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Atlantic Deep-Sea Red Crab (*Chaceon quinquedens*)
MSY Reevaluation

Prepared by the

Red Crab PDT

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Red Crab Advisory Panel

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1.0 Executive Summary

This document updates and expands upon information and analysis provided in the 2006 stock assessment for red crab (NEFSC 2006) and in the report of the Data Poor Stocks Working Group (DPSWG) (Northeast Data Poor Stocks Working Group 2009). In particular, this assessment incorporates:

- Additional results from the Depletion-Corrected Average Catch (DCAC) Model (MacCall 2009b) using a depletion DELTA calculated from the difference between the abundance of harvestable males estimated from the 1974 survey and the 2003-2005 survey. This approach differs from the assumed zero depletion DELTA that was used to produce the model results that were presented to the DPSWG.

- Two analyses of the relationship between maximum sustainable yield (MSY) and the sustainable yield estimates produced by the DCAC Model. One analysis was provided by Alec MacCall, developer of the DCAC Model and the other was done by the PDT.

- Inclusion of the confidence intervals surrounding the sustainable yield estimates provided by the DCAC Model.

- Analysis of expected size distribution of male crabs relative to exploitation rates based on an age/carapace width (CW) model (Mellville-Smith 1989) for the closely related Namibian red crab (*Geryon maritae)*, and a CW/weight model (Farlow 1980) for Atlantic deep-sea red crab (*Chaceon quinquedens)*.

- Analysis of the possible future trajectories of red crab biomass and landings following the known history of exploitation and various stock-recruitment assumptions by analogy with the life history characteristics of *G. maritae* as incorporated into a stochastic simulation model.

- Yield-per-recruit analysis based on analogy with *G. maritae*.

- Consideration of length at capture and length at sexual maturity as indicators of the appropriate relationship between fishing mortality rate and natural mortality rate.

This report also recommends regulatory reference points (overfishing limit (OFL), and allowable biological catch (ABC)) for consideration by the Science and Statistical Committee (SSC) of the New England Fishery Management Council (Council). Exploitation-based reference points are likely to be most important for red crab due to lack of ongoing abundance data and infrequent stock assessments.

This document responds to the recommendation from the SSC that: "The MSY proxy is highly uncertain and should be reevaluated" and the motion by the Council "to direct the PDT [Plan Development Team] and the SSC to review the SSC recommended interim ABC for red crab to determine if it should be revised."

Recommendations for MSY, OFL, ABC, ACL and TAL.

The Red Crab PDT agreed on recommendations for OFL, ABC, annual catch limit (ACL), and total allowable landings (TAL) for male red crab based on a preponderance of the evidence from multiple indicators of sustainable yield as described in the PDT MSY Reevaluation document. The PDT considers the historical landings to be the best indicator of sustainable landings of male red crab when considered in conjunction with the biomass estimates obtained from the two camera/trawl surveys and the lack of any evidence of significant declines in landings per unit of effort or total biomass over the history of the fishery. The PDT chose to use the average landings from fishing years (FY) 2002 through 2007 (i.e., since the start of the fishery management plan) as being the most reliable and representative of both the long-term and recent history of the fishery.

The PDT also chose to use the depletion-corrected average catch (DCAC) model as the best indicator of MSY and, by extension, OFL, when the sustainable yield estimates from the DCAC model are adjusted to account for the expected relationship between the DCAC results and MSY, i.e., the DCAC results are expected to represent between 50% and 72% of MSY. The PDT noted that the use of average landings as the basis for a TAL, when combined with the use of the adjusted DCAC model results produces a logical relationship between the elements of the specifications that meets the expectations of the National Standard 1 and 2 Guidelines. The recommendations are based on the use of a value of 0.10 as the most appropriate value for natural mortality. The PDT chose M=0.10 value based on estimates of M for the closely related Namibian red crab (Mellville-Smith 1989), modeling exercises that point to M=0.10 – 0.15 to produce the size distribution that was observed during the 1974 survey, and an accumulating body of opinion resulting from previous reviews of red crab biology and stock status. The PDT therefore recommends the following specifications for 2011 through 2013:

Table 1- PDT recommendations for male red crab specifications for 2011 through 2013.

	mt	% of Lower Risk Neutral MSY/OFL	% of Higher Risk Neutral MSY/OFL	% of Average of LRN and HRN MSY/OFL
Total Allowable Landings of Male Red Crabs (TAL)	1850	75%	61%	68%
Dead Discards (5% of 30% of Total Catch)	40			
ACL (10% buffer for Management Uncertainty)	1890			
ABC	2100	85%	70%	77%
*Lower Risk Neutral MSY/OFL	2469			
Avg of Lower Risk Neutral and Higher Risk Neutral MSY/OFL	2740			
*Higher Risk Neutral MSY/OFL	3011			
20% CI on Lower Risk Neutral MSY/OFL	2294			
20% CI on Higher Risk Neutal MSY/OFL	2744			

* Risk neutral refers to the median DCAC model result divided by 0.72 to provide an estimate of MSY given the model and the assumptions incorporated into the model and the expected relationship between DCAC sustainable yield estimates and MSY. The use of a zero depletion DELTA to produce the "lower risk neutral" MSY/OFL estimate and the use of the 0.72 divisor to adjust from the DCAC results to MSY could be considered precautionary considering the expected range of 0.50 to 0.72. The use of an F_{MSY} to M ratio of 0.8 in the DCAC model may also be precautionary.

Justifications for Recommendations:

1. The 2003-2005 survey indicated an increase in biomass for all red crab categories except males over 114 mm CW after 35 years of fishing with recorded average annual landings of 1,775 mt. Actual landings were likely higher than recorded landings prior to FY 2002, but the magnitude of any underestimation of landings is unknown. The PDT noted that the observed increase in biomass could have been the result of natural fluctuations in stock productivity or population dynamics that result in an increase in smaller males and females when the predation and competition from large males is reduced.

2. Landings in FY 2001 were 4003 mt, the highest on record. For the period FY 2001-2005 landings averaged 2424 mt. No decline in mean size landed was noted for any individual survey strata over the period 2001-2005 (NEFSC 2006).

3. The 2006 stock assessment concluded that the "average male crab [in the 2003-2005 survey] is smaller in size while the average female is the same size as in 1974, and young crabs of both sexes are relatively abundant" (section 5.1, NEFSC 2006). These observations imply that discard mortality on females has been low and the reproductive capacity of the stock has been adequate to maintain good recruitment.

4. The Review Panel for the DPSWG expressed a preference for the results of the DCAC model as an estimate of MSY. Since that time, further clarification and analysis by Alec MacCall (Personal Communication), the developer of the model,

and by the PDT have shown that DCAC sustainable yield estimates are likely to be in the range of 50-72% of MSY.

5. The National Standard 1 and 2 Guidelines specifically prohibit the Council from asking the SSC (and by inference the PDT) to make a policy decision regarding the acceptable risk of overfishing that is embodied in the ABC and ACL. The PDT attempted to provide recommendations that clearly indicate the degree to which the methods used and the inputs to the recommendations may be considered to be inherently precautionary. The use of a multitude of methods with varying degrees of precaution results in a range of estimates that by its nature reflects varying degrees of risk.

6. The DPSWG noted that "based on the last stock assessment (NEFSC 2006a; 2006b), there is no evidence of serious problems in the red crab population (fishery induced mortality rates are $<0.1\ y^{-1}$) and recruitment was apparently occurring during 2003-2005."

7. The DPSWG pointed to concerns raised by the decline in the biomass of large males. As suggested by the SSC, the PDT used a life history model based on an age/CW model for the closely related *G. maritae* and a CW/weight model for *C. quinquedens*, with M=0.10, to analyze the observed decline in large male biomass relative to that which would be expected in the transition from an unexploited to an exploited resource. The PDT did not find any indication that the decline was beyond that which would be expected from the fishing mortality rates that have been calculated for red crab as being approximately $0.5M$ if M=0.10.

8. The PDT reviewed additional references regarding mating and fecundity that relate to the concerns expressed by the DPSWG about the potential impacts of the reduction in biomass of large males. Evidence from other crab resources indicates that the size of mating pairs fluctuates with changes in size distribution of male crabs, that large males tend to out-compete smaller males for female partners, and that male crabs employ various strategies to conserve and distribute sperm among multiple females depending on the prevailing sex ratio (Rondeau and Sainte-Marie 2001, Zheng and Kruse 2003, Mellville-Smith 1987). Despite these strategies, sperm limitation may still occur in male-only crab fisheries. Cooperative research now underway is aimed at gathering more information on growth, maturation, and fecundity of red crabs.

9. The PDT considered the uncertainty surrounding the validity of the biomass estimates from the 1974 survey from a number of perspectives. Work is underway to further analyze the photos from the 1974 survey to evaluate the density estimates from that survey. The PDT also considered references related to the possibility that the reduction in large males could bring about an increase in the equilibrium stock size. The PDT noted research on other species showing an increase in abundance of smaller animals as the population was fished intensively (Momot 1995; Zipkin et al. 2008; Schroder, Persson & de Roos 2009).

10. The PDT noted that the DPSWG recommended “a catch limit that mimics both recent and long term mean annual landings…” The PDT also noted that “catch limit” is a step in the process of setting OFL, ABC, and ACL. The PDT is hopeful that careful use of newly developing terminology will avoid any misunderstanding concerning the PDT recommendations.

11. The PDT concluded that the relatively low exploitation rate (below 0.10) for red crab is likely to make it difficult to separate any fishery dependent indicator signals from the noise created by natural fluctuations.

12. The PDT notes that all of the yield estimates from a variety of methods (Figure 24) would represent a continuation of fishing mortality rates generally between 0.03 and 0.08 if applied to the biomass of fishable males estimated from the 2003-2005 survey (Figure 25).

13. The PDT notes that a TAL set at recent historical landings is likely to have the effect of keeping average future landings below recent historical landings because there will not be any opportunity to average landings higher than the TAL with landings lower than the TAL.

Table of Contents

1.0 EXECUTIVE SUMMARY 2
RECOMMENDATIONS FOR MSY, OFL, ABC, ACL AND TAL. 3
LIST OF FIGURES 8
LIST OF TABLES 11
2.0 FISHERY AND MANAGEMENT 12
3.0 BIOLOGICAL CHARACTERISTICS 20
4.0 DATA AVAILABILITY 29
5.0 CURRENT STOCK STATUS 33
6.0 RED CRAB OVERFISHING DEFINITION 38
6.1 CURRENT REFERENCE POINTS 41
6.2 LOGIC AND JUSTIFICATIONS 41
6.3 REFERENCE POINT WEAKNESSES 42
7.0 OPTIONS AND RECOMMENDATIONS 44
7.1 BIOMASS-BASED BIOLOGICAL REFERENCE POINTS 45
7.2 OPTIONS FOR BIOMASS-BASED BRPS 45
7.3 OPTIONS FOR EXPLOITATION BASED BRPS 48
7.4 MODELS BASED ON GERYON MARITAE GROWTH MODEL 58
7.5 IMPLICATIONS OF POPULATION CYCLING FOR FISHERY MANAGEMENT 71
7.6 THE SIZE-DISTRIBUTION ISSUE 72
7.7 SUMMARY OF RESULTS 75
7.8 RECOMMENDATIONS FOR MSY, OFL, ABC, ACL AND TAL. 80
7.9 RECOMMENDATIONS FOR AN ABC CONTROL RULE 84
8.0 SCIENTIFIC RISKS AND UNCERTAINTIES. 84
9.0 RESEARCH RECOMMENDATIONS 86
10.0 REFERENCES 86
APPENDICES. 90
APPENDIX 1. RED CRAB SIZE COMPOSITION ANALYSIS 90
APPENDIX 2A. EXPLANATION OF DCAC MODEL 93
APPENDIX 2B. ALEC MACCALL'S COMPARISON OF MSY AND DCAC SUSTAINABLE YIELD. 97
APPENDIX 2C. DCAC OUTPUT (-0.20 DEPLETION DELTA) WITH CONFIDENCE INTERVALS 99
APPENDIX 2D. DCAC/MSY EVALUATION 105
APPENDIX 3. 2-POINT BOUNDARY MODEL 109
APPENDIX 4. YIELD PER RECRUIT CALCULATIONS 117
APPENDIX 5. STOCHASTIC MODELING RESULTS 118

List of Figures

Figure 1- Red crab landings from 1973 through 2008. 13

Figure 2- Red crab essential fish habitat by life stage. The extent of the fishery is reported by the industry to be the narrow band of continental slope between 400-800 meters. 15

Figure 3- Limited access vessel red crab trips as reported on Vessel Trip Reports. Based on the known distribution of red crabs, some plotted locations are obviously misreported or misplaced. All red crab landings are taken from the narrow strip between 200-1300 meters as indicated for adult distribution in Figure 2. 16

Figure 4- Size distribution from selected red crab trips in 1979 compared with port sampling data from 2004-2008. 17

Figure 5- Figure D4.3 from NEFSC 2006 Stock Assessment. Trends in landings (lb) per trip by vessels with large amounts of crab landings in dealer reports. Fishery selectivity has moved to smaller acceptable sizes over the history of the fishery. 18

Figure 6- Figure D4.4 from the 2006 stock assessment. Trend in catch per day at sea for vessel trip reports from four limited access vessels recently (as of 2006) targeting red crab. The data were normalized using each vessel's landings per day mean and standard deviation for the time series. 19

Figure 7- Figure D4.5 from the 2006 stock assessment. Trends in catch per trap haul for vessel trip reports from four limited access vessels targeting red crab. The data were normalized using each mean and standard deviation for the time series. 19

Figure 8- Trip weights (lb) for butchered crabs landed by the Fall River, MA fleet from 1978 through 1990. (Industry data published with permission of the vessel owners.) 20

Figure 9- Live equivalent crab trip weights landed by the Fall River, MA fleet from 1978 through 1990 and 2000 through 2004. (Industry data published with permission of the vessel owners.) 20

Figure 10- Pounds per day between landings (minus one with a maximum of ten) for the F/V Frank H. Wetmore for 1984 through 1991 and 2001 through 2004. Vessels landing butchered crab were required to land the product within ten days of catching it, creating an upper limit on trip length. (Industry data published with permission of the vessel owner.) 20

Figure 11- Size distribution of male red crabs caught in monkfish trawl surveys, excluding tows in the Gulf of Maine. 31

Figure 12- Size distribution of female red crabs caught in monkfish trawl surveys, excluding tows in the Gulf of Maine. 32

Figure 13- Size distribution of male crabs caught in the Gulf of Maine during the 2004 and 2009 NEFSC Cooperative Monkfish Trawl Surveys. 32

Figure 14- Size distribution of female crabs caught in the Gulf of Maine during the 2004 and 2009 NEFSC Cooperative Monkfish Trawl Surveys. 33

Figure 15- Catch per 30-minute trawl by size in the 1974 survey (top) and 2003-2005 surveys (DPSWG 2009). 36

Figure 16- This map shows the geographic sectors that were established for the 1974 survey and used again in the 2003-2005 survey. 38

Figure 17- MRAG (1996) provides guidance on the relationship between the length at which 50% of animals are captured (as a fraction of asymptotic length) and the ratio of Fmsy to M. The x-axis is the Lc50 with a range of 0.2 to 0.7 and the y-axis is the Fmsy/M ratio with a range of 0 to 4. The solid line is for species with a length at 50% maturity of 0.6 times the asymptotic length and the dotted line is for species with a length at 50% maturity of 0.5 times the asymptotic length. 51

Figure 18- Length-weight comparison for *G. maritae* and *C. quinquedens*. 58

Figure 19- Yield per recruit curve for red crab using *Geryon maritae* age-CW model (Mellville-Smith 1989), *Chaceon quinquedens* CW-weight model (Farlow 1983), M=0.10, and selectivity for northwestern Atlantic red crab fishery (NEFSC 2006). Numbers in boxes indicate the point on the YPR curve that would be implied by fishing at the indicated F if the fishable biomass equaled 79,910,136 lb (36,247 mt) as estimated from the 2003-2005 survey. 64

FIGURE 20- YIELD PER RECRUIT FOR RED CRAB USING *GERYON MARITAE* AGE-CW MODEL (MELLVILLE-SMITH 1989), *CHACEON QUINQUEDENS* CW-WEIGHT MODEL (FARLOW 1983), M=0.10, AND SELECTIVITY FOR NORTHWESTERN ATLANTIC RED CRAB FISHERY (NEFSC 2006) WITH A RANGE OF MINIMUM SIZES CONSTRAINING SELECTIVITY AT THE LOWER END. THE APPROXIMATE RANGE OF $F_{0.1}$ IS SHOWN BY THE GREEN SHADED RECTANGLE. 64
FIGURE 21- THE OBJECTIVE OF THE MODELING EXERCISE WAS TO FIT A POPULATION MODEL TO THE KNOWN DATA POINTS, GIVEN A GROWTH MODEL AND A RANGE OF PLAUSIBLE NATURAL MORTALITY RATES. 67
FIGURE 22- FRACTION OF UNEXPLOITED BIOMASS REMAINING WITH INCREASING F. 74
FIGURE 23- MALE CRAB SIZE DISTRIBUTION WITH INCREASING F COMPARED TO 2003-2005. 75
FIGURE 24- RANGE OF YIELD ESTIMATES PRODUCED BY THE VARIOUS METHODS, WITH 10 AND 20% CONFIDENCE INTERVALS WHERE AVAILABLE. 80
FIGURE 25- FISHING MORTALITY RATES CORRESPONDING TO THE RANGE OF SUSTAINABLE YIELD ESTIMATES BASED ON THE BIOMASS OF FISHABLE MALES OF 36,247 MT ESTIMATED FROM THE 2003-2005 SURVEY. 80
FIGURE 26- PLOT OF RECOMMENDED REFERENCE POINTS IN COMPARISON TO THE MULTITUDE OF YIELD ESTIMATES DEVELOPED BY THE RED CRAB PDT. HRN STANDS FOR HIGH RISK-NEUTRAL AND LRN STANDS FOR LOW RISK-NEUTRAL. 82
FIGURE 27- SUSTAINABLE YIELD ESTIMATES CALCULATED EACH YEAR BY THE DCAC MODEL DURING THE HISTORY OF A MODELED FISHERY WITH KNOWN MSY, KNOWN BIOMASS, KNOWN LARGE MALE NATURAL MORTALITY, AND KNOWN CATCHES. 106
FIGURE 28- DCAC MODEL RESULTS FOR A MODELED FISHERY WITH EXPLOITED BIOMASS LESS THAN INITIAL BIOMASS. 107
FIGURE 29- DCAC MODEL RESULTS FOR A MODELED FISHERY WITH EXPLOITED BIOMASS HIGHER THAN INITIAL BIOMASS. 108
FIGURE 30- FIG A3-1 FROM APPENDIX 3 OF DPSWG WORKING PAPER. SENSITIVITY ANALYSIS OF RECRUITMENT, AVERAGE F AND EQUILIBRIUM CATCH FOR MALE RED CRAB TO VARYING LEVELS OF SURVIVAL RATE. 115
FIGURE 31- FIG. A3-2 FROM APPENDIX 3 OF THE DPSWG WORKING PAPER. SENSITIVITY ANALYSIS OF RECRUITMENT, AVERAGE F AND EQUILIBRIUM CATCH FOR FEMALE RED CRAB TO VARYING LEVELS OF SURVIVAL RATE. 116
FIGURE 32- TYPICAL RESULTS FROM A STOCHASTIC POPULATION MODEL USING A RICKER SRR PLUS EXCESS JUVENILE MORTALITY PROPORTIONAL TO LARGE MALE BIOMASS. RECRUITMENT AND NATURAL MORTALITY INCLUDE A RANDOM VARIABILITY TERM. 119
FIGURE 33- HISTOGRAM FOR STOCHASTIC RICKER WITH JUVENILE MORTALITY PROPORTIONAL TO BIOMASS OF MALES 116+ MM CW AND TUNED TO MATCH 1974 BIOMASS AND SIZE STRUCTURE. MEAN M = 0.126. DETERMINISTIC MSY = 9.2 MILLION LB. DETERMINISTIC FMSY = 0.525. 120
FIGURE 34- TYPICAL RESULTS FROM STRONGLY OVER-COMPENSATORY RICKER SRR WITH NO ADDITIONAL MORTALITY ON JUVENILES FROM LARGE MALE PREDATION. 122
FIGURE 35- HISTOGRAM FOR STOCHASTIC RICKER WITH NO EXCESS JUVENILE MORTALITY AND TUNED TO MATCH 1974 BIOMASS AND SIZE STRUCTURE. MEAN M = 0.145. DETERMINISTIC MSY = 5.1 MILLION LB. DETERMINISTIC FMSY = 0.185. 122
FIGURE 36- SAMPLE OF RESULTS FROM STOCHASTIC MODEL THAT INCORPORATES A MODERATELY COMPENSATORY BEVERTON-HOLT SRR AND JUVENILE MORTALITY PROPORTIONAL TO LARGE MALE BIOMASS. DETAILED INPUTS AND OUTPUTS ARE PROVIDED IN TABLE 34. 125
FIGURE 37- HISTOGRAM FOR STOCHASTIC RICKER WITH JUVENILE MORTALITY PROPORTIONAL TO BIOMASS OF MALES 116+ MM CW. MODEL IS TUNED TO MATCH 1974 BIOMASS AND SIZE STRUCTURE. MEAN M = 0.127. DETERMINISTIC MSY = 8.14 MILLION LB. DETERMINISTIC FMSY = 0.298. 125
FIGURE 38- THIS MODEL USED AN UNEXPLOITED BIOMASS EQUAL TO TWICE THE ESTIMATED BIOMASS FROM THE 1974 SURVEY WITH THE SAME SIZE DISTRIBUTION AS WAS OBSERVED IN 1974. IT WAS THEN TUNED TO PRODUCE THE ESTIMATED 2003-2005 BIOMASS AFTER REMOVING THE REPORTED LANDINGS FROM 1973-2008. 128
FIGURE 39- HISTOGRAM STOCHASTIC BEVERTON-HOLT WITH JUVENILE MORTALITY PROPORTIONAL TO BIOMASS OF OLDER SIBLINGS THROUGH AGE 11. MODEL IS TUNED WITH 1974 SIZE STRUCTURE AND INFLATED BIOMASS. MEAN M = 0.10. DETERMINISTIC MSY = 4.3 MILLION LB. DETERMINISTIC FMSY = 0.127. 128

FIGURE 40- THE BEVERTON-HOLT SRR USED IN THIS MODEL PROVIDES ONLY PROPORTIONAL PRODUCTION AS STOCK BIOMASS DECLINES. HOWEVER, MORTALITY ON JUVENILES DECLINES IN PROPORTION TO THE DECLINE IN RECRUITMENT, WHICH PROVIDES A COMPENSATORY MECHANISM. 131
FIGURE 41- HISTOGRAM FOR AN ALMOST LINEAR B-H SRR WITH JUVENILE MORTALITY PROPORTIONAL TO THE BIOMASS OF AGES 1-11. THE RESULTS ARE CONDITIONED ON THE BIOMASS OF 116+ MM CW MALES STAYING ABOVE 25% OF THE 1974 BIOMASS INFLATED TO TWICE THE ESTIMATED LEVEL. 131
FIGURE 42- RESULTS FROM A POPULATION MODEL TUNED TO PRODUCE A STABLE POPULATION AND SIZE STRUCTURE THAT MATCHES THAT ESTIMATED FROM THE 2003-2005 SURVEY BOTH BEFORE AND AFTER THE REMOVAL OF THE HISTORIC REPORTED LANDINGS. THE INSET DEPICTS THE RICKER SRR. NO ADDITIONAL MORTALITY ON JUVENILES IS INCLUDED IN THIS MODEL. 134
FIGURE 43- HISTOGRAM SHOWING RESULTS FOR RICKER SRR TUNED TO PRODUCE THE SAME FISHABLE BIOMASS IN 1974 AS WAS ESTIMATED FROM THE 2003-2005 SURVEY AND WITH THE REMOVAL OF THE HISTORIC RECORDED LANDINGS BETWEEN 1973 AND 2008. 134

List of Tables

Table 1- PDT recommendations for male red crab specifications for 2011 through 2013. 4
Table 2- Comparisons between *Chaceon quinquedens* and *Geryon maritae* (after Mellville-Smith, 1985). 22
Table 3- Total annual mortality due to fishing (landings and mortal discard) during 2003-2005, by sex, using the best available estimate of discard mortality. 34
Table 4- Biomass estimates, standard errors and CVs from deep-sea red crab camera/bottom trawl surveys. The standard errors for 1974 estimates are approximations based on the assumption that CVs for variability among samples was the same during 1974 as during 2003 to 2005. The differences in CVs between the two periods are due do differences in assumed effective sample size. 35
Table 5- Comparison of Male/Female sex ratios by sector as calculated from abundance estimates obtained from the 1974 and 2003-2005 surveys. 37
Table 6- Caddy (2004) provides a list of positive and negative supplementary factors that provide insight into the vulnerability of stocks. 39
Table 7- Confidence intervals for sustainable yield estimates produced by the DCAC model with two approaches to the depletion DELTA. Additional detail provided in Appendix 2b. 57
Table 8- Parameters for von Bertalanfy equation that fits the growth model developed by Mellville-Smith (1989) for *G. maritae*. 59
Table 9- Yield per recruit schedule for red crab using an age-CW model for Geryon maritae (Mellville-Smith 1989), CW-weight model from Farlow (1983), M=0.10 and selectivity as estimated by the 2006 red crab stock assessment (NEFSC 2006). The yield lost column uses Fmax as a reference. The biomass of fishable males was estimated at 79,910,136 lb by the 2006 stock assessment. 63
Table 10- Yield estimates for the red crab management unit, revised and expanded from Table 3 in the DPSWG report. 76
Table 11- The DCAC model produces sustainable yield estimates that are likely to be in the range of 50-72% of MSY (See Appendix 2a). Table 11 converts the sustainable yield estimates to MSY estimates by dividing the sustainable yield estimates by 0.72. 78
Table 12- Deterministic and stochastic model results. 79
Table 13- Summary of alternative yield estimates as plotted in Figure 24. 79
Table 14- PDT recommendations for male red crab specifications for 2011 through 2013. 81
Table 15- Alec MacCall comparison of DCAC results to MSY. 98
Table 19- Results for DCAC model with M=0.05 and zero depletion DELTA with histogram. 102
Table 20- DCAC model results with M=0.10 and zero depletion DELTA with histogram. 103
Table 21- DCAC model results with M=0.15 and zero depletion DELTA with histogram. 104
Table 22- Estimated Survey Biomass of Male and Female Red Crab, 1974 and 2004. 111
Table 23- Summary of Annual Landings (mt) of Red Crab in U.S. 112
Table 24- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.15 (S=0.861). 113
Table 25- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.05 (*S*=0.95). 114
Table 26- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.1 (*S*=0.905). 114
Table 27- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.2 (*S*=0.819). 115
Table 28- Yield per recruit calculations based on age/CW model for *Geryon maritae* and CW/weight model (Farlow 1980) for *Chaceon quinquedens* with M=0.10. 117
Table 29- Descriptive statistics for stochastic Ricker with juvenile mortality proportional to biomass of males 116+ mm CW and tuned to match 1974 biomass and size structure. Mean M = 0.126. Deterministic MSY = 9.2 million lb. Deterministic Fmsy = 0.525. 120

TABLE 30- SUMMARY TABLE OF INPUT PARAMETERS AND OUTPUT RESULTS FOR STOCHASTIC POPULATION MODEL WITH VARIABLE RICKER SRR, VARIABLE M, AND JUVENILE MORTALITY PROPORTIONAL TO THE BIOMASS OF LARGE MALES. 121
TABLE 31- DESCRIPTIVE STATISTICS FOR STOCHASTIC RICKER WITH NO EXCESS JUVENILE MORTALITY TUNED TO MATCH 1974 BIOMASS AND SIZE STRUCTURE. MEAN M = 0.145. DETERMINISTIC MSY = 5.1 MILLION LB. DETERMINISTIC FMSY = 0.185. 123
TABLE 32- STOCHASTIC 2. INPUTS AND OUTPUTS FOR STOCHASTIC MODEL USING STRONG RICKER SRR WITH NO ADDITIONAL MORTALITY ON JUVENILES FROM LARGE MALE PREDATION. 124
TABLE 33- DESCRIPTIVE STATISTICS FOR STOCHASTIC BEVERTON-HOLT WITH JUVENILE MORTALITY PROPORTIONAL TO 116+ MM CW MALE BIOMASS. 126
TABLE 34- STOCHASTIC BEVERTON-HOLT WITH JUVENILE MORTALITY PROPORTIONAL TO 116+ MM CW MALE BIOMASS. 127
TABLE 35- DESCRIPTIVE STATISTICS FOR STOCHASTIC BEVERTON-HOLT SRR STARTING WITH BIOMASS EQUAL TO TWICE THAT ESTIMATED FROM THE 1974 SURVEY AND WITH THE SAME SIZE STRUCTURE. 129
TABLE 36- STOCHASTIC BEVERTON-HOLT SRR STARTING WITH BIOMASS EQUAL TO TWICE THAT ESTIMATED FROM THE 1974 SURVEY AND WITH THE SAME SIZE STRUCTURE. 130
TABLE 37- DESCRIPTIVE STATISTICS FOR AN ALMOST LINEAR B-H SRR WITH JUVENILE MORTALITY PROPORTIONAL TO THE BIOMASS OF AGES 1-11. THE RESULTS ARE CONDITIONED ON THE BIOMASS OF 116+ MM CW MALES STAYING ABOVE 25% OF THE 1974 BIOMASS INFLATED TO TWICE THE ESTIMATED LEVEL. 132
TABLE 38- INPUT AND OUTPUT VALUES FOR AN ALMOST LINEAR B-H SRR WITH JUVENILE MORTALITY PROPORTIONAL TO THE BIOMASS OF AGES 1-11. 133
TABLE 39- DESCRIPTIVE STATISTICS FOR RICKER SRR TUNED TO PRODUCE THE SAME FISHABLE BIOMASS IN 1974 AS WAS ESTIMATED FROM THE 2003-2005 SURVEY AND WITH THE REMOVAL OF THE HISTORIC RECORDED LANDINGS BETWEEN 1973 AND 2008.. 135
TABLE 40- MODEL INPUTS AND OUTPUTS FOR RICKER SRR TUNED TO PRODUCE THE SAME FISHABLE BIOMASS IN 1974 AS WAS ESTIMATED FROM THE 2003-2005 SURVEY AND WITH THE REMOVAL OF THE HISTORIC RECORDED LANDINGS BETWEEN 1973 AND 2008. 136
TABLE 41- SUMMARY RESULTS FROM STOCHASTIC MODELS. 137

2.0 Fishery and Management

A small experimental fishery for red crab was established in the early 1970s, with sustained fishing beginning around 1977. Before the initial targeted survey for red crab (Wigley et al. 1975), fishery landings were small and sporadic. Landings increased dramatically from 1973 to 1984, when landings reached almost 3,800 mt (Figure 1). Landings dropped quickly in the mid-1980s, then peaked again before beginning a generally steady decline to zero in 1994. Throughout the history of the fishery, fishing effort and landings have been highly influenced by and inconsistent due to market demand that fluctuated with the supplies of alternative crab products.

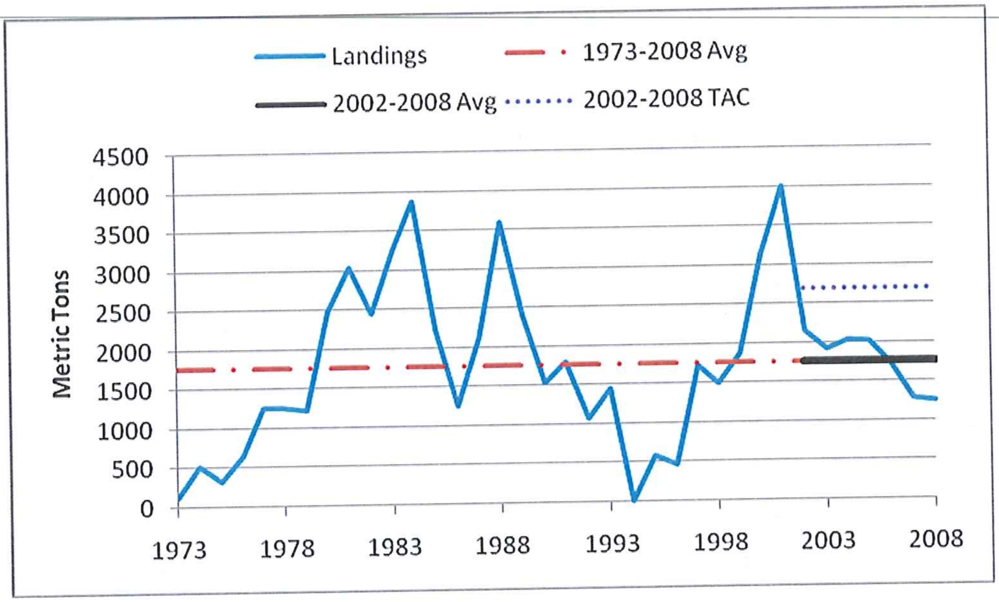

Figure 1- Red crab landings from 1973 through 2008.

Annual U.S. commercial landings of red crab during the period of 1982-2005 ranged from 466 mt (1996) to 4,000 mt (2001); there appears to have been a very low number of landings in 1994, apparently the result of low market demand and large supplies of Alaskan snow crab. However, reported landings prior to the implementation of the FMP (2002) are considered low estimates because reporting requirements for red crab were not yet in place.

Particularly, in 1995, industry members active in the fishery at the time reported that landings were significantly higher than the 572 mt reported. In the absence of specific red crab reporting requirements prior to 2002, and with much of the landed crab being sent to Canada for processing, the red crab industry believes that some portion of the catch went unreported because neither the vessel nor the dealer were required to report (REFERENCE PDT/AP/SSC report by J. Williams). The likelihood of underreporting prior to 2002 has the effect of underestimating landings during the period 1974-2001.

In 2002 the FMP excluded two large vessels that had recently entered the fishery, reducing fishing effort significantly. The FMP also controlled fishing effort and landings by the five limited access permits that qualified to remain in the fishery. With the reduction in boats and a limited market, landings did not reach the target TAC of 2688 mt that was in effect from 2002 through 2008. Until 2009, red crabs have competed in a world-wide commodity market for generic crab meat. Landings continue to be influenced by market demand. In recent years all of the production from the U.S. Atlantic deep-sea red crab fishery had gone through one processor and been consumed by one major restaurant chain. The menu and purchasing decisions of that restaurant chain determined the volume of red crab landings in recent years. In 2009 a new processing plant for red crab opened in New Bedford, MA and the red crab fishery was certified as sustainable by the Marine Stewardship Council. These developments may lead to more consistent market demand for red crab in the future.

Since the FMP was implemented in 2002, landings have been well-documented and relatively stable at about 1853 mt per year. Prior to 2009, the regulations allowed 780 fleet days-at-sea (DAS) and a target total allowable catch (TAC) of 2,688 mt. The DAS allocation and target TAC were reduced under a Secretarial emergency action on April 6, 2009, as a result of the Data Poor Stocks Working Group report that was released in January 2009 (NDPSWG 2009). Under the emergency action, MSY was set at 1700mt, the lower bound of the range of MSY recommended by the DPSWG Peer Review Panel. OY was set at 95% of MSY, as indicated in the FMP, resulting in a target TAC of 1,615 mt for FY 2009. The fleet was allocated 582 DAS based on recent average landings per DAS.

The FMP contains a provision that allows a permit holder to declare out of the fishery in advance of a fishing year. The fleet DAS allocation is divided equally among the active vessels. One permit has been declared out of the fishery each year since 2004. In 2009 a second permit was declared out of the fishery. Three boats are expected to be active in FY 2010. Each of the vessels is approximately 30+ m long and fishes with a trap limit of 600. The vessels generally haul all 600 traps each day during trips that last from five to ten days. The traps are left on the bottom between trips. The vessels that are currently active use specially designed conical traps exclusively, although small amounts of landings are also taken in lobster traps. Fishing occurs year round but landings have shown a marked seasonal pattern that is related to both processing requirements and catch rates. Fishing occurs primarily along a narrow strip of steeply sloping sea bottom at the edge of the continental shelf from the Canadian border (Hague Line), at the eastern edge of Georges Bank, to Cape Hatteras, North Carolina, in depths ranging from 400 to 800 m (Figure 2 and Figure 3). The geographical distribution of fishing effort has remained relatively constant since 2002. Previous reports of a shift in fishing effort in response to localized depletion were based on incomplete catch reports and are not supported by the complete data set.

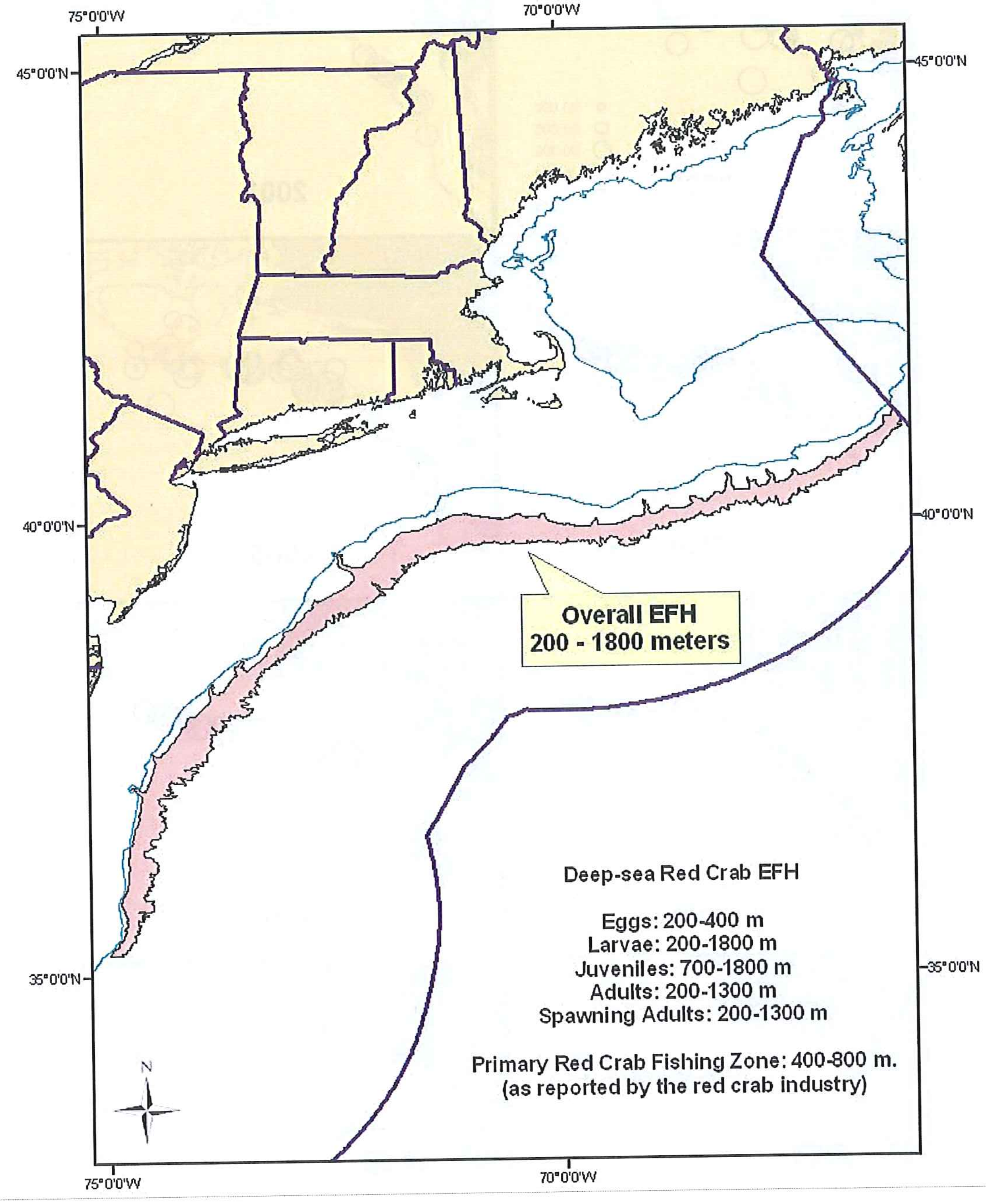

Figure 2- Red crab essential fish habitat by life stage. The extent of the fishery is reported by the industry to be the narrow band of continental slope between 400-800 meters.

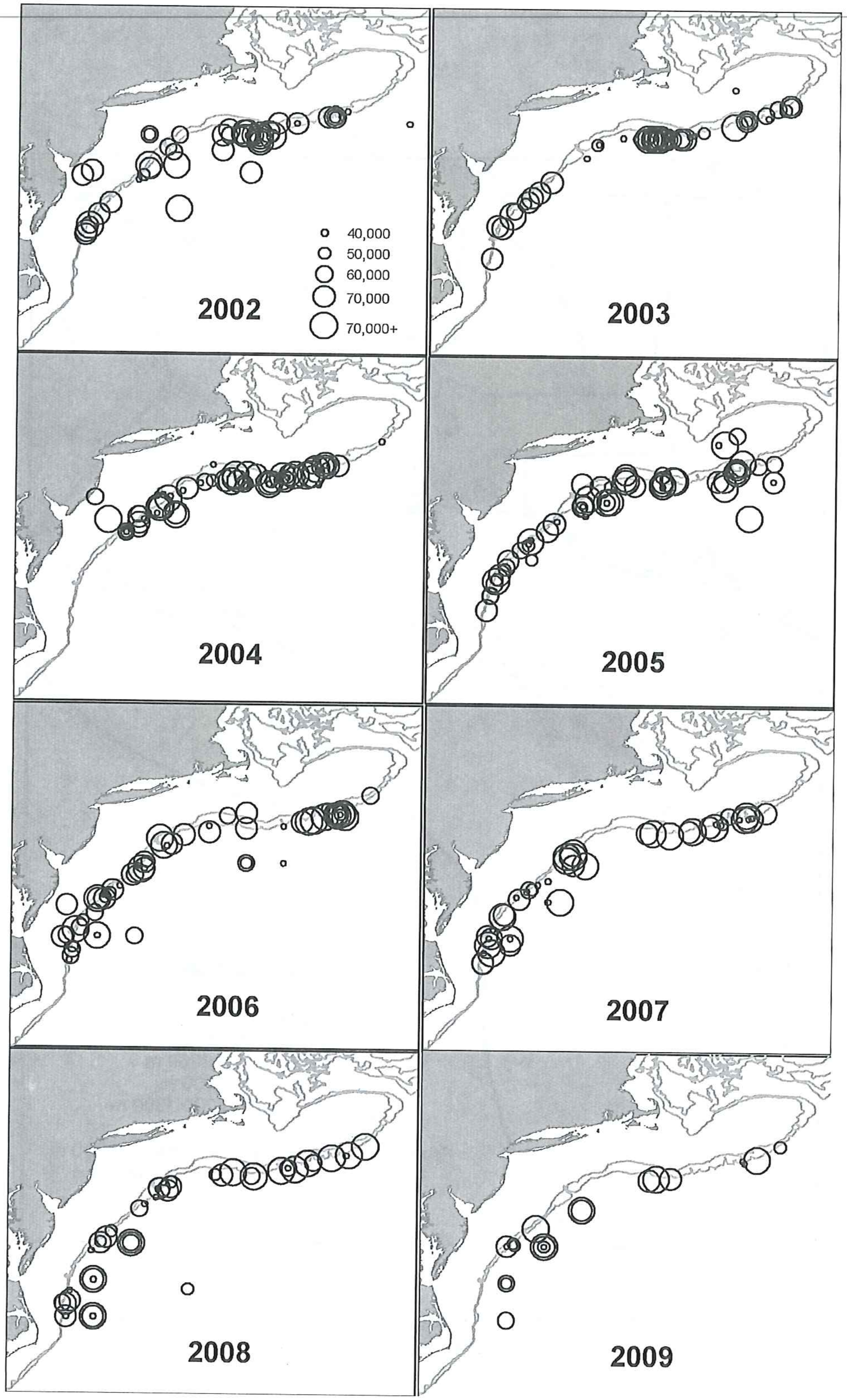

Figure 3- Limited access vessel red crab trips as reported on Vessel Trip Reports. Based on the known distribution of red crabs, some plotted locations are obviously misreported or misplaced. All red crab landings are taken from the narrow strip between 200-1300 meters as indicated for adult distribution in Figure 2.

Minimum market sizes and fishery size selectivity have decreased since the 1970s, as is to be expected with a previously unfished resource. The minimum market size for male red crab in the 1970s was ~ 114+ mm CW. Port sampling data for the 1980s and 1990s cannot be located, making it difficult to estimate either the minimum or the average size of landed crabs prior to 2002. The minimum market size in the early and mid-2000s had decreased to approximately 85+ mm CW. Fishery size selectivity during 2004-2005 was estimated to have an $L_{50} = 92$ mm CW.

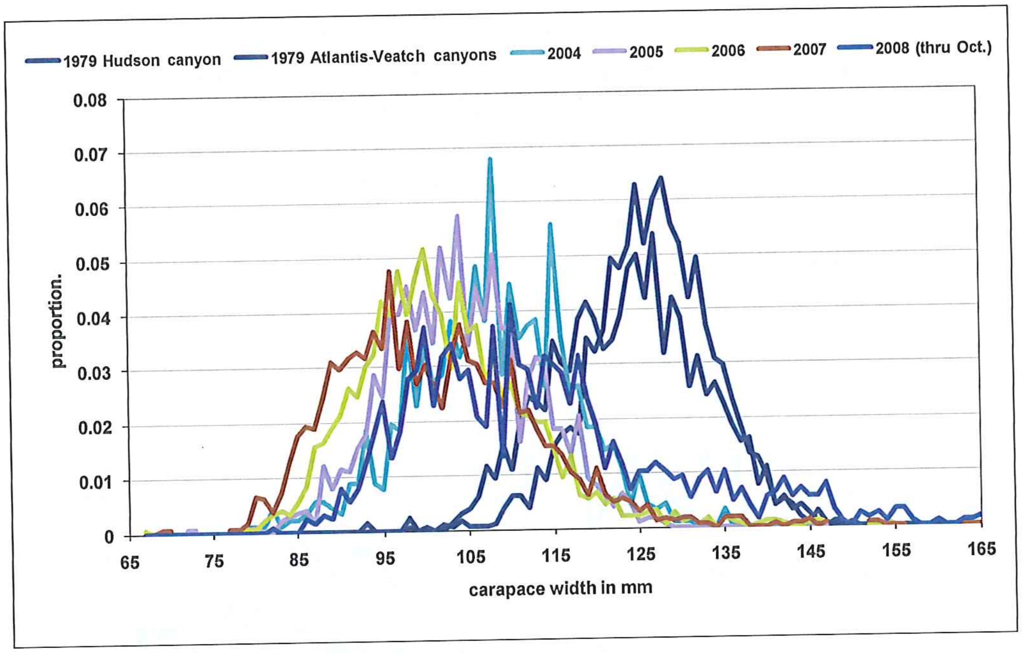

Figure 4- Size distribution from selected red crab trips in 1979 compared with port sampling data from 2004-2008.

The red crab fishery was recently certified as "sustainable" by the Marine Stewardship Council (MSC), and, as a condition of certification, the red crab fleet has agreed to voluntarily increase the size of landed males over the next 5 years. This requirement responds to concerns about the declining average size of landed male crabs. The Marine Stewardship Council requires annual reviews of certified fisheries and requires a re-assessment every five years. Whereas maintaining the MSC certification may be critical to expanding the red crab market, the certification process is likely to provide additional incentives for the industry to evaluate the condition of the resource and adopt precautionary management strategies.

The FMP prohibits the landing of female crabs in excess of one standard tote. In 2009 an experimental fishing permit was authorized to allow limited access red crab vessels to land female red crabs as part of a research project aimed at fulfilling the research needs identified in previous stock assessments and to determine if a market for female red crab could be sustainable. The project is fully funded by the New England Red Crab Harvesters' Association and is intended to expand the red crab market and increase efficiency in the harvesting process by converting discards into landings. The project sponsors requested up to 1 million lb of females to be harvested within the DAS limits.

Landings data are available from the experimental fishing of the early 1970s, and accuracy probably improved starting in 1982 as the result of changes in the port sampling system; however, neither fishing permits nor reporting were required until 2002. Port sample size data are available from recent landings but port sampling data prior to 2002 cannot be located. Limited sea sample data are also available from a cooperative research program involving one vessel during 2004-2005 and from reports from the at-sea observer program.

Commercial catch rate data (LPUE) have been difficult to evaluate for red crab because of differences in reporting protocols practiced by different captains. An analysis of LPUE conducted by NEFMC Council staff for the 2006 stock assessment is in the process of being updated. Figure 5 - Figure 7 contain selected graphics pertaining to LPUE from the 2006 stock assessment. Additional detail is provided in NEFSC 2006.

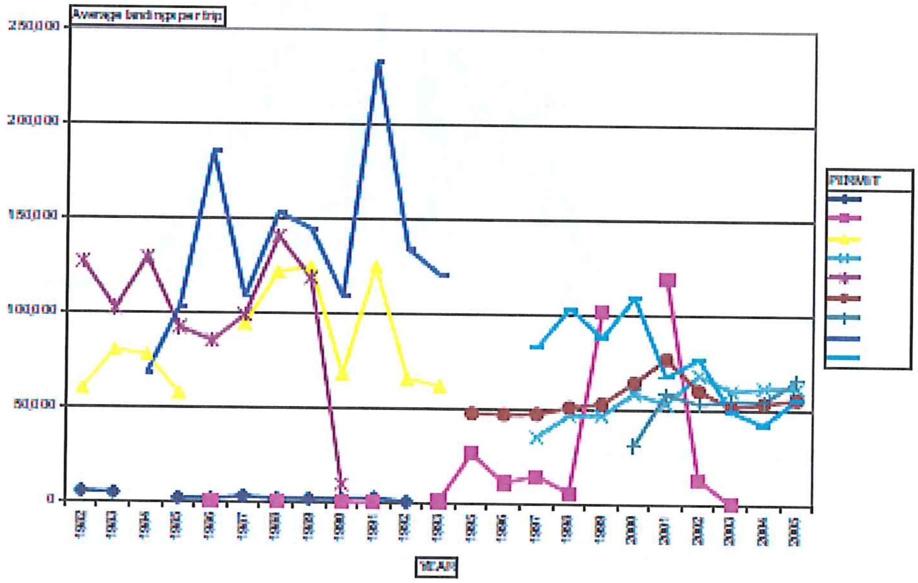

Figure 5- Figure D4.3 from NEFSC 2006 Stock Assessment. Trends in landings (lb) per trip by vessels with large amounts of crab landings in dealer reports. Fishery selectivity has moved to smaller acceptable sizes over the history of the fishery.

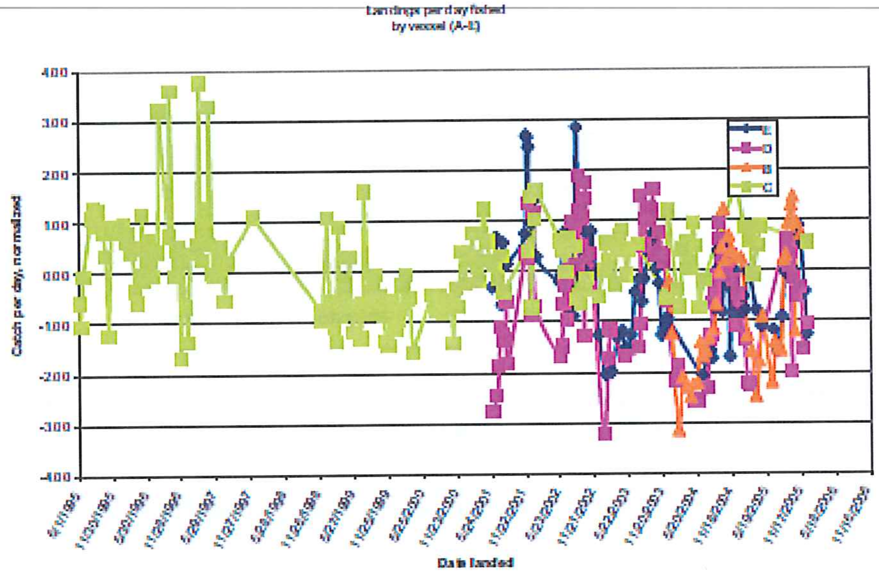

Figure 6- Figure D4.4 from the 2006 stock assessment. Trend in catch per day at sea for vessel trip reports from four limited access vessels recently (as of 2006) targeting red crab. The data were normalized using each vessel's landings per day mean and standard deviation for the time series.

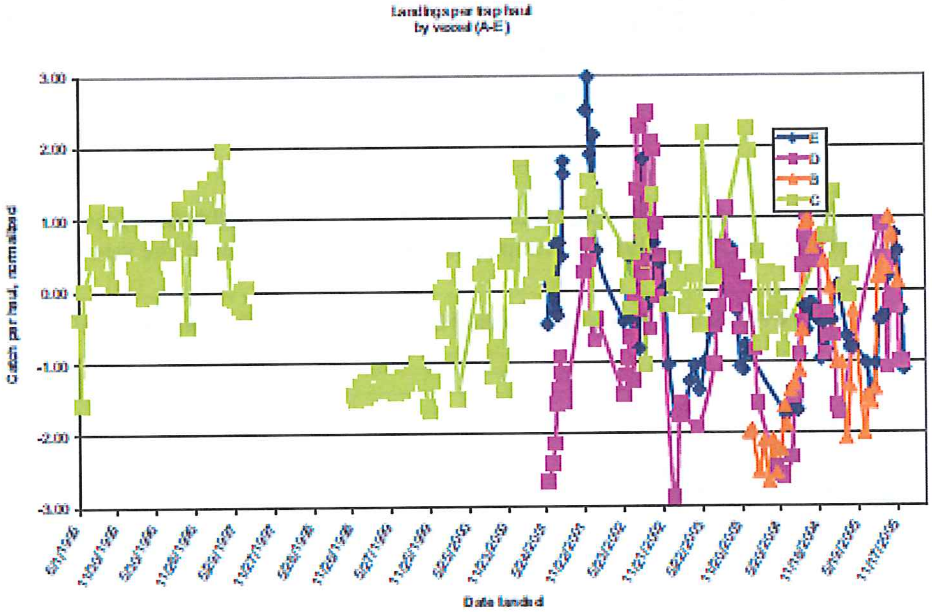

Figure 7- Figure D4.5 from the 2006 stock assessment. Trends in catch per trap haul for vessel trip reports from four limited access vessels targeting red crab. The data were normalized using each mean and standard deviation for the time series.

The red crab industry made available to the PDT data on landings from the principle vessels that had participated in the fishery since 1978. This data was plotted to determine whether any significant trends were apparent. Figure 8, Figure 9, and Figure 10 display data provided by vessels that landed in Fall River, MA from 1978 through 2004.

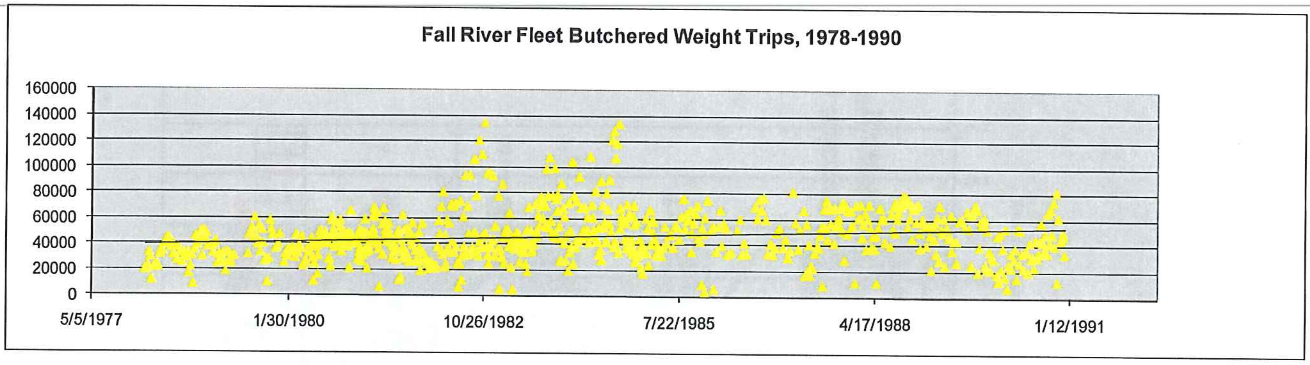

Figure 8- Trip weights (lb) for butchered crabs landed by the Fall River, MA fleet from 1978 through 1990. (Industry data published with permission of the vessel owners.)

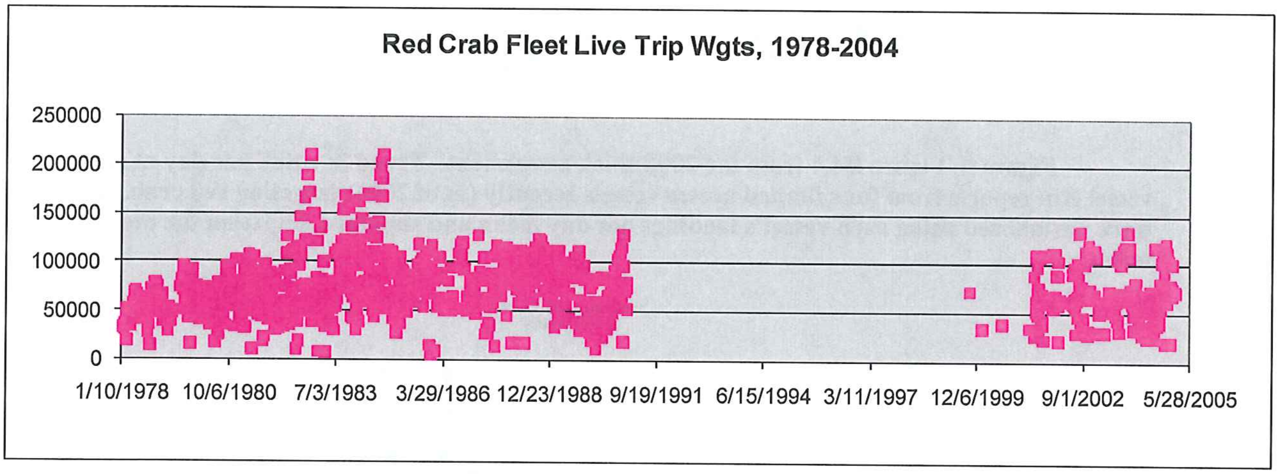

Figure 9- Live equivalent crab trip weights landed by the Fall River, MA fleet from 1978 through 1990 and 2000 through 2004. (Industry data published with permission of the vessel owners.)

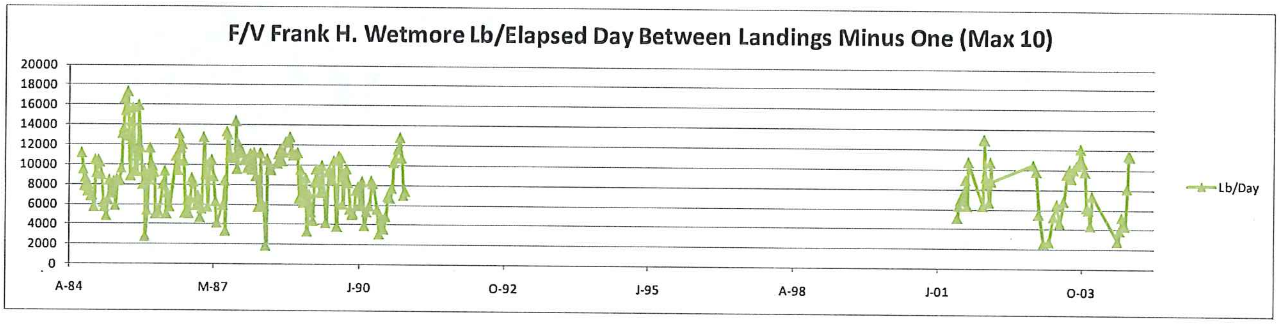

Figure 10- Pounds per day between landings (minus one with a maximum of ten) for the F/V Frank H. Wetmore for 1984 through 1991 and 2001 through 2004. Vessels landing butchered crab were required to land the product within ten days of catching it, creating an upper limit on trip length. (Industry data published with permission of the vessel owner.)

3.0 Biological Characteristics

Information in this section is summarized primarily from Steimle et al. (2001) and Wahle et al. (2008).

Deep-sea red crab (*Chaceon quinquedens*) are a brachyuran crab (family Geryonidae) inhabiting the edge of the continental shelf and slope from Emerald Bank, Nova Scotia, the Gulf of Maine, and south through the Mid-Atlantic Bight and into the Gulf of Mexico. According to Weinberg et al. (2003), genetic differences between deep-sea red crabs from Southern New England and the Gulf of Mexico indicate that crabs in the two areas belong to different biological populations. Red crab in Southern New England and the Mid- Atlantic Bight (south of Georges Bank) and the Gulf of Maine (north of Georges Bank) are assumed to be the same stock, although fishing occurs primarily off Southern New England. Red crab in the Gulf of Maine are typically smaller and little directed fishing for red crab occurs there.

Deep-sea red crab live at depths of 400–1800 m, where temperatures are between 5 and 8 °C. Adult crab are segregated incompletely by sex. Adult females generally inhabit shallower water than adult males, and juveniles tend to be deeper than adults, suggesting a deep-to-shallow migration as the crabs mature. This distribution may explain why females are observed mating with larger males.

Information on the growth, longevity and mortality of red crab is scarce. Mellville-Smith (1989) developed a growth model for the closely related Namibian red crab *Geryon maritae*. Melville-Smith actually used growth data for *C. quinquedens* to extend the range of data that he incorporated into his model, pointing out that: "the two species resemble each other so closely, that they were confused with each other up until 1981 (see Manning & Holthuis, 1981). Furthermore, they reach approximately the same sizes, live at about the same depths and show similar behavioural characteristics (Table 2- Comparisons between *Chaceon quinquedens* and *Geryon maritae* (after Mellville-Smith, 1985).), all factors that justify comparisons in growth between the species." Mellville-Smith noted other similarities between *C. quinquedens* and *G. maritae*:

> Kelley et al. (1982) estimated that *G. quinquedens* [now *C. quinquedens*] requires between 23 and 125 days from hatching until the megalopa settles, depending on water temperature. From fig. 1 [not reproduced] in Van Heukelem et al. (1983), it appears that the species settles out from its larval stages at 4 mm CW and moults five times before reaching 22 mm CW. Although growth factors are apparently high (? 50 per cent) for three of the five moults, the factors for the last two moults are about 30 per cent, which agrees with the predicted growth factor for *G. maritae* of that size from the relationship in fig. la. A growth model for *G. maritae* has been predicted in table III [not reproduced], by assuming that moult increments and intermoult periods for *G. quinquedens* and *G. maritae* are similar for animals <20 mm CW in both species.

The same reasoning has been used in this assessment to construct a life history model for *C. quinquedens* based on Mellville-Smith's growth model for *G. maritae*.

Table 2- Comparisons between *Chaceon quinquedens* and *Geryon maritae* (after Mellville-Smith, 1985).

Comparisons of some morphological and behavioural characteristics of *Chaceon quinquedens* (off north-eastern U.S.A.) and *Geryon maritae* (off Namibia)

Parameters	*C. quinquedens* observations	Source of information	*G. maritae* observations	Source of information
Depths of high red crab concentrations	320-640 m	Wigley et al., 1975	400-900 m	Mellville-Smith, 1985
Temperature at above depths	5-8°C	Wigley et al., 1975	4-8° C	Stander, 1964
Maximum density estimate	382 crabs ha^{-1}	Wigley et al., 1975	350 crabs ha^{-1}	Mellville-Smith, 1985
Depths at which females predominate	320-503 m	Wigley et al., 1975	<400 m	Beyers & Wilke, 1980
Maximum size male and female sampled	142; 121 mm CW	Wigley et al., 1975	165; 120 mm CW	Mellville-Smith, 1985
Size at which most females mature	80-91 mm CW	Haefner, 1977	84-100 mm CW	Mellville-Smith, 1985

Natural mortality rates were assumed to be 0.2 y^{-1} in Serchuk (1977) and 0.15 y^{-1} in the FMP. Mellville-Smith (1989) reported the largest Namibian red crab at 165 mm CW, which he translated into an age of 25 years or more based on his growth model. An assumed longevity of 30 or more years corresponds to $M = 0.1$ y^{-1}. Magnusson and Hilborn (2007) state that M can be accurately estimated if the data include the catch age composition from a nearly unfished population. Size distribution data for the red crab population is available from 1974, when very little fishing had taken place. When this data is combined with the age-CW model for Namibian red crab (Mellvile-Smith 1989) and the CW-weight model for C. quinquedens (Farlow 1982), a natural mortality rate of 0.146 is required to produce the size distribution that was observed in the 1974 survey, before any significant fishing on red crab had taken place, assuming that the stock was in equilibrium. The modeling exercises also indicate that size distribution would have varied over a broad range if the population was cyclical before fishing started. Differential mortality on newly settled crabs has been proposed as a cause of cycling in crab populations (Sainte-Marie 1996). This mechanism would also cause the overall natural mortality rate to fluctuate. This re-evaluation presents results of model runs with a range of natural mortality rates of 0.5 y^{-1} to 0.15 y^{-1}, however the PDT has concluded that M=0.1 y^{-1} is most likely.

On the basis of limited laboratory data, red crab are believed to require 5–6 years to attain a size of 114 mm carapace width (CW). Results from tagging the closely related Namibian red crab (*Geryon maritae)* show males of that species taking 13-14 years to reach 114 mm. Mellville-Smith (1989) hypothesized that segregation of males and females, with females inhabiting the shallower, warmer depths could explain an apparently shorter intermoult period for immature females compared to males. Mellville-Smith cited Hartnoll (1982), as demonstrating that temperature is the primary extrinsic factor affecting the intermoult period. Male red crab are estimated to mature at about 75 mm CW and to reach a maximum size of about 180 mm CW and about 1.7 kg (3.74 lb). Female red crab begin to mature at somewhat smaller sizes and reach a smaller maximum size of about 136 mm CW and about 0.7 kg (1.54 lb) (McElman and Elner 1982 as cited in 43rd SAW Assessment Report). As in other brachyuran crabs, the mating male is larger than the female and forms a protective "cage" around the female while she molts and becomes receptive to copulation. The protective copulatory period may last as long as 2–3 weeks in red crab. The minimum size of males relative to females required for successful mating is unknown. Information about sperm storage is not available for female red crabs but is known to occur with other crustaceans. Mellville-Smith (1987) reported that the reproductive cycle of the Namibian red crab is asynchronous, which would create the opportunity for a single male to mate with multiple females.

Information on the biology and distribution of red crab larvae and postlarvae is scant. Laboratory rearing studies suggest that red crab larvae may require 23-125 days to settle (Kelly et al., 1982). Larval settlement is believed to occur near the base of the continental slope (Roff et al. 1986). Recruitment to the benthos is thought to be episodic with potentially long intervals between successful cohorts (Hines 1990 as cited in Hastie 1995). Sainte-Marie, Sevigny and Smith (1997) suggest that the year-class strength for crab populations is likely to be established prior to, or shortly after settlement.

The likely form for the stock-recruitment relationship for red crab was considered in the working paper prepared for the DPSWG and has given rise to considerable discussion by the PDT. In its evaluation of the application of the Schaefer surplus production model to red crab, the working paper stated that: "The assumption that $B_{MSY} = 1/2B_0$ (Schaefer surplus production curve) is reasonable, if the underlying spawner-recruit relationship is a Ricker curve. However, $B_{MSY} < 1/2B_0$, if the underlying spawner-recruit relationship is a Beverton-Holt curve." The Data Poor Working Group assumed that Beverton-Holt recruitment dynamics were more likely for red crab, citing the lack of evidence for a biological mechanism that might result in maximum recruitment at intermediate spawning biomass levels. However, literature on a number of better-studied crab taxa (including snow crab (*Chionoecetes opilio*), Dungeness crab (*Cancer magister*), blue crab (*Callinectes sapidus*), and green crab (*Carcinus maenas*)) suggest that Ricker stock-recruitment dynamics tend to be more likely (Wahle 2003).

The modeling exercises reported below indicate that a Ricker SRR is necessary to match the history of landings and the resulting biomass that was estimated after 30 years of fishing. The most optimistic Beverton-Holt model (constant recruitment with declining stock size) cannot produce the biomass that was estimated in the 2003-2005 survey in the absence of additional juvenile mortality that is proportional to the adult stock size, which has the effect of making the Beverton-Holt relationship into a Ricker SRR.

NMFS (2000) reported that trends in recruitment for crab stocks are difficult to predict and appear to be linked to environmental factors rather than biomass. As discussed below, however, research on Canadian Atlantic snow crab populations discount environmental factors and describe population cycling related to cannibalism and saturation of favorable settlement habitat, creating a recruitment bottleneck (Sainte-Marie et al. 1996). As has been the case with red crab, Alaskan crab fisheries have harvested male crabs only and the reproductive capacity of these populations is measured in terms of "effective spawning biomass," which is defined as the spawning biomass of females that would be expected to be fertilized by the available mature males. Alaskan crab fisheries generally employ a stair-step approach that provides for harvesting of 0-20% of mature males depending on the level of effective spawning biomass. NMFS (2000) reports a suspicion that "advection of larvae by ocean currents to the nursery areas and cannibalism within the limited nursery areas from older crab cohorts are contributors to recruitment success or failures" for snow crabs in the North Pacific. The asynchronous reproductive cycle reported by Mellville-Smith (1989) for *G. maritae* would seem to increase the likelihood that a portion of the year's reproductive output would find favorable environmental conditions.

Sainte-Marie, Sevigny, and Smith (1997) studied the causes of recruitment variability in the Canadian Atlantic snow crab fishery. Recent and historical data suggested to them that recruitment to that population and fishery followed an approximately 8-year cycle over the past 25 years. The spring time series indicated that the strength of a year class with respect to other year classes was established before the end of the second year of benthic life and was subsequently conserved until recruitment to adulthood was initiated. They report that for snow crab in Atlantic Canada:

> The relative strength of a year class may be determined before, at, or soon after settlement. Numerical dominance of the population by adult females and adolescent and adult males in 1989-1990 was completely reversed in favor of immature females and males in 1993-1995. The recruitment trough had particularly striking effects on adult females, as their numbers plummeted from 8.3 million in 1990 to 0.9 million in 1994. A reduction in the number of adult males also occurred, from approximately 11.5 million in 1990 to 2.8 million in 1994. Changes in the operational sex ratio and size structure of breeding males imply that the levels of male competition for mates will vary considerable across the years, which may affect the quantity and quality of sperm that primiparous females can acquire for storage and future use in fertilizing egg clutches (Sainte-Marie and Carriere 1995, Sainte-Marie et al. in press). Over the 1996-1997 period, the predictable rarefication of large adult males, much greater abundance of adolescent and small adult males, and sharply female-biased operational sex ratios, should favor breeding of small adult and adolescent males with primiparous females and increase the proportion of multiparous females relying on stored sperm to fertilize a new clutch of eggs. In the eastern Bering Sea, trawl surveys have shown extended troughs in the CW frequency distributions for both *Chionoecetes bairdi* and *C. opilio* (Somerton 1981). Cycling populations of *C. opilio* appear to be in synchrony over much of the Gulf of Saint Lawrence.

Camera/bottom trawl survey data (abundance and size composition data) for the U.S. deep sea red crab are available from surveys during 1974 and 2003-2005. Biomass estimates from the 2003-2005 survey and length composition data from the 1974 and 2003-2005 surveys appear reliable. The reliability of biomass estimates from the 1974 survey has been questioned because the 2003-2005 survey showed an increase in stock abundance compared to the unfished biomass in 1974. This result could be seen as inconsistent with expected results after 30 years of fishing. It should be noted, however, that the observed result could be explained by a variety of causes, including: 1)Crab populations are known for their dramatic fluctuations both with and without fishing; 2) The highly variable history of exploitation of the red crab resource could produce changes in abundance that would not be typical of fisheries with relatively constant or continually increasing fishing pressure; 3)Cannibalism is a possible density-dependent control mechanism that might be weakened by fishing on the cannibalistic portion of the population; and, 4) The level of fishing pressure is sufficiently low that natural fluctuations might overwhelm any impacts from fishing.

One theory for the increased abundance of red crabs after 30 years of fishing follows the hypothesis that Waewood and Elner (1982) proposed for snow crab in Atlantic Canada, as reported by Sainte-Marie et al. (1996). Waewood and Elner suggested that:

> Pre-fishery populations of *C. opilio* were maintained in a stagnant phase by larger males which monopolized niche space and restricted resources available to pre-recruits. By removing large males, the fishery presumably relaxed competition and allowed greater survival and/or faster growth of pre-recruits, thereby contributing to increased stock productivity.

Momot (1998) reported on a similar population control mechanism for northern crayfish. In that case, the "removal of adult males allowed prerecruitment survival rates of crayfish to the fishery to increase. As a result, expansion of the population took place despite increased trapping pressure."

Sainte-Marie and colleagues (1996) conducted an extensive sampling program that led them to conclude that year-class strength for snow crabs is determined close to the time of settlement and that cycling is an endogenous characteristic of Atlantic Canada snow crab that pre-dates the fishery. They discounted, but did not completely dismiss, the predatory or competitive role of large males in determining year-class strength because large males are spatially segregated from the early benthic stages. Rather, research done by Lovrich and Sainte-Marie (1997) led them to conclude that predation on settling and young crabs is a primary cause of year-class strength and the predators consist of intermediate size crabs of both sexes. They based that conclusion on examination of the stomach contents of crabs collected in the field and complementary laboratory studies:

St. Marie et al. (1996) found that predation on snow crabs by other snow crabs was relatively prominent as determined from stomach contents. Predation on smaller snow crabs was more common by mature females than by males. Indications of cannibalized crabs were most common in the stomachs of intermediate sized male crabs compared to large crabs, in which no crab remains were found in the 32 male crabs in the largest size group sampled. Sainte-Marie et al. (1996) concluded that "the high prevalence of cannibalism in out study relative to others is consistent with the hypothesis that cannibalism of early benthic stages by larger snow crabs may represent an intrinsic density-dependent mechanism for maintaining a regular recruitment periodicity."

Sainte-Marie et al. (1996) also reported that: "the [8-year] cycle [of snow crab year-class strength] is apparently endogenous and may result primarily from negative, density-dependent interactions between a settling age class and age classes established in the preceding 6 years. Cycles cause striking changes in population features … The size, condition, and maturity composition of both sexes are affected, and marked fluctuations occur in adult sex ratio and female spawning biomass. Cycles may be reflected in the fishery by periodic shifts in the maturity and size composition of legal-sized males and in catch rates and landings."

Sainte-Marine et al. (1996) explained the possible causes of population cycling for snow crab:

> Two nonexclusive density-dependent recruitment processes have been proposed to explain the establishment of recruitment troughs for C. opilio (Sainte-Marie and Dufour 1994, 1995, Sainte-Marie et al. 1995). The first emphasizes a role for cannibalism and resource limitation (space and/or food) at or soon after settlement. Lovrich et al. (1995) provided evidence that instars I-V are cryptic and tend to concentrate in a narrow segment of the overall C opilio habitat where, moreover, they may depend on microhabitat offering refuge from predators. According to this hypothesis, the limiting cryptic habitat becomes saturated through successive settlements and subsequent settlers are cannibalized by larger immature crabs or forced to use inhospitable grounds where they are subject to high mortality rates. Successful recruitment to the population would not occur again until the older year classes have at least partially vacated the settlement grounds, through the onset at instars VII-IX of annual migratory behavior and dispersal to deeper grounds. Cannibalism on settlers has been suggested to regulate recruitment in some decapod crustaceans (Botsford and Wickham 1978, Stevens et al. 1982, Kurihara and Okamoto 1987, Zeldis 1989, Fernandez et al. 1993).

The second hypothesis offered by Sainte-Marie et al. (1996) to explain snow crab cycling "is that recruitment troughs result from a marked reduction in the supply of postlarvae, as they appear to be generated in years when female spawning biomass is at a minimum." They "surmise," however, that "changes in the female spawning biomass are mainly a consequence, rather than a cause of population cycles."

Interestingly, Sainte-Marie et al. (1996) cite unpublished data from laboratory experiments that indicates that "the mortality rate of first instar scales exponentially to cannibal CW." From that they conclude that "the relative contribution of larger cannibals to population cycling could be more important than that of small cannibals…" They note that the difference in the mean age between the age group being affected and the age groups causing the effect determines the period of the population cycling, which will be about twice the age difference.

Sainte-Marie et al. (1996) conclude that:

> The bottom line is that even in the absence of exploitation the biomass of legal-sized male C. opilio will fluctuate extensively due to natural mortality and changes in recruitment intensity and size structure, as is the case for the unexploited adult females.
>
> In the case of C opilio, the fishery probably does not directly impact any of the life stages which may promote population cycling. Therefore, any fishery effect on the cycle would likely be indirect. Conceivable effects of the fishery on population dynamics, which may or may not affect population cycling, are (1) increased survivorship for those small and intermediate-sized crabs which control the abundance of instar I, through a reduction in the competition/cannibalism by

legal-sized crabs; (2) a cyclic reduction in female fertility from fishery-exacerbated fluctuations in operational sex ratio; and (3) a reduction in the frequency of skip-molting for adolescent males owing to relaxed competition between legal-sized adult males and fishery pre-recruits (i.e., a derivation of Waiwood and Elner's 1982 hypothesis).

Based on research published on other crab fisheries, the potential reasons for an increase in the biomass of smaller males and females between 1974 and 2003-2005 include the relaxation of cannibalism by the larger males that were being removed by the fishery and natural cycling of the population that is common to crab populations.

It is also possible that the 1974 survey underestimated crab biomass. Potential reasons for underestimation of population density in 1974 include questions about the area effectively sampled by the cameras and movement of the crabs away from the sled. The PDT has undertaken an analysis of photos from the 1974 survey to determine whether there is evidence of more or less camera avoidance and to reevaluate the area sampled by the camera.

Concerns about Male Reproductive Output

Both the absolute and the relative abundance of large males (114+ mm CW) declined between 1974 and 2003-2005, as would be expected in the transition from an unexploited stock to a stock with moderate fishing pressure. The extent of the observed decline relative to the expected decline is analyzed below. The decline in the proportion of large males has led to a concern that reduced abundance of large males may reduce reproductive output. Observations of mating pairs show that the male is always larger than the female. It is not known whether this reflects a morphological constraint or the relative success of large males in competition for females or the size and sex segregation that has been noted in surveys. Zheng and Kruse (2003) point out that "large oldshell mature males outcompete small newshell males in mating with females" in snow and Tanner crab populations.

Whereas red crabs are segregated by size, with the large males separating the smaller males and the preponderance of females, the observed mating sizes may be a result of the size and sex distribution of the population rather than a biological requirement. Specific data on mating pairs are very limited to a total of 14 observations. During camera surveys during 2003-2005, researchers observed 11 mating pairs in which the males averaged 51% larger than the females, ranging from 18-72% (Wahle unpublished). Elner (1987) observed three mating pairs of *C. quinquedens* in captivity in which males were 10.2, 15.1, and 20.6 % larger than the females. These females were later found to contain sperm masses.

Sainte-Marie, Sevigny, and Smith (1996) inferred that the size composition of males in mating pairs of snow crabs had changed over the years, citing evidence from direct observations in Bonnie Bay (Ennis eta al. 1990, Comeau et al. 1991, Conan et al. 1992) in relation to the passing of troughs and waves of recruitment with corresponding changes in the size distribution of the population.

Rondeau and Sainte-Marie (2001) conducted laboratory experiments to determine the effect of sexual competition on male mate-guarding time, sperm allocation, and the mating success of female snow crabs:

> Two laboratory experiments investigated mate guarding and sperm allocation patterns of adult males with virgin females of the snow crab, *Chionoecetes opilio,* in relation to sex ratio. Although females outnumbered males in treatments, operational sex ratios were male-biased because females mature asynchronously and have a limited period of sexual attractiveness after their maturity molt. Males guarded females significantly longer as the sex ratio increased: the mean time per female was 2.9 d in a 2♂:20♀ treatment compared to 5.6 d in a 6♂:20♀ treatment. Female injury and mortality scaled positively to sex ratio. Males that guarded for the greatest number of days were significantly larger, and at experiment's end had significantly smaller vasa deferentia, suggesting greater sperm expense, than males that guarded for fewer days. In both experiments, the spermathecal load (SL)—that is, the quantity of ejaculate stored in a female's spermatheca—was independent of molt date, except in the most female-biased treatment, where it was negatively related. The SL increased as the sex ratio increased, mainly because females accumulated more ejaculates. However, similarly sized males had smaller vasa deferentia and passed smaller ejaculates, such that, at a given sex ratio, the mean SL was 55% less in one experiment than in the other. Some females extruded clutches with few or no fertilized eggs, and their median SL (3–4 mg) was one order of magnitude smaller than that of females with well-fertilized clutches (31–50 mg), indicating sperm limitation. Males economized sperm: all females irrespective of sex ratio were inseminated, but to a varying extent submaximally; each ejaculate represented less than 2.5% of male sperm reserves; and no male was fully exhausted of sperm. Sperm economy is predicted by sperm competition theory for species like snow crab in which polyandry exists, mechanisms of last-male sperm precedence are effective, and the probability that one male fertilizes a female's lifetime production of eggs is small.

Concerns about reproductive output are tempered by the fact that overall biomass appears to have increased after 35 years of fishing and there was evidence of strong recent recruitment during the 2003-2005 survey. *C. quinquedens* probably exhibits the same asynchronous reproductive cycle noted by Mellville-Smith (1987) for *G. maritae*, creating more opportunity for a single male to mate with multiple females, as is known to be the case for multiple crab species (Zheng and Kruse 2003).

Discards and Discard Mortality

Based on limited logbook, sea and port sampling information, discards of female and undersized male red crab appear to average about 30% of total catch, but can range from about 10% to 69% of total red crab catch. Discard mortality from being brought to the surface and handled on deck averages about 5%, according to Tallack (2007). The absence of any change in the size structure of the female red crab population has been taken as evidence that discard mortality on females has not been sufficient to change the size structure. Bycatch of red crab in fisheries directed at other species is minor, with the possible exception of the monkfish trawl fishery in deep water. The red crab industry has adopted the use of escape rings in traps based on Tallack's (2007) discard studies, but few crabs escape from the traps during normal fishing operations because the traps are hauled on a 24-hour soak and the bait keeps crabs in the traps even if they could escape through the rings.

The major fishery related uncertainties for red crab are discards, discard mortality, as well as historical and recent fishery size composition and CPUE as an indication of abundance trends. In addition, the expected response of the stock to fishing in terms of growth and recruitment are uncertain but not totally uninformed.

Especially important to red crab, given the scarcity of fishery-independent data and the small size of the fleet, is the effect of market conditions. The fleet has worked more cooperatively since the adoption of limited entry in 2002, and began operating under a cooperative harvesting agreement in 2008. Market conditions have influenced landings and fishing behavior (season, size selectivity). The degree to which market conditions have influenced the red crab fishery is difficult to quantify.

The infrequency of stock assessments is another key uncertainty for red crab management. Only two stock assessments have been completed for red crab (Serchuk 1977; NEFSC 2006a). Both were based on the camera/trawl surveys completed just prior to the assessment.

There is no recreational fishery for the species. Red crab in the U.S. are managed as a single stock, although red crab in the Gulf of Maine are not considered in calculation of reference points, biomass estimates, or other management analyses because there are no appreciable landings from that area. Because landings have not exceeded the specified MSY, by definition overfishing is not occurring. The status of the stock relative to the overfished level is unknown. Based on fishable biomass estimates from the 2003-2005 survey and male landings, fishing mortality was approximately $F = 0.055\ y^{-1}$ during 2005.

4.0 Data Availability

The principle fishery data for red crab are landings data from dealer reports starting in 1973, logbooks (i.e., Vessel Trip Reports, or VTRs) that start in 1994 but were not required for red crab vessels until 2002, size composition data for marketable males from port samples, and sea sample data for females and all males from a pilot program involving one vessel during 2004-2005. Landings data from 1973 -1976 should be considered experimental, as there was not yet a sustained fishery prior to 1977. In addition, landings data from 1977 through 2002 should be considered minimal estimates of actual landings, as red crab reporting was not required until 2002. Depending on the analytic method being used, the dealer reported landings data from 1994 should be considered an outlier because the absence of landings represents a lack of fishing effort rather than resource conditions. Similarly, industry members have noted that the actual landings in 1995 and possibly 1996 were higher than reported. For example, the NMFS dealer database shows just over one million lb of landings in 1995 and again in 1996. One member of the Advisory Panel reports that his vessel landed that amount and he knows that there was an additional significant producer fishing at the time. All years, including 1994, are included in the DCAC and 2-Point Boundary Model runs because the purpose of the models is to determine the effect of total landings on the stock biomass over the entire time period. For that purpose, the effect on stock biomass from a year with no landings is just as important as the effect from significant landings.

VTR landings should be considered a low estimate prior to 2002 because there was no Federal red crab permit prior to the FMP being implemented. Because there was no Federal red crab permit, a that vessel fished exclusively for red crab (or fished for lobster, or another species in Federal waters that did not require VTR reports) was not required to submit VTRs until 2002. Data necessary to calculate landings per unit effort are available from VTRs but are difficult to interpret because captains have not been consistent in their interpretation of the appropriate data to enter under a given heading. The calculation of LPUE requires checking back with captains to clarify the meaning of certain VTR entries. As described above, discard estimates are available from limited sea and port sampling and VTR data. Size selectivity estimates for the recent commercial fishery (2005) are available from a comparison of sea and port sample data. Because the fishery occurs primarily south of Georges Bank, there is virtually no data from the Gulf of Maine. Although the Gulf of Maine population is substantial, it is not included in the assessment of overall resource status.

The principle fishery independent data for red crab are from two camera sled/bottom trawl surveys, conducted during 1974 and 2003-2005. The surveys were conducted on red crab habitat between Maryland and the eastern tip of Georges Bank. Camera data provide information about red crab density and bottom tow data provide information on sex and size composition. The survey data from 2003-2005 are generally combined and treated as one survey.

The 2003-2005 survey attempted to replicate the 1974 survey as much as was practical. The camera and trawl tows were generally from the same sites and sample locations. The two surveys used bottom trawls of the same design and trawling protocols, although different vessels were used. Efforts were made to make camera data for the two surveys as compatible as possible.

There is uncertainty in the biases of both surveys, because the cameras and sled were not identical. Wahle et al. (2008) attempted to quantify the bias in the 2003-2005 study by estimating the likelihood that crabs moved away from the camera sled, which would result in underestimates of density. The study concluded that crabs occurred more frequently in the background of an image than in the foreground, and, therefore, may have moved away from the sled before the image was taken. The authors concluded that "[i]mages from the 1974 survey were not available to conduct the same evaluation, but we suspect that this artifact might not have been as strong then, given the larger area (31.8 m^2) sampled by the camera during that survey. On that basis, the proportion by which population density may have been underestimated in 1974 is likely less than that for the 2003-2005 surveys" (Wahle et al. 2008). Recently, the original 1974 images were located, and the PDT is in the process of re-xamining those images. It is reasonable to conclude that both surveys experienced bias that may have underestimated population density, however, the degree to which each may have underestimated density is unknown.

Data from a variety of research bottom trawl surveys are of limited use because catches are very low, with the exception of the NMFS Cooperative Monkfish Survey. NMFS has been involved in monkfish industry-based trawl surveys in 2001, 2004, and 2009. Information on size and sex from the 2001 survey were summarized in the 2004 Red Crab Specification Document. All surveys began in February, but due to weather delays the legs were sporadic and in some cases the last leg did not end until the beginning of June. The 2004 and 2009 surveys went into the Gulf of Maine. Size distribution data was analyzed separately for the Gulf of Maine, where there is no directed fishery. The peak size for males outside the Gulf of Maine is higher in 2001 and 2009 compared to 2004, perhaps further evidence of the recruitment pulse that appeared in the 2003-2005 red crab survey. The peak size of female crabs was higher in 2004 and 2009 compared to 2001. The size distribution of male and female red crab caught in the monkfish trawl surveys in the Gulf of Maine is shown in Figure 13 and Figure 14, for comparative purposes. The average size of both male and female crabs is smaller in the Gulf of Maine than it is for the remaining stock area, despite the fact that there is no directed fishery in the Gulf of Maine.

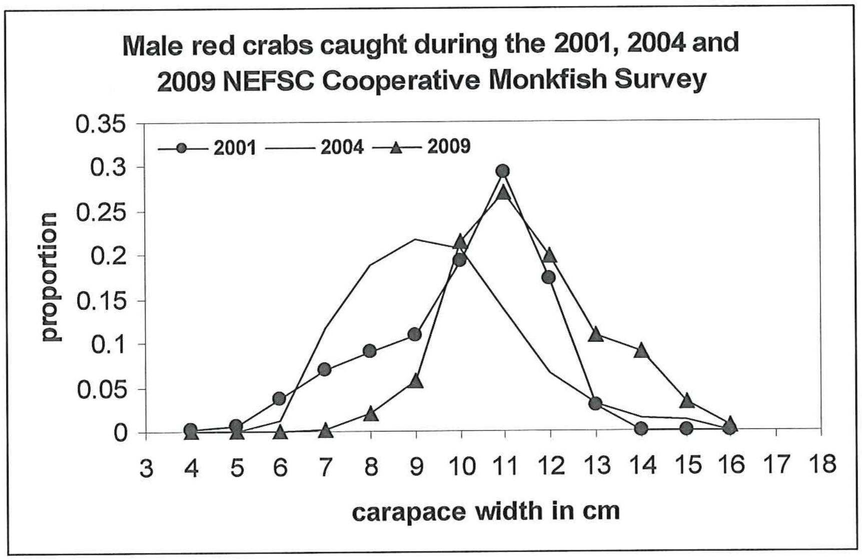

Figure 11- Size distribution of male red crabs caught in monkfish trawl surveys, excluding tows in the Gulf of Maine.

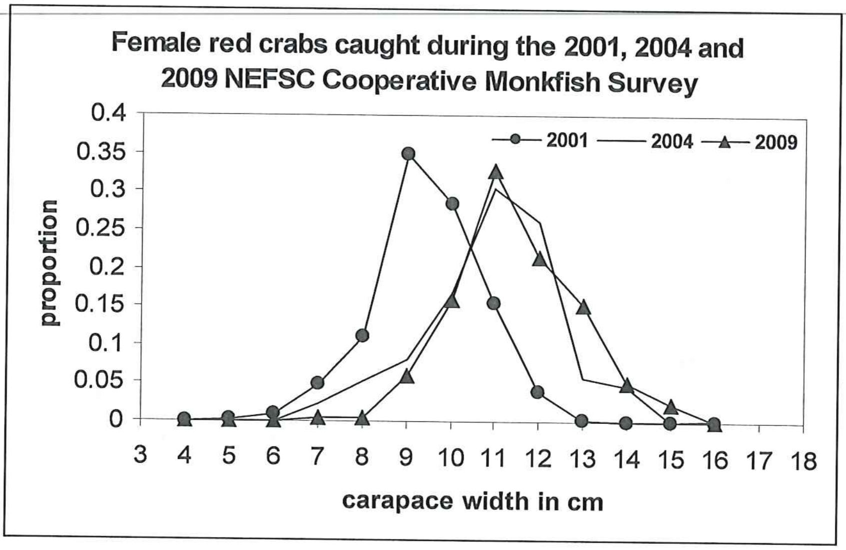

Figure 12- Size distribution of female red crabs caught in monkfish trawl surveys, excluding tows in the Gulf of Maine.

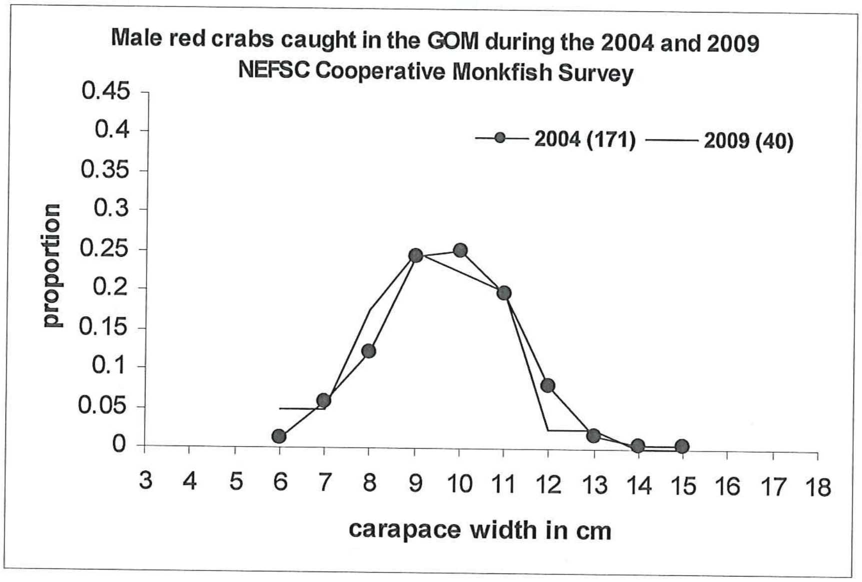

Figure 13- Size distribution of male crabs caught in the Gulf of Maine during the 2004 and 2009 NEFSC Cooperative Monkfish Trawl Surveys.

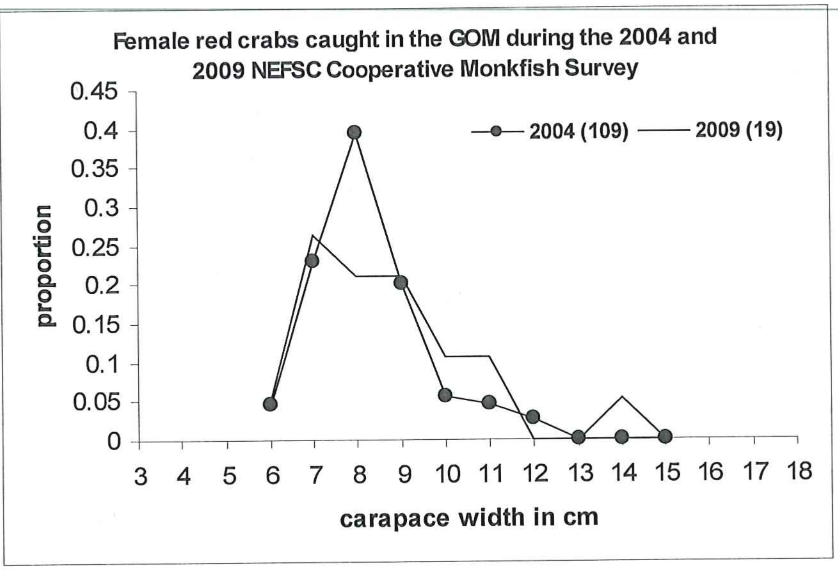

Figure 14- Size distribution of female crabs caught in the Gulf of Maine during the 2004 and 2009 NEFSC Cooperative Monkfish Trawl Surveys.

5.0 Current Stock Status

Information in this section is summarized from NEFSC (2006a).

The deep sea red crab population and fishery appear to be at sustainable levels. The red crab fishery has had a noticeable impact on the stock of large male red crabs >114 mm carapace width which were considered marketable in 1974. Since 1974 the abundance of large males has decreased by 42%, probably in response to fishing. However, the biomass of currently marketable male crabs which includes smaller individuals has increased by 5%. Small red crabs less than about 60 mm appear to be abundant relative to 1974. Current landings during 2002-2005 averaged approximately 2000 mt (4.4 million lbs), and were comparable to average landings of about 2300 mt (5 million lbs) during 1982-2001 as the population was being fished down from the virgin state. Results of this stock assessment are consistent with the hypothesis that the red crab population has been fished down from a virgin state over the past 30 years and is currently at a productive biomass level. There are, however, several key issues that contribute uncertainty to this conclusion (i.e. lack of biological information about growth and longevity that could be used to estimate stock productivity and information about discard mortality, see below).

The most recent assessment concluded that overfishing was not occurring because red crab landings during 2005 (2,013 mt) were less than the MSY proxy (2,830 mt, see below) specified in the FMP. Recent landings have also been less than more recent estimates of MSY (1700-1900 mt). Recent fishing mortality estimates were available, but not used in the assessment to determine if overfishing was occurring because there are no *F*-based reference points, nor was there a proxy for F_{MSY}.

Based on the most recent assessment, the average fishing mortality rate (landings/fishable biomass) on male red crab was estimated to be $F = 0.055$ (SE 0.008) y^{-1} during 2003-2005. This estimate may be an underestimate because it does not consider potential mortality due to discarding of undersized males and all females. However, the DPSWG Review Panel noted that "the female size structure has not changed substantially suggesting discard mortality may not be a significant factor." Fishing mortality estimates are calculated using biomass estimates from the 2003-2005 survey. (See above for potential bias in estimates.) Red crab biomass in the Gulf of Maine has not been estimated but is considered to be appreciable. This biomass was not included in the calculation of recent fishing mortality rates.

Alternate fishing mortality estimates including discards and based on the best available discard estimates for sea and port samples are given below (Table 1) for males only, females only, and males plus females. The current best estimate of discard mortality indicates that about 5% of discarded red crab die from being brought to the surface and handled on deck (Tallack 2007). Discard rates (discard / total catch) were from sea and port samples during 2003-2004 (Table D4.5 in NEFSC 2006a).

In this exercise, fishing mortality for red crab was approximated as catch (landings + discards) divided by total biomass (excluding the Gulf of Maine) and catch divided by 90+ mm CW (i.e., fishable) biomass (the use of the exploitation fraction as an approximation for the instantaneous fishing mortality rate (*F*) is relatively precise because mortality rates are low). Calculations using total biomass may understate fishing mortality because total biomass includes small size groups probably not taken in traps, although the potential bias may be small because small crabs have low weight. Calculations using 90+ mm CW biomass may overstate fishing mortality because red crab of sizes smaller than 90+ mm CW make up the bulk of the discards, which are included in the calculation of the exploitation rate.

Table 3- total annual mortality due to fishing (landings and mortal discard) during 2003-2005, by sex, using the best available estimate of discard mortality.

	Males	Females	Total
Average 2003-2005 landings (mt)	1,992	0	1,992
Discard/(total male + female catch)	0.11	0.18	0.29
Catch (mt, includes all discards)	2,238	2,429	4,667
Discard (mt)	246	2,429	2,675
Discard mortality rate (best estimate)		0.05	
Mortal discard (mt)	12.3	121.45	133.75
Landings + mortal discard (mt)	2,004	121	2,126
Total biomass (mt)	56,443	74,689	131,132
90+ CW biomass (mt)	38,220	55,279	93,499
F relative to total biomass	0.04	0.00	0.02
F relative to 90+ biomass	0.05	0.00	0.02

Based on the most recent assessment)), fishable red crab biomass during 2003-2005 was approximately 36,000 mt. Overfished status was not determined because an adequate B_{MSY} estimate or proxy (see below) was lacking. Potential bias in both the 1974 survey and the 2003-2005 survey indicate that both surveys likely underestimate abundance. The potential bias in the 2003-2005 survey is better understood and the estimate of fishable biomass is considered reliable. The estimate of fishable biomass from 2003-2005 is higher than that from 1974 despite 30 years of variable exploitation.

Comparisons of biomass estimates from the two surveys are uncertain, because of uncertainty in both surveys biases. However, biomass estimates from the two surveys (Table 4) indicate that male fishable biomass (based on current fishery selectivity) increased by about 20% from 1974 to 2003-2005. Female biomass increased substantially, by 150% - 250%. In contrast, total male biomass increased by only 75%, and biomass of large (114+ mm CW) males decreased by about 43%. Size composition data from the surveys indicates that both male and female red crab have benefited from strong recruitment in recent years (Figure 15). The reduction in the large (114+ mm CW) male biomass and relatively modest increase in biomass of males 90+ mm CW can most likely be attributed to size-selective fishing (Weinberg and Keith 2003). The reduction in the biomass of large males would be expected under both selective and non-selective fishing but would be more pronounced with size-selective fishing at the same fishing mortality rate. The increase in biomass of males 90+ mm CW could be explained by the release of competitive pressures or predation on the smaller males by the larger males or by a recruitment event.

Table 4- Biomass estimates, standard errors and CVs from deep-sea red crab camera/bottom trawl surveys. The standard errors for 1974 estimates are approximations based on the assumption that CVs for variability among samples was the same during 1974 as during 2003 to 2005. The differences in CVs between the two periods are due do differences in assumed effective sample size.

		Males			Females			Total	
Year Size Groups (mm CW)	Biomass (mt)	SE (mt)	CV (mt)	Biomass (mt)	SE (mt)	CV (mt)	Biomass	SE	CV
1974									
90+	29,991	6,298	0.21	15,654	3,719	0.24	45,645	7,314	0.16
114+	23,794	4,303	0.18	2,106	433	0.21	25,900	4,325	0.17
Fishable	30,302	6,363	0.21	NA	NA	NA	NA	NA	NA
All	32,190	5,001	0.16	20,674	5,221	0.25	52,864	7,230	0.14
2003 to 2005									
90+	38,220	4,298	0.11	55,279	7,033	0.13	93,499	8,242	0.09
114	13,770	1,334	0.1	5,224	576	0.11	18,994	1,453	0.08
Fishable	36,247	4,612	0.13	NA	NA	NA	NA	NA	NA
All	56,443	4,646	0.08	74,689	10,102	0.14	131,132	11,119	0.08

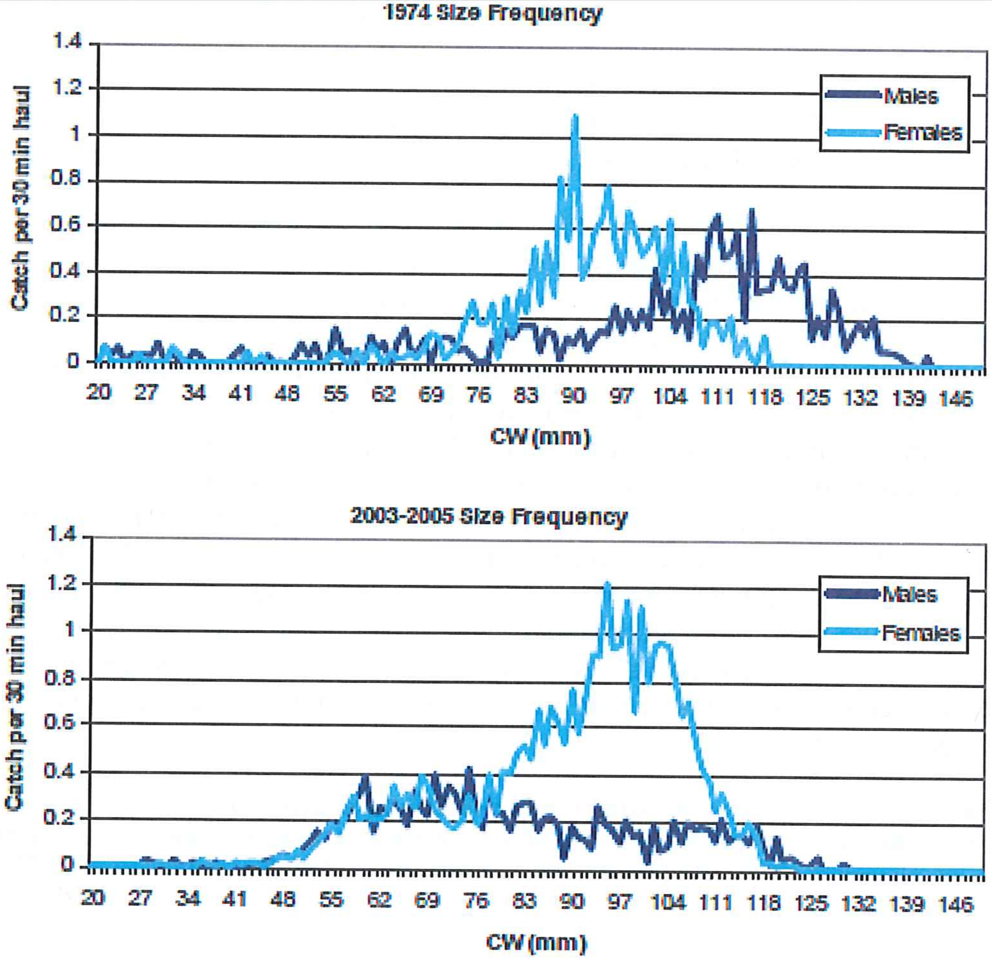

Figure 15- Catch per 30-minute trawl by size in the 1974 survey (top) and 2003-2005 surveys (DPSWG 2009).

With variable recruitment combined with fishery exploitation rates on male crabs only that have fluctuated widely over the past 35 years, the sex ratio of the red crab population may provide an indication of the status of the red crab stock. Table 5 provides the sex ratios by geographic sector (Figure 16).

Table 5- Comparison of Male/Female sex ratios by sector as calculated from abundance estimates obtained from the 1974 and 2003-2005 surveys.

Sector	1974	2003-2005
A	0.68	0.75
B	1.72	0.35
C	1.15	0.27
D	0.89	0.83
All	1.02	0.50

The 1974 survey shows the expected 1:1 sex ratio for all areas combined, but with widely varying ratios by area. The 2003-2005 survey shows that males are one-half as abundant as females for the population as a whole, but with considerable variation by area.

Rule of thumb MSY calculations such as Gulland (1970) that rely on a logistic growth model predict abundance of fully exploited populations at 50% of the unexploited population level. The rule of thumb models are based on density-dependent population controls that may not respond as expected when fishing is selective for a portion of the population only. The common logistic growth model depicts density-dependent controls that are symmetrical around 0.5K. Most stock-recruitment relationships are not symmetrical around 0.5K, with the result that maximum surplus production occurs with biomass <0.5K.

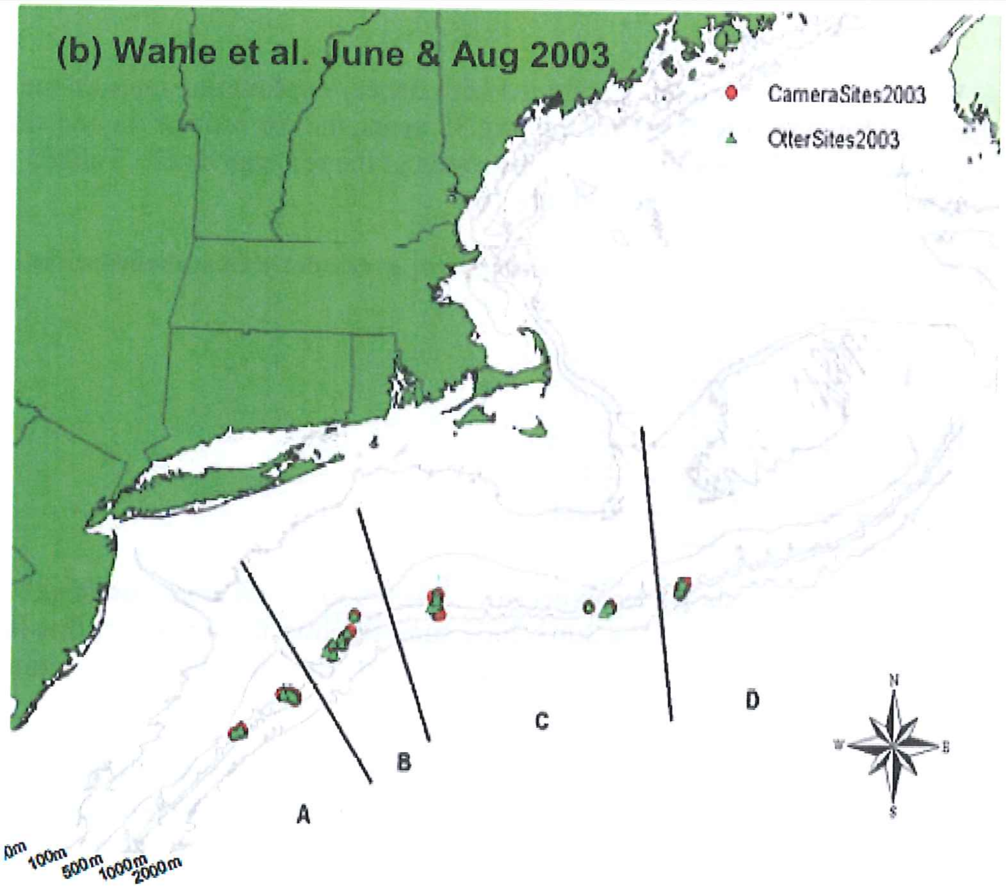

Figure 16- This map shows the geographic sectors that were established for the 1974 survey and used again in the 2003-2005 survey.

6.0 Red Crab Overfishing Definition

The Magnuson-Stevens act includes the requirement that all FMPs "specify objective and measurable criteria for identifying when the fishery to which the plan applies is overfished." The National Standard Guidelines (NSGs) require the specification of "status determination criteria" (74 FR 3178). These criteria are to be "expressed in a way that enables the Council and Secretary to monitor the stock or stock complex and determine annually whether overfishing is occurring and whether the stock or stock complex is overfished."

The National Standard Guidelines define overfished stock conditions and overfishing. According to the NSGs, an overfished stock is one "whose size is sufficiently small that a change in management practices is required in order to achieve an appropriate level and rate of rebuilding." A stock is considered overfished when its size falls below the minimum stock size threshold (MSST). The Magnuson-Stevens Act requires a rebuilding plan for stocks that are overfished. According to the NSGs, overfishing "occurs whenever a stock or stock complex is subjected to a rate or level of fishing mortality that jeopardizes the capacity of a stock or stock complex to produce

MSY on a continuing basis." Overfishing is considered to occur if the maximum fishing mortality threshold (MFMT) is exceeded for one year or more.

Caddy (2004) suggested that "RPs should be regarded as critical values of indicators and may be derived from analysis, from observation, by expert judgement [sic], or by comparison with data from earlier periods in the fishery when productivity was higher and sustained and also, but not exclusively, from population models." Caddy (2004) also states that: "model-based RPs reflect expert judgement at two levels: (*i*) that the model is appropriate to the situation and species applied to and (*ii*) that the indicator value chosen as an RP has some relevance to events in the population, past, present, or future, as judged by experts. At some stage, then, a precautionary judgement must be made that when an indicator approaches an agreed LRP, this corresponds to an unacceptable risk of some negative event occurring. Such an acceptable level of risk must be decided on when reacting to critical indicator values (Prager et al. 2003)." The NS 2 Guidelines state that judgment concerning acceptable risk is a policy consideration that should be made by Councils and the Secretary and not by stock assessment scientists, peer review panels, or a Council's SSC. This implies that Councils should be provided with estimates of risk that are associated with different values for RPs.

Table 6- Caddy (2004) provides a list of positive and negative supplementary factors that provide insight into the vulnerability of stocks.

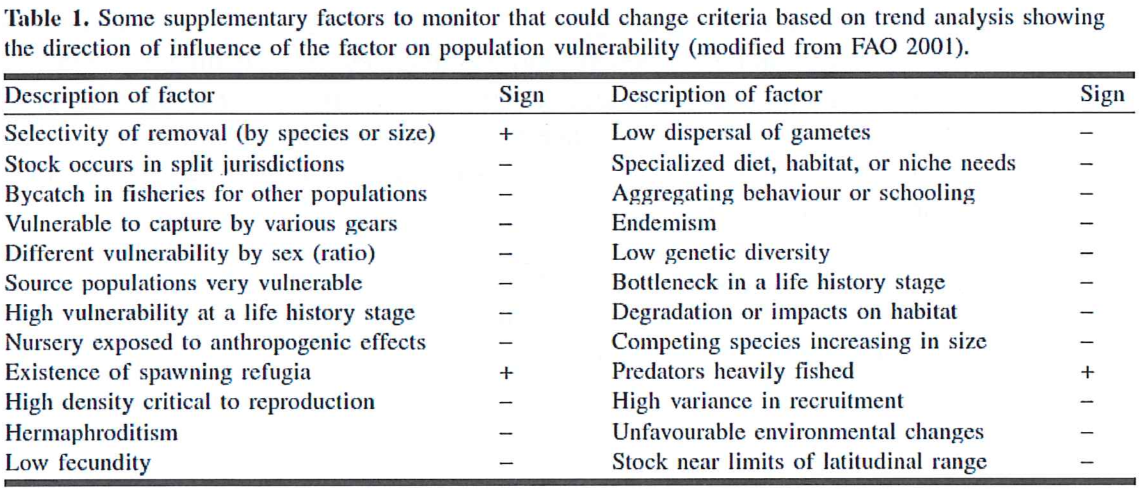

Table 1. Some supplementary factors to monitor that could change criteria based on trend analysis showing the direction of influence of the factor on population vulnerability (modified from FAO 2001).

Description of factor	Sign	Description of factor	Sign
Selectivity of removal (by species or size)	+	Low dispersal of gametes	−
Stock occurs in split jurisdictions	−	Specialized diet, habitat, or niche needs	−
Bycatch in fisheries for other populations	−	Aggregating behaviour or schooling	−
Vulnerable to capture by various gears	−	Endemism	−
Different vulnerability by sex (ratio)	−	Low genetic diversity	−
Source populations very vulnerable	−	Bottleneck in a life history stage	−
High vulnerability at a life history stage	−	Degradation or impacts on habitat	−
Nursery exposed to anthropogenic effects	−	Competing species increasing in size	−
Existence of spawning refugia	+	Predators heavily fished	+
High density critical to reproduction	−	High variance in recruitment	−
Hermaphroditism	−	Unfavourable environmental changes	−
Low fecundity	−	Stock near limits of latitudinal range	−

Reference point approaches for red crab do not establish a fixed metric or approach to measuring stock biomass or exploitation. Based on the current FMP, overfished stock status and overfishing for red crab should be defined in terms of the best available measures of stock biomass and exploitation or fishing mortality relative to the value of the measures under MSY conditions. Choice of the particular measure or proxy depends on best available data and circumstances but a list of potential proxies and conditions is described in the FMP. In particular, based on the FMP, the red crab stock will be considered to be in an overfished condition if one of the following three conditions is met:

- Condition 1 -- The current biomass of red crab is below ½ B_{MSY} in the New England Council's management area (excluding the Gulf of Maine).

- Condition 2 -- The annual fleet average CPUE, measured as marketable crabs landed per trap haul, continues to decline below a baseline level for three or more consecutive years.

- Condition 3 -- The annual fleet average CPUE, measured as marketable crabs landed per trap haul, falls below a minimum threshold level in any single year.

Similarly two potential approaches or proxies for identifying overfishing are described:

- Proxy #1: F / F_{MSY} -- It is common for data sparse stocks to estimate trends in fishing mortality as an exploitation ratio, i.e., landings or catch divided by an index of abundance, usually from a survey. As a proxy for F_{MSY}, Councils in the past have selected an exploitation level that existed during a time with no trend in biomass at an intermediate biomass level.

- Proxy #2: Landings / MSY – In the absence of other information, overfishing can be defined as landings in excess of an estimate of MSY. Although crude, provides an indication of current fishing effort relative to MSY conditions. (The reference point used as a fishing mortality threshold was MSY = 2,830 mt (6.24 million lb) from 2002-2008, and is currently 1700 mt (3.75 million lb)).

The FMP describes a default control rule (Figure 3) that could be used by managers, although this has proved impractical due to lack of biomass, exploitation, natural mortality and reference point estimates.

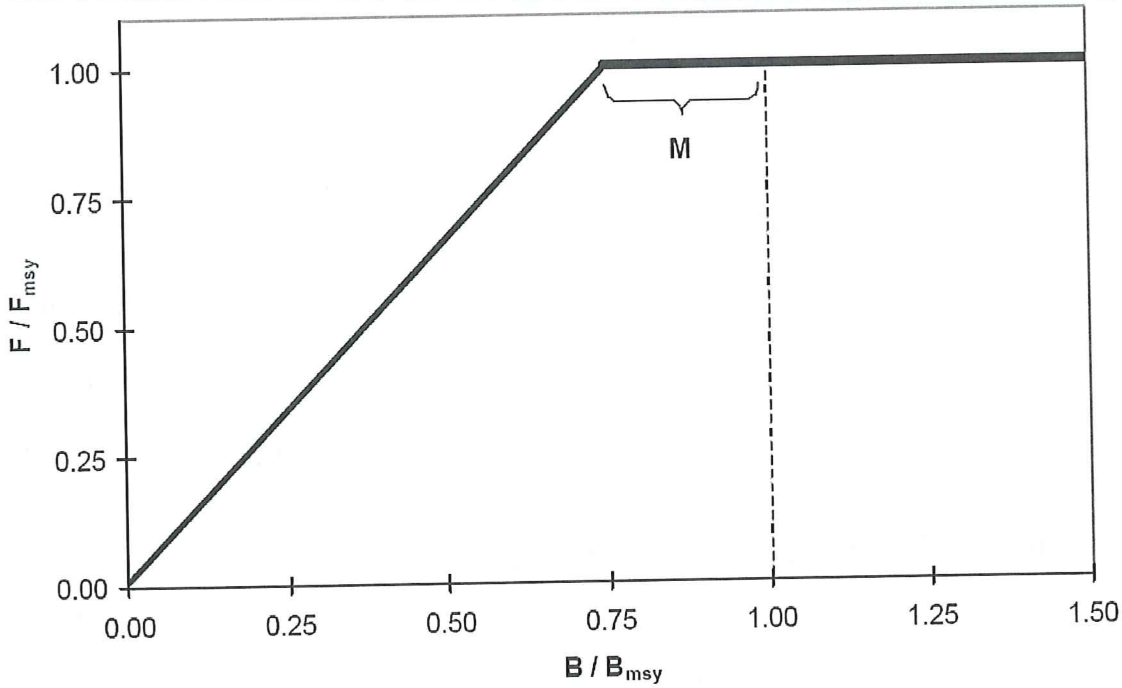

Figure 3. Default MSY control rule in the FMP for deep-sea red crab.

6.1 *Current Reference Points*

Information in this section is summarized from NEFSC (2006b).

The reference point used as a fishing mortality threshold was MSY = 2,830 mt (6.24 million lb) from 2002 through 2008. Since April 6, 2009 MSY has been set at 1700 mt (3.75 million lb).

The reference point used as a biomass target is B_{MSY} = 18,867 mt (41.6 million lb) of male red crab 102+ mm CW (4" CW).

The reference point used as a biomass threshold is ½B_{MSY} = 9,434 mt (20.8 million lb) of male red crab 102+ mm CW (4" CW).

A suggested CPUE baseline is 26-29 market size crab per trap, before adjustment for an equivalent number of 102+ mm CW (4" CW) market-size crab. This is the CPUE for market size crabs that was calculated in 1974 for what was assumed to be a virgin resource.

6.2 *Logic and Justifications*

In view of survey data limitations and infrequency of stock assessments for red crab, a landings-based biological reference point (BRP), for example, an estimate of MSY, for overall exploitation is appropriate for use as a threshold for exploitation rates.

Serchuk's (1977) original MSY estimate (1,247 mt, or 2.75 million lb) assumed an underlying Schaefer surplus production model, and used estimated biomass for male red crab 114+ mm CW (the minimum marketable size at the time) from the 1974 camera/trawl survey as an estimate of virgin biomass, or B_0. Based on the Schaefer surplus production model, MSY = ½ MB_0 and it was assumed that $F_{MSY} \cong M$. For the original red crab estimate, $M = 0.2y^{-1}$ and $B_0 = 24{,}948$ mt of male red crab 114+ mm CW.

The MSY estimate (2,903 mt) that was incorporated into the FMP was made using the same formula and revised values for M and B_0. The revised value for natural mortality $M = 0.15\ y^{-1}$ was thought to be a better estimate than $M = 0.2y^{-1}$ for red crab. The original B_0 value was adjusted downward to account for part of the survey being in Canadian waters, then adjusted upward to include male red crab down to 102 mm CW and larger, as compared to the 1974 marketable size of 114+ mm CW, and adjusted upward again to account for the fact that the area fished is larger than the area surveyed. The adjustments took away biomass which now belongs to Canada, and added biomass to account for the area of the fishery south of the survey boundary to Cape Hatteras.

6.3 Reference Point Weaknesses

In the most recent stock assessment (NEFSC 2006) the current MSY and B_{MSY} estimates for red crab were criticized and judged unreliable due to uncertainty about biological parameters and the model used to calculate MSY. New estimates were not developed due to the lack of information about growth, longevity, and trends in abundance.

Relatively little new information has become available since the last assessment. However, limited data for related species (*G. maritae*; Mellville-Smith 1998) suggests that M may be as low as $0.1\ y^{-1}$, which is lower than previous estimates (0.15 and $0.2\ y^{-1}$). Melville-Smith (1989) also published a growth model for *G. maritae* that is based in part on data for *C. quinquedens* and provides useful parameters for modeling the population dynamics of *C. quinquedens*.

The current B_{MSY} estimate of 18,867 mt in the FMP for male red crab (102+ mm CW; 4" CW) is not representative of current fishery conditions. During the early and mid-2000s the fishery was landing male red crab 80+ mm CW, and the L_{50} fishery selectivity was 92 mm CW. Advisory Panel members report that the industry has taken steps to increase the size selectivity in the fishery in response to conditions imposed on certification of the fishery by the Marine Stewardship Council.

The survey biomass from the 1974 survey may under-estimate B_0 because of statistical variance in the estimate, uncertainty about the effective area sampled by the camera sled, or because some fishing had taken place prior to 1974. However, we have no way to estimate the uncertainty around that estimate. Further, total biomass for male red crab during the 2003-2005 survey may also be biased low because of the likelihood that crabs were in burrows or had moved away from the sled before the picture could be taken. Wahle et al (2003) attempted to quantify the degree to which crabs were moving away from the camera sled and determined that crabs were significantly more likely to occur in the background of the image than in the foreground. The original film from the 1974 survey has been located and an analysis is underway to evaluate the area visible in the pictures and any other sources of bias that become evident.

The Data Poor Species Working Group was concerned that the total biomass for male red crab during the 2003-2005 survey (56,443 mt) exceeds the estimate for the 1974 survey (32,190 mt), despite significant exploitation. This concern was apparently one factor that led to the use of a zero depletion delta in the DCAC model, rather than the depletion delta indicated by the survey abundance estimates. However, any number of factors could have caused the population to increase over time. Substantial fluctuations in recruitment to crab populations are common in the literature. The pelagic environment in which red crab eggs and larvae exist during their early life stages is highly dynamic. Sainte-Marie et al. (1996) hypothesized that fluctuations in eastern Canadian snow crab populations result from alternating saturation of nursery grounds and cannibalism by first settlers on the generations that follow, until the strong generation moves out of the nursery grounds, clearing the way for another dominant generation.

Evidence from other crab fisheries indicates that the red crab population is likely to fluctuate both with and without harvesting. The red crab population may have been at a relatively low point in 1974. Harvesting of large males may have reduced predation on smaller males by large males. Red crabs inhabit an area where food appears to be limited, increasing the likelihood of cannibalism. Female abundance nearly tripled since 1974 (NEFSC 2006, Wahle et al. 2008) if the survey biomass estimates are equally biased. In the absence of harvesting, a similar result in male red crab might be expected. Further, considering the size-selectivity of the fishery, the likelihood of a Ricker stock-recruitment relationship, and the highly variable landings caused by market conditions, the potential for an increase in biomass seems plausible. Possible biomass trajectories are evaluated below with a population model based on an age-CW model for *Geryon maritae,* a CW-weight model for *Chaceon quinquedens*, and candidate stock-recruitment relationships. In the absence of any definitive evidence that the 1974 survey underestimated the unexploited biomass, evidence for an increase in biomass should not be dismissed.

The fishery appears to have reduced the abundance of the largest (114+ mm CW) male red crab by approximately 42%, leaving 58% of the unexploited biomass of large males. There is concern that reduced abundance of large male crab may lead to sperm limitation and reduced levels of egg production (see Appendix 1). However, the abundance of egg bearing female red crab appears to have been higher in the more recent survey and the proportion of egg-bearing females does not appear to have changed. There is also evidence of strong recruitment in the 2003-2005 survey, an indication of reproductive success. Therefore, concern regarding the depletion of the largest males to date may not be warranted. Continued research into this topic should be encouraged and is part of an industry-based proposal recently submitted to the Saltonstall-Kennedy Program. Zheng and Kruse (2003) provide evidence from the Alaskan snow crab fishery that one male crab can mate with up to eight females when the ratio of males to females is low. They also noted that male snow crabs are sperm conservers, rationing the amount of sperm transferred to each female in proportion to the sex ratio. These behaviors may ameliorate but do not necessarily prevent sperm limitation because sperm conservation by males may still result in low fertilization rates. Female snow crabs and other crustaceans are also known to store sperm for multiple fertilizations from one mating.

Catch per unit of effort (CPUE) is mentioned in the FMP as a baseline stock biomass indicator for red crab, but CPUE data requires onboard sampling. Applegate, in NEFSC 2006a, analyzed landings per unit effort for the first three years of required reporting. Additional analysis of landings per unit effort is underway. Red crab vessels carry sea samplers when requested. Sea sampling data is being analyzed for its usefulness in tracking catch per unit effort. The red crab industry will be required to improve data collection and analysis to maintain MSC certification.

7.0 Options and Recommendations

This section outlines a range of options for exploitation and biomass based biological reference points (BRPs) and for specifying MSY, OFL, and ABC.

The exploitation BRPs described here are thresholds specified in terms of landed weight (i.e., yield). Yield-based approaches are the only practical approach for red crab because the only data routinely available for red crab are fishery dependent landings. The options for yield-based BRPs are intended as proxies for landings at F_{MSY}.

Options outlined below emphasize the most reliable information sources for red crab, which are landings since 1982 and biomass, abundance, and size composition data from the two camera/bottom trawl surveys, 1974 and 2003-2005.

Fishing for Female Red Crab

All options outlined in this report assume a male only fishery for red crab. None are applicable to a fishery involving female red crab. If a female red crab fishery is established, then all yield and biomass based BRPs should be reevaluated.

Marketable Sizes and Fishery Selectivity

In laying out options for BRPs, we generally assume that fishery selectivity in the future will be the same as during 2003-2005. As described above, fishery selectivity for red crab has changed over time. Marketable size males were 114+ mm CW during the late 1970s. Based on the last stock assessment, the selectivity pattern in the current fishery follows an increasing logistic pattern with selectivity near 0% at 80 mm CW, 50% selectivity at 92 mm CW, and nearly 100% at 120 mm CW. If fishery selectivity changes, then all yield and biomass-based BRPs should be reevaluated.

One of the conditions attached to certification of the red crab fishery as sustainable by the Marine Stewardship Council is that the industry undertake a program to increase the average size of landed crabs. This requirement is likely to bring about a change in size selectivity that should be evaluated in terms of the appropriate yield and biomass-based BRPS. The stochastic modeling exercises conducted for this review assumed a decline in the minimum size of males crabs from 1.1 lb (approximately 116 mm CW) in 1973 to 0.54 lb (approximately 90 mm CW) in 2008 and increasing again over a ten year period to 0.96 lb (approximately 111 mm CW).

7.1 Biomass-Based Biological Reference Points

As described above, biomass-based reference points can be outlined for red crab, but data limitations and infrequent assessments will probably undermine their utility. Exploitation (yield-based) reference points are likely to be more important in a practical sense for red crab. For these reasons, the PDT did not re-evaluate the biomass-based biological reference points that were reviewed by the DPSWG.

Some MSY analyses and estimates described in this report for red crab assume virgin or near-virgin biomass conditions during 1974. Many are basically trend analyses which assume that biomass estimates for 1974 and 2003-2005 are directly comparable. (See Appendices.) The results of these analyses are uncertain to the extent that biomass estimates for both surveys are uncertain. The 1974 survey estimates are uncertain because of questions about the area of the sea floor the camera sled was able to illuminate and photograph clearly during the 1974 survey, and the effect of avoidance behavior, resulting in most likely underestimates of stock biomass. Biomass estimates from the more recent 2003-2005 survey are better understood, better documented, and the area covered by the cameras is well defined. However, the 2003-2005 survey estimates were affected by some avoidance behavior that resulted in negative bias and some underestimation of stock biomass. Reviewing the recently recovered original photographs may resolve some of the uncertainty in these estimates. Nevertheless, both surveys' estimates are most likely underestimating the actual stock biomass, such that the results based on these estimates should be considered conservative. Pending further analysis of the film from the 1974 survey, there is no basis on which the relative accuracy of the two surveys can be determined. Both surveys represent the best available information.

7.2 Options for Biomass-Based BRPs

The NSGs require biomass-based BRPs that describe target and threshold biomass levels. It is possible to define biomass based BRPs for red crab, but they are likely to be of little use because of the lack of stock assessments, lack of useful survey data, and difficulties interpreting fishery catch rates (LPUE). None of the options proposed by the DPSWG for biomass BRPs involved commercial catch rates (LPUE) because they have proven difficult to interpret for red crab (NEFSC 2006). The longer time series now available and cooperation between assessment scientists and vessel captains should lead to improved usefulness of LPUE data from the fishery. Reconstruction of historical LPUE would be particularly useful in combination with the fluctuating landings, which would provide an estimate of the surplus production of the stock over time.

It should be noted that the general rules regarding biomass-based reference points assume that both sexes are being exploited. In many cases, reference points are based on female biomass under the assumption that the spawning biomass of females is of most importance to the productivity of the fishery. The red crab fishery has taken only males throughout most of its history, leaving the female spawning biomass essentially intact. As long as the male population is capable of fertilizing the females, reproductive output should remain close to that of an unfished population.

Three proposed options for B_{MSY} estimates that could be used as target BRPs for red crab are described below. In each case, the threshold BRP would be half of the B_{MSY} estimate or proxy.

Option	B_{MSY} (males only)
1	18,867 mt (90+ mm CW)
2	16,904 mt (fishable sizes)
3	36,253 mt (fishable sizes)

7.2.1 Option 1: Status quo, or no action.

The biomass based target B_{MSY} = 18,867 mt of male red crab 90+ mm CW and the approximation $B_{MSY} = ½\,B_0$, where B_0 was the estimated biomass of male red crab during the 1974 survey, with adjustments for areas not sampled in the survey. The biomass threshold that defines overfished stock biomass conditions is ½ B_{MSY} = 9,434 mt.

This option was not recommended by the DPSWG because it ignores the likelihood that $B_{MSY} < ½\,B_0$. The assumption that $B_{MSY} = ½\,B_0$ is based on the logistic growth curve, which implies that the effects of density dependent controls are symmetrical around ½ B_0. Neither the Beverton-Holt nor the Ricker stock-recruitment relationships are symmetrical, with the result that $B_{MSY} < ½\,B_0$. B_{MSY} moves to smaller fractions of B_0 as the SRR becomes more compensatory, whether it follows a Beverton-Holt model or a Ricker model. B_{MSY} also moves toward a smaller fraction of B_0 as the point where the replacement line crosses the SRR curve moves to the right. If the increase in fishable male biomass that was estimated from the 1974 and 2003-2005 surveys is real, it implies a highly hyper-compensatory SRR, with a correspondingly lower ratio of B_{MSY} to B_0.

The PDT discussed the likelihood that the SRR for red crab follows a Ricker model, but did not come to any conclusion regarding the relationship between that likelihood and B_{MSY}.

7.2.2 Option 2:

Option 2 would use the updated estimate of MSY (to be selected, see below) and current fishable biomass for the most recent assessment to estimate B_{MSY}. The biomass threshold that defines overfished stock biomass conditions is ½ B_{MSY}.

The main advantage to this option is ensuring that biomass BRPs are consistent with exploitation based BRPs. If the virgin biomass is very uncertain, then it may be better to base biomass reference points on the MSY proxy or estimate of sustainable landings. The main disadvantage is that it necessitates additional information about stock productivity. In addition, it may provide a poor estimate of B_{MSY} if the F_{MSY} proxy is inaccurate or the estimate of sustainable yield is substantially different from MSY. It may also be misleading if the biomass in 2003-2005 resulted from a combination of highly variable removals in previous years and population dynamics that were in the process of adjusting productivity to those removals.

In particular, assume $F_{MSY} = cM$ where $c = 0.7$ (see below) and the natural mortality rate, $M = 0.15$ y^{-1} (see below), then MSY = $F_{MSY} B_{MSY} = 0.7(0.15) B_{MSY} = 0.105 B_{MSY}$ and B_{MSY} = MSY / 0.105 = 9.52 MSY.

For example, if MSY = 1,775 mt (the long term average landings and within the range of sustainable yield and MSY proxy options given below), then the biomass target $B_{MSY} = 9.52 \times 1{,}775 = 16{,}904$ mt fishable biomass and the biomass threshold $B_{MSY}/2 =$ 8,452 mt fishable biomass.

(If $M = 0.10$ y^{-1} as suggested by the DPSWG, B_{MSY} =MSY / 0.07 = 14.29 * MSY. In this case, if MSY = 1775 mt, $B_{MSY} = 14.29 \times 1{,}775 = 25{,}365$ mt and the biomass threshold $B_{MSY}/2 =$ 12,682.)

(If $F_{MSY} = cM$ and $c=>1$ (Hilborn 2010; MRAG 1996) for stocks with a recruitment steepness of 0.5 or higher and $L_c>0.5*L_\infty$, B_{MSY} =MSY/0.10 = 10 * MSY. In this case, if MSY = 1775 mt, $B_{MSY} = 10 \times 1{,}775 = 17{,}775$ mt and the biomass threshold $B_{MSY}/2 =$ 8888 mt.)

(The MSY control rule for king and Tanner crabs is the mature biomass of a stock under prevailing environmental conditions, or proxy thereof, exploited at a fishing mortality rate equal to a conservative estimate of natural mortality. SY in a given year is the MSY rule applied to the current spawning biomass. Overfishing occurs if the SY is exceeded for more that one year. (NMFS 2000)

7.2.3 Option 3:

Option 3 would use the most recent estimate of fishable biomass from the last assessment (36,247 mt) as B_{MSY}. The biomass threshold that defines overfished stock biomass conditions is ½ B_{MSY}.

The main advantage of this option is that it is based on the relatively reliable 2003-2005 biomass estimate. As described above, uncertainties about the 1974 biomass estimate for red crab may preclude its use in estimating virgin biomass. The stock shows signs of fishing down (reduction in abundance of large males) expected under fishing. Current fishing mortality rates appear to be relatively low ($F = 0.055 y^{-1}$ in the managed stock area ignoring discards, and no more than 0.1 y^{-1} including discards). These fishery induced mortality estimates are comparable to the range of F_{MSY} levels ($F_{MSY} = 0.6M$ to $0.8M$, or $F_{MSY} = 0.06$-0.16, with $M = 0.1$ - 0.2 y^{-1}) that might be considered for red crab and potentially sustainable. The main disadvantage is the possibility that current biomass is substantially larger or smaller than B_{MSY}. Crab populations are known to exhibit high variability. Modeling results presented below indicate the possibility that the history of variable landings in the red crab fishery may have introduced significant stock fluctuations into the indefinite future. The likelihood that the population was not in equilibrium in 2003-2005 makes it risky to assume that the estimated biomass represents B_{MSY}.

7.2.4 Recommendations of the DPSWG with Comments from the PDT

The second option (use the updated estimate of MSY to specify B_{MSY}) was recommended by the DPSWG but was not accepted by the Peer Review Panel. Option 1, the status quo, was left in place by the Peer Review panel. Option 3 was not recommended by the DPSWG because it implies MSY = $F_{MSY}B_{MSY}$ levels of about 0.7(0.1)* 36,253 = 2,538 mt per year. This estimate is substantially larger than the long term average landings which have had a pronounced, but not unexpected, effect on the relative abundance of large males.

Although the biomass estimated from the 2003-2005 survey may not represent B_{MSY}, it might still be appropriate to consider in the calculation of the overfishing limit.

The precaution that was embedded in the estimate of MSY derived from the DCAC/long-term average catch model and recommended by the DPSWG is evident from the discussion on page 192 of the DPSWG Report concerning the alternatives for estimating Bmsy. The DPSWG Review Panel chose MSY to equal the long-term average catch that results from running the DCAC model with a zero depletion DELTA. That implies that the biomass at the end of the time period is Bmsy. In the case of red crab, we have a high degree of confidence in the ending biomass estimate of 36, 247 metric tons of fishable size males. The DPSWG specifically rejected the ending biomass as an estimate of Bmsy because "it implies MSY=Fmsy*Bmsy levels of about 0.7 (0.1) * 36,253 = 2,538 mt per year." Whereas the effect on the relative abundance of large males is no more pronounced than one would expect, the estimates of Bmsy and MSY in Option 3 seem to have a desirable congruence, with the caveat that the red crab stock may exhibit high variability as the result of either endogenous cycling or fluctuations introduced by the interaction between highly variable landings and the population dynamics of the stock.

7.3 Options for Exploitation Based BRPs

All of the options for exploitation-based BRPs in this report are specified in terms of landings (yield) because landings are the only data consistently available for the fishery. Landings based BRPs are also desirable for red crab because they are simple and easy for managers to use outside of the formal stock assessment process and without extensive review.

Ideally, all exploitation-based BRPs would be MSY estimates or proxies to be used as thresholds that define overfishing. In principal, these BRPs are not used as targets. In particular, current NSGs indicate that managers may specify any annual catch limit (ACL) as long as exploitation is below the exploitation threshold BRP, which constitutes the overfishing limit (OFL) as modified to account for scientific uncertainty, resulting in an acceptable biological catch (ABC) that incorporates a level of risk that is acceptable to the Council. In other words, Councils are expected to inform their SSCs regarding the risk that they are willing to tolerate that the threshold reference point will be exceeded with catches at the recommended ABC level. In this report, we focus primarily on scientific uncertainties about the reference points themselves. We include uncertainties that affect the probability that the catch will actually be constrained to the ACL in the buffer that we recommend between ACL and ABC.

A number of methods used to calculate potential exploitation-based BRPs are estimators for "sustainable" landing levels, rather than estimates or proxies for MSY. There is no guarantee that sustainable landing levels calculated for red crab are near MSY. The nature of the sustainable yield curve results in a wide range of sustainable yields that may be produced from biomass levels that range from underexploited to seriously depleted. Sustainable yield estimates are often estimates of average landings during a time when biomass was considered to be relatively stable, with adjustments for unsustainable "windfall" landings that may occur as virgin stock is fished down towards B_{MSY}. MSY is the maximum sustainable harvest level at biomass levels usually less than ½ virgin biomass. In the case of red crab, data is not available or has not been analyzed to determine whether biomass has been stable for any significant period of time. The expectation of "windfall" landings is confounded by the apparent increase in fishable male biomass that was estimated from the 2003-2005 survey compared to 1974.

With the exception of the stochastic model results, the methods used in this report to calculate potential exploitation-based BRPs are equilibrium estimators that assume constant recruitment, growth, and mortality over the period of years in the model. Equilibrium estimators are often used in data poor circumstances, but they tend to perform poorly in non-equilibrium situations, which is clearly the case with red crab. Size composition data from the 1974 and 2003-2005 surveys indicate changes in recruitment because small male and female red crab were more abundant during the latter survey. Changes in growth and recruitment would, in fact, be expected as the near virgin stock in 1974 was fished down over several decades. Results of the equilibrium estimators are uncertain to the extent that equilibrium assumptions may have been violated. The highly variable nature of red crab exploitation rates assures that the equilibrium assumption does not hold, but it also avoids the "one-way trip" experience that is characteristic of many fisheries. If a reliable history of CPUE could be established, so could the response of the red crab fishery to different levels of exploitation.

> Gabriel and Mace (1999) suggest that:
> For a fishery where annual quotas remain constant over a prolonged period (perhaps because there are insufficient data to update stock assessments), such quotas should be set at a level of 60-90% of the equilibrium or static estimate of *MSY*, with the high end of the scale applying to species with low natural variability or low *M*, and the low end applying to species with high natural variability or high *M*.

Mace and Sissenwine, (1989) discuss proxies for data poor fisheries as follows:

> *Proxies for F_{MSY} in Data Poor Fisheries*
> The natural mortality rate M has often been considered to be a conservative estimate of F_{MSY}; however, it is becoming more and more frequently advocated as a target or limit for fisheries with a modest amount of information.
> In fact, in several fisheries, $F=0.8*M$ and $F=0.75*M$ have been suggested as default targets for data-poor cases (Thompson, 1993; NMFS, 1996). In data-poor situations, M may not be reliably estimated either, however.

The PDT is not aware of guidelines that consider species for which age-specific natural mortality rates may vary significantly.

The PDT used six methods for estimating MSY or proxies and 23 individual approaches:

7.3.1 Option 1: Status Quo from FMP

The FMP used the Gulland (1972) yield equation to estimate MSY at 2,830 mt.

7.3.2 Option 2: Long-term Average Landings

We can make the argument that if CPUE, in pounds per day at sea, has been relatively stable, and the biomass of currently marketable red crab has not changed much from 1974 to 2005, then the level of fishing on the population since the 1970s must be sustainable. If summed recorded landings from 1973-2007 (35 years) = 62,132 mt, then the mean average take of red crab has been 1,775 mt, which is slightly less than mean landings since 2002. One of the problems with this approach is that our knowledge of biomass levels during the period of fluctuating landings is uncertain at best. Following the theory inherent in the logistic growth model, we would have expected CPUE and the fished biomass to decline by about one-half if the unexploited stock were fished down to B_{MSY}. The fishing mortality rate may have been low enough over the course of the fishery to make natural fluctuations more prominent than changes due to fishing. Fairly recent reductions in size selectivity imply little or no fishing in previous years on the lower end of the currently selected population. We do have evidence that good recruitment was taking place immediately following years of high landings. The PDT calculated average landings for a variety of time periods (Table 10).

The PDT recommends the use of average landings from 2002-2007 (1853 mt) as representing the sustainable level of landings of male crab that can be taken from the red crab resource. This period of years was selected based on the reliability of landings records and its congruence with both longer time series and with the low side of the central tendency of a range of sustainable yield estimates. The PDT reasoning included the likelihood that longer time series are under-estimates of the true landings. The PDT also noted information from the 2006 stock assessment that indicated that landings averaging xxxx from 2001-2005 had not produced any decline in average size. The size distribution of landed crabs in 2008 showed an increase compared to 2001-2007.

7.3.3 Option 3: Alternative Yield Equations

The equation used to calculate MSY in the FMP was Y = (0.5)(M)(B_0) = (0.5)(0.15)(B_0 of males > 114 mm CW). However, $B_{MSY} < ½ B_0$, is more accepted at present. There is less agreement concerning the ratio of F_{MSY} to M. Walters and Martell (2004) found that the ratio of F_{MSY} to M at maximum sustainable yield is less than 1 for most fisheries. More recently, however, Hilborn (2010) found that "at low [recruitment] steepness the harvest rate must be much lower (15–35%) than natural mortality to achieve PGY (Pretty Good Yield), but at high steepness the harvest rate that achieves PGY is generally greater than natural mortality (100–330%)."

Hilborn and ??? () point out that the F_{MSY} to M ratio depends heavily on the age at entry into the fishery compared to the age of sexual maturity. They concluded that animals that get to spawn at least once before entering the fishery may have F_{MSY} to M ratios of 1 or more.

MRAG (1996) cites Polovina (1987) as the source of the following simple rule for setting effort levels:

- if Lc50<Lm50 then set $F=M$
- if Lc50 > Lm50 then set $F=2M$

where Lc50 and Lm50 are the 50% lengths at capture and maturity respectively expressed as ratios with the asymptotic length. MRAG (1996) simplifies this rule further by suggesting that: "if Lc=0.5, the best F is approximately $F=M$, whereas if Lc=0.6, then $F=2M$ is allowable. If this criterion is followed, it would not be necessary to estimate L_m in order to maximise yield to within a reasonable tolerance." MRAG (1996) considered a rule that sets fishing mortality equal to natural mortality to be precautionary if Lc=0.5.

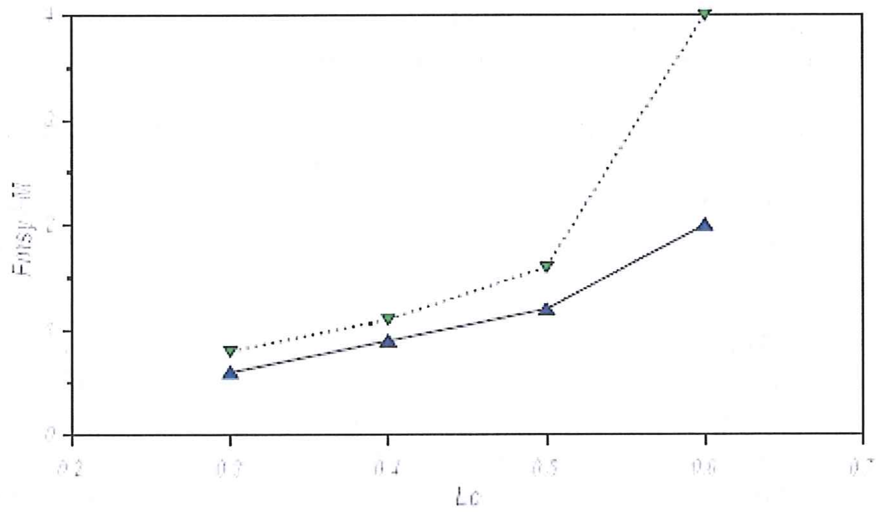

Figure 17- MRAG (1996) provides guidance on the relationship between the length at which 50% of animals are captured (as a fraction of asymptotic length) and the ratio of Fmsy to M. The x-axis is the Lc50 with a range of 0.2 to 0.7 and the y-axis is the Fmsy/M ratio with a range of 0 to 4.

The solid line is for species with a length at 50% maturity of 0.6 times the asymptotic length and the dotted line is for species with a length at 50% maturity of 0.5 times the asymptotic length.

Haefner (1977) reports the size at maturity of red crabs off Virginia was between 80-91 mm CW. Several studies reported ovigerous crabs are found primarily at sizes between 80-130 mm CW (Wigley et al. 1975; Haefner 1977; Hines 1988), although some egg-bearing red crabs were observed as small as 61 mm CW (Elner et al. 1987). Lawton and Duggan (1998) report that preliminary research on Canadian red crab (an extension of the U.S. Atlantic stock) found all males over 75 mm CW (of 347 animals sampled) to be mature. While egg-bearing females of 75 mm CW were noted, some females (of 423 sampled) were still virgin at 94 mm CW. Lawton and Duggan apparently combined the fact that some females were still virgin at 94 mm with the presumption that females require larger males for mating to suggest that males smaller than 115 mm CW may be functionally immature. It would seem more appropriate to suggest that males smaller than 115 mm may not be able to fertilize some portion of the female population.

With no fishing on females prior to 2009, and minimal fishing on females in 2009, one would not expect there to have been any significant effects of fishing on the female spawning stock. For male red crabs, the length at 50% selectivity was estimated to be about 90-94 mm in 2004-2005 (NEFSC 2006). With a maximum CW of 180 mm, L_c50 is therefore 0.5, which would indicate a fishing mortality rate equal to or greater than M under the rule of thumb suggested by MRAG for deep water fish in the Indian Ocean. L_c50 would also appear to be larger than L_m50, with some uncertainty created by the effect of mating size requirements on the effective spawning biomass.

Polovina (1993) concluded that a fishing mortality rate equal to 1.7 times M, in conjunction with an appropriate minimum harvest size, would not cause a decline in CPUE in the Hawaiian lobster fishery. The MSY control rule for king and Tanner crabs is the mature biomass of a stock under prevailing environmental conditions, or proxy thereof, exploited at a fishing mortality rate equal to a conservative estimate of natural mortality. SY in a given year is the MSY rule applied to the current spawning biomass. Overfishing occurs if the SY is exceeded for more that one year. (NMFS 2000)

MRAG (1996) discussed the influence of density dependent recruitment on yield and resilience. They concluded that: "Generally, underestimating the density dependence of a species means that higher yields are obtained than were expected, whereas overestimating it can lead to a false sense of security about the stock's tolerance to high effort."

Wahle (2003) found that Ricker (dome-shaped) stock-recruitment dynamics were more prevalent than Beverton-Holt (asymptotic) stock-recruitment dynamics for a number of well-studied crab taxa, including snow crab, Dungeness crab, blue crab, and green crab. For these crabs, cannibalism is the density-dependent mechanism that operates at high densities. The PDT concluded that Ricker dynamics seem likely for red crab.

For a male-only fishery like red crab has been, where the opportunity for females to spawn is unfettered, the issue is more likely to be the potential for sperm limitation at some critical sex ratio and male size distribution.

The yield equations must be updated to match the conditions of the current red crab fishery. For example, the B_0 must be for males smaller than the 114+ mm CW for which yield was originally calculated. As indicated in the discussion above, a coefficient c should be applied to M that may be higher or lower than 1 depending on the resilience of the stock-recruitment relationship. The equation is then $Y = (0.4)(c)(M)(B_0$ fishable males). The PDT used a range of values for M and c and calculated MSYs based on both the 1974 and 2003-2005 survey biomass of fishable males.

Option 3a: Updated yield equation using $F_{MSY} = c * M$ and $B_{MSY} = 0.4 * B_0$, with c=0.8

The equation used to calculate MSY in the FMP was $Y = (0.5)(M)(B_0) = (0.5)(0.15)(B_0$ of males > 114 mm CW). However, $B_{MSY} < ½B_0$ if the underlying spawner-recruit relationship is not symmetrical. Also, the ratio of F_{MSY} to M at maximum sustainable yield has been found to be less than 1 for most fisheries (Walters and Martell 2004). To update this equation to match the conditions of the current red crab fishery, the B_0 must be for males smaller than the 114+ mm CW for which it was originally calculated. So that leaves the equation $Y = (0.4)(c)(M)(B_0$ fishable males).

If the unexploited biomass of males 90+ mm was 34,300 mt as estimated from the 1974 survey, with a value for c of 0.8 and M=0.10, MSY would be 1098 mt. Table 10 lists values of MSY for a range of possible values for M with c=0.8.

Option 3b: Updated yield equation using $F_{MSY} = c * M$ and $B_{MSY} = 0.4 * B_0$, with c=1.0.

The equation used to calculate MSY in the FMP was $Y = (0.5)(M)(B_0) = (0.5)(0.15)(B_0$ of males > 114 mm CW). The ratio of F_{MSY} to M at maximum sustainable yield has been found to be less than 1 for most fisheries (Walters and Martell 2004), but greater than 1 for animals that are allowed to spawn once before entering the fishery and have an Lc50 of 0.5 or more. To update this equation to match the conditions of the current red crab fishery, the B_0 must be for males smaller than the 114+ mm CW for which it was originally calculated. So that leaves the equation $Y = (0.4)(c)(M)(B_0$ fishable males).

If c (ratio of F_{MSY} to M) =1, and M=.10, and the biomass of fishable males was 30,302 mt, MSY would be 1818 mt. Table 10 lists values of MSY for a range of possible values for M with c=1.0.

Option 3c: Updated yield equation using $F_{MSY} = c * M$ and $B_{MSY} = 0.4 * B_0$, with c=0.8 with 2003-2005 biomass.

The equation used to calculate MSY in the FMP was $Y = (0.5)(M)(B_0) = (0.5)(0.15)(B_0$ of males > 114 mm CW). The ratio of F_{MSY} to M at maximum sustainable yield has been found to be less than 1 for most fisheries (Walters and Martell 2004), but greater than 1 for animals that are allowed to spawn once before entering the fishery and have an Lc50 of 0.5 or more. To update this equation to match the conditions of the current red crab fishery, the B_0 must be for males smaller than the 114+ mm CW for which it was originally calculated. So that leaves the equation Y = (0.4)(*c*)(*M*)(B_0 fishable males).

If c (ratio of Fmsy to M) =0.8, and M=.10, and the biomass of 90+ mm males was 36,247 mt, MSY would be 1160 mt.

***Option 3d**: Updated yield equation using $F_{MSY} = c * M$ and $B_{MSY} = 0.4 * B_0$, with c=1.0 with 2003-2005 biomass.*

The equation used to calculate MSY in the FMP was Y = (0.5)(*M*)(B_0) = (0.5)(0.15)(B_0 of males > 114 mm CW). The ratio of F_{MSY} to *M* at maximum sustainable yield has been found to be less than 1 for most fisheries (Walters and Martell 2004), but greater than 1 for animals that are allowed to spawn once before entering the fishery and have an Lc50 of 0.5 or more. To update this equation to match the conditions of the current red crab fishery, the B_0 must be for males smaller than the 114+ mm CW for which it was originally calculated. So that leaves the equation Y = (0.4)(*c*)(*M*)(B_0 fishable males).

If *c* (ratio of F_{MSY} to *M*) =1, and *M*=.10, and the biomass of 90+ mm males was 36,247 mt, MSY would be 1450 mt.

***Option 3e and f**: Garcia, Sparre and Csirke (1989)*

The yield equation published by Garcia, Sparre, and Csirke (1989) has the advantage of using current biomass and current landings. The biomass estimated from the 2003-2005 survey is considered more reliable than the unexploited biomass estimated from the 1974 survey and landings during 2003-2005 are considered reliable.

e. *MSY estimator based on Schaeffer Model.*

$$MSY = \frac{(F_{MSY} B_c)^2}{2F_{MSY} B_c - Y_c}$$

In the special case that $F_{MSY} = M$, the estimator becomes

$$MSY = \frac{(MB_c)^2}{2MB_c - Y_c}$$

MSY=(0.8*M*Bc)^2/2*M*0.8*Bc-Yc

MSY=(0.8*0.1*36247)^2/2*0.1*0.8*36247-2040

MSY=2237 mt

f. *MSY estimator based on Fox Model*

$$MSY = F_{MSY} B_c \exp\left(\frac{Y_c}{F_{MSY} B_c} - 1 \right)$$

In the special case where Fmsy=M, the estimator becomes

$$MSY = MB_c \exp\left(\frac{Y_c}{MB_c} - 1 \right)$$

MSY=.8*.1*36247exp(2040/(.8*.1*36247)-1)

MSY=2156 mt

7.3.4 Option 4: Depletion-corrected average catch (DCAC) model.

The availability of biomass estimates from surveys in 1974 and 2003-2005 allowed the use of a depletion-corrected average catch model that uses length frequency or abundance data from two points in time to look at potential sustainable yields. Ideally, the DCAC model input consists of summed annual landings, an estimate of *M*, an estimate of the F_{MSY} to *M* ratio, the amount of depletion between the two surveys, and the number of years between them. It calculates a sustainable yield after accounting for the "windfall" which occurs at the beginning of the fishery as the standing stock is fished down to the B_{MSY} level under the classic logistic growth model assumptions. The DCAC model was run using several different estimates of *M* and with different assumptions regarding biomass estimates from the two surveys. These assumptions are critical to the model results. The model was run using an F_{MSY} to *M* ratio of 0.8, which may be precautionary considering the relationship between the length at capture, the maximum length, and the length at sexual maturity.

This report presents the confidence intervals surrounding the DCAC model estimates of sustainable yield for both the zero depletion delta and the -0.2 depletion delta. The DCAC model was run from the NOAA Fisheries Tool Box with 10,000 iterations using stochastic combinations of input parameters. The model results therefore cover a wide range, with the most probable results appearing at a higher frequency. This report presents a histogram of sustainable yield results and the associated confidence intervals. This information provides a basis for evaluating the risk associated with different OFLs based on the DCAC model results, assuming that the model accurately represents the characteristics of the resource and the variability of those characteristics.

The relationship between DCAC estimates of sustainable yield and MSY are also critical to the use of DCAC results in estimating MSY. Appendices 2b and 2d contain analyses of this relationship, one done by Alec MacCall, the creator of the DCAC model, and one done by the PDT. The analysis done by Alec MacCall indicates that the DCAC estimate of sustainable yield is likely to be 72% of MSY for a fishery producing MSY at equilibrium. The analysis done by the PDT uses the DCAC model on modeled fisheries with known parameters. This analysis indicates that the relationship between the DCAC results and MSY depends on the particular history of a fishery and its interaction with the stock dynamics.

Option 4a: ***Depletion-corrected average catch (DCAC) model – Zero DELTA.***

The DCAC model results that were presented to the DPSWG did not use the actual amount of depletion between the two surveys, contrary to the explanation of the model that was given in the DPSWG working paper. The decision to assume a "zero depletion delta," (no change in biomass from one survey to the other) apparently resulted from a judgment that it would not be in the spirit of the model to accept an increase in harvestable male biomass after 35 years of fishing. This assumption results in a "zero DELTA" in DCAC terms. A zero DELTA gives a value of zero to the term that gives the DCAC model its meaning. When there is little or no trend in abundance, the DCAC model is the same as calculating the average landings. This explains the "congruence between the DCAC model results and the long-term average catch" that appealed to the DPSWG Review Panel. (For an explanation of the DCAC model, see Appendix 2. Note that the explanation does not necessarily coincide with the procedures or values used for red crab during the DPSWG.) The PDT considers the use of an assumed zero depletion DELTA that does not reflect the survey abundance estimates to be precautionary compared to the use of a depletion DELTA calculated from the survey abundance estimates.

Option 4b: ***DCAC model with -0.2 delta.***

The PDT considered possible explanations for an increase in fishable biomass after 30 years of highly variable landings. Such an increase would be possible with a Ricker stock-recruitment relationship if one of the density-dependent control mechanism were cannibalism of the smaller males by the larger males. In that case, the reduction in the population of large males that was seen in the 2003-2005 survey may have led to a corresponding increase in the survival of smaller males. The PDT also noted research on other species that showed an increase in abundance of smaller animals as the population was fished intensively (Momot 1995; Schroder 2009; Zipkin 2008) .

Table 7- Confidence intervals for sustainable yield estimates produced by the DCAC model with two approaches to the depletion DELTA. Additional detail provided in Appendix 2b.

	-0.2 Depletion Delta		0 Depletion Delta	
M=0.05				
Average DCAC	3441		1870	
Median DCAC	2761		1781	
	LCI	UCI	LCI	UCI
1% - 99% CI =	-4028	17833	1181	3553
5% - 95% CI =	1862	7177	1340	2639
10% - 90% CI =	2007	5154	1434	2356
20% - 80% CI =	2210	3898	1545	2114
M=0.10				
Average DCAC	2193		1797	
Median DCAC	2168		1777	
	LCI	UCI	LCI	UCI
1% - 99% CI =	1711	3567	1419	2367
5% - 95% CI =	1833	2907	1528	2123
10% - 90% CI =	1896	2668	1586	2025
20% - 80% CI =	1975	2454	1652	1930
M=0.15				
Average DCAC	2050		1786	
Median DCAC	2019		1777	
	LCI	UCI		
1% - 99% CI =	1732	2669	1520	2131
5% - 95% CI =	1813	2398	1602	1993
10% - 90% CI =	1854	2285	1645	1934
20% - 80% CI =	1904	2176	1691	1875

Whereas DCAC estimates tend to be less than 72% of MSY, the PDT estimated MSY by dividing the DCAC results by 0.72. The confidence intervals around the DCAC estimates of sustainable yield represent the uncertainty incorporated into the model input parameters. These values provide an indication of the probability that the true sustainable yield (given the model and assumptions) falls outside the indicated confidence interval. The following assumptions were incorporated into the DCAC model runs:

- Standard deviation of 0.25 for ln*M* in DCAC model inputs
- Standard deviation of 0.05 for F_{MSY} to *M* ratio of 0.8
- Standard deviation of 0.10 for depletion DELTA of either 0 or -0.20

7.3.5 Option 5: 2-Point Boundary Model

The two-point boundary model uses abundance data from 2 points in time, and was run using various values of *M*. Estimates of median recruitment of males and females of various sizes, average *F*, and catch at equilibrium were derived for male and female red crabs from the 1974 and 2003-2005 surveys, and landings from 1974 to 2003. For model details see appendix 3.

7.4 Models Based on Geryon maritae Growth Model

The National Standard 2 guidelines state that: “analysis of related stocks or species is a powerful tool for inferring the likely traits of stocks for which stock-specific data are unavailable or are not sufficient to produce reliable estimates.” In a similar vein, Hilborn and Liermann (1998) emphasize the importance of using knowledge gained from studies of stocks similar to those under examination.

Information on growth rates specific to *C. quinquedens* is currently sparse. However, Mellville-Smith (1985, 1987, 1989) studied the closely related Namibian red crab, *G. quinquedens*. Mellville-Smith noted that: “the two species resemble each other so closely, that they were confused with each other up until 1981 (see Manning & Holthuis, 1981).” Mellville-Smith (1989) provided evidence (Table 2) concerning the similarity between the species to support his use of juvenile growth data for *C. quinquedens* in the construction of his growth model for *G. maritae*.

A comparison of length/weight relationships derived for *G. maritae* (Mellville-Smith 1989) and *C. quinquedens* (Farlow 1980) shows *C. quinquedens* being slightly lighter for the same CW, with a maximum difference in weight of -10% at 170 mm CW.

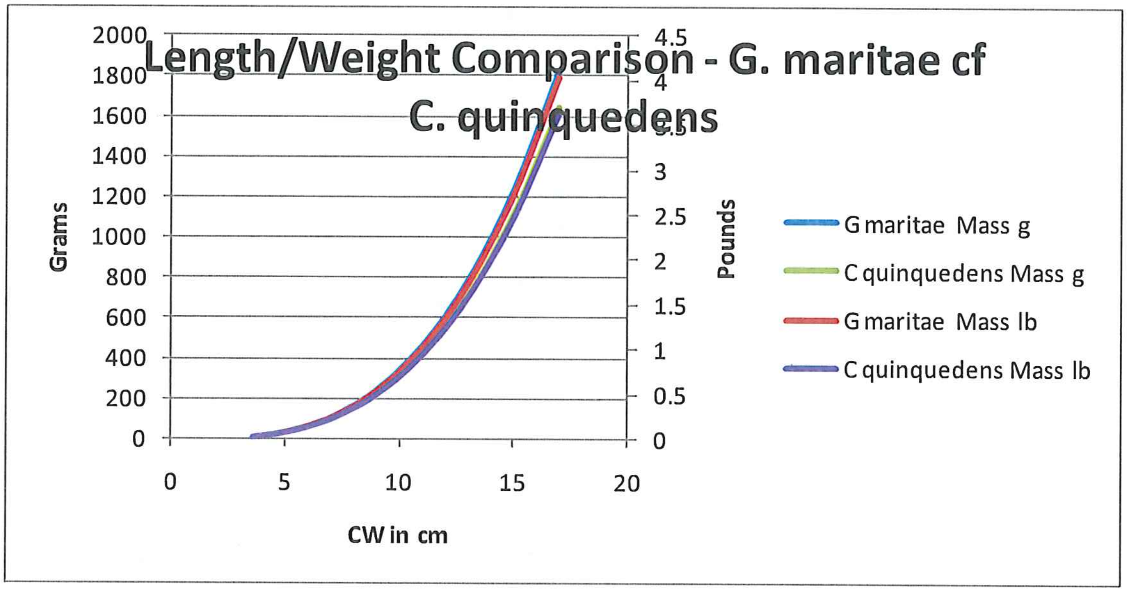

Figure 18- Length-weight comparison for *G. maritae* and *C. quinquedens*.

The PDT followed the same reasoning in using Mellville-Smith’s growth model for Namibian red crab in constructing life history models for the northwestern Atlantic red crab. The parameters for the von Bertalanfy equation that fits the growth model developed by Mellville-Smith (1989) for the Namibian red crab are shown in (Table 8).

Table 8- Parameters for von Bertalanfy equation that fits the growth model developed by Mellville-Smith (1989) for *G. maritae*.

L_∞	191.5667
K	0.063771
t_0	-0.52991
b	3.180817

7.4.1 Yield-per-Recruit Model Using *Geryon maritae* Growth Model

The PDT evaluated yield-per-recruit (YPR) using growth parameters for the closely-related Namibian red crab. The results are presented in

Table 9. The model indicates that Fmax for Namibian red crab with an assumed natural mortality rate of 0.10 would be 0.210.

Table 9 also indicates that F0.1, or the fishing mortality rate at which the YPR curve would have a slope of 10% of the slope at the origin, would be 0.10.

Table 9 also shows the catch that would result from the indicated fishing mortality rates with a fishable biomass level of 79,910,136 lb, which was estimated by the 2006 stock assessment.

Table 9- Yield per recruit schedule for red crab using an age-CW model for Geryon maritae (Mellville-Smith 1989), CW-weight model from Farlow (1983), M=0.10 and selectivity as estimated by the 2006 red crab stock assessment (NEFSC 2006). The yield lost column uses Fmax as a reference. The biomass of fishable males was estimated at 79,910,136 lb by the 2006 stock assessment.

F	YPR	Yield	TAC with Biomass of	
		Lost	†79910136.2	
0.010	0.06061	77%	Lbs	MT
0.020	0.10601	59%	1,598,203	725
0.030	0.14047	46%	2,397,304	1087
0.040	0.16691	36%	3,196,405	1450
0.050	0.18738	28%	3,995,507	1812
0.060	0.20335	22%	4,794,608	2175
0.070	0.21588	17%	5,593,710	2537
0.080	0.22575	13%	6,392,811	2900
0.090	0.23355	10%	7,191,912	3262
*0.100	0.23973	8%	7,991,014	3625
0.110	0.24462	6%	8,790,115	3987
0.120	0.24848	4%	9,589,216	4350
0.130	0.25152	3%	10,388,318	4712
0.140	0.25391	2%	11,187,419	5075
0.150	0.25575	2%	11,986,520	5437
0.160	0.25716	1%	12,785,622	5800
0.170	0.25821	1%	13,584,723	6162
0.180	0.25897	0%	14,383,825	6524
0.190	0.25950	0%	15,182,926	6887
0.200	0.25982	0%	15,982,027	7249
0.210	0.25999	0%	16,781,129	7612
**0.220	0.26002	0%	17,580,230	7974
0.230	0.25994	0%	18,379,331	8337
*$F_{0.1}$				
**F_{max}				
† Fishable biomass estimated from 2003-2005 survey				

As a point of reference, if the long-term average landings of 1775 mt were used as a TAC with a biomass of 36,247 mt, it would represent a reduction in yield of approximately 33% compared to Fmax. The 1615 mt TAC proposed for 2010 would represent a loss in yield of approximately 38% compared to Fmax if the biomass is still 36,247 mt.

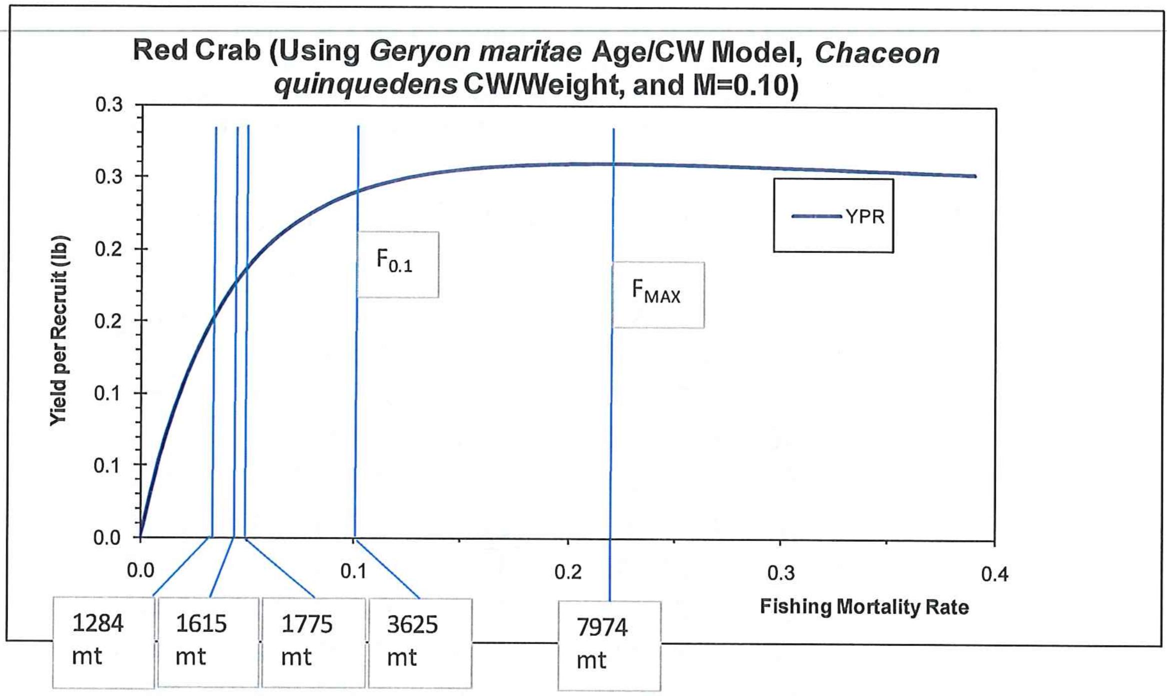

Figure 19- Yield per recruit curve for red crab using *Geryon maritae* age-CW model (Mellville-Smith 1989), *Chaceon quinquedens* CW-weight model (Farlow 1983), M=0.10, and selectivity for northwestern Atlantic red crab fishery (NEFSC 2006). Numbers in boxes indicate the point on the YPR curve that would be implied by fishing at the indicated F if the fishable biomass equaled 79,910,136 lb (36,247 mt) as estimated from the 2003-2005 survey.

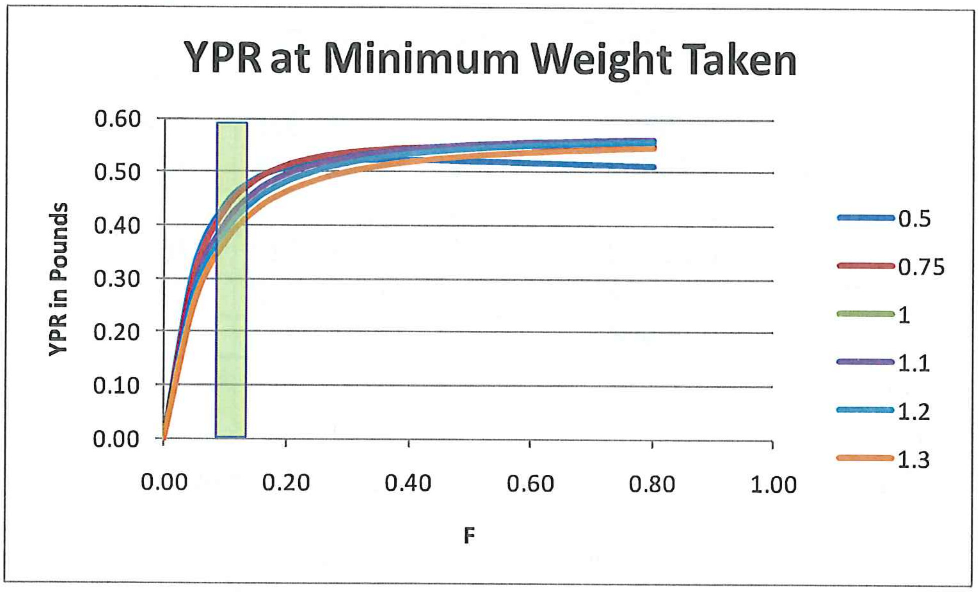

Figure 20- Yield per recruit for red crab using *Geryon maritae* age-CW model (Mellville-Smith 1989), *Chaceon quinquedens* CW-weight model (Farlow 1983), M=0.10, and selectivity for northwestern Atlantic red crab fishery (NEFSC 2006) with a range of minimum sizes constraining selectivity at the lower end. The approximate range of $F_{0.1}$ is shown by the green shaded rectangle.

7.4.2 Population Projection Model

The Review Panel for the DPSWG noted that: "a key assumption made in all of the analyses brought forward by the DPSWG for this population was that the harvest pattern was a sample from a stationary population. This extent to which this assumption is met is unknown, and introduces considerable uncertainty into the BRPs."

The DPSWG also noted that the increase in fishable biomass that was seen in the 2003-2005 survey after 30 years of fishing would normally not be expected. This increase gives rise to two competing hypotheses: 1) the 1974 survey underestimated biomass; and 2) some feature of red crab population dynamics allowed portions of the stock to increase as fishing reduced the large male population. The development of the red crab fishery contrasts with other expectations as well. Rather than a general increasing trend in fishing effort and landings over the history of the fishery, landings were highly variable over the first 30 years of fishing.

Certain characteristics of the red crab population lend support to the theory that larger males may cannibalize the smaller males (and females, which also increased after a substantial decline in the large male population). Those factors include the segregation of the population into smaller males, larger males, and females, by depth, and the known incidence of cannibalism in other crab and crustacean species. Wahle's (2003) review of stock-recruitment and juvenile-recruitment relationships for large-bodied crustacea states that:

> "Reports of cannibalism were exclusively found among the crabs surveyed (Table 4). Inter-cohort cannibalism in blue crab, *C. sapidus* (Hines and Ruiz, 1995), Dungeness crab, *Cancer magister* (e.g., Fernandez et al., 1993a,b), and snow crab, *Chionoecetes opilio* (Lovrich and Sainte-Marie, 1997), has been invoked as a possible explanation for over-compensatory juvenile-to-recruit relationships in these species. Cannibalism by older cohorts on younger ones can cause population cycling, a dominant feature of the dynamics of at least two of the crabs reviewed here: *C. magister* (Botsford, 1986; Botsford and Hobbs, 1995) and *C. opilio* (Sainte-Marie et al., 1996)."
>
> Wahle (2003) concluded that:
>
> Post-settlement density-dependence seems to be more the rule than the exception among the taxa surveyed. For virtually all the species in which juvenile to- fishery recruit relationships have been documented, non-linear relationships provide the best statistical fit. These range from power functions for the species with the weakest density effects, such as *P. cygnus*, to Ricker functions among the species, such as *C. sapidus*, for which fecundity, larval retention and settlement is high, and for which there is evidence of strong density-dependent post-settlement cannibalism.

Wahle et al. (2008) commented specifically on the increase in red crab biomass estimated from the 2003-2005 survey:

An alternative hypothesis for the increase in smaller crabs could be a decrease in competition and cannibalism by larger crabs. Brachyurans are notorious for engaging in cannibalistic behaviour, with direct demographic consequences (e.g. Carcinus maenas, Moksnes and van Montfrans, 1998; Paralithodes camtschaticus, Lovrich and Sainte-Marie, 1997; Calinectes sapidus, Hines and Ruiz, 1995; Cancer magister, Smith and Jamieson, 1991, and Fernandez, 1999; and Chionoecetes opilio, Sainte Marie et al., 1996, and Stevens and Swiney, 2005). An analysis by Cartes (1993) of the diet of Geryon longipes off Spain found that up to 11.7% of stomachs contained a crab of some kind, but many were unidentified, so the degree of cannibalism was unclear. Another study of both G. longipes and Chaceon mediterraneus off Spain found no crabs in the stomachs, but concluded that crustaceans were an important component of the diet (Kitsos et al., 2005).

Sainte-Marie, Sevigny, Smith and Lovrich (1996) suggest that cannibalism on settlers by larger immature crabs and crowding of the most hospitable grounds plays a more significant role in population control for snow crabs than does cannibalism by large males on juveniles. They cite other sources that suggest that cannibalism on settlers as a recruitment regulatory mechanism in decapod crustaceans (Botsford and Wickham 1978, Stevens et al. 1982, Kurihara and Okamoto 1987, Zeldis 1989, Fernandez et al. 1993).

They also suggest that if the first post-settlement instar (0+ age group) represents the most vulnerable benthic life stage in C. opilio (Lovrich et al. 1995), and cannibalism on instar I is caused by sumpatric instars III (I+ age group) to IX (6+ age group), as observed by Sainte-Marie and Sevigny (unpubl. data), one would expect the population to cycle with a period of ~7 years. However, in laboratory experiments the mortality rate of first instar scales exponentially to cannibal CW (Sainte-Marie and Sevigny unpubl. data), so the relative contribution of larger cannibals to population cycling could be more important than that of small cannibals, thereby lengthening the cycles period.

Zheng and Kruse (2003) cite the hypothesis offered by Sainte-Marie et al. (1996) that "density-dependent mortality in juvenile nurseries may cause alternating periods of strong and weak recruitment for snow crab. A strong crab cohort may colonize and saturate available nurseries such that settling megalopae from subsequent cohorts are cannibalized by larger immature crab or are forced to use suboptimal habitats, which may lower survival rates (Sainte-Marie et al., 1996). Once the resident cohort achieves sexual maturity, they move offshore to join the reproductive population, thus vacating the nursery areas for recolonization by a subsequent year class. While this hypothesis has not been proven, it is intriguing as it may help to explain the apparent circular S–R pattern for snow crab in the eastern Bering Sea and Northwest Atlantic."

Wahle et al. (2008) also noted a shift in the distribution of crabs by depth between 1974 and 2003-2005. In 1974 the shallower depths were dominated by females, the mid-range depths were dominated by larger males, and the deepest areas were dominated by smaller males. If cannibalism by the larger males is a significant demographic control, the reduction in the large male population could explain the less segregated nature of the population in 2003-2005. Cannibalism, or at least aggression, provides an explanation for the relatively low density of smaller males in the warmer, and presumably more favorable, depths in which larger males predominate. The theory that crab larvae settle in deeper water and migrate up-slope lacks a credible mechanism to produce such a settlement pattern. An equally plausible explanation for size segregation would be that crabs that settle in the midst of the larger male population have substantially lower survival rates.

As we pull together what we know about the red crab resource (and closely related species), the range of alternatives for the remaining unknowns shrinks. We have a reasonable level of confidence in the following population attributes:

1. The age-CW relationship by analogy with *Geryon maritae*;
2. The CW-weight relationship for *Chaceon quinquedens*;
3. A natural mortality rate between 0.10 and 0.15 by analogy with G maritae and by that necessary to produce the size distribution that was observed in 1974, given the age-weight relationship.
4. The historical landings, which may be under-reported to some extent in some years, but are likely close to actual landings in most years;
5. The abundance by size estimated from the 2003-2005 survey.
6. There is more uncertainty surrounding the population estimate from the 1974 survey. This uncertainty arises from the unexpected increase in abundance of fishable males after 30 years of fishing, and our inability, as yet, to evaluate the potential bias in the 1974 survey.

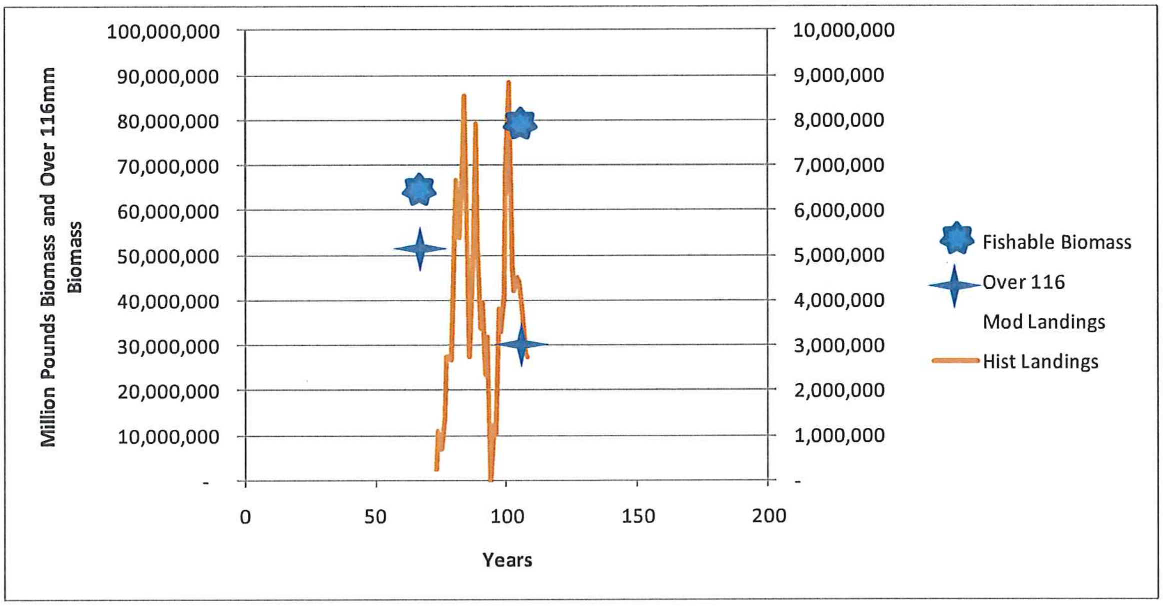

Figure 21- The objective of the modeling exercise was to fit a population model to the known data points, given a growth model and a range of plausible natural mortality rates.

A primary objective of the population simulation modeling exercise was to determine whether density-dependent population controls could explain the apparent increase in the biomass of smaller males and females that was indicated by the 1974 and 2003-2005 surveys. The model also provided insights into possible past and future population trajectories that might result from the highly variable history of landings under different stock-recruitment assumptions.

The PDT used Mellville-Smith's (1989) age/CW model for Namibian red crab and Farlow's (1980) CW/weight model for *C. quinquedens* to construct a male crab stock simulation model that might provide some insight regarding the impact of the recorded landings on the northwestern Atlantic red crab stock.

The modeling exercise followed these steps:

1. Establish a progression of cohorts using the age-length relationship for *G. maritae* (Mellville-Smith 1989).
2. Convert length to weight using the length-weight relationship for *C. quinquedens* (Farlow 1980).
3. Start with M=0.10 and age one recruitment that will produce a fishable biomass equal to 66,803,000 lb, the biomass of fishable males estimated by the 1974 survey. Adjust M and recruitment to match the biomass of both the fishable males and the over-115 mm CW males.
4. Allow 72 years for the population to equilibrate.
5. Assume a schedule of minimum market sizes starting at 114 mm CW (approximated as 1.1 lb) in 1973 and declining over time to 90 mm CW (0.54 lb) in 2008.
6. With selectivity calculated for the 2006 stock assessment, assign fishing mortality rates that produce the historical recorded landings with various candidate stock-recruitment relationships that meet one or both of the following criteria:
    a. Prevent the stock from collapsing under the impact of the historical landings;
    b. Produce a fishable biomass of approximately 79,910,000 lb in the early 2000s.

General Comments on Modeling Results

1. The most optimistic Beverton-Holt stock-recruitment relationship, tuned to produce the necessary recruitment to replace the initial fishable biomass with M=0.10-0.15, could not prevent the stock from collapsing under the impact of the historic recorded landings if fishing began with an equilibrium

population of the size estimated from the 1974 survey and no additional mortality on juveniles was included in the model.

2. Two conditions, either separately or in combination, proved capable of preventing the 1974 estimated stock from collapsing under the impact of the historical landings and instead increasing to the 80 million lb fishable biomass in the early 2000s:

3. A highly domed Ricker stock-recruitment relationship with the initial biomass replacement point on the right descending limb of the stock-recruitment curve (providing increasing recruitment as biomass declined);

4. A excess juvenile mortality term that increased natural mortality on juvenile crabs smaller than a threshold size (generally 1 lb) with juvenile mortality proportional either to the biomass of male crabs over 1.1 lb or to the biomass of older juveniles.

5. It should be noted that none of the scenarios tested could replicate the ratio of fishable biomass to over-115 mm CW biomass that was estimated from the 2003-2005 survey. If the model were tuned to produce the 80 million lb fishable male biomass in the early 2000s, the biomass of males larger than 115 mm CW was invariably higher than that estimated from the 2003-2005 survey. This size distribution is likely the result of good recruitment noted during the 2003-2005 survey.

6. Model results were very sensitive to the juvenile mortality term.

7. In the absence of excess juvenile mortality, *M* had to be higher than 0.10 to produce the ratio of fishable male biomass to over 115 mm CW biomass that was estimated from the 1974 survey, if we assume that the 1974 population represents the equilibrium stock structure.

8. All of the scenarios that began with the 1974 biomass and in which the stock did not collapse under the impact of the historical landings, but rebounded to a level higher than the initial biomass, were characterized by highly variable biomass into the indefinite future (90 years beyond 2010). Relatively high fishing mortality rates (0.15-0.20) after 2010 dampened the modeled biomass oscillation.

9. All of the modeled scenarios demonstrate the likelihood that biomass declined significantly in response to the high landings in the 1980s. The relatively high biomass estimated from the 2003-2005 survey seems unlikely to have represented equilibrium conditions if the 1974 estimated biomass accurately represented the unfished equilibrium.

10. An alternative hypothesis that can be modeled to explain the estimated biomass in 2003-2005 after 30 years of substantial but highly variable landings is that the 1974 population was equal to or higher than the estimated

> population. In the case where the 1974 biomass was assumed to be underestimated by one-half, an optimistic Beverton-Holt stock-recruitment model (or a Ricker model) proved capable of supporting the landings and producing the biomass estimated in 2003-2005.

The results presented here incorporate natural mortality rates of 0.10-0.15 for male crabs larger than one pound. The models that include juvenile mortality proportional to the abundance of larger males (over 1.1 lb or approximately 116 mm carapace width) were set to make the smaller males subject to that excess natural mortality until they reached a weight of one pound. The cannibalism proportionality constant used in these results is noted on the graphs.

The use of a natural mortality rate for smaller males that is proportional to the biomass of larger males is based on the theory that cannibalism by the larger males on the smaller males acts as a density dependent control on the red crab population. This mechanism has been proposed as a potential explanation for the increase in estimated abundance of smaller males and females after thirty years of fishing. This mechanism would also imply that a Ricker stock-recruitment relationship may be more appropriate for red crab than a Beverton-Holt relationship. The implementation of the model separates the cannibalism effect from the basic stock-recruitment model – cannibalism can be implemented along with B-H recruitment.

Some models incorporated predation on juveniles by their older siblings, either in direct proportion to the biomass of older siblings, or scaled exponentially to the biomass of older siblings. For those models that include cannibalism by larger juveniles on smaller juveniles, the oldest animals that were cannibalized were age 10 (0.57 lb) and the oldest animals that cannibalized the younger crabs were age 11 (0.69 lb). In the case where predation on juveniles was scaled exponentially to the biomass of older juveniles, susceptibility to predation by older juveniles declined exponentially with age.

The model was run with speculative parameters for both a Ricker stock-recruitment model and a Beverton-Holt model. Both deterministic and stochastic versions of the model were reviewed by the PDT. The stochastic models used the NORMINV function of Excel to generate random recruitment with a mean equal to the recruitment predicted by the S-R relationship and a standard deviation close to the mean recruitment.

The model compiled results for fishable male biomass, large male biomass, and landings over a 200-year period. Fishing started in year 73, corresponding to 1973 for ease of matching results to years. The fishing mortality rates in years 73 through 108 were adjusted to produce the recorded landings. Fishing mortality rates in years after 2010 (110) were self-adjusting to keep the landings around a TAC determined by the user. Whereas the control mechanism worked by adjusting *F*, large fluctuations in fishable biomass made it difficult for the control mechanism to keep the catches close to the TAC.

7.4.2.1 Deterministic Model Results

The model results indicated that various combinations of stock-recruitment relationships and natural mortality could induce a population rebound similar to that indicated by the increase in population estimated by the 2003-2005 survey compared to the 1974 survey (Table 4). Research on other crab stocks suggested two potential sources of additional mortality on either settling crabs or juvenile male crabs. One modeling scenario made mortality on smaller males proportional to the biomass of larger males. Another modeling scenario made mortality on settling and juvenile crabs scaled exponentially by age to the biomass of the higher age groups up to age 11, with exponentially decreasing susceptibility to predation with age. If juvenile mortality is proportional to the abundance of large males, the highly variable landings history would have created size distribution changes that would interact with this natural mortality pattern.

Two important results of the model runs to note are the significant decline in red crab biomass indicated for the years following the peak in the late 1990s, under all conditions modeled. Also noteworthy is the long-term cycle of fluctuating abundance that may have been introduced by the highly variable landings over the history of the fishery. If these modeled cycles illustrate conditions in the fishery, they will make it difficult to make judgments concerning the impact of the current fishery on stock abundance, assuming that we develop information on stock abundance through either CPUE or future surveys. (It is important to note that modeled recruitment prior to year 110 in all cases is deterministic. The benefits of any random spike in recruitment that might have occurred in the years prior to 2010 would not be evident in the model runs.)

One piece of the puzzle that remains unanswered by the model results is the relatively low abundance of large males compared to the increase in abundance of smaller males and females in the 1990s. Most of the model scenarios show an increase in the large male population along with the smaller male biomass after fishing pressure was relaxed following high landings in the 1980s. The scenario in which settling and juvenile crabs are cannibalized by their older siblings produces continuing changes in the ratio of large males to smaller males that encompass the range seen in the two surveys. The modeled ratio changes rapidly, requiring precise timing of the modeled variability to match the size distribution observed in the surveys.

Modeling results are presented in Appendix 5.

7.5 Implications of Population Cycling for Fishery Management

The potential for red crab population cycling is indicated both by experience in other crab fisheries and by modeling results presented above. Sainte-Marie, et al. (1996) suggest that changes in catch rates and in the mean CW may be more informative of real population trends than total landings and condition of crabs when populations are cyclical, citing Tremblay et al. 1994.

Sainte-Marie et al (1996) concluded that the cyclic nature of *C. opilio* allowed a re-interpretation of a decrease in the mean CW for male crabs landed in the southwest Gulf of St. Lawrence. Rather than being caused by intense exploitation, they suggested, the decline probably reflected the impact of the presumed 1969-1971 recruitment trough. A subsequent increase in mean CW could be attributed to the entry of a recruitment wave to the fishery. They also concluded that the fishery collapse of 1987-1990 probably resulted from the passing of the 1977-1979 recruitment trough, not from overfishing or mismanagement. Another increase in commercial biomass reflected the 1980-1984 recruitment wave. They noted that both legal-sized males and adult females are likely to fluctuate extensively in the absence of fishing. In the case of *C. opilio*, these authors suggest that biological and economic stability probably cannot be achieved and that industry and management must learn to adjust their strategies to the cyclic nature of the resource. They provide a number of possible strategies to respond to this possibility.

The highly variable exploitation history of the U.S. Atlantic red crab resource makes it difficult if not impossible to determine whether the population is naturally cyclical. It will take some time to determine whether the stock is highly cyclical, whether from endogenous characteristics or as a result of the history of exploitation.

7.6 The Size-Distribution Issue

The report of the DPSWG and the Review Panel both expressed considerable concern over the decline in the abundance of large males (greater than 114 mm CW) between 1974 and 2003-2005. The Panel agreed with the DPSWG (Chute et al. 2008 Working Paper 1: Red crab) that the MSY level developed in the original Fishery Management Plan (FMP) is no longer reliable as a foundation for setting BRPs and stated that: "this determination was made on the assumptions that reductions in the size structure of landings that have been observed indicate that previous higher landings were not at a sustainable MSY levels as had been previously assumed."

The 2006 stock assessment (NEFSC 2006) noted the decline in abundance of male crabs over 114 mm CW, but apparently considered that decline to be a normal consequence of fishing down a virgin stock:

> The deep sea red crab population and fishery appear to be at sustainable levels. The red crab fishery has had a noticeable impact on the stock of large male red crabs >114 mm carapace width which were considered marketable in 1974. Since 1974 the abundance of large males has decreased by 42%, probably in response to fishing. However, the biomass of currently marketable male crabs which includes smaller individuals has increased by 5%. Small red crabs less than about 60 mm appear to be abundant relative to 1974. Current landings during 2002-2005 averaged approximately 2000 mt (4.4 million lbs), and were comparable to average landings of about 2300 mt (5 million lbs) during 1982-2001 as the population was being fished down from the virgin state. Results of this stock assessment are consistent with the hypothesis that the red crab population has been fished down from a virgin state over the past 30 years and is currently at a productive biomass level. There are, however, several key issues that contribute uncertainty to this conclusion (i.e. lack of biological

information about growth and longevity that could be used to estimate stock productivity and information about discard mortality, see below).

The Report of the DPSWG is somewhat ambivalent, as is evident from the following excerpts:

> Based on the last stock assessment (NEFSC 2006a; 2006b), there is no evidence of serious problems in the red crab population (fishery induced mortality rates are $< 0.1\ y^{-1}$) and recruitment was apparently occurring during 2003-2005.
>
> Some of the methods used to calculate biological reference points in this report rely heavily on landings data collected during a period when exploitation levels were relatively low. Historical catches may understate MSY to the extent that fishing mortality has been less than F_{MSY} during recent years. Thus, there is appreciable risk that reference points in this report will result in unnecessarily foregone catches.

The 2006 stock assessment notes a trend toward landing smaller crabs during 2001-2005 when data from all areas was combined. The assessment report also points out that: "the apparent trend for all areas combined may have been driven by relatively few samples in the Mid-Atlantic region because no trend is evident in samples from the Georges Bank region (Figure D4.14). Changes in culling, landings of female crabs, changes in location fished, or sampling bias may also be responsible. Plots of mean size by year for each survey strata do not show trends over time during 2001-2005 (Figure D4.15)." The fact that plots of mean size by year for each survey strata do not show any trend over the years 2001-2005 indicate either a constant stock structure or fishery selectivity patterns that maintain a constant mean size despite variations in stock size structure. The latter seems improbably because a change in stock structure would bring about a change in the size distribution above any market-imposed minimum size.

It should be noted that landings in 2001 were 4003 mt, the highest on record. For the period 2001-2005, over which no decline in mean size landed was noted for individual survey strata, landings averaged 2424 mt.

Numerous statements in the DPSWG working paper and the Review Panel report imply that the reduction in the abundance of males larger than 114 mm CW is problematic. Neither document addresses the reduction in biomass that would be expected under sustainable fishing mortality rates. The PDT used a life history model based on an age-CW model for *G. maritae* (Mellville-Smith 1989) and a CW-weight model for *C. quinquedens* (Farlow 1980) to assess the expected reduction in biomass for a range of fishing mortality rates. The received wisdom indicates that a fishing mortality rate corresponding to $0.7\text{-}1{*}M$ would be a conservative estimate of Fmsy. If M is assumed to have a value of 0.10, the relevant fishing mortality rate would be 0.07-0.10. The fishing mortality rate that was calculated for red crab by the 2006 stock assessment was estimated to be 0.055 +- 0.008 y-1 during 2003-2005. The 2006 stock assessment also indicated that 58% of the 1974 biomass of male crabs larger than 114 mm CW remained in 2003-2005. The life history model would lead one to expect the remaining biomass to be from 30-50% of the initial biomass for that range of fishing mortality rates (Figure 22).

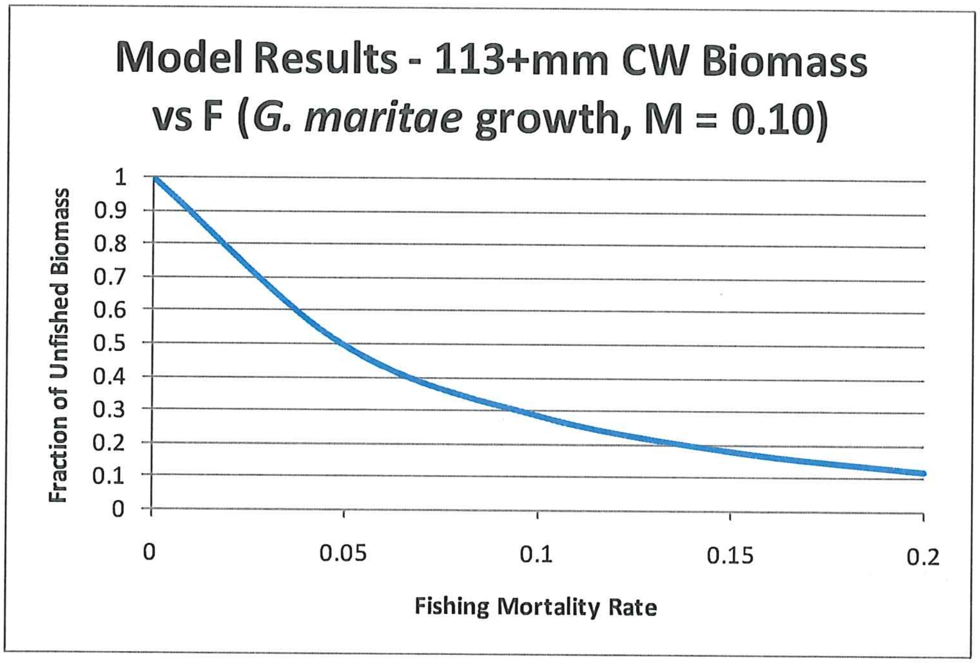

Figure 22- Fraction of unexploited biomass remaining with increasing F.

Figure 23 indicates that the proportion of the male biomass represented by crabs larger than 113 mm CW in 2003-2005 was less than would be predicted by the life history model under equilibrium conditions. The 2006 stock assessment noted apparent good recruitment that had led to an increase in the abundance of smaller males and females. That recruitment pulse would explain the relatively low proportion of large males.

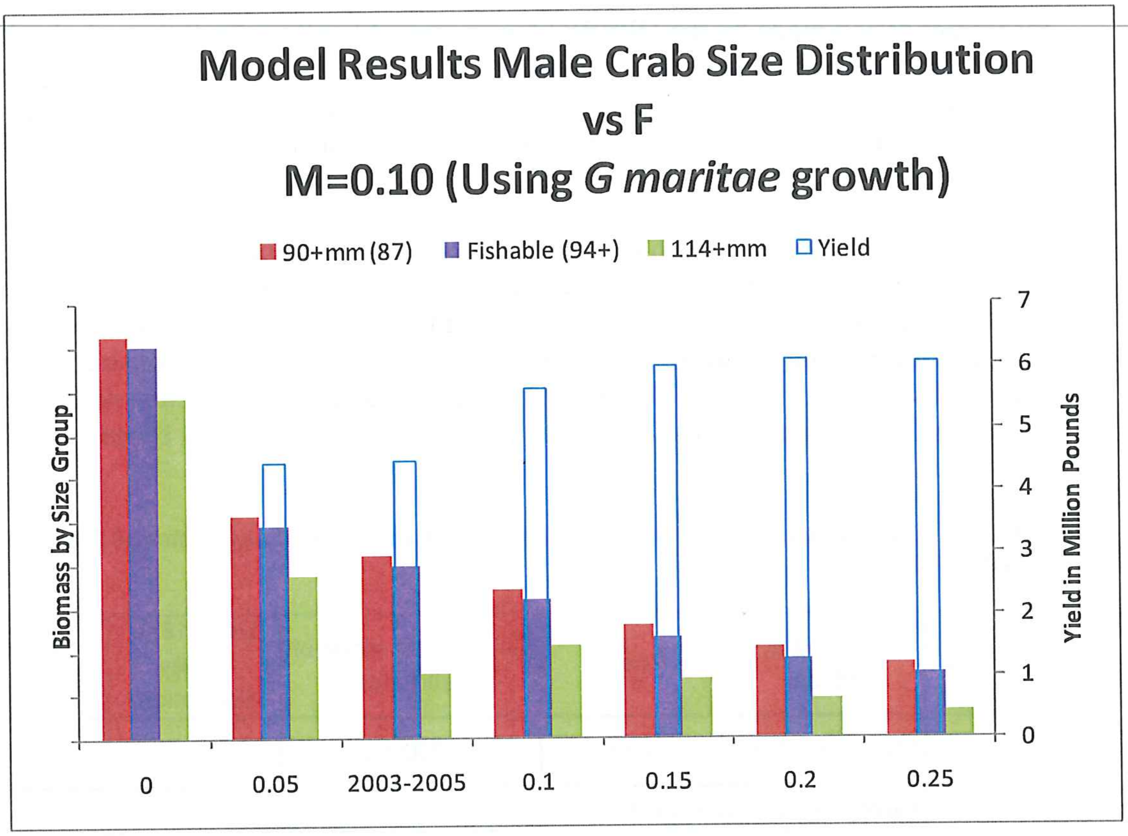

Figure 23- Male crab size distribution with increasing F compared to 2003-2005.

Various assessment documents have expressed concern about the apparent decline in the acceptable market size, and thus minimum landed size, in recent years. These concerns have been connected to the concern for the abundance of large males in the population. Simulation modeling indicates that the biomass of large males (>1.1 lb or approximately116 mm CW) would be about 20% larger with a minimum size of 1.1 lb compared to a minimum size of 0.5 lb at a fishing mortality rate of 0.05 and about 40% larger at a fishing mortality rate of 0.10. Yield per recruit could be expected to decline by about 12% in the first case and about 8% in the second.

7.7 Summary of Results

Most of the yield based reference points presented in this report (Table 10) are lower than the current estimate of MSY (2,884 mt) and target TAC (2,688 mt). Most are lower than the highest observed landings. Estimates of sustainable yield based on average landings (e.g. long-term average landings and DCAC estimates) are reasonably consistent. The similarity of many of the new sustainable yield estimates to the long-term average landings (from 1973-2007, 1,775 mt) supports the idea that this level of landings is most likely sustainable if there is no evidence of a decline in biomass or in the mean size of the exploited portion of the population beyond that which would be expected in the transition from an unexploited to an exploited resource. Recent landings, from 2002 to 2007 (1,853 mt) have been at the lower end of this range of sustainable yield estimates. The red crab industry reports that landings of less than 1300 mt per year in 2007 and 2008 were the result of a lack of orders. The PDT agrees with the recommendation made by the DPSWG for an annual landings limit that mimics both recent and long-term mean annual landings. The PDT also agrees with the suggestion from the DPSWG that the MSY specified in the FMP of 2,830 mt should not be relied upon unless and until additional information supports this level of productivity for the red crab resource.

The yield values in Table 10 are a mixture of MSY and sustainable yield estimates. The sustainable yield estimates are strongly dependent on average landings. As described below, under “Scientific Risks and Uncertainties,” there is a risk that average landings may understate sustainable yields and MSY for an apparently lightly exploited stock like red crab. The DCAC model is expected to produce sustainable yield estimates that range from 50-72% of MSY (Alec MacCall, personal communication) (See Appendix 2a).

Table 10- Yield estimates for the red crab management unit, revised and expanded from Table 3 in the DPSWG report.

Method	Method or Model	Result	Estimate or range of estimates	Uses 1974 survey Information?	Equilibrium Estimator
1	Status quo MSY	MSY	2830 mt	Yes	No
2	**Long-Term Average Landings**				
2a	1973 – 2007	Sustainable Yield	1,775.2 mt	No	Yes
2b	1977 – 2007	Sustainable Yield	1,953.9 mt	No	Yes
2c	1982 – 2007	Sustainable Yield	1,975.2 mt	No	Yes
2d	1977 – 2007, excluding 1994	Sustainable Yield	2,002.1 mt	No	Yes
2e	1977 – 2007, excluding ’94 - 96	Sustainable Yield	2,125.5 mt	No	Yes
2f	1982 – 2007, excluding 1994	Sustainable Yield	2,061.6 mt	No	Yes
2g	1982 – 2007, Excluding ’94 - ’96	Sustainable Yield	2,185.0 mt	No	Yes
2h	2002 – 2007 (FMP)	Sustainable Yield	1,852.7 mt	No	Yes

3	**Updated Yield Equation (MSY = (0.4)(*c*)(*M*)(B_0 fishable ♂)**				
	1974 Fishable Male Biomass with c=0.8				
	M=0.05	MSY	549	Yes	No
3a	M=0.10	MSY	1098	Yes	No
	M=0.15	MSY	1646	Yes	No
	1974 Fishable Male Biomass with c=1.0				
	M=0.05	MSY	686	Yes	No
3b	M=0.10	MSY	1372	Yes	No
	M=0.15	MSY	2058	Yes	No
	2003 – 2005 Fishable Male Biomass with c=0.8				
	M=0.05	MSY	580	No	No
3c	M=0.10	MSY	1160	No	No
	M=0.15	MSY	1740	No	No
	2003 – 2005 Fishable Male Biomass with c=1.0				
	M=0.05	MSY	725	No	No
3d	M=0.10	MSY	1450	No	No
	M=0.15	MSY	2175	No	No
	Garcia, Sparre and Csirke (1989) with Fmsy=M=0.10				
3e	**Based on Schaeffer**	MSY	2237	No	Yes
3f	**Based on Fox**	MSY	2156	No	Yes

4	**DCAC (DCAC sustainable yield estimates shown to be generally less than 72% of MSY)**				
	DCAC model Zero Depletion Delta	Sustainable yield	1785-1862 mt*	Yes*	Yes
	M=0.05	20%-80% CI	1545-2114		
4a	M=0.10	20%-80% CI	1652-1930		
	M=0.15	20%-80% CI	1691-1875		
	DCAC model - 0.20 Depletion Delta	Sustainable yield	2019 - 2762 mt**	Yes	Yes
	M=0.05	20%-80% CI	2210-3899		
4b	M=0.10	20%-80% CI	1976-2454		
	M=0.15	20%-80% CI	1904-2177		
	2-point boundary model				
	2-point boundary model	Equilibrium catch	1987-2044 mt	Yes	Yes
	M=0.05	90% CI	1819-2152		
5	M=0.10	90% CI	1932-2058		
	M=0.15	90% CI	2023-2064		

* Range of average DCAC model results for three values of M with an assumed zero depletion delta rather than the depletion delta calculated from the survey biomass estimates.

A zero depletion delta makes the DCAC model into a calculation of the long term average catch with variability introduced by the inclusion of the standard deviation of M and the standard deviation of the depletion delta.

** Range of median estimates from DCAC model using three values for M and the biomass estimates for fishable males from the two surveys, which makes the depletion delta equal to -0.20, as indicated below.

			1974 Survey	2003-5 Survey	Depletion Delta
Fishable Biomass of Males			30302	36247	-0.20

Table 11- The DCAC model produces sustainable yield estimates that are likely to be in the range of 50-72% of MSY (See Appendix 2a). Table 11 converts the sustainable yield estimates to MSY estimates by dividing the sustainable yield estimates by 0.72.

4	**DCAC Sustainable Yield Estimates Divided by 0.72**				
4a	DCAC model Zero Depletion Delta	MSY	2479-2586 mt		
	M=0.05	20%-80% CI	2146-2936		
	M=0.10	20%-80% CI	2294-2681		
	M=0.15	20%-80% CI	2349-2604		
4b	DCAC model -0.20 Depletion Delta	MSY	2804 -3836 mt		
	M=0.05	20%-80% CI	3069-5415		
	M=0.10	20%-80% CI	2744-3408		
	M=0.15	20%-80% CI	2644-3024		

Table 12- Deterministic and stochastic model results.

Method	Model	B_0 mt	B_{MSY} mt	B_{MSY}/B_0	Determin MSY mt	Determ F_{MSY}	%Yrs<0.5 Bmsy @ 1615 mt TAC	Stochastic Max Yield >0.25*B_{0116} + mm	Stochastic FMax Yield >0.25*B_{0116} + mm
	Models that Match 1974 Biomass and Size Structure								
6a	Ricker matching 1974 biomass and size structure with juvenile mortality proportional to large male biomass	30,302	16,735	0.55	4,164	0.525	0%	2,751	0.251
6b	Ricker with no excess juvenile mortality	30,302	22,384	0.74	2,318	0.185	0%	1,812	0.118
6c	Beverton-Holt with excess juvenile mortality	30,302	27,402	0.90	4,265	0.320	0%	2,974	0.214
	Models that Inflate 1974 Biomass								
6d	B-H with predation on juveniles from ages 1-11	60,349	28,640	0.47	1,939	0.127	0%	1,662	0.081
6e	Almost linear B-H with predation on juveniles proportion to biomass of ages 1-11	56,689	24,015	0.42	2,090	0.142	0%	1,996	0.09
	Models Based on Zero Depletion Delta between 1974 and 2003-2005								
6f	Zero depletion delta and Ricker SRR with no additional mortality on juveniles	36,135	24,984	0.69	2,849	0.207	0%	2,286	0.139
	Average				2,937			2,247	
	Average excluding highest and lowest				2,284			1,769	

Table 13- Summary of alternative yield estimates as plotted in Figure 24.

Plot #	Method	Y Est	20% CI	10% CI
1	1	2830		
2	2a	1775		
3	2b	1954		
4	2c	1975		
5	2d	2002		
6	2e	2126		
7	2f	2062		
8	2g	2185		
9	2h	1853		
10	3a	1098		
11	3b	1372		
12	3c	1160		
13	3d	1450		
14	3e	2237		
15	3f	2156		
16	4a	1777	1652	1586
17	4b	2168	1976	1897
18	4c	2468	2294	2203
19	4d	3011	2744	2635
20	5	1996		1932
21	6a	2751	2615	2576
22	6b	1812	1774	1763
23	6c	2974	2856	2822
24	6d	1662	1630	1621
25	6e	1996	1966	1958
26	6f	2286	2237	2224

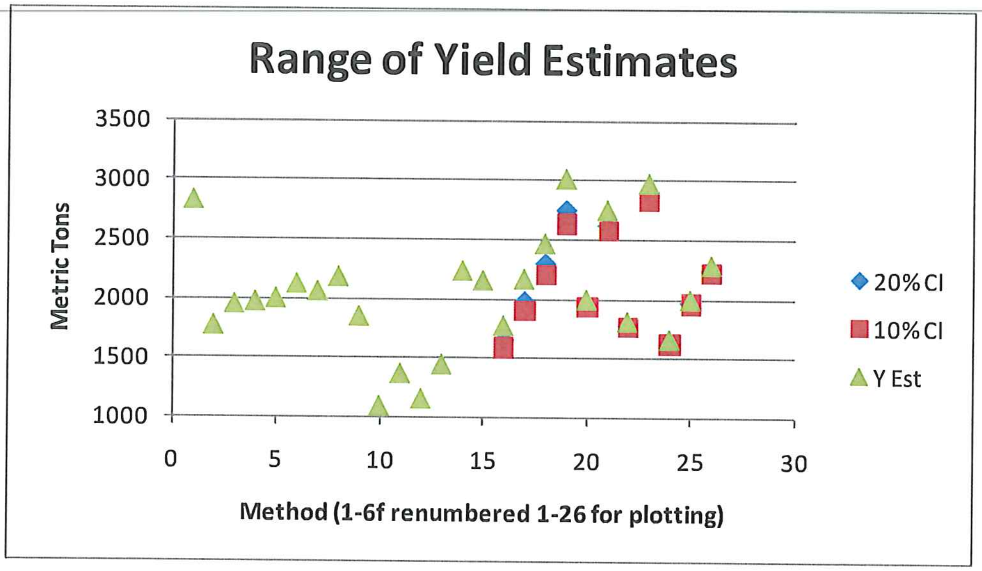

Figure 24- Range of yield estimates produced by the various methods, with 10 and 20% confidence intervals where available.

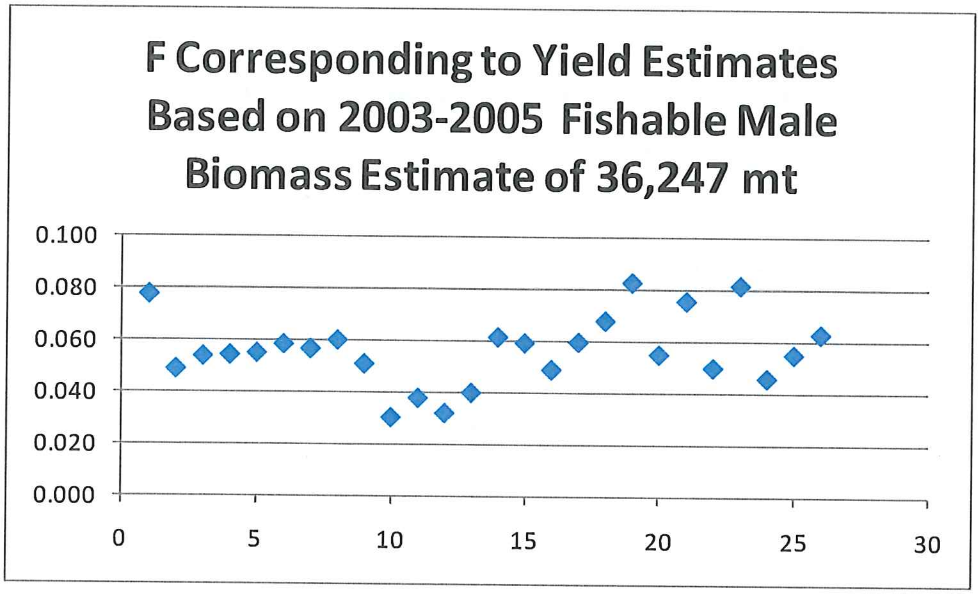

Figure 25- Fishing mortality rates corresponding to the range of sustainable yield estimates based on the biomass of fishable males of 36,247 mt estimated from the 2003-2005 survey.

7.8 Recommendations for MSY, OFL, ABC, ACL and TAL.

The Red Crab PDT agreed on recommendations for OFL, ABC, annual catch limit (ACL), and total allowable landings (TAL) for male red crab based on a preponderance of the evidence from multiple indicators of sustainable yield as described in the PDT MSY Reevaluation document. The PDT considers the historical landings to be the best indicator of sustainable landings of male red crab when considered in conjunction with the biomass estimates obtained from the two camera/trawl surveys and the lack of any evidence of significant declines in landings per unit of effort or total biomass over the history of the fishery. The PDT chose to use the average landings from fishing years (FY) 2002 through 2007 (i.e., since the start of the fishery management plan) as being the most reliable and representative of both the long-term and recent history of the fishery.

The PDT also chose to use the depletion-corrected average catch (DCAC) model as the best indicator of MSY and, by extension, OFL, when the sustainable yield estimates from the DCAC model are adjusted to account for the expected relationship between the DCAC results and MSY, i.e., the DCAC results are expected to represent between 50% and 72% of MSY. The PDT noted that the use of average landings as the basis for a TAL, when combined with the use of the adjusted DCAC model results produces a logical relationship between the elements of the specifications that meets the expectations of the National Standard 1 and 2 Guidelines. The recommendations are based on the use of a value of 0.10 as the most appropriate value for natural mortality. The PDT chose M=0.10 value based on estimates of M for the closely related Namibian red crab (Mellville-Smith 1989), modeling exercises that point to M=0.10 – 0.15 to produce the size distribution that was observed during the 1974 survey, and an accumulating body of opinion resulting from previous reviews of red crab biology and stock status. The PDT therefore recommends the following specifications for 2011 through 2013:

Table 14- PDT recommendations for male red crab specifications for 2011 through 2013.

	mt	% of Lower Risk Neutral MSY/OFL	% of Higher Risk Neutral MSY/OFL	% of Average of LRN and HRN MSY/OFL
Total Allowable Landings of Male Red Crabs (TAL)	1850	75%	61%	68%
Dead Discards (5% of 30% of Total Catch)	40			
ACL (10% buffer for Management Uncertainty)	1890			
ABC	2100	85%	70%	77%
*Lower Risk Neutral MSY/OFL	2469			
Avg of Lower Risk Neutral and Higher Risk Neutral MSY/OFL	2740			
*Higher Risk Neutral MSY/OFL	3011			
20% CI on Lower Risk Neutral MSY/OFL	2294			
20% CI on Higher Risk Neutal MSY/OFL	2744			

* Risk neutral refers to the median DCAC model result divided by 0.72 to provide an estimate of MSY given the model and the assumptions incorporated into the model and the expected relationship between DCAC sustainable yield estimates and MSY. The use of a zero depletion DELTA to produce the "lower risk neutral" MSY/OFL estimate and the use of the 0.72 divisor to adjust from the DCAC results to MSY could be considered precautionary considering the expected range of 0.50 to 0.72. The use of an F_{MSY} to M ratio of 0.8 in the DCAC model may also be precautionary.

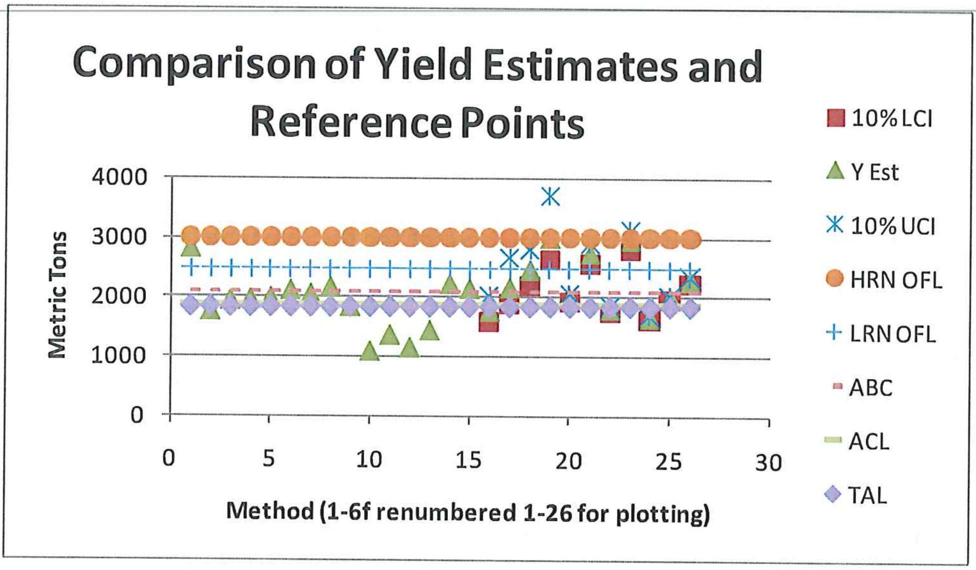

Figure 26- Plot of recommended reference points in comparison to the multitude of yield estimates developed by the red crab PDT. HRN stands for high risk-neutral and LRN stands for low risk-neutral.

Justifications for Recommendations:

11. The 2003-2005 survey indicated an increase in biomass for all red crab categories except males over 114 mm CW after 35 years of fishing with recorded average annual landings of 1,775 mt. Actual landings were likely higher than recorded landings prior to FY 2002, but the magnitude of any underestimation of landings is unknown. The PDT noted that the observed increase in biomass could have been the result of natural fluctuations in stock productivity or population dynamics that result in an increase in smaller males and females when the predation and competition from large males is reduced.

12. Landings in FY 2001 were 4003 mt, the highest on record. For the period FY 2001-2005 landings averaged 2424 mt. No decline in mean size landed was noted for any individual survey strata over the period 2001-2005 (NEFSC 2006).

13. The 2006 stock assessment concluded that the "average male crab [in the 2003-2005 survey] is smaller in size while the average female is the same size as in 1974, and young crabs of both sexes are relatively abundant" (section 5.1, NEFSC 2006). These observations imply that discard mortality on females has been low and the reproductive capacity of the stock has been adequate to maintain good recruitment.

14. The Review Panel for the DPSWG expressed a preference for the results of the DCAC model as an estimate of MSY. Since that time, further clarification and analysis by Alec MacCall (Personal Communication), the

developer of the model, and by the PDT have shown that DCAC sustainable yield estimates are likely to be in the range of 50-72% of MSY.

15. The National Standard 1 and 2 Guidelines specifically prohibit the Council from asking the SSC (and by inference the PDT) to make a policy decision regarding the acceptable risk of overfishing that is embodied in the ABC and ACL. The PDT attempted to provide recommendations that clearly indicate the degree to which the methods used and the inputs to the recommendations may be considered to be inherently precautionary. The use of a multitude of methods with varying degrees of precaution results in a range of estimates that by its nature reflects varying degrees of risk.

16. The DPSWG noted that "based on the last stock assessment (NEFSC 2006a; 2006b), there is no evidence of serious problems in the red crab population (fishery induced mortality rates are $<0.1\ y^{-1}$) and recruitment was apparently occurring during 2003-2005."

17. The DPSWG pointed to concerns raised by the decline in the biomass of large males. As suggested by the SSC, the PDT used a life history model based on an age/CW model for the closely related *G. maritae* and a CW/weight model for *C. quinquedens*, with M=0.10, to analyze the observed decline in large male biomass relative to that which would be expected in the transition from an unexploited to an exploited resource. The PDT did not find any indication that the decline was beyond that which would be expected from the fishing mortality rates that have been calculated for red crab as being approximately $0.5M$ if M=0.10.

18. The PDT reviewed additional references regarding mating and fecundity that relate to the concerns expressed by the DPSWG about the potential impacts of the reduction in biomass of large males. Evidence from other crab resources indicates that the size of mating pairs fluctuates with changes in size distribution of male crabs, that large males tend to out-compete smaller males for female partners, and that male crabs employ various strategies to conserve and distribute sperm among multiple females depending on the prevailing sex ratio (Rondeau and Sainte-Marie 2001, Zheng and Kruse 2003, Mellville-Smith 1987). Despite these strategies, sperm limitation may still occur in male-only crab fisheries. Cooperative research now underway is aimed at gathering more information on growth, maturation, and fecundity of red crabs.

19. The PDT considered the uncertainty surrounding the validity of the biomass estimates from the 1974 survey from a number of perspectives. Work is underway to further analyze the photos from the 1974 survey to evaluate the density estimates from that survey. The PDT also considered references related to the possibility that the reduction in large males could bring about an increase in the equilibrium stock size. The PDT noted research on other species showing an increase in abundance of smaller animals as the

population was fished intensively (Momot 1995; Zipkin et al. 2008; Schroder, Persson & de Roos 2009).

20. The PDT noted that the DPSWG recommended "a catch limit that mimics both recent and long term mean annual landings…" The PDT also noted that "catch limit" is a step in the process of setting OFL, ABC, and ACL. The PDT is hopeful that careful use of newly developing terminology will avoid any misunderstanding concerning the PDT recommendations.

21. The PDT concluded that the relatively low exploitation rate (below 0.10) for red crab is likely to make it difficult to separate any fishery dependent indicator signals from the noise created by natural fluctuations.

22. The PDT notes that all of the yield estimates from a variety of methods (Figure 24) would represent a continuation of fishing mortality rates generally between 0.03 and 0.08 if applied to the biomass of fishable males estimated from the 2003-2005 survey (Figure 25).

23. The PDT notes that a TAL set at recent historical landings is likely to have the effect of keeping average future landings below recent historical landings because there will not be any opportunity to average landings higher than the TAL with landings lower than the TAL.

7.9 Recommendations for an ABC Control Rule

The PDT recommends continuing efforts to develop an abundance index for red crab for the purpose of implementing an ABC control rule.

8.0 Scientific Risks and Uncertainties.

Risks and uncertainties regarding BRPs for red crab are important in the context of choosing among BRP options and setting ACLs once BRPs are chosen and a discussion of the risks and uncertainties is below.

Biomass-based BRPs are difficult to evaluate for red crab due to lack of routinely available information about biomass levels and trends and infrequent stock assessments. Therefore, risks and uncertainties regarding exploitation-based BRPs are particularly important.

The following key uncertainties are listed in approximate order of importance:

a. There is a great deal of uncertainty about fundamental life history parameters in red crab, including longevity and natural mortality, growth and maturity (such as, if red crab experience a terminal molt), and reproductive biology (for example, the extent to which female red crab can store sperm). Information on these life history parameters will be gathered as part of a cooperative research project that is now underway.

b. There is no available information about the spawner-recruit pattern and recruitment variability in red crab. There is uncertainty about the potential productivity of red crab due to uncertainty about fundamental life history parameters and recruitment (see above).

c. Minimum marketable sizes and fishery size selectivity have changed since the early 1970s and processors were accepting smaller male red crab in recent years. There are no management measures regulating minimum size; however, the red crab industry has agreed to increase the landed size of male red crab as a condition of their MSC Certification. Thus, future selectivity patterns are uncertain.

d. Based on the last stock assessment (NEFSC 2006a; 2006b), there is no evidence of serious problems in the red crab population (fishery induced mortality rates are $< 0.1\ y^{-1}$) and recruitment was apparently occurring during 2003-2005. However, survey size composition data from 1974 and 2003-2005 show reduced abundance of large males (114+ mm CW), probably due to fishing. There are questions whether loss of large males may affect reproductive capacity of the red crab stock. These questions have a sound logical basis, but have not been fully investigated. Evidence of sufficient reproductive capacity can be found in the comparable proportions of egg-bearing females in the population in 2003-5 compared to 1974 and evidence of recent good recruitment in 2003-5. Additional information on maturity, mating, and fecundity is needed to inform concerns about potential sperm limitation.

e. Discards of undersize males and females are thought to be about 30% of total catch, but the estimates are uncertain. Mortality of discarded crab was relatively low (~5%) in a recent study, but is uncertain and may be higher or lower during routine fishing.

f. Some methods used to calculate BRPs in this report rely heavily on landings data collected during a period when exploitation levels were relatively low. Historical landings data may understate MSY to the extent that fishing mortality has been less than F_{MSY} during recent years. Thus, there is appreciable risk that reference points in this report will result in unnecessarily forgone landings. In addition, there was no requirement to report landings of red crab before the FMP was implemented in 2002. All estimates of average landings prior to 2002 should be considered low estimates.

g. Some of the methods used to calculate BRPs in this report involved equilibrium assumptions that may not be justified for red crab. The potential effects of these assumptions are uncertain.

h. As noted above, biomass estimates from the camera/bottom trawl survey in 1974 are uncertain because of questions about the effective area searched by the camera. Uncertainty in the 1974 biomass estimate increases uncertainty in BRP calculations that evaluate long term biomass trends or use the 1974 survey to characterize virgin of near-virgin stock levels.

i. Recent red crab biomass estimates from the 2003-2005 survey have a negative bias due to a statistically significant level of red crab avoidance behavior. The magnitudes of red crab avoidance behavior and bias have not been evaluated.

j. There is uncertainty about whether new NEFSC bottom trawl surveys will provide useful information about red crab. Available data from comparative fishing experiments provide little evidence one way of the other in this regard.

9.0 Research Recommendations

a. Establish a regular schedule for surveys that provide useful information about red crab. This is the most important research recommendation for red crab.

b. Develop practical survey approaches for red crab in deep water. Recent cooperative work indicates that towed body video surveys are accurate and useful for sea scallops. It is likely the same equipment and approaches would be useful for red crab.

c. Evaluate the importance of large male red crab in reproduction, considering the size distribution and molting cycle of females, sperm storage, length of the mating season, duration of copulation, and other key parameters.

d. Studies to refine estimates of growth parameters, longevity, natural mortality, and reproductive parameters are needed.

e. Insure that sampling protocols employed by observers are appropriate and that observer data is analyzed to inform management.

f. Develop and implement a protocol for gathering LPUE and CPUE data from a combination of VTR reports, observer data, and additional industry sampling as necessary.

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Appendices.

Appendix 1. Red Crab Size Composition Analysis[1]

The impact of fishing on the abundance of large male crabs has raised concerns about the effective spawning biomass of sexually mature male crabs. Information on the size requirements for successful mating comes from laboratory studies and from photographs of mating pairs. Specific data are very limited to a total of 14 observations of mating red crab pairs. During camera surveys of 2003-2005 we observed 11 mating pairs in which males averaged 51% larger than females, ranging from 18-72% (Wahle unpublished). Elner (1987) observed three mating pairs of *C. quinquidens* in captivity in which males were 10.2, 15.1, and 20.6% larger than the females. These females were later found to contain sperm masses. These observations lead to an assumption that males must be at least 10% larger than females to successfully mate. Research on other crab species has indicated that the relative size of mating pairs varies with changes in stock structure (Sainte-Marie ???). Relative size may also result from the superior competitive ability of large males to secure females (Stevens et al., 1993; Paul et al., 1995; Sainte-Marie et al., 1999), which is undoubtedly enhanced by the fact that the spatial distribution of the red crab population puts the bulk of the large males in closer proximity to the bulk of the females and between the females and the smaller males.

This analysis examines the impact of the fishery on the size structure of the population, specifically with regard to the ratio of the number of males to the number of females small enough for the males to fertilize.

Direct analysis of survey results has the benefit of being able to explore sex ratio in terms of observed densities of crabs, but does not often provide the ability to interpret those results in terms of a reference point of no fishing. It may be possible to interpret the 1974 survey as representing size distributions under light fishing, so that 1974 could serve directly as a reference distribution.

Direct Analysis of Survey Densities

Table 1a shows summary statistics of mature red crab from the 1974 and 2003-2005 surveys. Estimates of female size at maturity are based on the smallest females

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[1] This exercise is a rather indirect way of projecting an impact of harvesting males on reproductive performance. A more direct measure of female reproductive output would be to compare egg production over the period. Although the depletion of large males gives reason for concern, the abundance of egg bearing female appears to have been higher in the more recent survey. By several measures (Table 1a in the DPWG Report; and Wahle et al. 2008), female abundance was considerably higher during 2003-05 than in the mid-1970s. Meanwhile, the proportion of egg-bearing females does not appear to have changed: Fig. 1 (below) compares the size composition of egg-bearing females in 1974-1976 (from Haefner 1977) to that in 2003-05 (from Wahle unpublished). A more thorough investigation of female reproductive performance relative to geographical differences in male abundance and sex ratio is one of the objectives of an industry-scientist proposal recently submitted to the Saltonstall-Kennedy Program.

observed to be ovigerous (Haefner, 1977; Wahle, unpublished). Male red crabs are physiologically mature at around 40mm, but are probably not functionally mature until that can embrace a mature female.

McElman and Elner (1982) estimated male sexual mortality at 75mm. Females are assumed to mature at **70 mm.** Elner (1987) observed successful mating with a male only 10% larger than his mate. Male functional maturity appears to occur at CW less than 90 mm. The densities of mature male crabs per 30-minute tow declined slightly from 1974 to 2003-2005, but the density of female crabs increased substantially in the later survey. This poses some difficulty for interpretation, with the main hypotheses being that it is due to imprecision (including differences in survey locations – all this needs to be explored), or alternatively that it is due to exploitation effects on a male population that otherwise would have been more abundant in the later period.

If the 1974 ratio of males to females is applied to the density of females in 2003-2005, the expected male density would have been approximately 30, in which case the observed value of 15 is presumably due to exploitation effects that would be expected in the transition from an unexploited to a sustainably fished resource. Mean size of females is similar in the two surveys, but mean size of males declined as would be expected from exploitation effects including a shift of minimum marketable size from 114mm to 90mm. By tabulating the sum of densities of females smaller than the minimum sized female each male size class is capable of mating with, table 1a below shows the mean number of females available to the males, weighted by the size frequency of males. Based on these calculations, the average male in 2003-2005 must mate with 2.33 times the number of females that it did in 1974 if each female requires mating for each fertilization.

Mellville-Smith (1987) noted that reproductive activity for the Namibian red crab is asynchronous, making it easier for one male to mate with multiple females. Zheng and Kruse (1998) determined that a male tanner crab "could mate, on average, with a maximum of five primiparous females and three multiparous females at high mature female density and one primiparous and one multiparous female at low mature female density. Therefore, a male can mate with up to eight females under ideal conditions and two females under the poorest conditions."

Zheng and Kruse (2003) discuss the similar reproductive characteristics of snow and tanner crabs and their implications:

> Many similarities exist between the reproductive biology of Tanner and snow crabs, such as storage of sperm by females for future egg fertilization and multiple female mating partners during a given mating season (Paul, 1984; Sainte-Marie and Lovrich, 1994; Sainte-Marie and Carrière, 1995). Like Tanner crab, large oldshell mature males outcompete small newshell males in mating with females (Stevens et al., 1993; Paul et al., 1995; Sainte-Marie et al., 1999). However, male snow crab are sperm conservers, partitioning sperm among successive matings, and female snow crab are polyandrous (Urbani et al., 1998; Rondeau and Sainte-Marie, 2001). Both mate-guarding time by males and the quantity of ejaculate stored in a primiparous female's spermatheca were positively

related to the sex ratio of males to females, but these relationships may change over time (Rondeau and Sainte-Marie, 2001). Therefore, lack of males for mating may rarely occur for snow crab, but sperm limitation can occur naturally if males allocate their sperm too parsimoniously among females (Rondeau and Sainte-Marie, 2001).

Table 1a. Summary of Size Composition Analysis.

Survey Date	**1974**		**2003-2005**	
	Males	Females	Males	Females
Size at maturity (mm)	90	70	90	70
Total Density (n per 30-min tow)	17.2	17.8	15.0	31.3
Mean Size of Mature Crabs	113.8	94.1	105.7	95.1
Mean ratio of size-dependent				
available females to males	25.3		58.9	

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Appendix 2a. Explanation of DCAC Model

Alec MacCall, NMFS/SWFSC/FED (draft 9/6/07) (see also MacCall 2009b)

Depletion-Corrected Average Catch Model

Unlike the classic fishery problem of estimating MSY, data poor fishery analysis must be content simple to estimate a yield that is likely to be sustainable. While absurdly low yield estimates would have this property, they are of little practical use. Here, the problem is to identify a moderately high yield that is sustainable, while having a low chance that the estimated yield level greatly exceeds MSY, and, therefore, is a dangerous overestimate that could inadvertently cause overfishing and potentially lead to resource depletion before the error can be detected in the course of fishery monitoring and management.

Perhaps the most direct evidence for a sustainable yield would be a prolonged period over which that yield has been taken, without indication of a reduction in resource abundance. The estimate of sustainable yield would be nothing more than the long-term average annual catch over that period. However, it is rare that a resource is exploited without some change in underlying abundance. If the resource declines in abundance (which is necessarily the case for newly-developed fisheries), a portion of the associated catch stream is derived from that one-time decline, and does not represent potential future yield supported by sustainable production. If that non-sustainable portion is mistakenly included in the averaging procedure, the average will tent to overestimate sustainable yield. This error has been frequently made in fishery management. Based on these concepts, we present a simple method for estimating sustainable catch levels when the data available are little more than a time series of catches. The method needs extensive testing, both on simulated data, and on cases where reliable assessments exist for comparison. So far, test cases indicate that it may be a robust calculation.

The Windfall/Sustainable Yield Ratio

The old potential yield formula $Y_{POT} = 0.5 * M * B_{UNFISHED}$ (Alverson and Pereyra, 1969; Gulland 1970), is based on combining two approximations: 1) that BMSY occurs at $0.5 * B_{UNFISHED}$, and 2) that $F_{MSY} = M$. In this, and the following calculations fishing mortality rage (F) and exploitation rate are treated as roughly equivalent. However, it is possible to take the potential yield rationale one step further and calculate the ratio of the one-time "windfall" harvest (W) due to reducing the abundance from $B_{UNFISHED}$ to the assumed B_{MSY} level. After that reduction in biomass has occurred, a tentatively sustainable annual yield (Y) is given by the potential yield formula. So we have the following simple relationships:

$$Y = 0.5 * M * B_{UNFISHED}$$
$$W = 0.5 * B_{UNFISHED}$$

Under the potential yield assumptions, the ration of one-time windfall yield to sustainable yield is the windfall/sustainable yield ration (or, simply the "windfall ratio)

$W/Y = 1/M$. For example, if $M = 0.1$, the windfall is equal to 10 units of annual sustainable yield.

An Update

The assumptions underlying the potential yield formula are out-of-date, and merit reconsideration. Most stock-recruitment relationships indicate that MSY occurs somewhat below the level of $0.5^* B_{UNFISHED}$. We replaced the value of 0.5 with a value of 0.4 as a better approximation of common stock-recruitment relationships.

The $F_{MSY} = M$ assumptions also require revision, as fishery experience has shown it tends to be too high, and should be replaced by a $F_{MSY} = c^*M$ assumption (Deriso, 1982; Walters and Martell, 2004). Walters and Martell suggest that coefficient c is commonly around 0.8, but may 0.6 or less for more vulnerable stocks. Figure 1 shows the distribution of c values for West Coast groundfish stocks assessed in 2005. The average c for those species is 0.62, but there is a substantial density of lower values. Because the risk is asymmetrical (ACLs are specifically intended to prevent overfishing), use of the average value is risk-prone. Consequently, we have used a value of $c = 0.5$ in the following calculations.

[The use of a value of $c = 0.5$ in the following calculations applies only to the explanation of the model, not the application of the model to red crab for the DPSWG or for the PDT assessment. It is also important to note that the National Standard 2 guidelines imply that decisions regarding an acceptable level of risk should be made by the Council and the Secretary, not by assessment scientists or the SSC.]

The yield that is potentially sustainable under these revised assumptions is:

$$Y = 0.4^* B_{UNFISHED}{}^*c^*M$$

or for $c = 0.5$,

$$Y = 0.2^* B_{UNFISHED}{}^* M$$

The windfall is based on the reduction in abundance from the beginning of the catch time series to the end of the series [Conventional population dynamics theory leads to the expectation that stock size will be reduced during the process of "fishing down" the stock to the MSY level. A portion of the catch during this time comes from fishing down the standing stock, rather than sustainable production. Macall refers to this as the windfall.] :

$$W = B_{BEGIN} - B_{END} = \Delta^* B_{UNFISHED}$$

where Δ is the fractional reduction in biomass from the beginning to the end of the time series, relative to unfished biomass. The analogous case to the potential yield formula is $B_{BEGIN} = B_{UNFISHED}$, and $B_{END} = 0.4^* B_{UNFISHED}$, in which case, $\Delta = 0.6$. In practice, B_{BEGIN} is rarely $B_{UNFISHED}$, and Δ is unlikely to be known explicitly. Although data may be insufficient for use in conventional stock assessment methods, an estimate (or range) of Δ, based on expert opinion, is sufficient for this calculation. The windfall ratio is now:

$W/Y = \Delta/(0.4*c*M)$,

or in the case of $c = 0.5$,

$W/Y = \Delta/(0.2*M)$.

For example, in the case of fishing down from $B_{UNFISHED}$ to near B_{MSY}, where $\Delta = 0.6$, if $c = 0.5$, then $W/Y = 3/M$. Thus, the revised calculation gives a much larger estimate of the windfall ratio. For the previous example of $M = 0.1$, the windfall ratio is now estimated at 30 unit of sustainable annual yield.

A Sustainable Yield Calculation

Assume that in addition to the windfall associated with reduction in stock size, each year produces one unit of sustainable yield. The cumulative number of annual sustainable yield units harvested from the beginning to the end of the time series is $n + W/Y$, where n is the length of the series. In this calculation, it should not matter when the reduction in abundance actually occurs in the time series because assumed production is not a function of biomass. Of course, in view of the probable domed shape of the true production curve, the temporal pattern of exploitation may influence the approximation.

The estimate of annual sustainable yield (Y_{SUST}) is:

$Y_{SUST} = \Sigma(C)/(n + W/Y)$

[Where $\Sigma(C)$ is the sum of the catch during n years.] In the special case of no change in biomass, $\Delta = 0$, $W/Y = 0$, and Y_{SUST} is the historical average catch. If abundance increases, Δ is negative, W/Y is negative, and Y_{SUST} will be larger than the historical average catch.

Examples

The widow rockfish fishery began harvesting a nearly unexploited stock in 1981 and for the first three years, fishing was nearly unrestricted (Table 1). Reliable estimates of sustainable yield based on conventional stock assessments were not available for many years afterward. By the mid-1990s, stock assessments were producing estimates of sustainable yield of approximately 5000 mt, with indications that abundance had fallen to 20-33% of $B_{UNFISHED}$. Application of depletion-corrected catch averaging indicates good performance of the method within a few years of the beginning of the fishery. Two alternative calculations are given in Table 1. The first calculation assumes $M = 0.15$, $c = 0.5$, and that biomass was near B_{MSY} at the end of the time period, so that $\Delta = 0.6$. The second calculation is closer to the most recent stock assessment (He et al., 2007) and assumes $M = 0.125$, $c = 0.5$, $\Delta = 0.75$ (ending biomass in year 2000 is about 25% of $B_{UNFISHED}$). Other examples would be worth exploring, especially were they can be compared with “ground truth” from a corresponding formal stock assessment.

Low biomasses

The yields given by these calculations can only be sustained if the biomass is at or above B_{MSY}. If the resource has fallen below B_{MSY}, the currently sustainable yield ($Y_{CURRENT}$) is necessarily smaller. A possible approximation would be based on the ratio of $B_{CURRENT}$ to B_{MSY},

$$Y_{CURRENT} = Y_{SUST} *(B_{CURRENT} / B_{MSY}); \text{ if } B_{CURRENT} < B_{MSY}$$

Implementation

This method is most useful for species with low natural mortality rates; stocks with low mortality rates tend to pose the most serious difficulties in rebuilding from an overfished condition. As natural mortality rate increases ($M > 0.2$), the windfall ratio becomes relatively small, and the depletion correction has little effect on the calculation. The relationship between F_{MSY} and M may vary among taxonomic groups of fishes, and among geographic regions, and would be a good candidate for meta-analysis. Uncertainty in parameter values can be represented by probability distributions. A Monte Carlo sampling system such as WinBUGS can easily estimate the output probability distribution resulting from specified distributions of the inputs.

With minor modifications, this method could also be applied to marine mammal populations. Although estimation of sustainable yields is not a central issue for marine mammals nowadays, the method would be especially well suited to analysis of historical whaling data, for example.

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Appendix 2b. Alec MacCall's Comparison of MSY and DCAC Sustainable Yield.

DCAC is a pretty simple model, but understanding what it really means can require quite a bit of thinking, and even then may not be very clear. Importantly, DCAC cannot estimate MSY. The DCAC value is usually (it is supposed to be) smaller than MSY, often in the range of 50% to 75% in my experience. The reason DCAC is not MSY is because it represents the production curve by a straight horizontal line. Let's assume that the true production curve is dome-shaped, such as the parabolic form from a classical Shaefer or ASPIC model. DCAC estimates the surplus production over some period and average stock size corresponding to some partial segment of that dome-shaped curve. So imagine a horizontal line (DCAC) that is about the same level as the average of the dome-shaped production curve for that range of stock sizes. Only if the range happens to fall from 40% to 60% of Bunfished will DCAC be near MSY. If the range is 30% to 70%, the horizontal DCAC line representing the average of the production curve will fall farther yet below the peak.

If the abundance range falls mostly on one side or the other of the peak, which most often is the case, DCAC has to falls well below the peak. That is why DCAC should tend to be less than MSY. I have recently been working on a stock assessment for a data-poor and very long-lived Sebastes (M=0.038), and was able to directly compare an 80-year DCAC with an MSY from ASPIC, and am getting DCAC about half of MSY (which makes good sense when you average over almost the entire range of the production curve). That is the only good direct comparison I know of, but I think more examples will be available in the next few years.

I did a really simple comparison (see attached spreadsheet in Table 15) of average production over the range of Bunfished down to 40% of Bunfished, and got a value of DCAC/MSY=72%. Of course this assumes that DCAC exactly reflects the production curve, equally weighted over the range. Reality is going to be a lot less precise. Still, it demonstrates what the relationship should look like. If the horizontal line is only a small portion of the high abundance end, DCAC will give a low value--exactly the same if it is an equal portion of the low abundance end. The problem is that DCAC is blind to actual abundance, and there is obviously a big practical difference between the high abundance end and low end of the production curve, even though surplus production might be the same.

Table 15- Alec MacCall comparison of DCAC results to MSY.

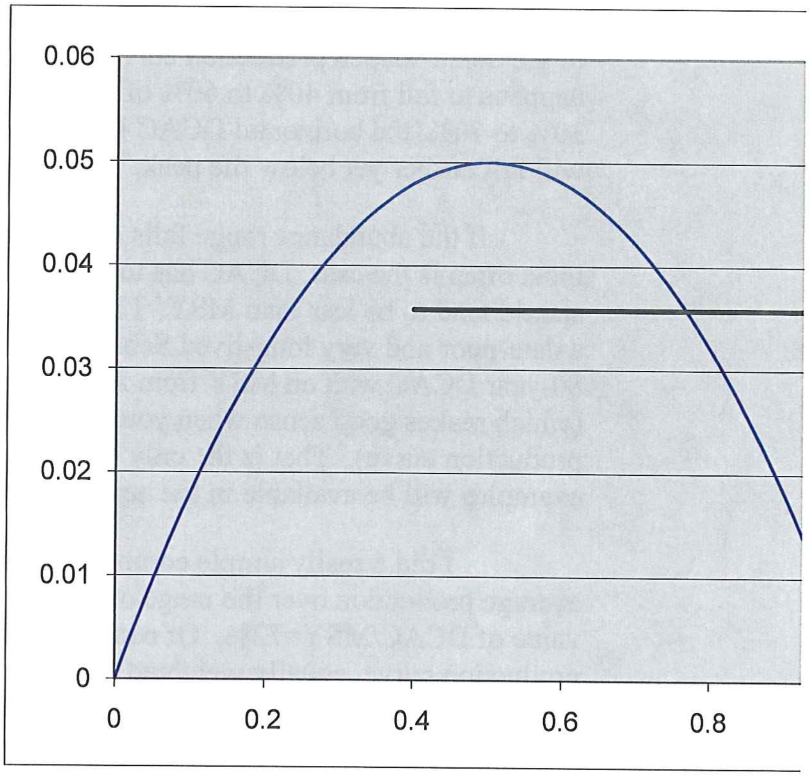
K	1
r	0.2

Biomass	Production
0	0
0.01	0.00198
0.02	0.00392
0.03	0.00582
0.04	0.00768
0.05	0.0095
0.06	0.01128
0.07	0.01302
0.08	0.01472
0.09	0.01638
0.1	0.018
0.11	0.01958
0.12	0.02112
0.13	0.02262
0.14	0.02408
0.15	0.0255
0.16	0.02688
0.17	0.02822
0.18	0.02952
0.19	0.03078
0.2	0.032
0.21	0.03318
0.22	0.03432
0.23	0.03542
0.24	0.03648
0.25	0.0375
0.26	0.03848
0.27	0.03942

DCAC-like average	0.0358
MSY	0.05
DCAC/MSY	0.716

$$Y = 0.4 * B_{UNFISHED} * c * M$$
$$W/Y = \Delta/(0.4 * c * M)$$
$$Y_{SUST} = \Sigma(C)/(n + W/Y)$$

M	0.1
c	0.8



Appendix 2c. *DCAC Output (-0.20 Depletion Delta) with Confidence Intervals*

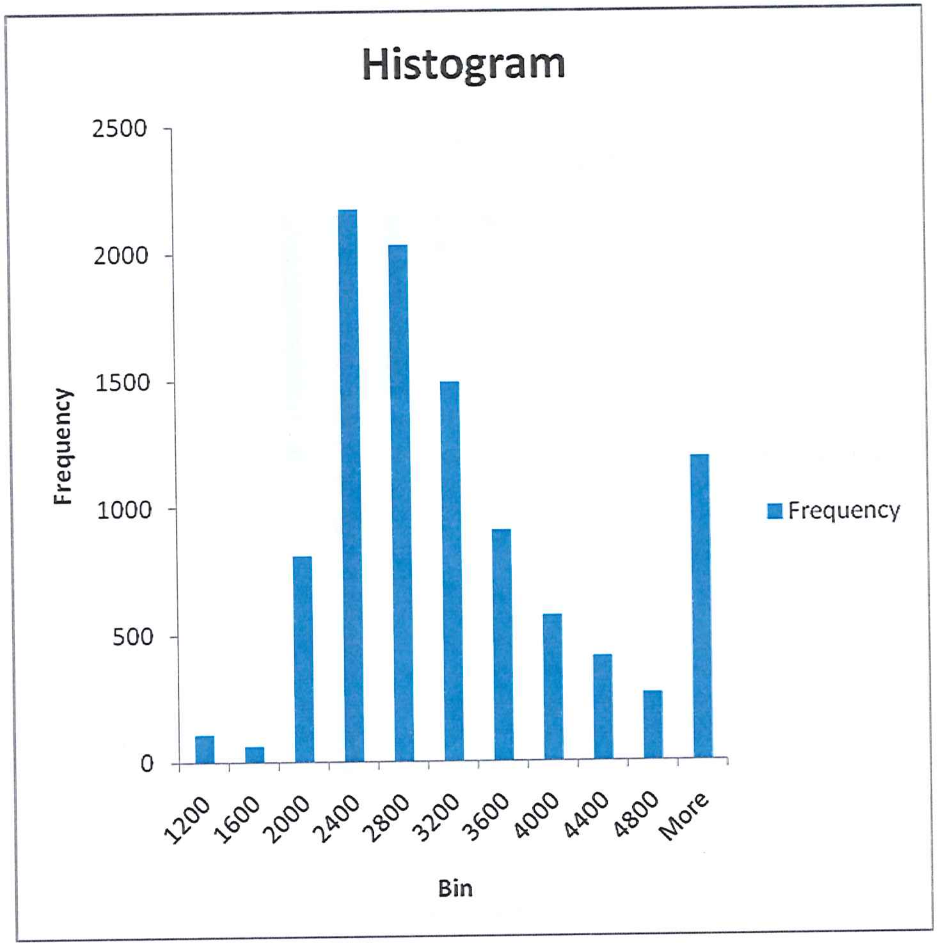
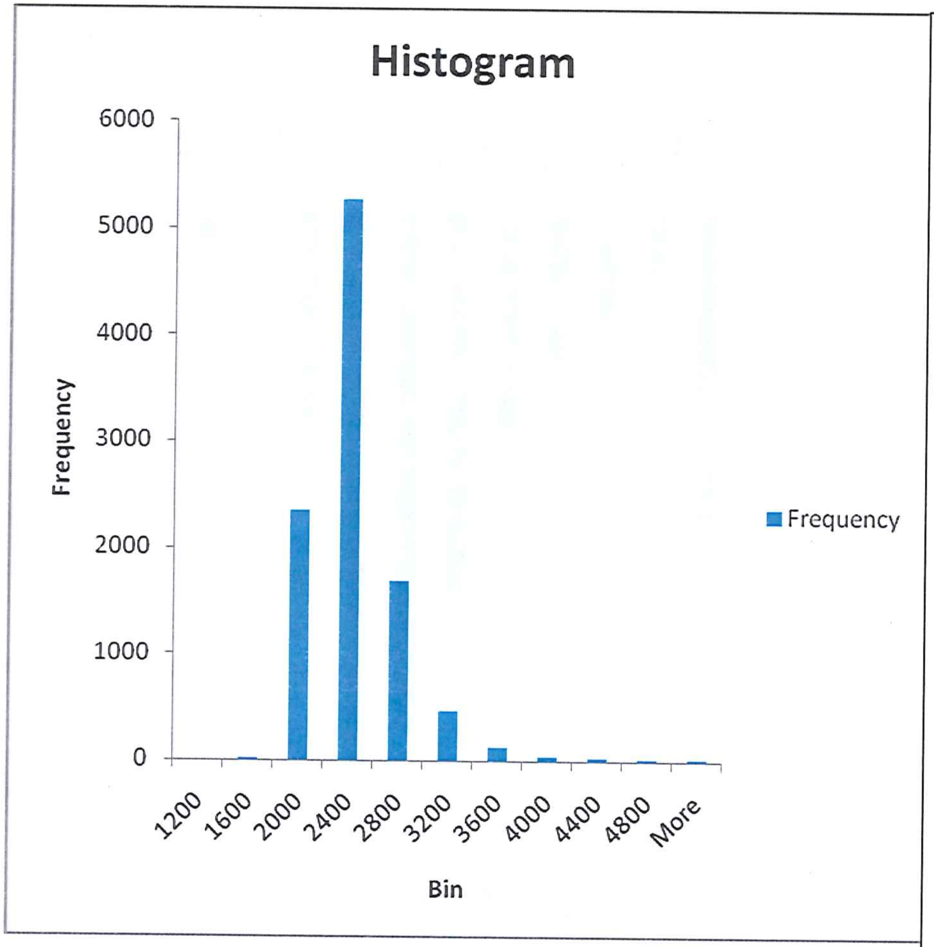


Table 16- DCAC model results with M=0.05 and depletion DELTA = -0.20 with histogram.

```
Table 1
Depletion Corrected Average Catch Model Version 1.1.1 (Calculation E

Warning -      104 Iterations Have Negative Values

Case Description: Minus pt2 dep delta m=05 sd 25 fmsy =08

Number of Years       =      35
Random Number Seed     =  29815167
Number of Iterations  =    10000

                          Value      STD Deviation

Sum of Catch          =    62132.0000
Natural Mortality     =      0.0500       0.2500
FMSY to M             =      0.8000       0.0500
Depletion Delta       =     -0.2000       0.1000

Uncorrected Avg. Catch =    1775.200000

Average DCAC           =    3441.107193
Median DCAC            =    2761.493856

1%   - 99% CI =  -4028.609061 -   17833.631206
5%   - 95% CI =   1862.373515 -    7177.449308
10%  - 90% CI =   2007.831882 -    5154.875708
20%  - 80% CI =   2210.387052 -    3898.547968

Minimum = -2763319.357482 - Maximum =  2308486.228268
```

Table 17- DCAC model results with M=0.10 and depletion DELTA = -0.2 with histogram.



```
Depletion Corrected Average Catch Model Version 1.1.1 (Calculation Engine)

Warning -        1 Iterations Have Negative Values

Case Description: Minus pt2 dep delta sd 1 m=1sd 25 fmsy =08 sd05

Number of Years        =       35
Random Number Seed     =  29815167
Number of Iterations   =     10000

                        Value        STD Deviation

Sum of Catch        =   62132.0000
Natural Mortality   =      0.1000       0.2500
FMSY to M           =      0.8000       0.0500
Depletion Delta     =     -0.2000       0.1000

Uncorrected Avg. Catch =    1775.200000

Average DCAC        =    2193.877073
Median DCAC         =    2168.012150

1%   - 99% CI =    1711.938690 -    3567.040166
5%   - 95% CI =    1833.489094 -    2907.854635
10%  - 90% CI =    1896.721951 -    2668.770194
20%  - 80% CI =    1975.836868 -    2454.328912
     Minimum = -507732.466462 - Maximum =     9221.308928
```

Table 18- DCAC model results with M=0.15 and depletion DELTA -0.20 with histogram.

```
Table 4
Depletion Corrected Average Catch Model Version 1.1.1 (Calculation E

Case Description: Minus pt2 dep delta sd 1 m=15 sd 25 fmsy =08 sd05

Number of Years        =      35
Random Number Seed     =  29815167
Number of Iterations   =    10000

                          Value       STD Deviation

Sum of Catch          =   62132.0000
Natural Mortality     =      0.1500      0.2500
FMSY to M             =      0.8000      0.0500
Depletion Delta       =     -0.2000      0.1000

Uncorrected Avg. Catch =   1775.200000

Average DCAC           =   2050.983893
Median DCAC            =   2019.131231

1%  - 99% CI =    1732.879967 -   2669.029912
5%  - 95% CI =    1813.670053 -   2398.034004
10% - 90% CI =    1854.408904 -   2285.355647
20% - 80% CI =    1904.156225 -   2176.858981

Minimum =    1593.860647 - Maximum =    5363.102346
```

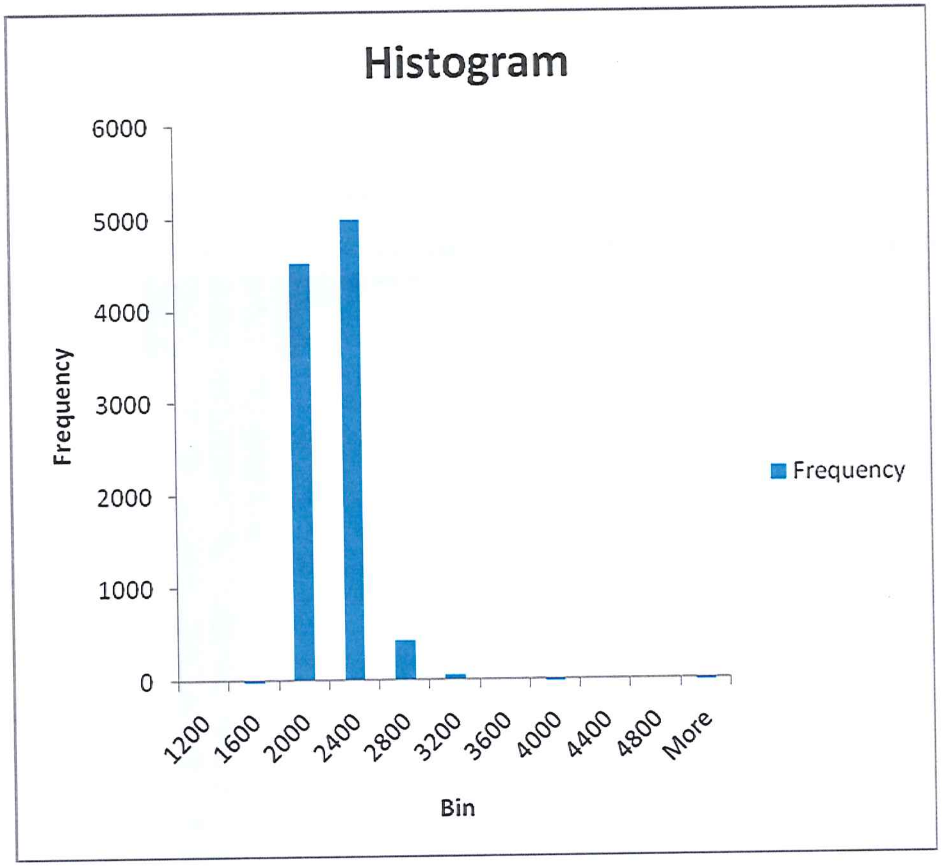
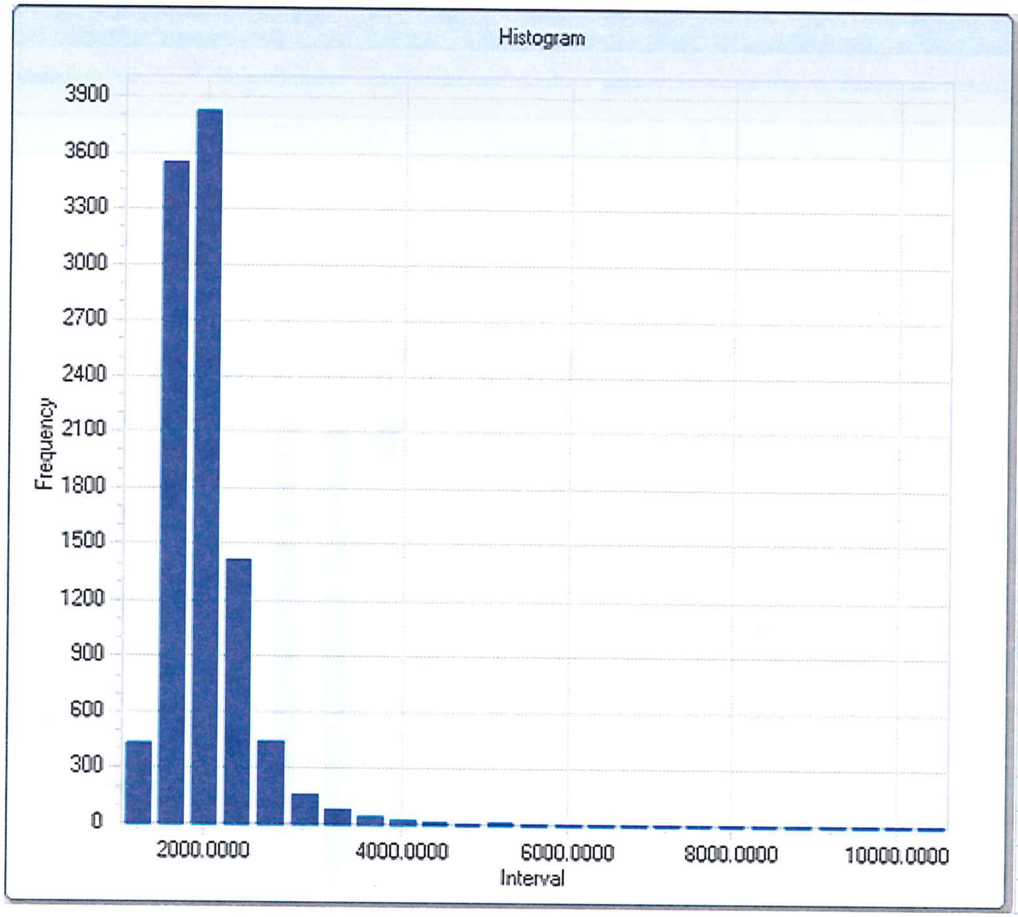
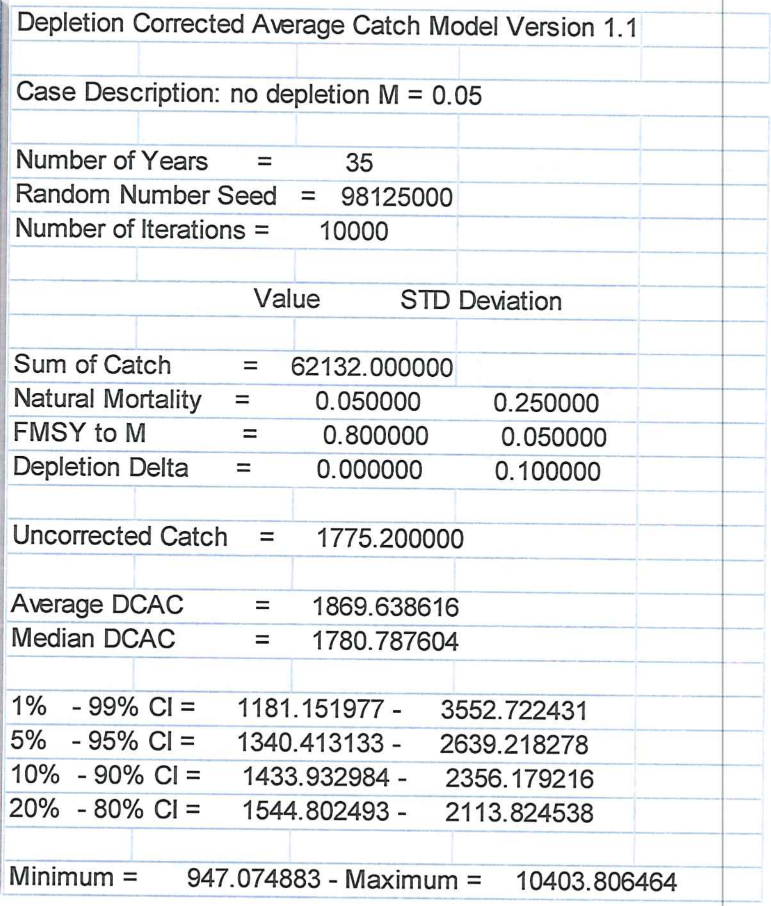


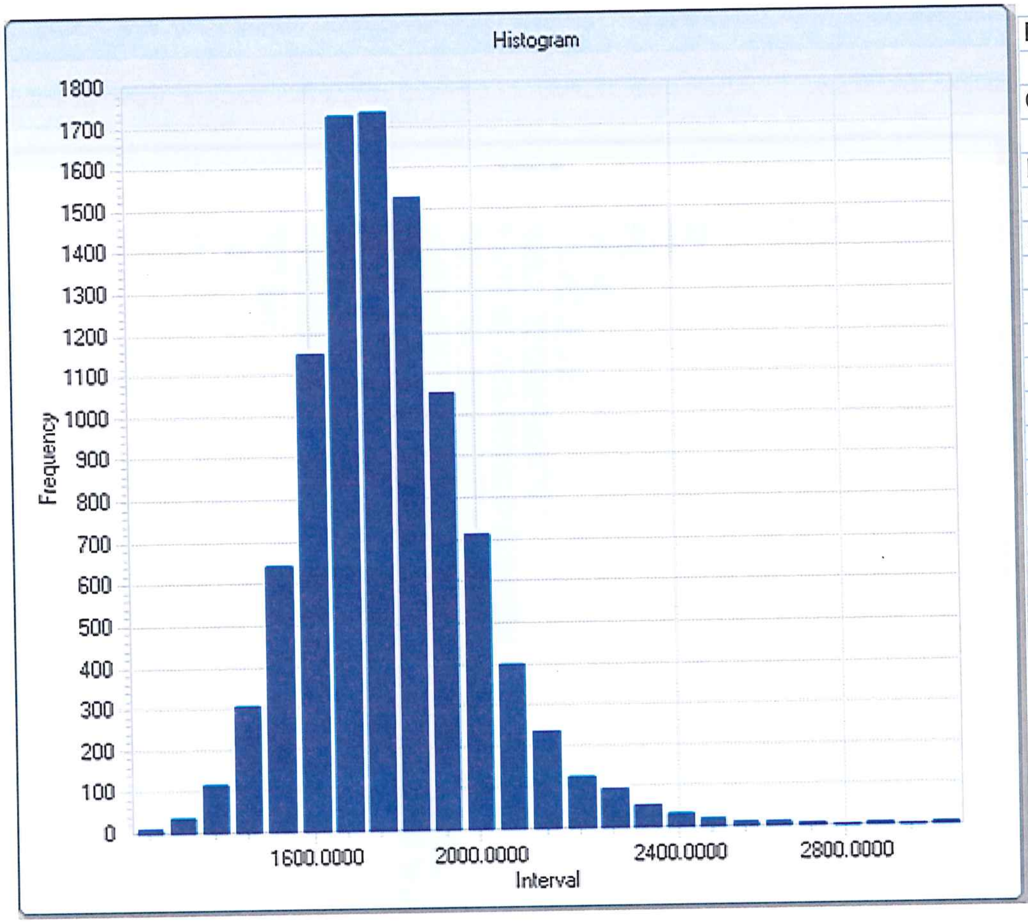
Table 19- Results for DCAC model with M=0.05 and zero depletion DELTA with histogram.

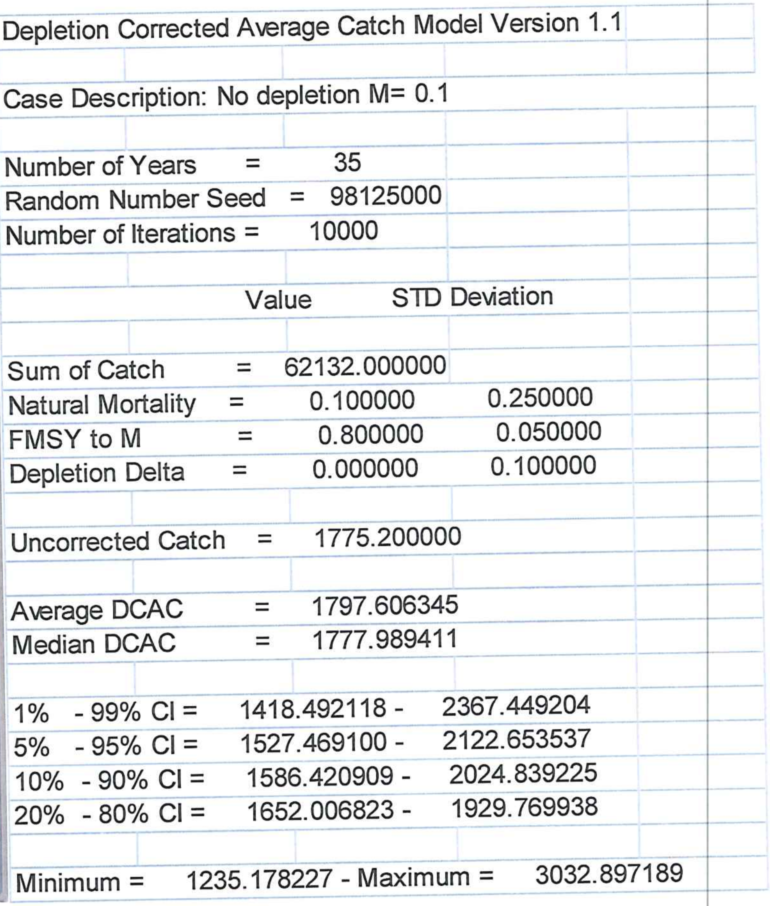




```
Depletion Corrected Average Catch Model Version 1.1

Case Description: no depletion M = 0.05

Number of Years        =     35
Random Number Seed   =  98125000
Number of Iterations =    10000

                         Value        STD Deviation

Sum of Catch          =  62132.000000
Natural Mortality    =     0.050000       0.250000
FMSY to M             =     0.800000       0.050000
Depletion Delta      =     0.000000       0.100000

Uncorrected Catch    =    1775.200000

Average DCAC          =    1869.638616
Median DCAC           =    1780.787604

1%   - 99% CI =    1181.151977 -    3552.722431
5%   - 95% CI =    1340.413133 -    2639.218278
10%  - 90% CI =    1433.932984 -    2356.179216
20%  - 80% CI =    1544.802493 -    2113.824538

Minimum =      947.074883 - Maximum =     10403.806464
```

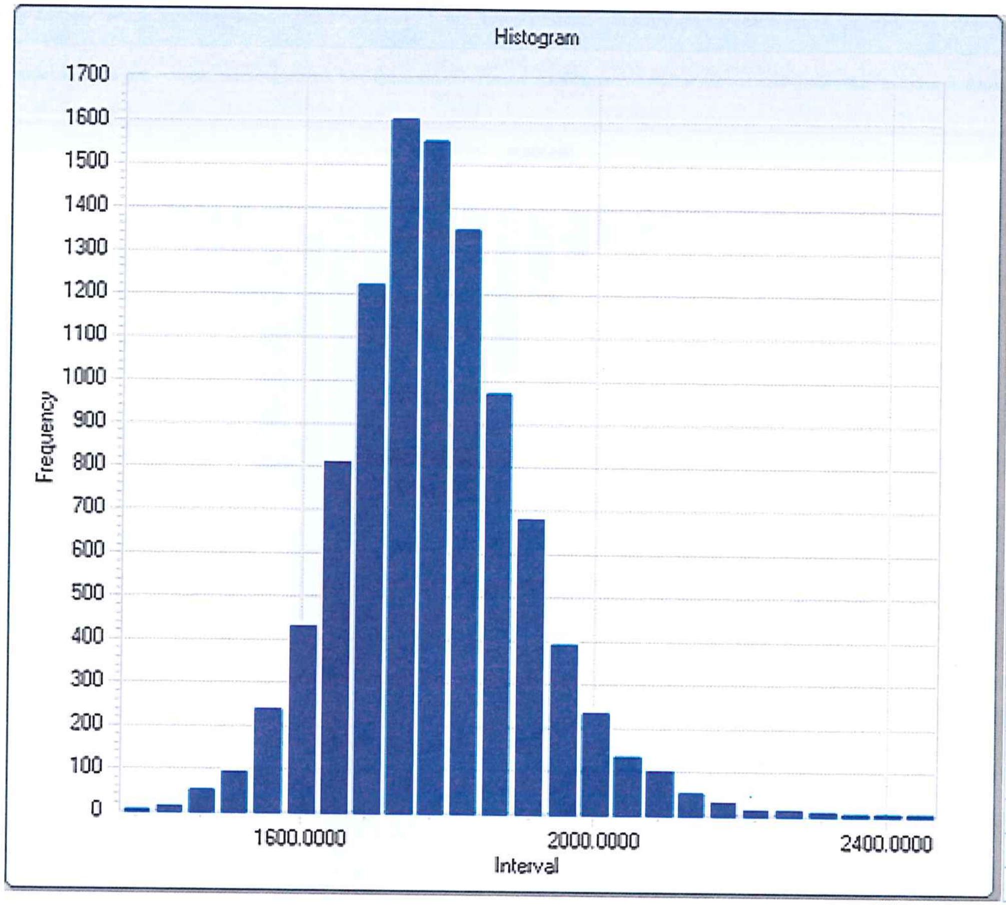
Table 20- DCAC model results with M=0.10 and zero depletion DELTA with histogram.

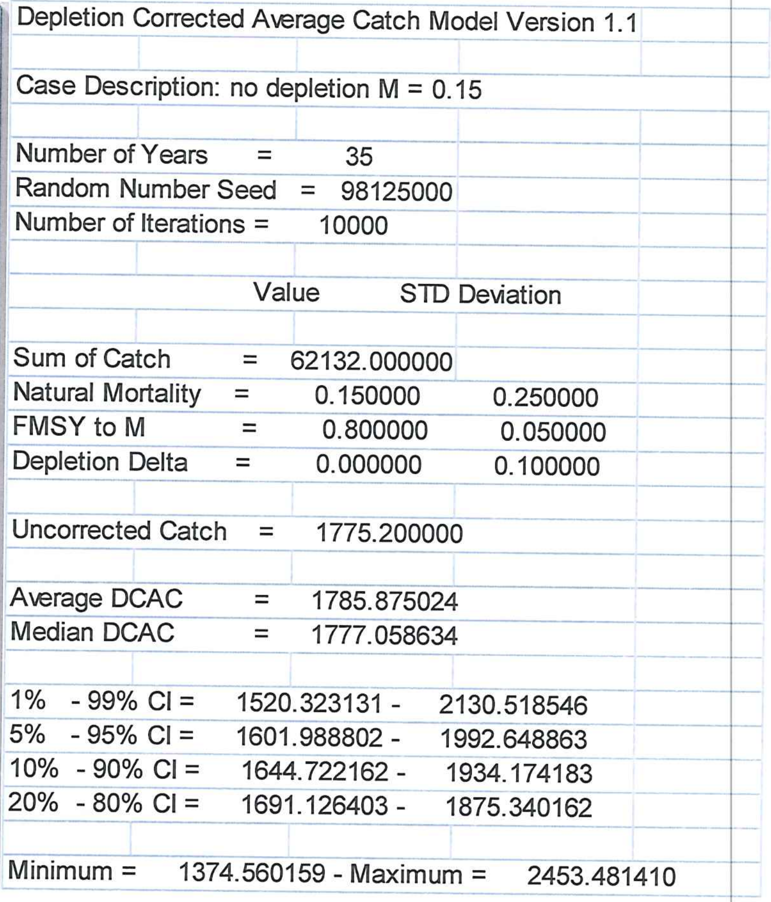




Depletion Corrected Average Catch Model Version 1.1			
Case Description: No depletion M= 0.1			
Number of Years	=	35	
Random Number Seed	=	98125000	
Number of Iterations	=	10000	
		Value	STD Deviation
Sum of Catch	=	62132.000000	
Natural Mortality	=	0.100000	0.250000
FMSY to M	=	0.800000	0.050000
Depletion Delta	=	0.000000	0.100000
Uncorrected Catch	=	1775.200000	
Average DCAC	=	1797.606345	
Median DCAC	=	1777.989411	
1% - 99% CI	=	1418.492118 -	2367.449204
5% - 95% CI	=	1527.469100 -	2122.653537
10% - 90% CI	=	1586.420909 -	2024.839225
20% - 80% CI	=	1652.006823 -	1929.769938
Minimum =		1235.178227 - Maximum =	3032.897189

Table 21- DCAC model results with M=0.15 and zero depletion DELTA with histogram.





```
Depletion Corrected Average Catch Model Version 1.1

Case Description: no depletion M = 0.15

Number of Years      =      35
Random Number Seed   =   98125000
Number of Iterations =   10000

                        Value          STD Deviation

Sum of Catch        =   62132.000000
Natural Mortality   =      0.150000      0.250000
FMSY to M           =      0.800000      0.050000
Depletion Delta     =      0.000000      0.100000

Uncorrected Catch   =    1775.200000

Average DCAC        =    1785.875024
Median DCAC         =    1777.058634

1%   - 99% CI =   1520.323131 -   2130.518546
5%   - 95% CI =   1601.988802 -   1992.648863
10%  - 90% CI =   1644.722162 -   1934.174183
20%  - 80% CI =   1691.126403 -   1875.340162

Minimum =    1374.560159 - Maximum =    2453.481410
```

Appendix 2d. DCAC/MSY Evaluation

Alec MacCall (personal communication) cautions that the DCAC model estimates sustainable yield, but not maximum sustainable yield. His analysis indicates that the DCAC model will produce estimates of sustainably yield that range between 50-72% of MSY. The PDT tested the relationship between DCAC model results and known MSY values for modeled fisheries.

Figure 27 illustrates DCAC model results calculated each year during the 100-year history of a modeled fishery with known parameters. The only thing that is not known by the DCAC model is modeled cannibalism on smaller males that is proportional to the abundance of larger males. Fishing commences in year zero on a population that is in equilibrium. The fishing mortality rate is the known Fmsy from year zero through year 100. The Fmsy to M ratio used in the DCAC model is 0.8. After 35 years of fishing at Fmsy, the DCAC model calculates a sustainable yield of 67% of the known MSY. After 100 years the DCAC sustainable yield is 85% of the known MSY.

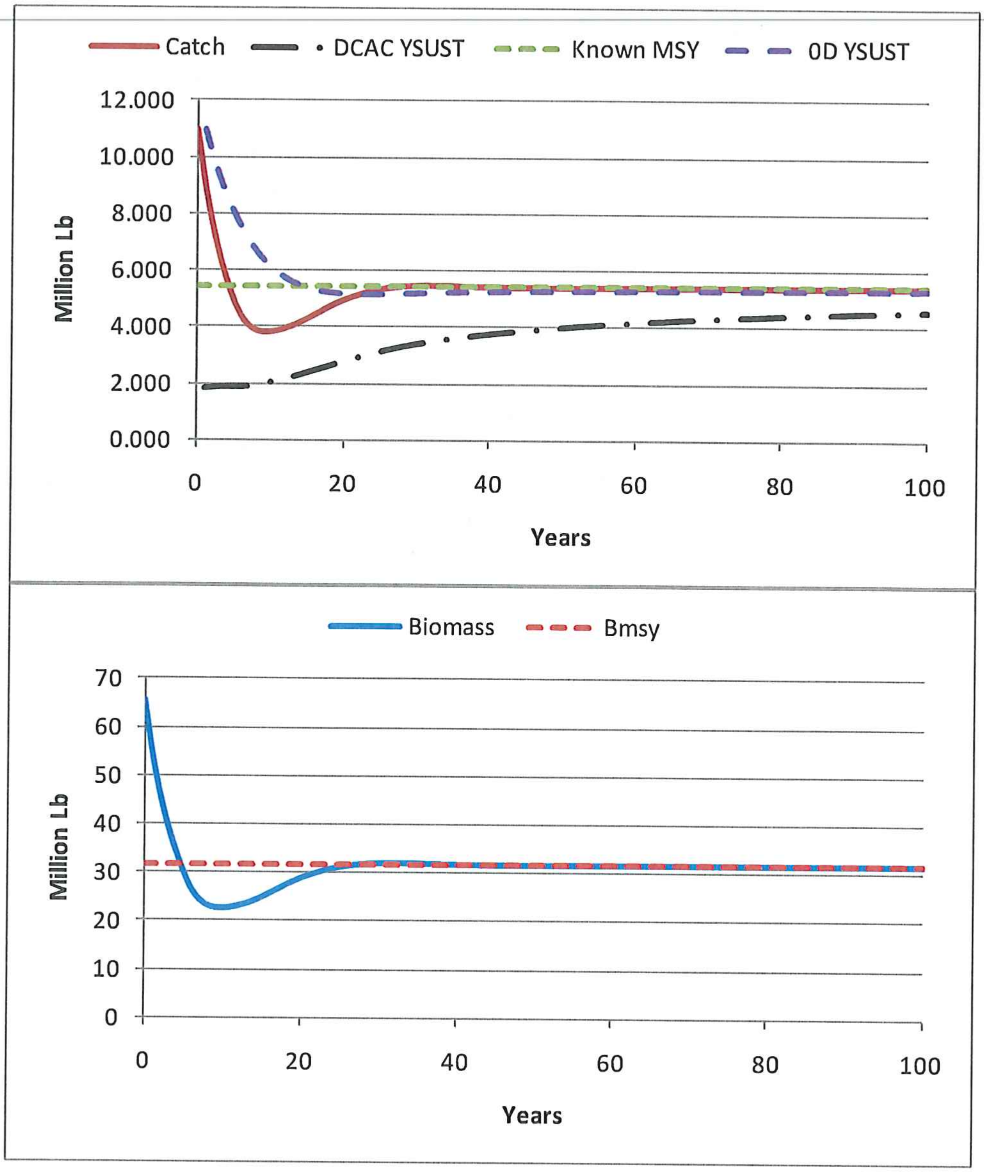


Figure 27- Sustainable yield estimates calculated each year by the DCAC model during the history of a modeled fishery with known MSY, known biomass, known large male natural mortality, and known catches.

Figure 28 illustrates the DCAC results for a modeled fishery in which the landings match the highly variable recorded landings of the red crab fishery. In this case, the DCAC results in year 35 are 59% of the known MSY.

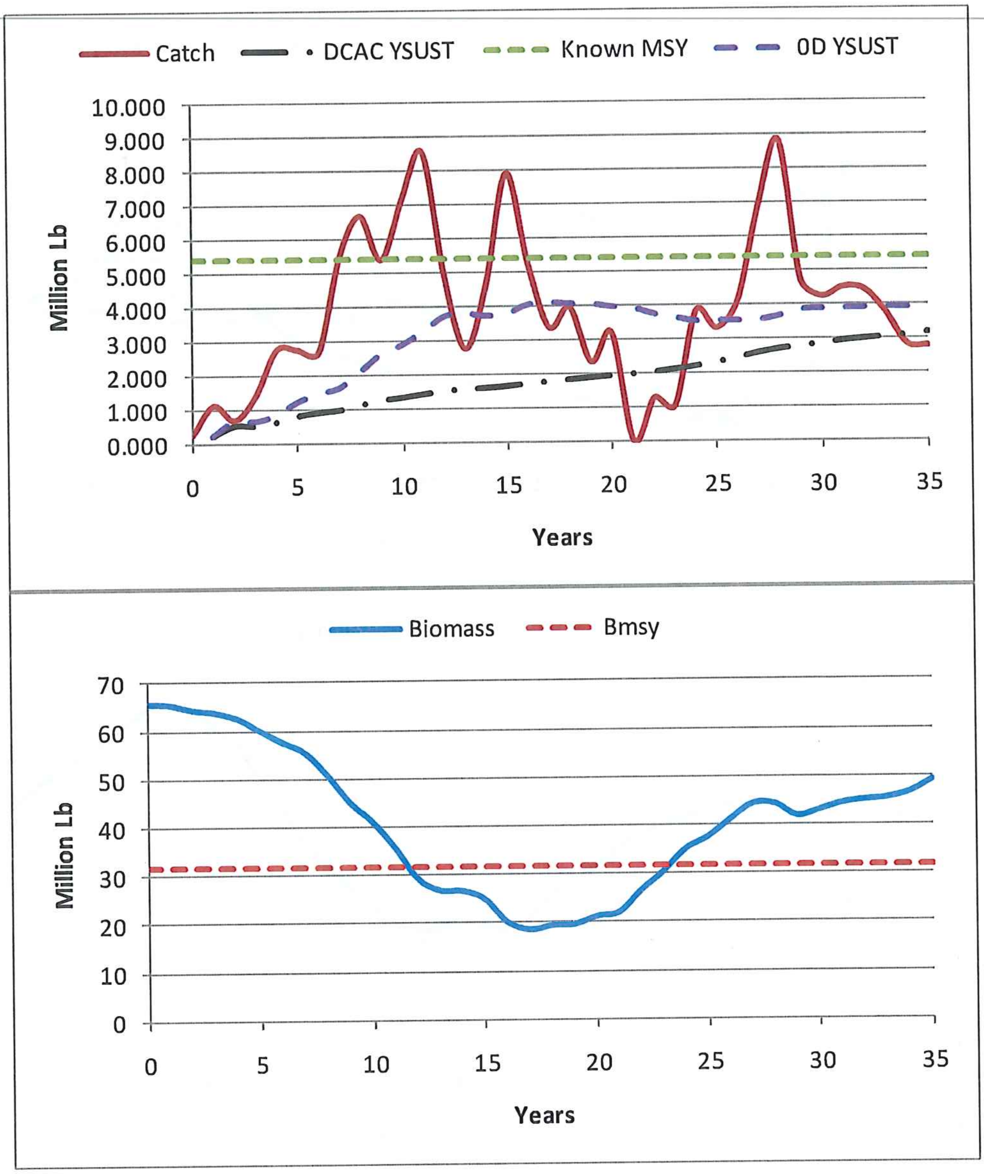


Figure 28- DCAC model results for a modeled fishery with exploited biomass less than initial biomass.

Figure 29 demonstrates the effect of strong density-dependent mortality and highly variable landings on the results from the DCAC model. The population modeled in Figure 29 has a highly-domed Ricker stock-recruitment relationship and additional mortality on smaller males that is proportional to the abundance of larger males. This combination produces a rebound above the initial biomass level when heavy fishing pressure is relaxed in years 17 through 25. This increase in population size causes the DCAC model to produce results that are in excess of the known MSY during the stock rebound. Under these circumstances, the DCAC model run with an assumed zero depletion delta estimates sustainable yield at approximately 75% of MSY.

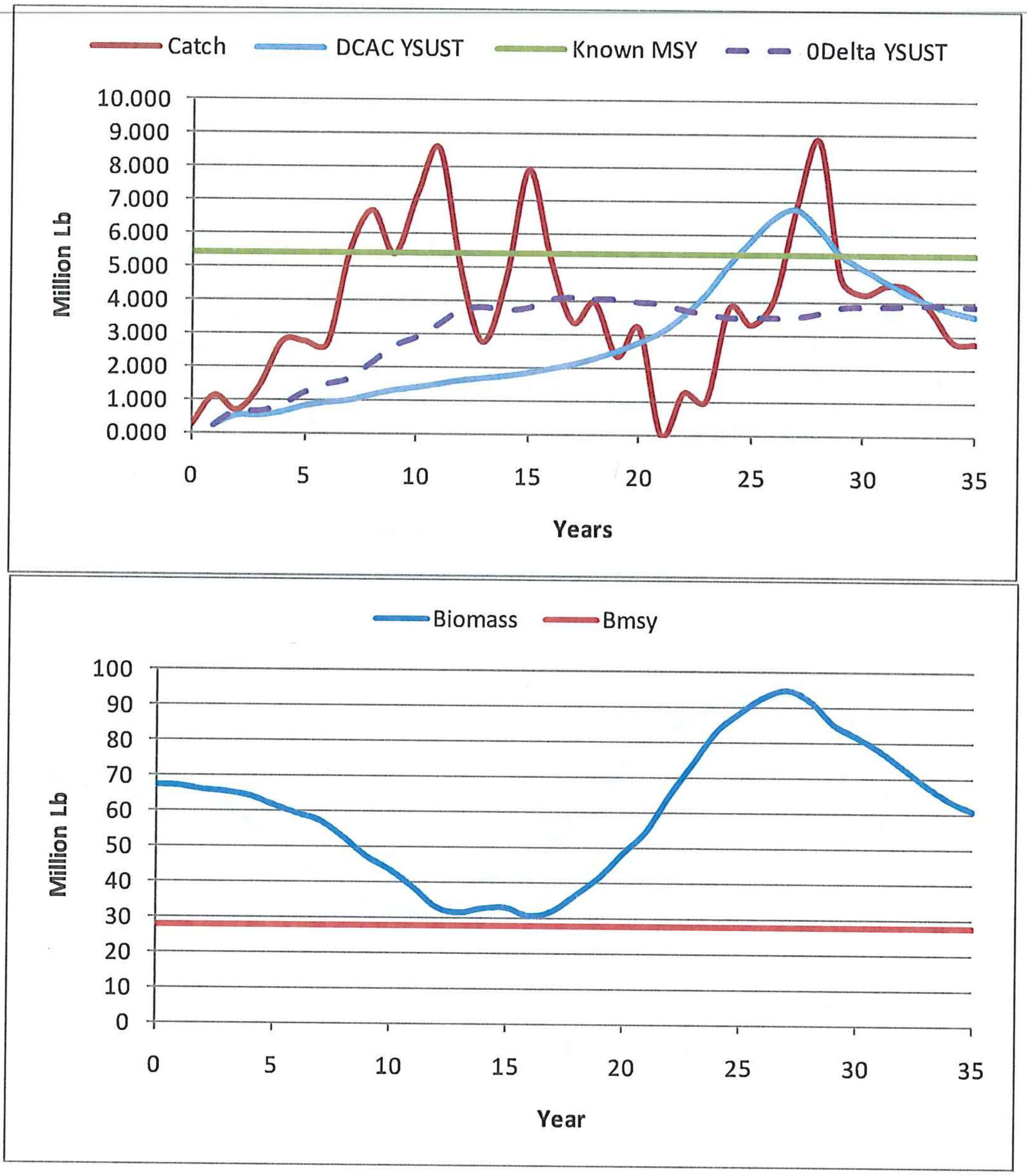


Figure 29- DCAC model results for a modeled fishery with exploited biomass higher than initial biomass.

Appendix 3. 2-Point Boundary Model

Estimation of Average Recruitment, Biomass Weighted F, and Equilibrium Catch

Two quantitative surveys of red crab abundance and long-term record of landings provide an opportunity to estimate the average recruitment necessary to support the observed time series of catch. This is accomplished by using a simple mass balance equation with boundary conditions defined as the initial and final survey values.

Process Equation

Let B_t represent the biomass at time t and specify the boundary conditions B_0 and B_T.

The biomass at time $t+1$ can be expressed as

$$B_{t+1} = (B_t - C_t + R_t)S \qquad (1)$$

Where C_t is the total catch and R_t is total recruitment of biomass to the population. The parameter S can be thought of as either the survival rate = e^{-M} or the difference between the instantaneous rate of growth G and M of $S = e^{-(G-M)}$. For this application, it was assumed that increments to population biomass via growth are included in the R_t term; therefore, $S = e^{-M}$. No information is available to estimate the annual recruitment to the population, Eq. 1 can be simplified to let R_t equal a constant, say R:

$$B_{t+2} = (B_{t+1} - C_{t+1} + R)S \qquad (2)$$

Substituting Eq. 1 into Eq. 2 recursively leads to:

$$B_{t+2} = (B_t - C_t + R)S - C_{t+1} + R)S$$

$$B_{t+3} = (B_{t+2} - C_{t+2} + R)S$$

$$B_{t+3} = (B_t - C_t + R)S - C_{t+1} + R)S - C_{t+2} + R)S$$

...

$$B_{t+T} = B_t S^{T-1} + \sum_{j=1}^{T-1} S^j R - \sum_{j=1}^{T-1} C_j S^{T-j} \qquad (3)$$

$$B_{t+T} = B_t S^{T-1} + \sum_{j=1}^{T-1} S^i R$$

If we let $B_t = B(0)$, $B_{t+T} = B(T)$, and assume S, then it is possible to estimate R as the average recruitment necessary to satisfy Eq. 3.

$$R = \frac{B(T) - B(0)S^{T-1} + \sum_{j=1}^{T-1} C_j S^{T-j}}{\sum_{j=1}^{T-1} S^j} \tag{4}$$

Given the average recruitment R, the year specific F_t can be estimated as

$$\hat{F} \approx \frac{C_t}{B_t + R} \tag{5}$$

The estimates of year specific F_t are unreliable since they depend on the average recruitment estimate R. However, the average F over the period can be estimate as:

$$\overline{F} = \sum_{j=1}^{T-1} \frac{\hat{F}_j}{T-1} \tag{6}$$

The average catch sufficient to maintain the population at it current size can be estimated by setting $B_{t+T} = B_T$ in Eq. 1 and solving for C as:

$$B_T = (B_T - \overline{C}_{EQ} + R)S$$

$$\overline{C}_{EQ} = R - \frac{B_T(1-S)}{S} \tag{7}$$

Eq. 4, 6, and 7 can now be used to estimate the average recruitment necessary to support the total removals between time t and $t+T$, the average biomass weighted F experienced by the population, and the average catch necessary to maintain the population at its current value of B_T.

Incorporating the Uncertainty in Population Size

The uncertainty in the initial and final population sizes has important implications for the uncertainty in the average R, Fbar, and C_{EQ}. This uncertainty can be approximated by convolving the distribution of initial population size with the final population size. Assume that the survey mean estimates are normally distributed. Let $B_t \sim N(\mu_t, \alpha_t^2)$, $B_{t+T} \sim N(\mu_{t+T}\alpha_{t+T}^2)$ and $\varphi(.)$ define the cdf of the normal distribution. The inverse of the normal cdf say $\varphi^{-1}(.)$, can be used to define population estimates for equal intervals.

$$B_{t,\alpha} = \varphi^{-1}(\mu_t, \alpha_t^2, \alpha), \quad \alpha = \alpha_{\min}, \ldots \alpha_{\max}$$

$$B_{T,\beta} = (\mu_t, \alpha_t^2, \beta), \quad \beta = \beta_{\min}, \ldots \beta_{\max} \tag{8}$$

Define $R_{\alpha,\beta}$ as the average recruitment obtained by substituting $B_{t,\alpha}$ and $B_{T,\beta}$ in Eq. 4 for B(0) and B(T), respectively. The sampling distribution of R, and by extension Fbar and Cbar, can now be obtained by simply matching all possible values of α with all possible values of β. More economically, one can define small step size, say δ and evaluate $R_{\alpha,\beta}$ for equal increments between the minimum and maximum values of the cdf. The sampling distributions of R, Fbar, and C_{EQ} is just the collection of discrete estimates $R_{\alpha,\beta}$ have equal probabilities of occurrence = δ^2 and the sum of all δ^2's is one.

Application to Red Crab

Estimates of R, Fbar, and C_{EQ} were derived for male and female red crab from the 1974 survey and 2004 fishery independent surveys (Table xx) and landings from 1974 to 2003 (Table zz). The distributions of R, Fbar, and C_{EQ} were based on convolution of 51 equal probability cut points representing a 95% confidence interval for the initial and final year biomass estimates. The convolution distribution was based on 2,601 (i.e. 51 x 51) evaluations of Eq. 4. Annual survival for the base runs was assumed to be 0.86 (i.e., $M = 0.15$).

Model results suggest that the median male recruitment is about 8,500 mt per year. Historical average F between 1974 and 2004 was about 0.04 (Table yy). Given the population size in 2004, catches of 2,060 mt would keep the population at its current size of about 36,000 mt. This is about 16% higher than the average catch between 1973 and 2007, but 10% less than landings since 2000.

Between 1974 and 2004, the female population (> 90 mm CW) increased nearly four-fold from 15 kt to 55 kt. Under the assumption that fishing mortality on females was essentially zero, the estimated median recruitment was 9,837 mt. The confidence intervals for median recruitment levels for males and females overlap which suggest comparable rates of biomass recruitment. The parameters for average recruitment and survival are confounded and the small differences in average recruitment estimates between male and female recruitment could be due to slightly different mortality rates or growth rates between the sexes. For example, assuming an $M = 0.13$ for females results in a median R of 7,810 mt, that is about the same size as the median R for males when $M= 0.15$.

The sensitivity of the R, Fbar, and C_{EQ} to changes in M are illustrated in Tables yy1 to yy3. Estimated average recruitment increases about three-fold as M increases (or S declines) from 0.05 to 0.20. The estimated equilibrium catch is relatively unchanged, remaining at about 2,000 mt. Figures 1 and 2 demonstrate that as S approaches 1, the long-term catch equals the estimated average recruitment.

Table 22- Estimated Survey Biomass of Male and Female Red Crab, 1974 and 2004.

Category	**Initial Biomass (SE)**	**Final Biomass (SE)**
Fishable Biomass of Males	30,302 (6,363)	36,247 (4,612)

Female Biomass (>90 mm CW)	15,654 (3,719)	55,279 (7,033)

Table 23- Summary of Annual Landings (mt) of Red Crab in U.S.

Year	Landings (mt)
73	112.5
74	503.1
75	307.3
76	637.9
77	1,244.6
78	1,247.6
79	1,210.8
80	2,481.2
81	3,031.8
82	2,445.6
83	3,252.4
84	3,875.0
85	2,236.7
86	1,248.7
87	2,110.3
88	3,592.7
89	2,393.2
90	1,526.7
91	1,791.0

92	1,061.2
93	1,439.9
94	0.3
95	572.0
96	465.6
97	1,752.2
98	1,501.1
99	1,869.2
00	3,129.4
01	4,002.7
02	2,142.5
03	1,920.0
04	2,404.3
05	2,013.2
06	1,716.0
07	1,284.0
08	

Table 24- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.15 (S=0.861).

Category	Recruitment	Fishing Mortality	Equilibrium Catch
Fishable Biomass of Males	7,928 (6,856; 9,068)	0.042 (0.036; 0.049)	2,044 (2,023; 2,064)
Female	9,044	0	72

Biomass (>90 mm CW)	(7,408; 10,785)		(53; 93)

Table 25- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.05 (*S*=0.95).

Category	**Recruitment**	**Fishing Mortality**	**Equilibrium Catch**
Fishable Biomass of Males	3,850 (3,402; 4,324)	0.047 (0.041; 0.054)	1,987 (1,819; 2,152)
Female Biomass (>90 mm CW)	3,427 (2,766; 4,127)	0	584 (419; 757)

Table 26- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.1 (*S*=0.905).

Category	**Recruitment**	**Fishing Mortality**	**Equilibrium Catch**
Fishable Biomass of Males	5,819 (5,095; 6,587)	0.044 (0.038; 0.051)	1,996 (1,932; 2,058)
Female Biomass (>90 mm CW)	6,049 (4,945; 7,224)	0	219 (157; 283)

Table 27- Estimated Median Recruitment, average *F*, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality (*M*) is assumed to be 0.2 (*S*=0.819).

Category	Recruitment	Fishing Mortality	Equilibrium Catch
Fishable Biomass of Males	10,159 (8,704; 11,707)	0.039 (0.034; 0.046)	2,110 (2,104; 2,116)
Female Biomass (>90 mm CW)	12,297 (10,.077; 14,658)	0	22 (16; 28)

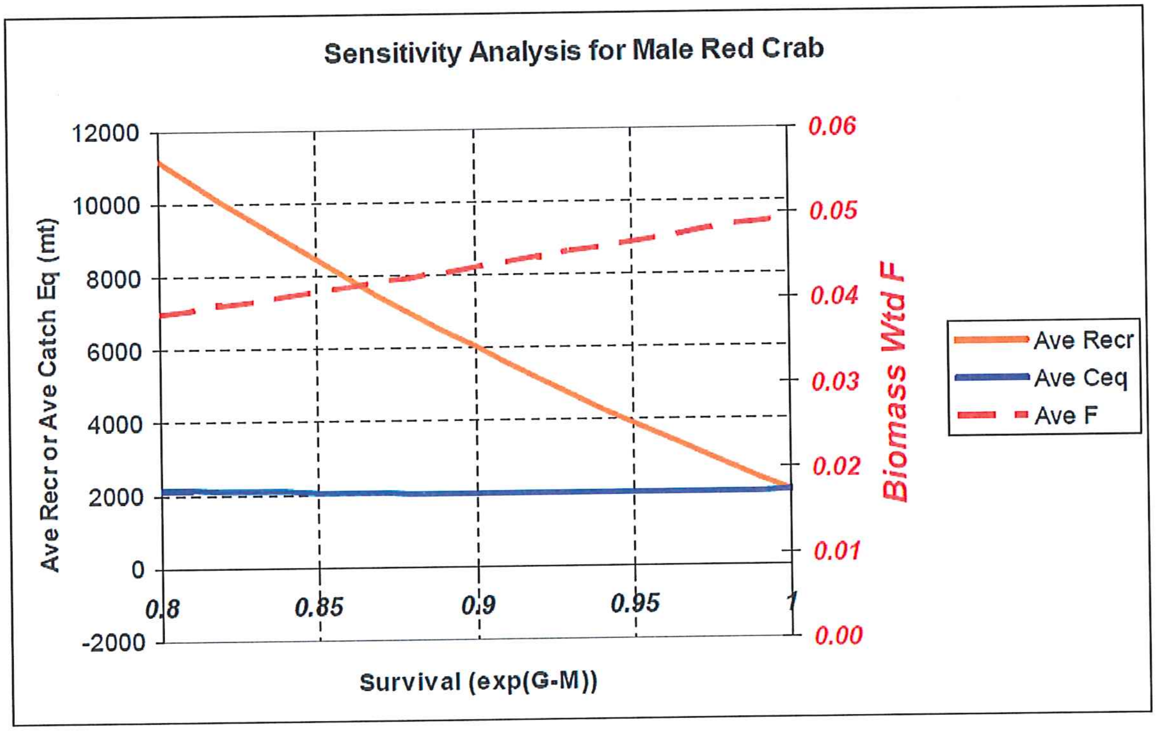


Figure 30- Fig A3-1 from Appendix 3 of DPSWG Working Paper. Sensitivity analysis of recruitment, average F and equilibrium catch for male red crab to varying levels of survival rate.

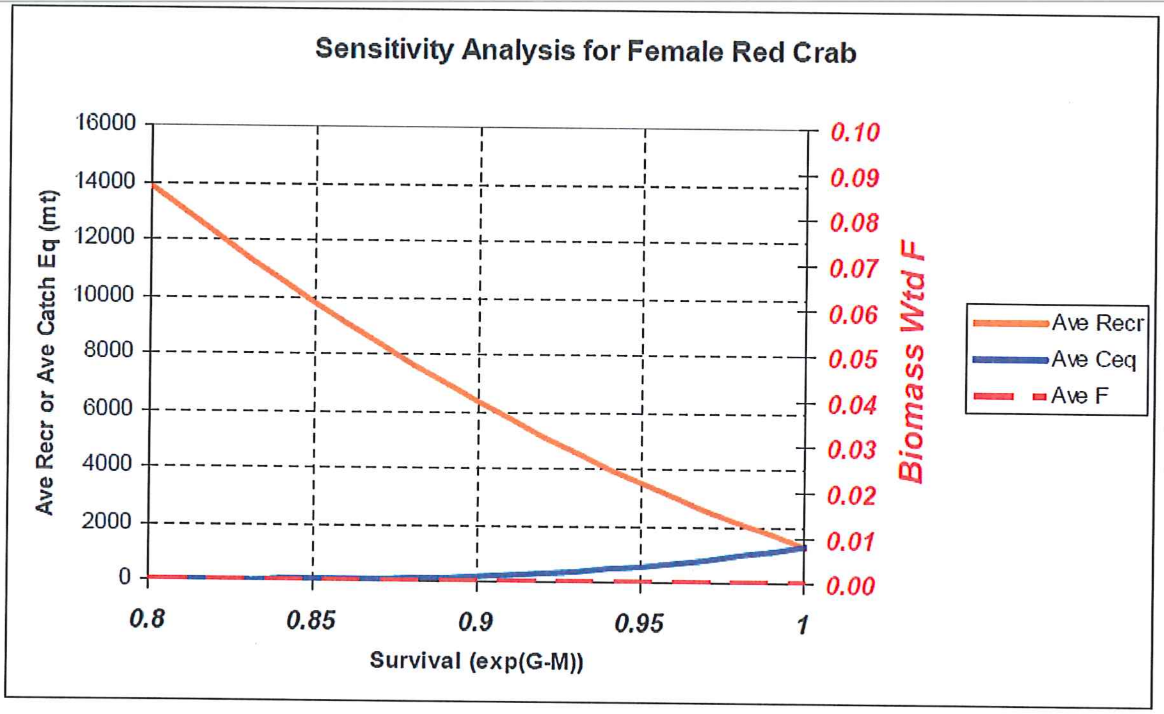


Figure 31- Fig. A3-2 from Appendix 3 of the DPSWG Working Paper. Sensitivity analysis of recruitment, average F and equilibrium catch for female red crab to varying levels of survival rate.

Appendix 4. Yield per Recruit Calculations

Table 28- Yield per recruit calculations based on age/CW model for *Geryon maritae* and CW/weight model (Farlow 1980) for *Chaceon quinquedens* with M=0.10.

Yield per Recriut of Red Crab				
M =	0.1			
	Weight	Proportion	Initial	
Age	in catch	Recruited	numbers	Yield
1	0.003	0.000	1.00000	0.00000
2	0.014	0.000	0.90484	0.00000
3	0.037	0.000	0.81873	0.00000
4	0.072	0.000	0.74082	0.00000
5	0.122	0.000	0.67032	0.00000
6	0.186	0.000	0.60653	0.00001
7	0.265	0.004	0.54877	0.00010
8	0.356	0.029	0.49619	0.00097
9	0.459	0.180	0.44638	0.00690
10	0.572	0.588	0.38961	0.02357
11	0.695	0.892	0.31341	0.03391
12	0.825	0.977	0.23725	0.03311
13	0.961	0.995	0.17656	0.02918
14	1.102	0.999	0.13093	0.02489
15	1.246	1.000	0.09701	0.02088
16	1.392	1.000	0.07187	0.01729
17	1.540	1.000	0.05325	0.01417
18	1.688	1.000	0.03945	0.01150
19	1.835	1.000	0.02922	0.00926
20	1.981	1.000	0.02165	0.00741
21	2.124	1.000	0.01604	0.00589
22	2.265	1.000	0.01188	0.00465
23	2.403	1.000	0.00880	0.00366
24	2.538	1.000	0.00652	0.00286
25	2.669	1.000	0.00483	0.00223
26	2.796	1.000	0.00358	0.00173
27	2.918	1.000	0.00265	0.00134
28	3.037	1.000	0.00196	0.00103
29	3.151	1.000	0.00145	0.00079
30	3.260	1.000	0.00108	0.00061
31	3.365	1.000	0.00080	0.00046
32	3.466	1.000	0.00059	0.00035
33	3.562	1.000	0.00044	0.00027
34	3.654	1.000	0.00032	0.00020
35	3.742	1.000	0.00024	0.00016
36+	3.750	1.000	0.00069	0.00045
			F	0.2000
				0.25982

F	YPR	slope	Reference	Yield
	0.2598		point	Lost
0.000	0.00000	#DIV/0!		100%
0.010	0.06061	6.061		77%
0.020	0.10601	4.540		59%
0.030	0.14047	3.446		46%
0.040	0.16691	2.644		36%
0.050	0.18738	2.047		28%
0.060	0.20335	1.597		22%
0.070	0.21588	1.253		17%
0.080	0.22575	0.987		13%
0.090	0.23355	0.780		10%
0.100	0.23973	0.618	= F0.1	8%
0.110	0.24462	0.489		6%
0.120	0.24848	0.386		4%
0.130	0.25152	0.304		3%
0.140	0.25391	0.238		2%
0.150	0.25575	0.184		2%
0.160	0.25716	0.141		1%
0.170	0.25821	0.105		1%
0.180	0.25897	0.076		0%
0.190	0.25950	0.052		0%
0.200	0.25982	0.033		0%
0.210	0.25999	0.016		0%
0.220	0.26002	0.003	= Fmax	0%
0.230	0.25994	-0.008		
0.240	0.25977	-0.017		
0.250	0.25952	-0.024		
0.260	0.25922	-0.031		
0.270	0.25886	-0.036		
0.280	0.25846	-0.040		
0.290	0.25803	-0.043		
0.300	0.25758	-0.046		
0.310	0.25710	-0.048		
0.320	0.25661	-0.049		
0.330	0.25610	-0.051		
0.340	0.25558	-0.052		
0.350	0.25506	-0.052		
0.360	0.25454	-0.053		
0.370	0.25401	-0.053		
0.380	0.25348	-0.053		
0.390	0.25296	-0.053		
0.400	0.252			
trial value of F				

Plus Group Equation Nt-1*EXP(-M-selectivity for Aget-1*F)/(1-EXP(-selectivity for Aget*F-M))

Appendix 5. Stochastic Modeling Results

The stochastic modeling exercises incorporated variable recruitment and variable natural mortality into the deterministic population models based on the age-CW relationship for *Geryon maritae* and the CW-weight relationship for *Chaceon quinquedens*. The stochastic models addressed two competing theories regarding the biomass estimates from the 1974 and 2003-2005 surveys. One set of models attempted to fit the population dynamics to both the 1974 biomass estimates and to the 2003-2005 estimates with landings equal to the reported landings from 1973-2008. The other set of models were based on the assumption that the 1974 biomass was underestimated and the actual biomass might have been as much as double the estimated biomass. That assumption is based on the fact that the fishable male biomass increased after 30 years of significant fishing pressure. The "zero depletion DELTA" scenario is one of those which assume a larger initial biomass than was estimated from the 1974 survey. One modeling scenario created a naturally cyclical population in which the mortality of settlers and juveniles scaled exponentially to the biomass of their older siblings, up to age 11 and the susceptibility of juveniles to predation by their siblings declined exponentially with age.

Conditional deterministic Fmsy, MSY, and Bmsy were determined by running Solver on the deterministic population parameters to obtain the highest long-term equilibrium yield with the condition that the biomass of 116+ mm CW males not fall below 25% of the initial biomass in any of the 89 years used to determine maximum long-term yield.

A separate condition was applied to determine whether a particular TAC would result in an overfishing condition. Overfished was defined as biomass falling below one-half Bmsy of fishable males. A Monte Carlo simulation macro was used to count the number of times that the biomass fell below the overfished definition over 26,700 years (300 iterations of 89 years each) with catches equal to the indicated TAC. The result was expressed as a percentage.

The model was run with deterministic values for all parameters through year 110, which corresponds to 2010. Fishing mortality was introduced in year 73, corresponding to 1973. The fishing mortality rate was adjusted to match the modeled landings to the historic reported landings.

The stochastic recruitment term was MAX(NORMINV(RAND(),SRR,StdDevRecr),0) and took effect in year 111, or 2011. Variable natural mortality was modeled as MAX(NORMINV(RAND(),meanM,STDDEVM),MINM). The mean M was determined by running Excel Solver to obtain a combination of recruitment and natural mortality (given a chosen proportionality constant to relate juvenile mortality to large male biomass) that would match the modeled biomass and size structure to that estimated from the 1974 survey. MINM for all models was set at 0.05.

Estimates of the conditional stochastic maximum yield and Fmaximum yield resulted from 100 iterations of 89 years each with variable recruitment and natural mortality in each year of each iteration. The condition was that the biomass of 116+ mm CW males in any year not fall below 25% of the initial biomass.

The model incorporates a TAC that is used to adjust the fishing mortality rate to attempt to keep the catch at the TAC. The highly variable biomass makes it difficult to adjust F quickly enough to avoid significant fluctuations in the catch around the TAC. The input parameters and output results are summarized in the tables of inputs and outputs.

The Fmsy to M ratios determined by the models are generally higher than one. However, the effective average natural mortality rate is considerably higher than the mean M used in the models that incorporate additional juvenile mortality. In those cases, mortality on juveniles can be very high and variable but is not captured in the mean M. One lesson from the models may be that if juvenile mortality plays a significant role in population regulation and is not considered in assumptions about M, models that rely on a standardized M assumption are likely to produce misleading results.

10.1.1 Models Tuned to 1974 Estimated Biomass and Size Structure

Ricker Stock-Recruitment Relationship with Initial Population and M to match 1974 Stock (With Differential Juvenile Mortality)

The model was tuned with equilibrium recruitment, baseline natural mortality, and juvenile natural mortality to match the 1974 survey estimates of population size and structure. With the replacement point near the peak of the S-R curve, the Ricker SRR was compensatory but not over-compensatory. The inclusion of juvenile mortality proportional to large male biomass made the model over-compensatory to achieve the increase in biomass estimated from the 2003-2005 survey.

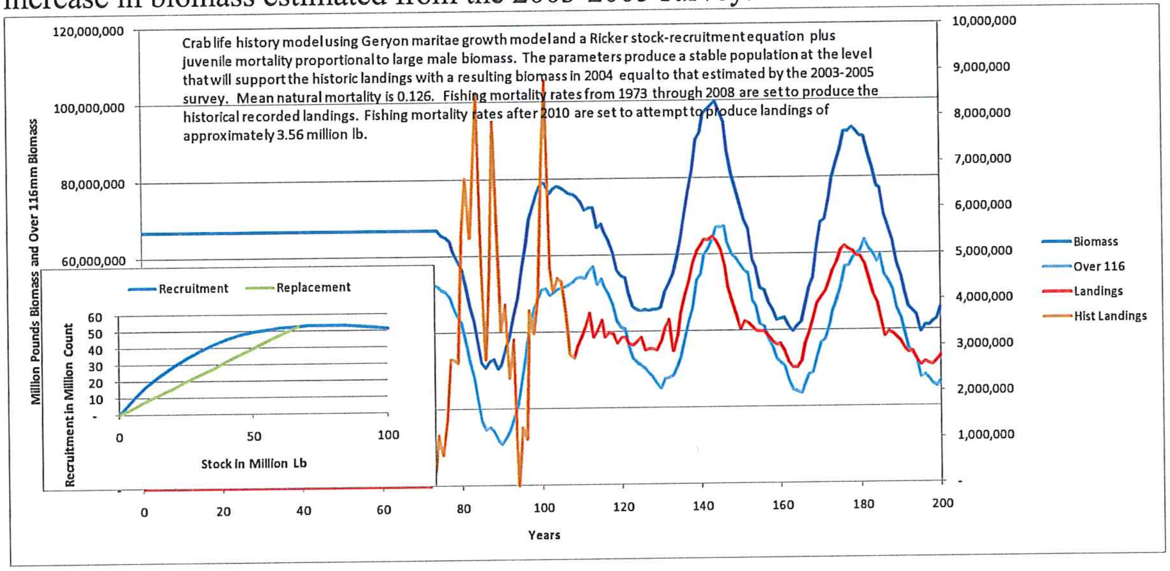

Crab life history model using Geryon maritae growth model and a Ricker stock-recruitment equation plus juvenile mortality proportional to large male biomass. The parameters produce a stable population at the level that will support the historic landings with a resulting biomass in 2004 equal to that estimated by the 2003-2005 survey. Mean natural mortality is 0.126. Fishing mortality rates from 1973 through 2008 are set to produce the historical recorded landings. Fishing mortality rates after 2010 are set to attempt to produce landings of approximately 3.56 million lb.

Figure 32- Typical results from a stochastic population model using a Ricker SRR plus excess juvenile mortality proportional to large male biomass. Recruitment and natural mortality include a random variability term.

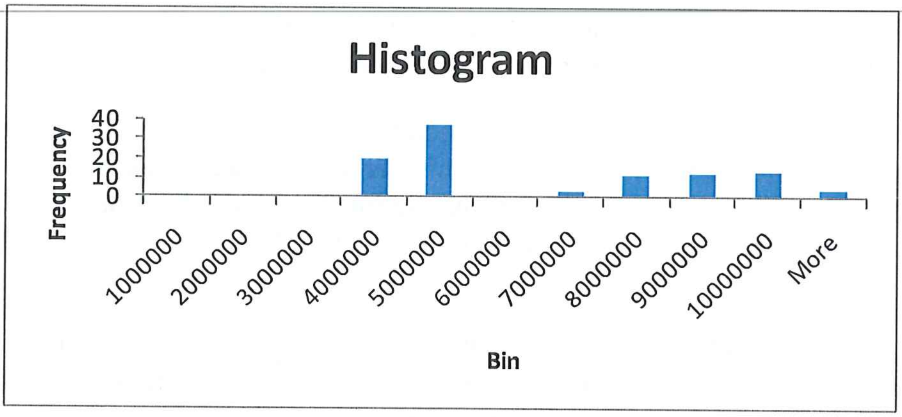


Figure 33- Histogram for stochastic Ricker with juvenile mortality proportional to biomass of males 116+ mm CW and tuned to match 1974 biomass and size structure. Mean M = 0.126. Deterministic MSY = 9.2 million lb. Deterministic Fmsy = 0.525.

Table 29- Descriptive statistics for stochastic Ricker with juvenile mortality proportional to biomass of males 116+ mm CW and tuned to match 1974 biomass and size structure. Mean M = 0.126. Deterministic MSY = 9.2 million lb. Deterministic Fmsy = 0.525.

Stochastic Yield Estimate	
Mean	6,065,140
Standard Error	232,161
Median	4,451,454
Mode	#N/A
Standard Deviation	2321610.662
Sample Variance	5.38988E+12
Kurtosis	-1.352809247
Skewness	0.53744284
Range	7,558,212
Minimum	3,592,054
Maximum	11,150,265
Sum	606,513,969
Count	100
Confidence Level(80.0%)	299,525
Confidence Level(90.0%)	385,478

Table 30- Summary table of input parameters and output results for stochastic population model with variable Ricker SRR, variable M, and juvenile mortality proportional to the biomass of large males.

Filename:			
Models that Match History of Fishery\Juv mort proportional to large males\[Conservative Stochastic Ricker s-r to match 1974 pop with excess juv mort 2.xlsm			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt threshold	1	Lb
	Offset (year lag x 8)	40	
	Cannibalism constant	4.2E-09	
	Minimum weight of cannibalistic males	1.1	Lb
Recruitment Parameters		Ricker	
Equation:	a* Fishable Male Stock*EXP(-b*Fishable Male Stock)		
	a	2.160684045	
	b	0.000000015	
	Lag	1	
Random Recruitment Equation			
	NORMINV(RAND(),a*Stock*EXP(-b*Stock),RandrecrSTD)		
	Random recruitment standard deviation	1	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	66,803,789	Lb
	.4 x Unexploited Fishable Biomass	26,721,516	Lb
	Average Biomass 2011-2100	63,876,713	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	96%	
	Over 116 mm CW Unexploited Biomass	52,456,252	Lb
	.4 x Unexploited over 116 Biomass	20,982,501	Lb
	Avg over-116 mm Biomass 2011-2100	43,462,730	Lb
	Percentage of unexploited over 116 mm	83%	
	Mean Natural Mortality (M)	0.126	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Fmsy*	0.525	
	Fmsy to M Ratio	4.17	
	Deterministic MSY*	9,179,828	Lb
	Derterministic Bmsy*	36,893,608	Lb
	Stochastic Max Yield*	6,065,140	
	Stochastic Fmaximum yield*	0.251	
*	Constrained to values that do not reduce average 89-yr biomass of 116+ mm CW males below 25% of 1974 estimated biomass.		
Monte Carlo Simulation			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings around TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for each year in MC simulation		
	Recruitment variable each year		

Stochastic Ricker SRR with No Excess Juvenile Mortality from Large Male Predation

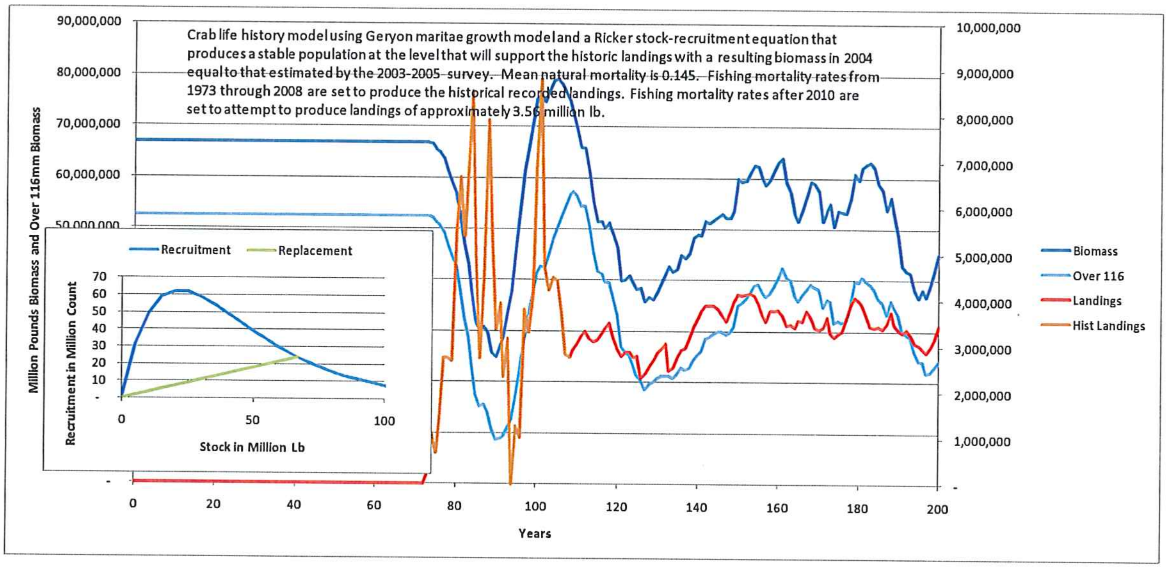


Figure 34- Typical results from strongly over-compensatory Ricker SRR with no additional mortality on juveniles from large male predation.

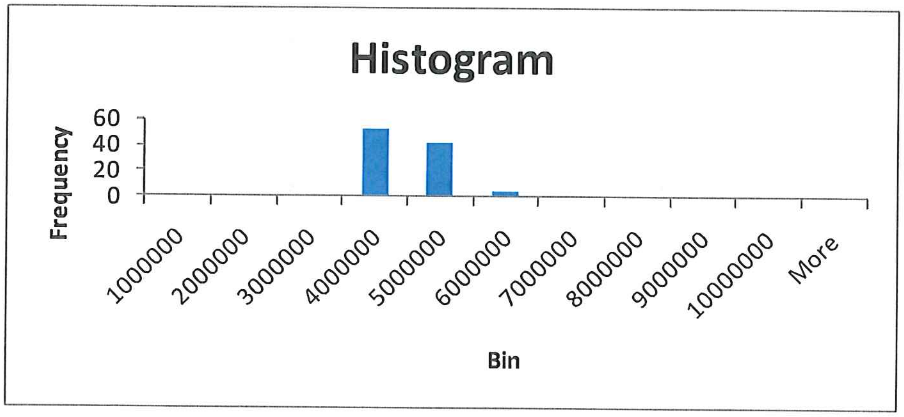


Figure 35- Histogram for stochastic Ricker with no excess juvenile mortality and tuned to match 1974 biomass and size structure. Mean M = 0.145. Deterministic MSY = 5.1 million lb. Deterministic Fmsy = 0.185.

Table 31- Descriptive statistics for stochastic Ricker with no excess juvenile mortality tuned to match 1974 biomass and size structure. Mean M = 0.145. Deterministic MSY = 5.1 million lb. Deterministic Fmsy = 0.185.

Stochastic Yield Estimate	
Mean	3,994,663
Standard Error	64,437
Median	3,911,268
Mode	#N/A
Standard Deviation	644374.2558
Sample Variance	4.15218E+11
Kurtosis	-0.85640591
Skewness	0.256853539
Range	2,839,621
Minimum	2,595,977
Maximum	5,435,598
Sum	399466319.3
Count	100
Confidence Level(80.0%)	83,135
Confidence Level(90.0%)	106,991

Table 32- Stochastic 2. Inputs and outputs for stochastic model using strong Ricker SRR with no additional mortality on juveniles from large male predation.

Filename:			
\Models\5G models\[Stochastic Ricker s-r with yearly M variability after 2011 match 1974 pop with no excess juv mort.xlsm			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt threshold	1	Lb
	Offset (year lag x 8)	40	
	Cannibalism constant	0	
	Minimum weight of cannibalistic males	1.1	Lb
Recruitment Parameters		Strong Ricker	
Equation:	a* Fishable Male Stock*EXP(-b*Fishable Male Stock)		
	a	7.788680373	
	b	0.000000046	
	Lag	1	
Random Recruitment Equation			
	NORMINV(RAND(),a*Stock*EXP(-b*Stock),RandrecrSTD)		
	Random recruitment standard deviation	20,000,000	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	66,803,789	Lb
	.4 x Unexploited Fishable Biomass	26,721,516	Lb
	Average Biomass 2011-2100	56,317,697	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	84%	
	Over 116 mm CW Unexploited Biomass	52,456,252	Lb
	.4 x Unexploited over 116 Biomass	20,982,501	Lb
	Avg over-116 mm Biomass 2011-2100	35,597,945	Lb
	Percentage of unexploited over 116 mm	68%	
	Mean Natural Mortality (M)	0.145	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Fmsy	0.185	
	Fmsy to M Ratio	1.27	
	Deterministic MSY*	5,109,991	Lb
	Deterministic Bmsy*	49,348,490	Lb
	Stochastic Max Yield*	3,994,663	Lb
	Stochastic Fmaximum yield*	0.118	
*	Constrained to values that do not reduce average 89-yr biomass of 116+ mm CW males below 25% of 1974 estimated biomass.		
Monte Carlo Simulation to Determine % Yrs B<0.5Bmsy			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings around TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for iteration, same each year within iteration		
	Recruitment variable each year		

Stochastic Beverton-Holt SRR Tuned to Match 1974 Biomass with Juvenile Mortality Proportional to Large Male Biomass

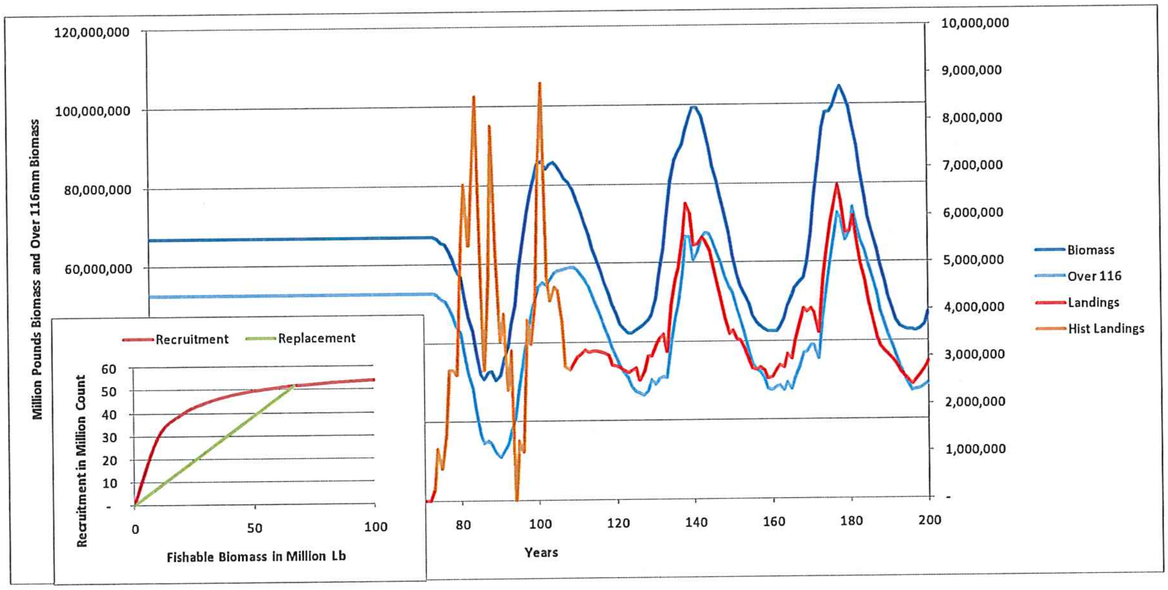


Figure 36- Sample of results from stochastic model that incorporates a moderately compensatory Beverton-Holt SRR and juvenile mortality proportional to large male biomass. Detailed inputs and outputs are provided in Table 34.

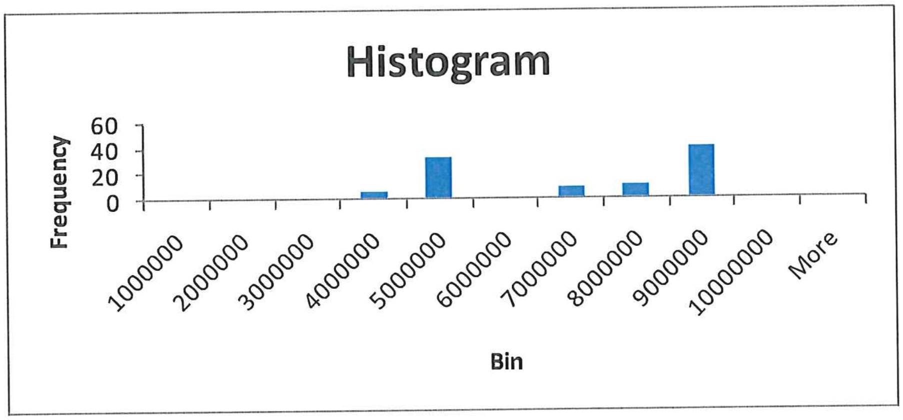


Figure 37- Histogram for stochastic Ricker with juvenile mortality proportional to biomass of males 116+ mm CW. Model is tuned to match 1974 biomass and size structure. Mean M = 0.127. Deterministic MSY = 8.14 million lb. Deterministic Fmsy = 0.298.

Table 33- Descriptive statistics for Stochastic Beverton-Holt with juvenile mortality proportional to 116+ mm CW male biomass.

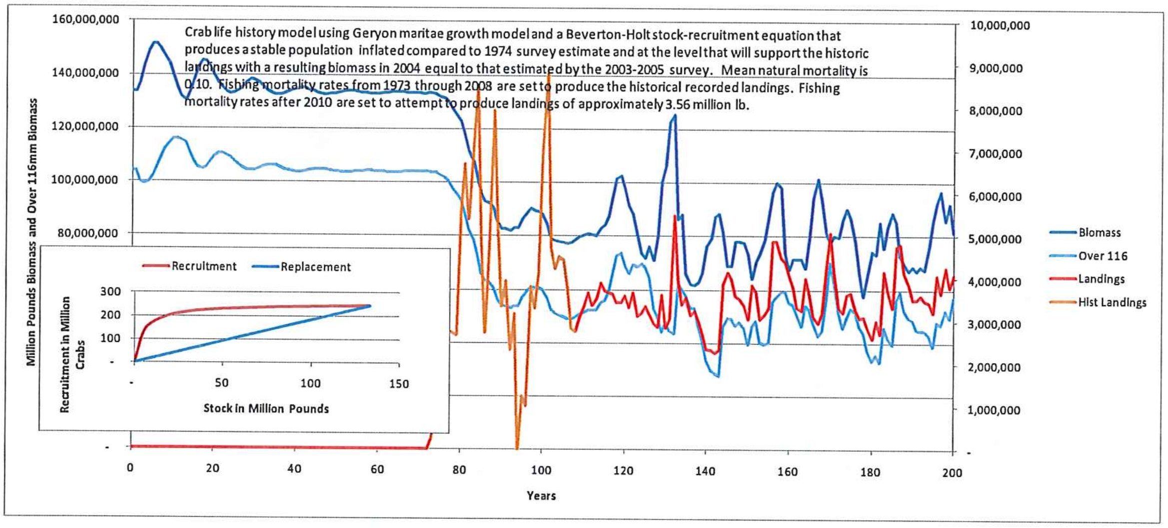
*Conditional Stochastic Max Yield**	
Mean	6,555,650
Standard Error	201,413
Median	7,321,632
Mode	#N/A
Standard Deviation	2014132.604
Sample Variance	4.05673E+12
Kurtosis	-1.742652758
Skewness	-0.306645612
Range	5,187,544
Minimum	3,852,977
Maximum	9,040,522
Sum	655,565,036
Count	100
Confidence Level(80.0%)	259,856
Confidence Level(90.0%)	334,425

Table 34- Stochastic Beverton-Holt with juvenile mortality proportional to 116+ mm CW male biomass.

Filename:			
Match History of Fishery\Juv mort proportional to large males\[Stochastic B-H s-r & true yearly M to match 197			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size (Terminal Molt)		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt threshold	1	Lb
	Offset (year lag x 8)	40	
	Cannibalism constant	4.15E-09	
	Minimum weight of cannibalistic males	1.1	Lb
Recruitment Parameters		Beverton-Holt	
Equation:	a*Fishable Male Stock/(1+b*Fishable Male Stock)		
	a	2.160684045	
	b	0.000000015	
	Lag	1	
Random Recruitment Equation			
NORMINV(RAND(),a*Male Stock/(1+b*Male Stock),RandrecrSTD)			
	Random recruitment standard deviation	20,000,000	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	66,803,789	Lb
	.4 x Unexploited Fishable Biomass	26,721,516	Lb
	Average Biomass 2011-2100	54,055,802	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	81%	
	Over 116 mm CW Unexploited Biomass	52,456,252	Lb
	.4 x Unexploited over 116 Biomass	20,982,501	Lb
	Avg over-116 mm Biomass 2011-2100	22,478,228	Lb
	Percentage of unexploited over 116 mm	43%	
	Mean Natural Mortality (M)	0.127	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Conditional Fmsy*	0.320	
	Fmsy to M Ratio	2.52	
	Deterministic Conditional MSY*	9,401,592	Lb
	Deterministic Conditional Bmsy*	60,410,907	Lb
	Stochastic Conditional Maximum Yield*	6,555,650	Lb
	Stochastic Conditional Fmaximum yield*	0.214	
*	Conditioned on biomass of 116+ mm CW males >0.25* 1974 biomass		
Monte Carlo Simulation to Determine % of Years B<0.5Bmsy			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings at TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for each year within iteration and between iterations		
	Recruitment variable each year		

10.1.2 Models Based on Inflated Values for 1974 Biomass

Stochastic Beverton-Holt with Juvenile Mortality Proportional to Biomass of Ages 1-11.



Crab life history model using Geryon maritae growth model and a Beverton-Holt stock-recruitment equation that produces a stable population inflated compared to 1974 survey estimate and at the level that will support the historic landings with a resulting biomass in 2004 equal to that estimated by the 2003-2005 survey. Mean natural mortality is 0.10. Fishing mortality rates from 1973 through 2008 are set to produce the historical recorded landings. Fishing mortality rates after 2010 are set to attempt to produce landings of approximately 3.56 million lb.

Figure 38- This model used an unexploited biomass equal to twice the estimated biomass from the 1974 survey with the same size distribution as was observed in 1974. It was then tuned to produce the estimated 2003-2005 biomass after removing the reported landings from 1973-2008.

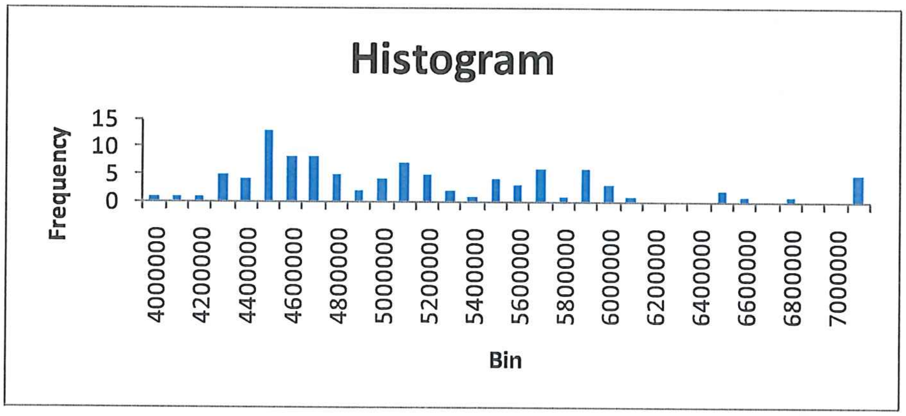


Figure 39- Histogram stochastic Beverton-Holt with juvenile mortality proportional to biomass of older siblings through age 11. Model is tuned with 1974 size structure and inflated biomass. Mean M = 0.10. Deterministic MSY = 4.3 million lb. Deterministic Fmsy = 0.127.

Table 35- Descriptive statistics for stochastic Beverton-Holt SRR starting with biomass equal to twice that estimated from the 1974 survey and with the same size structure.

Stochastic Conditional Maximum Yield	
Mean	3,663,461
Standard Error	54,303
Median	3,754,374
Mode	#N/A
Standard Deviation	543033.0362
Sample Variance	2.94885E+11
Kurtosis	0.272833882
Skewness	-0.453143821
Range	2,842,784
Minimum	2,321,983
Maximum	5,164,767
Sum	366,346,112
Count	100
Confidence Level(80.0%)	70,060
Confidence Level(90.0%)	90,165

Table 36- Stochastic Beverton-Holt SRR starting with biomass equal to twice that estimated from the 1974 survey and with the same size structure.

Filename:			
Stochastic B-H s-r with yearly M variability after 2011 inflated 1974 pop with predation on juveniles from ages 1-11			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt threshold	1	Lb
	Offset (year lag x 8)	8	
	Cannibalism constant	0.000000005	
	Minimum weight of cannibalistic males	1.1	Lb
Recruitment Parameters		Beverton-Holt	
Equation:	a* Fishable Male Stock*EXP(-b*Fishable Male Stock)		
	a	30	
	b	0.0000002	
	Lag	1	
Random Recruitment Equation			
	NORMINV(RAND(),a*Stock*EXP(-b*Stock),RandrecrSTD)		
	Random recruitment standard deviation	200,000,000	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	133,044,501	Lb
	.4 x Unexploited Fishable Biomass	53,217,800	Lb
	Average Biomass 2011-2100	73,966,391	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	56%	
	Over 116 mm CW Unexploited Biomass	103,505,441	Lb
	.4 x Unexploited over 116 Biomass	41,402,176	Lb
	Avg over-116 mm Biomass 2011-2100	42,159,038	Lb
	Percentage of unexploited over 116 mm	41%	
	Mean Natural Mortality (M)	0.100	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Conditional Fmsy*	0.127	
	Fmsy to M Ratio	1.27	
	Deterministic Conditional MSY*	4,274,813	Lb
	Deterministic Conditional Bmsy*	63,139,209	Lb
	Stochastic Conditional Max Yield*	3,663,461	
	Stochastic Conditional Fmaximum Yield*	0.081	
*	Conditioned on Biomass of 116+ mm CW males staying above 25% of unexploited biomass in each of 100 iterations of 89-yr simulation		
Monte Carlo Simulation			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings around TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for each year in MC simulation		
	Recruitment variable each year in MC simulation		

Almost Linear B-H with Juvenile Mortality Proportional to Biomass of Ages 1-11

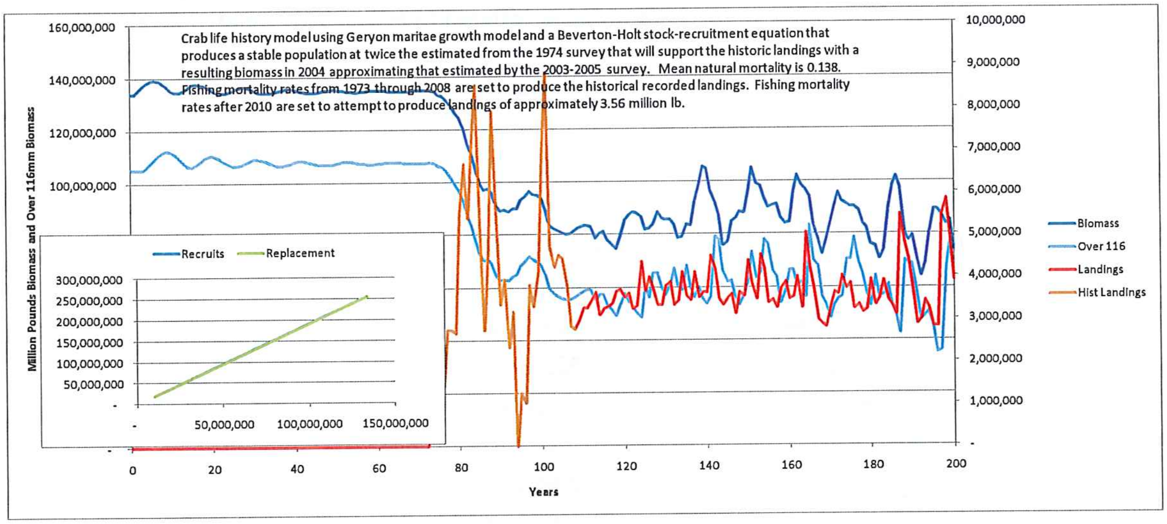


Figure 40- The Beverton-Holt SRR used in this model provides only proportional production as stock biomass declines. However, mortality on juveniles declines in proportion to the decline in recruitment, which provides a compensatory mechanism.

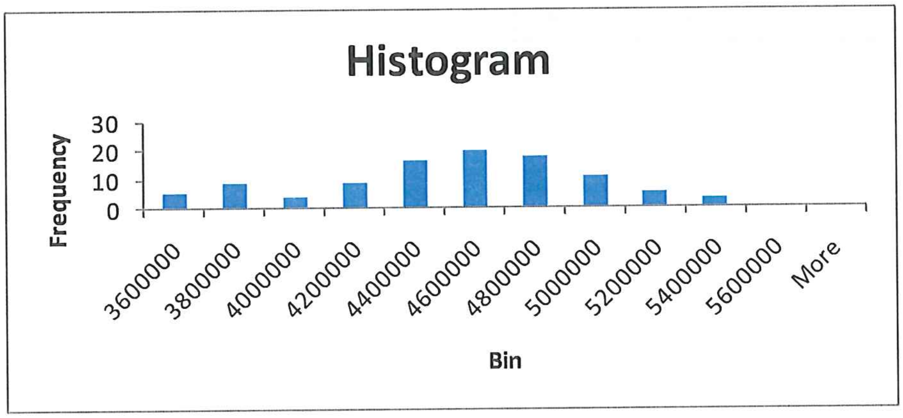


Figure 41- Histogram for an almost linear B-H SRR with juvenile mortality proportional to the biomass of ages 1-11. The results are conditioned on the biomass of 116+ mm CW males staying above 25% of the 1974 biomass inflated to twice the estimated level.

Table 37- Descriptive statistics for an almost linear B-H SRR with juvenile mortality proportional to the biomass of ages 1-11. The results are conditioned on the biomass of 116+ mm CW males staying above 25% of the 1974 biomass inflated to twice the estimated level.

Conditional Maximum Stochastic Yield	
Mean	4,400,991
Standard Error	51,149
Median	4,491,576
Mode	#N/A
Standard Deviation	511489.5792
Sample Variance	2.61622E+11
Kurtosis	4.550634843
Skewness	-1.347389852
Range	3,436,462
Minimum	1,920,643
Maximum	5,357,105
Sum	440,099,144
Count	100
Confidence Level(80.0%)	65,990
Confidence Level(90.0%)	84,927

Table 38- Input and output values for an almost linear B-H SRR with juvenile mortality proportional to the biomass of ages 1-11.

Filename:			
Stochastic most conservative B-H s-r inflated 1974 pop with predation on juveniles from ages 1-11-3.xlsm]Table of inputs & outputs			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt maximum	0.69	Lb
	Offset (year lag x 8)	N/A	
	Cannibalism constant	6.3E-09	
	All ages <12 cannibalize younger crabs		
Recruitment Parameters		Beverton-Holt	
Equation:	a* Fishable Male Stock*EXP(-b*Fishable Male Stock)		
	a	1.927215856	
	b	1E-10	
	Lag	1	
Random Recruitment Equation			
	NORMINV(RAND(),a*Stock*EXP(-b*Stock),RandrecrSTD)		
	Random recruitment standard deviation	200,000,000	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	124,976,494	Lb
	.4 x Unexploited Fishable Biomass	49,990,597	Lb
	Average Biomass 2011-2100	66,636,232	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	53%	
	Over 116 mm CW Unexploited Biomass	98,062,180	Lb
	.4 x Unexploited over 116 Biomass	39,224,872	Lb
	Avg over-116 mm Biomass 2011-2100	41,061,412	Lb
	Percentage of unexploited over 116 mm	42%	
	Mean Natural Mortality (M)	0.138	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Fmsy*	0.142	
	Fmsy to M Ratio	1.03	
	Deterministic MSY*	4,607,408	Lb
	Deterministic Bmsy*	52,942,392	Lb
	Stochastic Max Yield*	4,400,991	
	Stochastic Fmaximum yield*	0.090	
*	Constrained to values that keep the minimum biomass of 116+ mm CW males above 25% of the modeled unexploited biomass (twice the 1974 estimated biomass) throughout each of 100 89-yr simulations.		
Monte Carlo Simulation			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings around TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for each year in MC simulation		
	Recruitment variable each year in MC simulation		

10.1.3 Model Results Based on Zero Depletion Delta Assumption

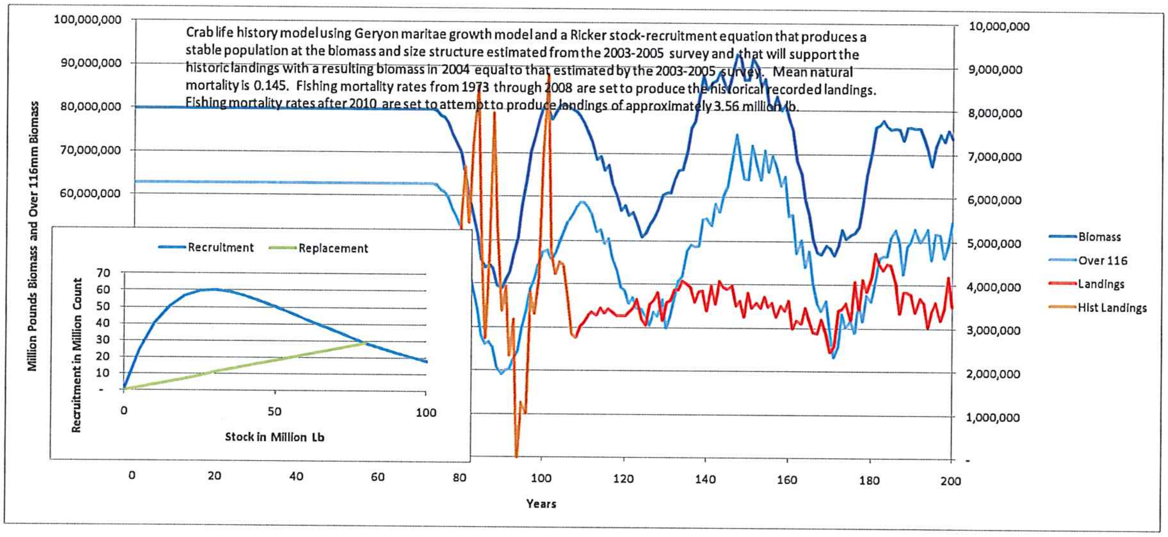


Figure 42- Results from a population model tuned to produce a stable population and size structure that matches that estimated from the 2003-2005 survey both before and after the removal of the historic reported landings. The inset depicts the Ricker SRR. No additional mortality on juveniles is included in this model.

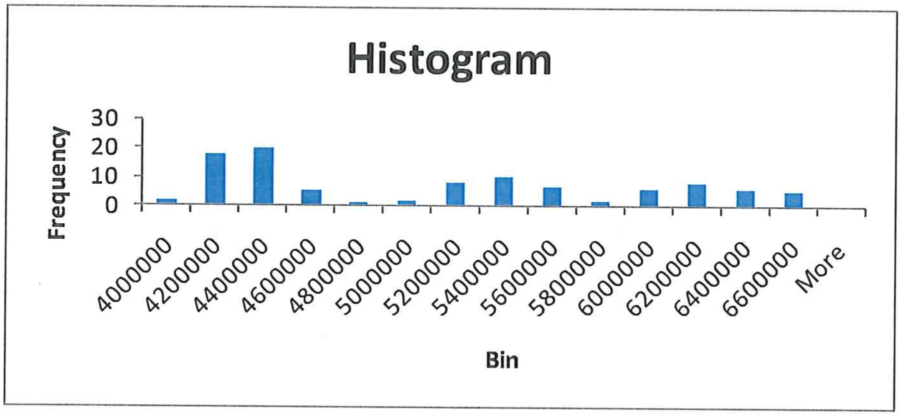
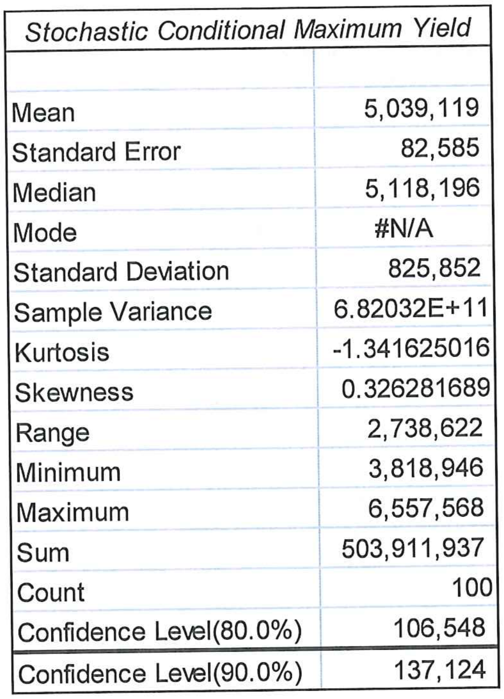


Figure 43- Histogram showing results for Ricker SRR tuned to produce the same fishable biomass in 1974 as was estimated from the 2003-2005 survey and with the removal of the historic recorded landings between 1973 and 2008.

Table 39- Descriptive statistics for Ricker SRR tuned to produce the same fishable biomass in 1974 as was estimated from the 2003-2005 survey and with the removal of the historic recorded landings between 1973 and 2008..



Stochastic Conditional Maximum Yield	
Mean	5,039,119
Standard Error	82,585
Median	5,118,196
Mode	#N/A
Standard Deviation	825,852
Sample Variance	6.82032E+11
Kurtosis	-1.341625016
Skewness	0.326281689
Range	2,738,622
Minimum	3,818,946
Maximum	6,557,568
Sum	503,911,937
Count	100
Confidence Level(80.0%)	106,548
Confidence Level(90.0%)	137,124

Table 40- Model inputs and outputs for Ricker SRR tuned to produce the same fishable biomass in 1974 as was estimated from the 2003-2005 survey and with the removal of the historic recorded landings between 1973 and 2008.

Filename:			
Zero Delta Stochastic Ricker s-r with yearly M variability after 2011 with no excess juvenile mortality.xlsm]Table of inputs & outputs			
Von Bertalanfy Parameters			
	Length at infinity	192	mm CW
	K	0.0638	
	Time at 0 length	-0.5299	
	Weight at infinity	5.9061	Lb
	b	3.1808	
Male Maximum Modeled Size		3.75	Lb
Selectivity Equation			
	sL= 1/(1 +(exp(26.86 – 0.2905L))		
Cannibalism Parameters			
	Cannibalized wgt threshold	0.96	Lb
	Offset (year lag x 8)	8	
	Cannibalism constant	0	
	Juveniles experience predation from older siblings with exp increasing predation with age and exp decreasing susceptibility with age		
Recruitment Parameters		Ricker	
Equation:	a* Fishable Male Stock*EXP(-b*Fishable Male Stock)		
	a	5.632795304	
	b	3.44E-08	
	Lag	1	
Random Recruitment Equation			
	NORMINV(RAND(),a*Stock*EXP(-b*Stock),RandrecrSTD)		
	Random recruitment standard deviation	20,000,000	Crabs
	Year when Randon Recruitment Starts	2011	
Biomass			
	Unexploited Fishable Biomass	79,664,058	Lb
	.4 x Unexploited Fishable Biomass	31,865,623	Lb
	Average Biomass 2011-2100	66,962,359	Lb
	At TAC Landings of	3,560,000	Lb
	Percentage of unexploited Biomass	84%	
	Over 116 mm CW Unexploited Biomass	62,501,646	Lb
	.4 x Unexploited over 116 Biomass	25,000,658	Lb
	Avg over-116 mm Biomass 2011-2100	45,003,951	Lb
	Percentage of unexploited over 116 mm	72%	
	Mean Natural Mortality (M)	0.145	
	Natural Mortality Standard Deviation	0.05	
	Deterministic Conditional Fmsy*	0.207	
	Fmsy to M Ratio	1.42	
	Deterministic Conditional MSY*	6,281,230	Lb
	Deterministic Conditional Bmsy*	55,079,955	Lb
Conditional Max Yield and F Monte Carlo Simulation			
	Stochastic Conditional Max Yield*	5,039,119	
	Stochastic Conditional Fmaximum yield*	0.139	
*	Conditioned on minimum B of 116+ mm CW males staying above 25% of unexploited level in each of 100 iterations of 89 years each		
Overfished Monte Carlo Simulation			
	Criteria = percentage of years B<.5Bmsy	0%	
	With 2011-2100 Landings around TAC of	3,560,000	Lb
	300 iterations of 89 years each		
	M changes for each year in MC simulation		
	Recruitment variable each year in MC simulation		

10.1.4Summary Results from Stochastic Models

Table 41- Summary results from stochastic models.

Models that Match 1974 Biomass and Size Structure								
Model	B_0 mt	B_{MSY} mt	B_{MSY}/B_0	Determin MSY mt	Determ F_{MSY}	%Yrs<0.5 Bmsy @ 1615 mt TAC	Stochastic Max Yield >0.25*B_{0116} + mm	Stochastic FMax Yield >0.25*B_{0116} + mm
Ricker matching 1974 biomass and size structure with juvenile mortality proportional to large male biomass	30,302	16,735	0.55	4,164	0.525	0%	2,751	0.251
Ricker with no excess juvenile mortality	30,302	22,384	0.74	2,318	0.185	0%	1,812	0.118
Beverton-Holt with excess juvenile mortality	30,302	27,402	0.90	4,265	0.320	0%	2,974	0.214
Models that Inflate 1974 Biomass								
B-H with predation on juveniles from ages 1-11	60,349	28,640	0.47	1,939	0.127	0%	1,662	0.081
Almost linear B-H with predation on juveniles proportion to biomass of ages 1-11	56,689	24,015	0.42	2,090	0.142	0%	1,996	0.09
Models Based on Zero Depletion Delta between 1974 and 2003-2005								
Zero depletion delta and Ricker SRR with no additional mortality on juveniles	36,135	24,984	0.69	2,849	0.207	0%	2,286	0.139