exceed critical reference points. At another level, targets can be set which are indicative of optimum population levels with respect to exploitation pressure, population productivity, or socioeconomic factors. Such targets also should be established since they act to achieve the management goal of a high-quality fishery, not simply one that is sustainable. In this context, we discuss and recommend a hierarchy of targets for blue crab in Chesapeake Bay (Table 41). As in all fishery assessments, the state of knowledge about blue crab biology and its responses to fishing remain to a degree uncertain. Thus, we recommend monitoring and research that can reduce uncertainty or fill the gaps in knowledge to improve management of blue crab in Chesapeake Bay.

8.1 Tier 1 - Sustainable Population Abundance Limit

Based upon the Baywide stock assessment for blue crab, Rugolo et al. (1997) concluded that the population was moderately to fully exploited and presently at average levels of abundance. That analysis and conclusion were based largely upon a belief that the period 1981-1990 witnessed above average abundance of blue crabs and that there was no indication of a decline in stock size below the long-term mean. The stock assessment implied that harvests of 100×10^6 lbs., which have been observed in some years (Figures 19 and 20) were sustainable. Using an alternative and more cautious interpretation, we believe that the apparent increased abundance in the mid-1980s resulted in large part from the reporting change in Maryland statistics. We also note an indication of increased abundance in the 1980s, but it is far less dramatic than reported in the CBSAC stock assessment (Figure 27). Our adjusted time series of abundances and landings indicate that they have varied relatively little over the 43-year period

(Figures 13 and 15).

There is no doubt that the 1981 harvest was absolutely larger than the 1980 harvest, regardless of any reporting change, the central issue is whether there was a persistent shift in the underlying average abundance of blue crabs in the Bay coincident with the reporting change that occurred in Maryland in that year. We believe, and think that our analyses have confirmed, that while there were individual years of increased abundance that there is no evidence for a persistent increase in the average level of abundance. Accordingly we have chosen to adjust the landings time series. The impacts of this change on the estimated targets is substantial. Thus, the conclusions should be interpreted with caution. However, the adjustment serves to lower the estimated targets, and thus is a risk averse strategy, rather than the risk prone strategy of leaving the landings time series unadjusted.

Our estimate of Baywide, long-term mean landings is $84.6 (\pm 15.9) \times 10^6$ lbs. (Figure 15), an annual yield considerably higher than the unadjusted mean landings, 69.7×10^6 lbs. We suggest that the long-term sustainable yield of blue crab in Chesapeake Bay may be $\sim 84.6 \times 10^6$ lbs. Calculations based upon this time series, combined with information from fishery-independent assessments, indicate that the annual mean abundance of harvestable crabs is $0.8 - 1.0 \times 10^{10}$ (Figures 29 and 30), suggesting that 1×10^{10} crabs represents a sustainable Baywide abundance.

It should be noted that estimates of stock size, based upon exploitation rates derived from the Calvert Cliffs time series, indicate a declining abundance since 1990 (Figure 29). This may suggest that current levels of exploitation are too high.

We developed an estimate of maximum sustainable yield from catch and effort statistics. Although its reliability is uncertain, our MSY estimate, based upon the adjusted landings data, was 99.7×10^6 lbs, suggesting that annual landings should not exceed that threshold level. Perhaps more importantly, the level of effort to attain MSY was estimated to be $\sim 450,000$ pot-hrs @month⁻¹, a level that has been greatly exceeded in recent years (Figure 20). Die and Caddy (1997) have reviewed several methods to estimate safe levels of harvest in difficult-to-assess species. Applying two of those methods (based upon approximate knowledge of catches, biomasses and mortality rates), one attributable to Cadima (in Troadec 1977) and one attributable to Garcia et al. (1989), the probable MSY levels so generated were in the range 89×10^6 to 112×10^6 lbs, levels roughly equivalent to recent catches.

Managing crabs based upon abundance targets may be impossible. Abundances must be considered with respect to fishing mortality (F) levels that affect them. Yield-per-recruit analyses are an important way to develop F targets and reference points. Many crustacean fisheries are managed using an $F_{10\%}$ threshold or target. The $F_{10\%}$ level of fishing mortality reduces the spawning potential per recruited crab to 10% of that of the unexploited population, but nevertheless is presumed to protect such stocks from recruitment failures. Examining a wide range of possible scenarios in which fecundity, maximum life expectancy and growth trajectories

were simulated, a conservative value for $F_{10\%}$ is ~ 0.9 , a level now exceeded in the Baywide fishery. Estimates of F levels over the 1945-1997 time series vary from $\sim 0.6 - 1.3$ (Figure 25). However, there is clear evidence of recent increases in F . Although there is no strong evidence to date that high recruitments cannot be sustained at present F levels, we believe that recent F levels are higher than a risk-averse approach would warrant.

It is important to note that estimated abundances of crabs in the last four years do show a declining trend (Figure 28) under increased exploitation rates (Figure 25 A). Moreover, after adjusting Maryland landings, CPUE appears to have declined continuously from 1945 to at least the mid-1980s (Figure 17), suggesting that abundance levels have declined. Abbe and Stagg (1996) documented a decrease in mean size of crabs recent years. Taken together, these features of the crab fishery indicate a heavily fished resource and the need for caution in its management. The fishery should be monitored closely.

8.2. Tier 2 - Overfishing Target

Regardless of the particular sustainable target or reference levels that could be selected, all indications are that reduced fishing effort and mortality will increase the efficiency of the blue crab fishery and probably improve the quality of the catch. Currently, the fishery is operating at too high an effort level to maximize yield-per-recruit and it is technically “growth overfished.” There is no evidence that recruitments of young crabs are reduced at present fishing levels but the quality of the fishery could be improved by reducing fishing effort. Managing the blue crab fishery to increase YPR is a tier 2 target. This would have economic benefits to the fishery in addition to being a risk-averse action. It would be ecologically beneficial as well, by ensuring an abundant and resilient crab population.

A common management target in many fisheries recently has been the $F_{0.1}$ reference level. This fishing mortality rate is a conservative measure that is applied to reduce fishing mortality to levels that protect against recruitment overfishing. Effort levels to achieve $F_{0.1}$ are significantly lower than those to attain F_{\max} , the level that maximizes yield-per-recruit. We estimated that $F_{0.1}$ for Chesapeake Bay blue crab was 0.35 to 0.47, which are levels very much lower than present F . The F_{\max} was estimated to lie in the range 0.54 to 0.79, also levels much lower than present F . Small gains in yield-per-recruit in the blue crab fishery could be realized by reducing F to F_{\max} , while small losses in yield-per-recruit would be experienced at $F_{0.1}$. While reductions in F to the $F_{0.1}$ level may be unwarranted, reductions of F from present levels (>1.0) would improve the quality of the blue crab fishery.

8.3. Management Approaches to Achieve Targets

The reductions in F implied by the recommended targets need not be achieved only by reducing overall effort. Our stage-based model indicated that reductions in overall F could be achieved most effectively by raising size limits which would reduce the fraction of age-1 crabs that recruit into the fishery in August and September. The stage-based model provides a possible

approach to determine the size limit needed to reach the target. Output from the stage-based model also suggested that reductions in effort in the winter dredge fishery would be an effective, although not totally sufficient, way to reduce Baywide F. The stage-based model, while promising, will require considerable additional development before it can be reliably used in management.

8.4. Monitoring and Research Needs

8.4.1. Resolution of Landings and Effort Data

The blue crab fishery is temporally and spatially expansive in Chesapeake Bay. Throughout its range in the Bay, the fishery targets different components of the population. We lack landings and effort data of sufficient resolution to estimate the proportions of catch represented by different components of the fishery in the seasonal harvest. The need for catch and effort data in the recreational fishery is clear. If the recreational fishery has been increasing its fraction of landings in recent years, this knowledge is required for accurate assessments and to improve management. Improving the temporal and spatial statistics on landings from all elements of the fishery is an important priority.

8.4.2. Fishery-independent Data

In a recent report, the National Research Council (NRC 1998) highlighted the importance of fishery-independent surveys to accurately monitor fish stocks and set reference points and targets for management. In the Chesapeake Bay, we are fortunate to have several surveys of extended duration (MD trawl, VIMS trawl and CC pot surveys). However, the spatial coverage and stages of blue crab life history monitored in these surveys differ. In the past decade, CBSAC has funded the winter dredge survey, the only Baywide survey of blue crab. It is important that the three other surveys be maintained for a sufficient period, so that each can be correlated with the winter dredge survey. The continuation of the winter dredge survey is essential for proper Baywide monitoring of the stock.

8.4.3 Growth Trajectories

There remains considerable uncertainty about the growth dynamics of blue crab. This is reflected in the variation in von Bertalanffy model parameters and in estimates of maximum expected life span, ". It is of fundamental importance that studies be instituted or continued that quantify the growth dynamics of blue crab in Chesapeake Bay. Understanding the growth dynamics will lead to more accurate stock assessments, better determination of exploitation rates through its impact on the partial recruitment vector of young crabs, improvements in delineation of biological reference points (and targets), and a better overall understanding of the population dynamics of crabs in Chesapeake Bay.

8.4.4. Spatially-explicit Management

The blue crab life history leads to spatially discontinuous distributions of its life-history stages. It is very probable that spatially-explicit management may be an important tool to achieve management goals and targets. However, at present there is insufficient understanding of the spatial pattern of exploitation, or of spatial variability in vital rates, e.g. growth and survival. Improvement in both areas would allow better stock assessments and understanding of exploitation patterns in Chesapeake Bay. In addition, improvements in knowledge of blue crab utilization of the spatial expanse of Chesapeake Bay may allow the objective identification of potential reserve areas as a potential management tool.

8.5. Concluding Statements

The blue crab fishery in Chesapeake is heavily exploited and fully utilized. Commercial catches, after adjustment for the statistical reporting change in Maryland beginning in 1981, have varied without significant trend since the 1940s. Catch-per-unit-effort declined consistently in the fishery from the 1940s until at least the mid-1980s. Maximum sustainable yield of the fishery may be in the range 85-100 $\times 10^6$ lbs. The long-term mean catch (1945-present) is 84.6 $\times 10^6$ lbs., which appears to be sustainable in the long term. Estimates of abundance and biomass of blue crabs in the Bay have not shown any major trends since 1945, although a minor increase did occur in the mid-1980s. Fishing effort in the present fishery is believed to be higher than is desirable to maintain a high-quality fishery in perpetuity. Optimum effort may be approximately 450,000 pot-hrs @month⁻¹, which is about 100,000 pot-hrs @month⁻¹ lower than effort levels recorded in recent years.

There is no evidence of any decline in recruitment levels since 1945 and, in this sense, the blue crab stock is healthy. Assuming that a spawning potential ratio of $F_{10\%}$ is a reasonably protective measure against recruitment failure, an appropriate F-level in the fishery is $F = 1.08$. Present F exceeds that level and should be stabilized and reduced as a risk-averse measure to insure continued high recruitment of crabs into the fishery. The F-level to maximize yield-per-recruit (F_{max}) is in the range 0.54 - 0.79. Levels of F in the fishery have ranged from 0.6 - 1.3, with highest levels occurring in recent years. The blue crab stock is technically 'growth overfished.' Marginal improvements in yield-per-recruit could be realized by reductions in fishing mortality to near the F_{max} range. While only marginal increases in yield would be associated with the lower fishing mortality rate, the quality of the blue crab fishery would improve, especially with respect to harvesting efficiency and economics.

Management options that may be effective to attain goals and targets, determined in part from stage based-modeling of blue crab, include increases in size limits during the fall fishery to reduce the fraction of age-1 crabs that reach recruitable size and become vulnerable to the fishery. Reductions in fishing effort in the winter dredge fishery also may be beneficial to stabilize long-term abundance in the population, although this approach alone would not be sufficient to achieve such stability. In our analysis, an overall reduction in fishing mortality of approximately 30% from present levels would benefit the fishery and would be protective of the

long-term ecological benefits that accrue from a healthy and resilient blue crab population in Chesapeake Bay.

Continuous monitoring of the blue crab stock is essential to know its status and to develop effective management actions. The present fishery appears to be essentially healthy, although productivity of the stock and quality of the fishery may be improved by reducing fishing mortality. The temporal variability in elements of the fishery and the spatially-explicit nature of the population and of the fishery must be understood better to improve modeling of the stock and its management. Programs to determine trends and variability in the recreational fishery need to be instituted, and the recreational landings eventually must be considered in stock assessments of blue crab in Chesapeake Bay.

Table 41. Recommended targets for Chesapeake Bay blue crab.

Tier	Target	Motivation
1. Sustainability Limit	$F_{10\%} \sim 0.9$	MSY $\sim 80\text{-}100 \times 10^6$ lbs; long-term mean harvest $\sim 84 \times 10^6$ lbs; Current $F > 1.0$
2. Efficiency Limit	$F_{0.1} = 0.4$	Precautionary, but allows high yield per recruit
3. Rebuilding Limit	$F < 0.5$	Ensures positive rate of population growth

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