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Working Paper: Red crab
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Deep sea red crab

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Note: Some background information is presented in this report but it is intended to be read after reading the most recent stock assessment for deep-sea red crabs (NEFSC 2006a). The assessment can be downloaded at http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0625/. A shorter assessment summary (NEFSC 2007b) intended for managers can be downloaded at: http://www.nefsc.noaa.gov/nefsc/publications/crd/crd0614/.

Executive summary

Deep sea red crab form a single stock in the management area (off Southern New England and the Mid-Atlantic Bight where the fishery occurs) and in the Gulf of Maine (which is not actively managed and where no fishing occurs). Very little information about growth and longevity are available such that it is difficult to judge potential stock productivity. The natural mortality rate is uncertain but usually assumed to be in the range M=0.1 to 0.15 per year. Recruitment patterns and reproductive biology are uncertain.

The fishery consists of a handful of vessels managed under limited entry with annual effort regulations designed to achieve a target TAC. Only males are harvested. Discard of undersize males and females is thought to be about 30% of total catch and discard mortality is thought to be small (~5%), but additional studies are required. Marketable size males were 114+ mm CW during the early 1970's but are currently smaller (about 90+ mm CW). Landings have varied without trend during recent years, presumably in response to market factors. Landings data are available since the early 1970s but accuracy probably improved starting in 1982. Port sample size data are available from landings. Limited sea sample data for are available from a pilot program involving one vessel during 2004-2005 are also available. Commercial catch rate data (LPUE) are difficult to evaluate for red crabs and not considered in this report for use in biological reference points.

Camera/bottom trawl survey data (abundance and size composition data) are available from surveys during 1974 and 2003-2005. Biomass estimates from the 2003-2005 surveys and length composition data from 1974 and 2003-2005 appear reliable. Biomass estimates from the 1974 survey appear less reliable because of questions about area effectively sampled by the cameras.

Recruitment has been good recently in the red crab stock, based on 2004-2005 survey size data. The relative abundance of large males (114+ CW) declined between 1974 and 2003-2005 due to size selective fishing on large males. Female red crabs must mate with larger males and there are concerns that reduced abundance of large males may reduce reproductive output.

Red crabs are not overfished and overfishing is not occurring. Based on fishable biomass from the 2003-2005 surveys and male landings, fishing mortality F =0.055 y-1 during 2005. Calculations indicate that discards would increase estimated fishing mortality only slightly.

This report outlines and recommends options that would cast red crabs in the Gulf of Maine and off Southern New England/Mid-Atlantic Bight as separate stocks, potentially establish a minimum size limit for male red crabs landed in the fishery, and establish biomass- and exploitation based biological reference points. Benefits, costs and risks are outlined for all of the options described.

Exploitation based reference points are likely to be most important for red crab due to lack of abundance data and infrequent stock assessments. The options for these reference points are MSY and sustainable landings estimates, because landings are the only data routinely available. The current estimate of MSY is outdated and should be replaced. The range of other options for MSY and sustainable yield are lower than the current estimate of MSY and current target harvest levels.

1. Terms of reference (TOR)

a) Recommend biological reference points (BRPs) and measurable BRP and maximum sustainable yield (MSY) proxies.

b) Provide advice about scientific uncertainty and risk for Scientific and Statistical Committees (SSCs) to consider when they develop fishing level recommendations for these stocks.

c) Consider developing BRPs for species groups for situations where the catch or landings can not be identified to species. Work on this objective will depends on, and needs to be consistent with, final guidance on implementing the Reauthorized Magnuson-Stevens Act, whenever that guidance becomes available. (This TOR not applicable to red crab)

d) Comment on what can be done to improve the information, proxies or assessments for each species.

2. Biological characteristics[1]

Information in this section is summarized primarily from Steimle et al. (2001) and Wahle et al. (2008). Deep-sea red crabs (*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 (figure 1). Red crabs 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 crabs in the Gulf of Maine are smaller and the bottom is rough so little fishing for red crab occurs there.

Deep-sea red crabs live at depths of 200–1800 m, where temperatures are between 5 and 8 ^{o}C. Adult crabs 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.

Information on the growth, longevity and mortality of red crabs is scarce. Natural mortality rates were assumed to be 0.2 y^{-1} in Serchuk (1977) and 0.15 y^{-1} in the FMP. An assumed longevity of 30 or more years corresponds to $M = 0.1$ y^{-1} (see below).

On the basis of limited laboratory data, red crabs are believed to require 5–6 years to attain a size of 114 mm carapace width (CW). Male red crabs are estimated to mature at about 75 mm CW and to reach a maximum size of about 180 mm CW. Females begin to mature at somewhat smaller sizes and reach a smaller maximum size of about 136 mm CW.
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 crabs. 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.

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[1] Based on Steimle et al. (2001) and Wahle et al. (2008).

The major biological uncertainties for red crab are longevity and natural mortality, growth and the importance to the stock of large males for successful reproduction.

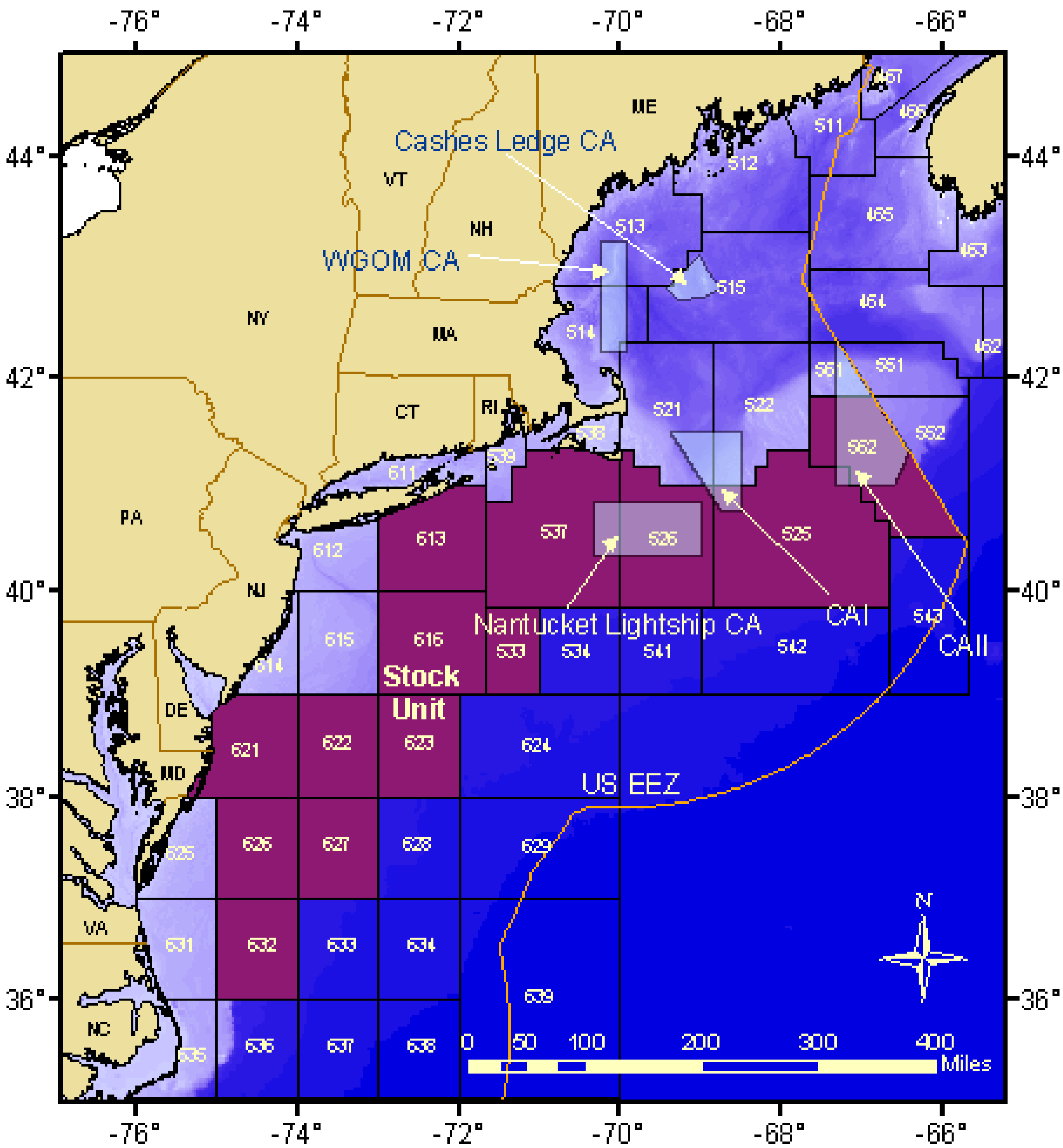


Figure 1. The management area used by the New England Fishery Management Council for deep-sea red crab. The portion of the stock in the Gulf of Maine is excluded.

3. Fishery and management

A small experimental fishery for red crabs was established in the early 1970s. Before the initial targeted survey for red crabs (Wigley et al. 1975), fishery landings were small and sporadic. In the 1980s and 1990s, fishing effort was inconsistent due to market demand. A directed fishery for male red crabs and consistent markets developed in the mid-1990s.

The current US fishery for male red crabs has limited entry and as of 2006 consisted of four or fewer vessels 30+ m long. The fishery uses specially designed traps almost exclusively, although small amounts of landings are taken also in lobster traps. Fishing occurs year round and landings are made along the continental shelf from the Canadian border (Hague Line), at the eastern end of Georges Bank, to Cape Hatteras, NC, USA, in depths ranging from 400 to 800 m.

Annual US commercial landings of red crabs during the period 1982–2005 ranged from 466 mt (1996) to 4000 mt (2001); there was no fishery in 1994. Since 2002, when the Fishery Management Plan (FMP) for Deep-Sea Red Crab was implemented, landings have been stable at about 2000 t per year. The current fishery is limited access with the fishery authorized to operate with a target TAC of 2688 mt, and an allocation of 780 days at sea. There is no recreational fishery for the species. Red crabs in the USA are managed as a single stock although red crabs in the Gulf of Maine are not considered in calculation of reference points, biomass estimates or other management analyses.

Minimum market sizes and fishery size selectivity have decreased since the early 1970s. The minimum market size for male deep sea red crabs in 1974 was 114+ mm CW. The minimum market size for male deep sea red crabs in recent years is about 85 mm CW. Fishery size selectivity has been estimated for the current fishery during 2004-2005 (L_{50}=92 mm CW) but no selectivity estimates are available for earlier years.

Based on limited log book, sea- and port sample information, discards of female and undersize male red crabs 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). Bycatch of red crab in fisheries directed at other species is minor.

The major fishery related uncertainties for red crab are discards, discard mortality, as well as historical and recent fishery size composition. In addition, the expected response of the stock to fishing in terms of growth and recruitment is uncertain.

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

4. Data availability

The principle fishery data for red crab are landings data from dealer reports starting in 1973, logbooks that start in 1994, size composition data for marketable males from routine port samples, and sea sample data for females and all males from a pilot program involving one vessel during 2004-2005. Landings data from dealer reports for years prior to 1982 are less reliable than data for later years. Landings per unit effort data are available from logbooks and dealer reports but are difficult to interpret. The fishery occurs off south of Georges Bank and virtually no fishery data are available for the Gulf of Maine. As described above, discard estimates based on limited sea-, port and logbook data are available and size selectivity estimates for the recent commercial fishery are available from comparison of sea- and port sample data.

The principle fishery independent data for red crab are from camera sled/bottom trawl surveys conducted during 1974 and 2003-2005 on red crab habitat between Maryland and the eastern tip of Georges Bank (excluding the Gulf of Maine). Camera data provide information about red crab density and bottom tow data provide information and sex- and size composition. The survey data for 2003-2005 are generally combined and treated as one survey. Data from a variety of research bottom trawl surveys is of limited use for red crab because catches are very low. The NMFS Cooperative Monkfish Survey may provide some useful information about red crab in the Gulf of Maine.

Camera and trawl tows were generally from the same sites and sample locations in the 1974 and recent surveys were similar. The two sets of surveys used bottom trawls of the same design and the same trawling protocols, although different vessels were used. Efforts were made to make camera data from the two surveys as compatible as possible but there is uncertainty about the effective area sampled (and therefore red crab density) by images collected during the 1974 survey. Density estimates from the recent survey are believed to be biased low because crab densities were significantly lower in the foreground (close to the camera sled) than in the background of the sampled area suggesting crabs were avoiding the camera, but the extent of the potential bias is unknown. The most reliable survey data are bottom trawl size compositions from both sets of surveys and density estimates from the most recent surveys.

5. Current stock status

Information in this section is summarized from NEFSC (2006a). The most recent assessment concluded that overfishing was not occurring because red crab landings during 2005 (2013 mt) were less than an MSY proxy (2830 mt, see below). Recent fishing mortality estimates were available but not used in determine overfishing because no F based reference point or proxy for F_{MSY} was available.

Based on the most recent assessment, average fishing mortality rate (landings / fishable biomass) on male red crabs was estimated to be F=0.055 (SE 0.008) y^{-1} during 2003-2005. This estimate is probably an underestimate because it does not consider potential mortality due to discarding of undersized male crabs and completely omits mortality due to discarding of females. Fishing mortality estimates are calculated using biomass estimates from surveys during 2003-2005, which are relatively certain but possibly biased low due to avoidance of the camera sled. Red crab biomass is appreciable but landings are currently near zero in the Gulf of Maine.

Alternate fishing mortality estimates including discards and based on best available discard estimates for sea- and port samples are given below (table 1) for males only, females only and males plus females. Results indicate that total fishing mortality (including discards) during 2003-2005 were $F \leq 0.08$ y^{-1} for both sexes and for the sexes combined. The alternative estimates are “worse-case” scenarios because they assume that 50% of discarded red crabs die, whereas the current best estimate of discard mortality indicate that about 5% of discarded red crabs 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 and catch divided by 90+ CW biomass (the approximation for F are 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 potential bias may be small because small crabs have low weight. Calculations using 90+ CW biomass may overstate fishing mortality because red crabs of sizes smaller than 90+ CW make up the bulk of the discard.

Table 1. Total annual mortality due to fishing (landings and mortal discard) during 2003-2005, by sex.

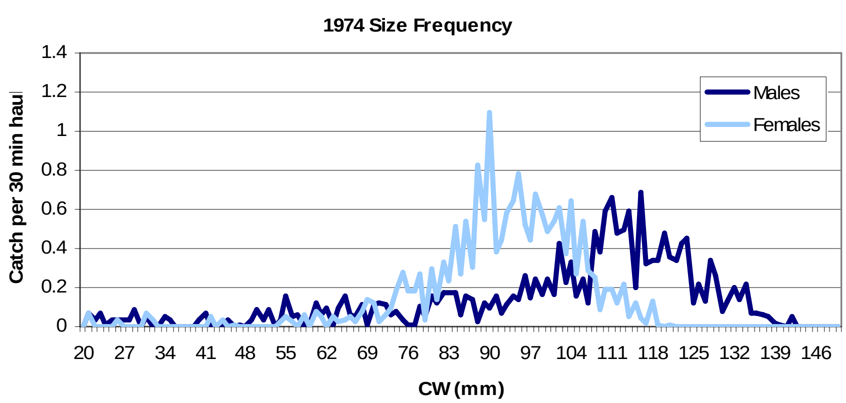
	Males	Females	Total
Average 2003-2005 landings (mt)	1,992	0	1,992
Discard/(total male + female catch)	0.11	0.18	0.29
Catch (mt, includes all discards)	2,238	2,429	4,667
Discard (mt)	246	2,429	2,675
Discard mortality rate (5 x best estimate)		0.5	
Mortal discard (mt)	123	1,215	1,338
Landings + mortal discard (mt)	2,115	1,215	3,330
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	0.02	0.03
F relative to 90+ biomass	0.06	0.02	0.04

Based on the most recent assessment (table 2), fishable red crab biomass during 2003-2005 was about 36,000 mt. Overfished status was not determined for lack of an adequate B_{MSY} estimate or proxy (see below).

Comparisons of biomass estimates from the two surveys are uncertain due to uncertainty about the effective area sampled by cameras during 1974. However, biomass estimates from the two sets of surveys (table 2) indicate that male fishable biomass (based on current fishery selectivity) increased by about 20% during 1974 to 2003-2005. Female biomass (total, 90+ and 114+ CW) increased substantially by 150%-250%. In contrast, total male biomass increased by only 75% and biomass of large (114+ CW) males decreased by about 43%. Size composition data from the surveys indicates that both male and female red crabs have benefitted from strong recruitment in recent years (figure 2). The loss of large (114+ CW) male biomass and relatively modest increase biomass of males 90+ mm CW can probably be attributed to size-selective fishing (Weinberg and Keith 2003).

Table 2: 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	Biomass (mt)	SE (mt)	CV	Biomass (mt)	SE (mt)	CV
1974	90+ mm	29,991	6,298	0.21	15,654	3,719	0.24	45,645	7,314	0.16
	114+ mm	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+ mm	38,220	4,298	0.11	55,279	7,033	0.13	93,499	8,242	0.09
	114+ mm	13,770	1,334	0.10	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	4,696	0.08	74,689	10,102	0.14	131,132	11,119	0.08



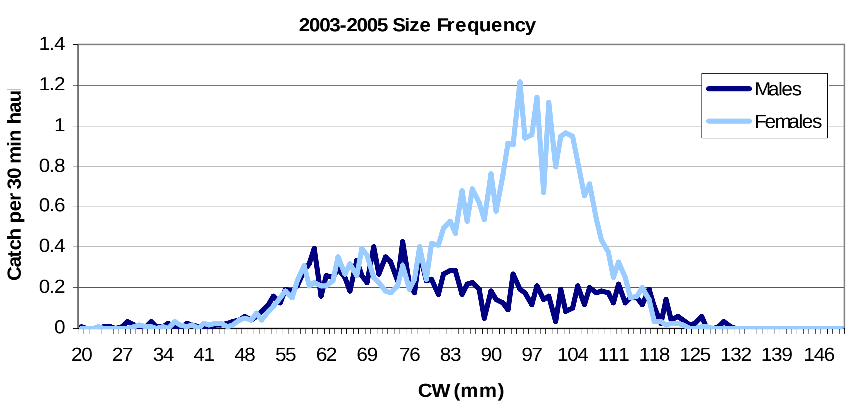


Figure 2. Catch per 30-minute trawl by size in the 1974 survey (top) and 2003-2005 surveys.

6. Red crab overfishing definitions

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" (63 FR 24212). 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.

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 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.

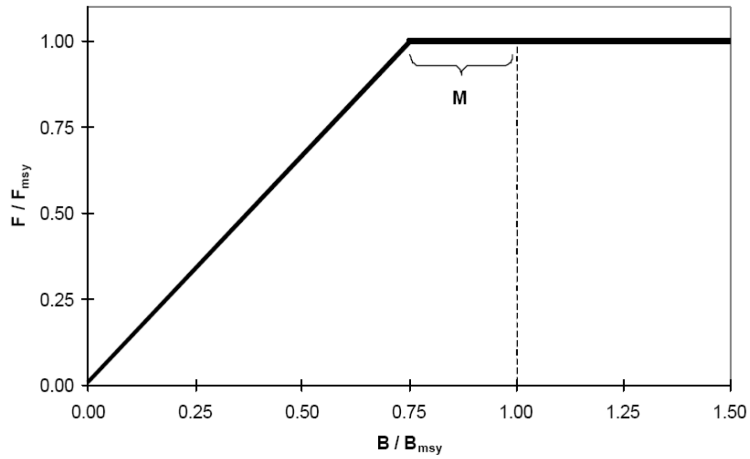


Figure 3. Default MSY control rule in the FMP for deep-sea red crab.

7. Current reference points

Information in this section is summarized from NEFSC (2006b). The reference point used as a fishing mortality threshold is MSY = 2,830 mt (6.24 million pounds).

The reference point used as a biomass target is B_{MSY} = 18,867 mt (41.6 million pounds) of male red crabs 102+ mm CW (4" CW). The reference point used as a biomass threshold reference point ½ B_{MSY} = 9,434 mt. A suggested CPUE baseline (presumably for use as a target) is 26-29 market-size crabs per trap, before adjustment for an equivalent number of 102 mm (4") CW market-size crabs.

8. Logic and justifications

In view of survey data limitations and infrequency of stock assessments for red crab, a landings-based BRP (e.g. 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 lbs) assumed an underlying Schafer surplus production model, and used estimated biomass for male red crabs 114+ mm CW from the 1974 camera/trawl survey as an estimate of virgin biomass B_0 (114 mm CW was the minimum marketable size at that time). Based on the Schaefer surplus production model, MSY= ½MB_0 and it was assumed that $F_{MSY} \cong M$. For the original red crab estimate, M=0.2 y^{-1} and B_0=24,948 mt of male red crabs 114+ mm CW.

The MSY estimate (2,903 mt) currently used by managers 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=0.2 y^{-1} for red crab. The original B_0 value was adjusted downward to account for part of the survey being in Canadian waters, adjusted upward to include male crabs 102 mm (4") CW and larger, as compared to the 1974 marketable size of 114 mm (4.5") 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.

9. Reference point weaknesses

In the most recent stock assessments (NEFSC 2006) the current MSY and B_{MSY} estimates for red crabs 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 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 (*Geryon maritae*; Mellville-Smith 1989) suggest that M may be as low as 0.1 y^{-1}, which is lower than the previous estimates (0.15 and 0.2 y^{-1}).

The assumption that $F_{MSY}=M$ has been criticized recently. Walters and Martell (2004) suggest that F_{MSY} is lower and approximately $0.8M$ for many species.

The assumption that $B_{MSY} = ½B_0$ (Schaefer surplus production curve) is reasonable if the underlying spawner-recruit relationship is a Ricker curve. However, $B_{MSY} < ½B_0$ if the underlying spawner-recruit relationship is a Beverton-Holt curve. Beverton-Holt recruitment dynamics are more likely for red crab because there is no known biological mechanism that might result in maximum recruitment at intermediate spawning biomass levels.

The current B_{MSY} estimate of 18,867 mt in the FMP for male red crabs (102+ mm or 4" CW) is not representative of current fishery conditions. The current fishery lands male red crabs 80+ mm and the L50 for current fishery selectivity is 92 mm CW.

The survey biomass for 1974 may be a poor estimate of B_0 because of statistical variance in the estimate, uncertainty about effective area sampled by the camera sled, or because some fishing had already taken place prior to 1974. The total biomass for male red crabs during 2003-2005 (56,443 mt) exceeds the estimate for 1974 (32,190 mt) despite consistent fishing indicating that the estimate for 1974 is a poor estimate of B_0.

The fishery appears to have substantially reduced the abundance of the largest male red crabs. Smaller male crabs may not be able to mate with large females. There is concern that reduced abundance of large male crabs may lead to sperm limitation and reduced levels of egg production if there are no males left in the population to mate with the larger females (see Appendix 1).

Landings per unit of fishing effort data (LPUE) are mentioned in the FMP as a baseline stock biomass indicator for red crab but LPUE data have proven difficult to interpret, particularly as long time series (NEFSC 2006a).

10. Options and recommendations

This section outlines a range of options for exploitation and biomass based biological reference points to be used managing deep-sea red crab in the management area outside the Gulf of Maine.

The exploitation BRPs described here are thresholds specified in terms of landed weight (yield). Yield based approaches are the only practical approach for red crab because the only fishery dependent or fishery independent data routinely available for red crabs are 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 the most recent camera/trawl survey conducted during 2003-2005, and size composition data from the original camera/trawl survey conducted during 1974. Biomass estimates from 1974 are less reliable and more uncertain because of questions about the effective area sampled by cameras in that survey. Uncertainty about biomass estimates makes trend analysis uncertain. Size composition data from 1974 are more reliable and are comparable to size composition data from 2003-2005 because bottom trawls and towing protocols used in 1974 were well documented and because trawls and protocols used in later years were the same.

Fishing for females

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

Marketable sizes and fishery selectivity

In laying out options for BRPs, we 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 a steeply 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.

OPTIONS for a Gulf of Maine stock

The management area for red crab excludes the Gulf of Maine and this situation complicates the development of biomass based BRPs. Red crabs in the Gulf of Maine (where little or no fishing occurs) and red crabs in the Southern New England and the Mid-Atlantic regions where (fishing occurs) are considered to be a single US stock. It is possible that depletion of red crabs south of Georges Bank might be “hidden” by including some level of unfished biomass in the Gulf of Maine as part of the stock as a whole, to the detriment of the entire stock and the fishery. Thus, the separation of red crabs into one management area and an area with no active management complicates specification and probably reduces the potential benefits of BRPs.

Under these conditions, it may be advisable to manage the areas north (Gulf of Maine) and south (Southern New England and Mid-Atlantic areas) as separate stocks. Red crab are a demersal species that migrate ontogenetically and seasonally from shallow to deep but there is no evidence of strong migratory movement of juveniles and adults along the coast. Thus, localized depletion may occur in red crabs due to continuous fishing in areas south of Georges Bank. The shallow waters and geography of Georges Bank effectively separate the Gulf of Maine from other habitat areas along the US coast. Red crabs in the Gulf of Maine appear to be smaller than red crabs in southern areas where the fishery is occurring, suggesting differences in growth rates and other biological characteristics. However, it is unlikely that red crabs in different areas off the northeast coast of the US differ genetically. It is also likely that recruitment is linked to some extent along the entire US coast due to transport of larvae in currents.
Two options are proposed.

- Option 1: Continue to manage a single US stock of red crabs. The main advantages of this option are minimization and simplicity of regulations. The main disadvantages are loss or potential benefits from BRPs.
- Option 2: Manage red crab in the Gulf of Maine and areas south of Georges Bank (Southern New England and Mid-Atlantic regions) as separate stocks.

Under this option, the exploitation BRP used to define overfishing for the Gulf of Maine stock would be F_{MSY} or the best available proxy. BRPs used to define the biomass target and biomass threshold for the Gulf of Maine would be B_{MSY} and $\frac{1}{2}B_{MSY}$ or the best available proxies. F_{MSY} and B_{MSY} for the Gulf of Maine are currently unknown and would have to be determined if interest in a Gulf of Maine red crab fishery develops. One or more special surveys designed to target red crabs would likely be required.

The main disadvantages of this option are increased regulations and complexity although any increases would be modest. The main advantage would be increased benefits of BRPs for red crab in the area were fishing occurs.

The second option (separate stocks) is recommended because the hypothesis of two stocks is scientifically credible, in view of restricted adult movement around Georges Bank and smaller red crabs in the Gulf of Maine, and because the potential utility of BRPs for the fished and unfished stock areas is increased. Under current legislation, BRPs used to define overfishing and overfished stock conditions must apply to entire stocks. Overfishing definitions for parts of stocks, such as the current management area for red crab, are apparently not allowed. Therefore, meaningful BRPs that address only red crab in the current management area appear impractical.

OPTIONS to regulate minimum legal size for male red crabs

Minimum size regulations may be desirable and should be evaluated for use in the red crab fishery. Minimum size regulations are used with some success in many crab and lobster fisheries. It is much easier to recommend biomass based reference points once the fishable stock (including minimum size) is clearly established and BRPs for a specified fishable stock are likely to be more meaningful and useful. Moreover, none of the options for exploitation and biomass based BRPs in this report deal effectively with concerns that sperm limitation that may result from removal of large males by fishing. Exploitation and biomass based BRPs are indirect approaches to dealing with these potential issues.

Because marketable sizes, fishery selectivity and potential sperm limitation are important, three options affecting minimum marketable sizes are presented for recommendation. Detailed analysis of this topic is an important area for research which should be carried out as soon as possible under any recommended option because the full range of cost and benefits to the stock and fishery have not bet identified.

- Option 1: No action. The main advantage is minimal impact on the fishery and minimal management costs. There is no evidence of serious problems in the fishery so that no actions to regulate minimum legal size are necessary. Minimum legal size regulations could be implemented in the future if required. The main disadvantage is the potential for changes in marketable sizes that tend to make BRPs for deep-sea red crabs moot. It is also possible that shifts in marketable sizes could exacerbate loss of large males which may be important for successful reproduction.
- Option 2: Specify a minimum legal size for red crab intended to protect some larger males in the population. This type of regulation would prohibit landings of male red crabs less than a specified CW. The minimum legal size would be close to the current minimum marketable size, i.e. 85-90mm CW, to minimize fishery impacts yet large enough to leave males suitable for mating with newly mature females. With this option in place further losses of large males and the potential for sperm limitation in the population might be minimized. BRPs for red crabs would be more meaningful and useful if the fishable stock is defined. The disadvantage of this option would be restrictions on flexibility in marketing red crabs.

- Option 3: Defer minimum legal size regulations until more analysis is carried out to determine the optimum minimum legal size from the fishery and biological perspectives. This option is basically a combination of options 1 and 2.

Option 2 is recommended to increase potential benefits of BRPs and to help avoid potential problems with loss of large males. Impacts on the current fishery would be minimal because current levels of discard would continue.

Biomass based biological reference points

As described above, biomass based reference points can be outlined for red crabs 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 deep-sea red crabs.

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. The results of these analyses are uncertain to the extent that biomass estimates for 1974 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. Biomass estimates from more recent 2003-2005 surveys are better understood, better documented and the area covered by the cameras is well defined. Recent estimates were affected by some avoidance behavior that resulted in negative bias and some underestimation of stock biomass. Avoidance behavior may affect 1974 estimates as well but uncertainty about the effective area of the camera is most important. Biomass estimates for 1974 are also uncertain because biomass estimates for all but large male crabs were substantially higher for 2003-2005 than for 1974, despite substantial fishery removals during 1974-2003.

OPTIONS for biomass based BRPs

Terms of Reference and NSGs require biomass based BRPs that describe target and threshold biomass levels. It is possible to define biomass based BRPs for red crabs but they are likely to be of little use because of lack of stock assessments, lack of useful survey data and difficulties in interpreting fishery catch rates (LPUE). None of the proposed options for biomass BRPs involve commercial catch rates (LPUE) because they have proven difficult to interpret for red crab (NEFSC 2006).

Three proposed options for B_{MSY} estimates that could be used as target BRPs for red crabs are described below. In each case, the threshold BRP would be ½ 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

- Option 1: Status quo or no action. The biomass based target B_{MSY} =18,867 mt of male red crabs 90+ mm CW and the approximation $B_{MSY} = ½MB_0$ where B_0 was the estimated biomass of male red crabs during 1974 with adjustments for areas not sampled in the survey. The biomass threshold that defines overfished stock biomass conditions is $½B_{MSY}$=9,434 mt. This option is not recommended because it accommodates neither adjustments to virgin biomass in approximating B_{MSY} to accommodate a Beverton-Holt type recruitment curve, which is probably for red crabs, nor an adjustment to M as a proxy for F_{MSY}.

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

The main advantage is ensuring that biomass BRPs are consistent with exploitation based BRPs. If 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.

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= 1775 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 x 1775 = 16,904 mt fishable biomass and the biomass threshold B_{MSY} /2 = 8,452 mt fishable biomass.

- Option 3: 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 at MSY levels. 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} =0.6 M to 0.8 M, with M=0.1-0.2 y-1) that might be considered for red crabs and potentially sustainable. The main disadvantage is the possibility that current biomass is substantially larger or smaller than B_{MSY}.

The second option (use the updated estimate of MSY to specify B_{MSY}) is recommended because virgin biomass is uncertain. Option 1 is not recommended because it involves poor approximations to F_{MSY} and B_{MSY}. Option 3 is not recommended 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 a pronounced effect on the relative abundance of large males.

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 crabs because they are simple and easy for managers to use outside the formal stock assessment process and without extensive review.

Ideally, all exploitation BRPs for red crabs based on landings 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. In other words, managers are expected to consider uncertainties and risks in setting ACLs in addition to not exceeding the threshold reference point. In this report, we focus primarily on uncertainties about the reference points themselves and ignore many of the uncertainties managers face in setting ACLs.

A number of the methods used to calculate potential exploitation based BRPs are estimators for "sustainable" landings levels, rather than estimates or proxies for MSY. There is no guarantee that sustainable landings levels calculated for red crab are near MSY. Sustainable yield estimates are often estimates of average landings 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.

A number of 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. Size composition data from surveys during 1974 and 2003-2005 indicate changes in recruitment because small male and female red crabs were 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.

We used 4 methods to estimate MSY or proxies thereof:

1) 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 crabs hasn't 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) equal 62,132mt, then the mean annual take of red crab has been 1,775mt, which is slightly less than mean landings since 2002.
2) Updated yield equation. The equation used to calculate MSY for the FMP was Y = (0.5) (M) (B_0) = (0.5) (0.15) (B_0 of males >114mm). However, $B_{MSY} < ½B_0$ if the underlying spawner-recruit relationship is a Beverton-Holt curve. Beverton-Holt recruitment dynamics are more likely for red crab because there is no known biological mechanism that might result in maximum recruitment at intermediate spawning biomass levels. Secondly, the ratio of F_{MSY} to M at maximum sustainable yield has been found to be less than one for most fisheries (Walters and Martell 2004). A coefficient c should be applied to M that is often 0.8 but for stocks more vulnerable to overfishing can be as low as 0.5. To update the equation to match the conditions of the current red crab fishery, the B_0 must be for males smaller than the >114mm CW it was originally calculated for. So that leaves the equation Y = (0.4) (c) (M) (B_0 fishable males). We used a range of M values and calculated MSYs based on both the 1974 and 2003-2005 survey biomass of fishable males.
3) Depletion-corrected average catch (DCAC) model. The addition of a second survey allowed us to run two models which use length frequency or abundance data from two points in time to

look at potential sustainable yields. 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 of a population after accounting for the “windfall” which occurs at the beginning of a fishery. We ran the model using several different estimates of M. For model details see appendix 2. When there is little or no trend in abundance, the DCAC model is the same as calculating the average landings.
4) 2-point boundary model. Also 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 landings 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.

Most of the yield based reference points presented in this report (Table 3) are lower than the current estimate of MSY (2884 mt) and target TAC (2688 mt). Most are lower than the observed landings during some years. Many estimates are reasonably consistent, possibly because they are based on average landings (e.g. average landings and DCAC estimates) or because they assume fishable stock biomass levels were similar during 1974 and 2003-2005. The similarity of many of the new MSY estimates (figure 4) to the long-term average landings (from 1973 to 2007, 1775 mt) supports the idea that this level of landings is most likely sustainable. Recent landings from 2002 to 2007 (mean 1853 mt) have been in this range, yet declining over the last few years. We recommend a landings limit that mimics both recent and long term mean annual landings, and suggest the current MSY of 2830 mt is a relatively poor estimate because it was calculated as MSY=1/2 M B0 instead of the updated formula MSY=cM(0.4) B_0.

The potential reference points in the table 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 crabs.

Table 3. Summary of exploitation based BRPs as MSY or MSY proxy options.

Method	description or model	Estimate	Estimate or range of estimates	Uses 1974 survey information	Equilibrium Estimator?
1	Status quo MSY	MSY	2830 mt	Yes	No
2	Average landings	Sustainable yield	1775 mt	No	Yes
3	Updated yield equation applied to 1974 biomass	MSY	549 - 1646 mt	No	No
4	Updated yield equation applied to 2003-2005 biomass	MSY	580 - 1740 mt	No	No
5	DCAC model	Sustainable yield	1785 - 1862 mt	Yes	Yes
6	2-point boundary model	Sustainable yield	1987 - 2044 mt	Yes	Yes

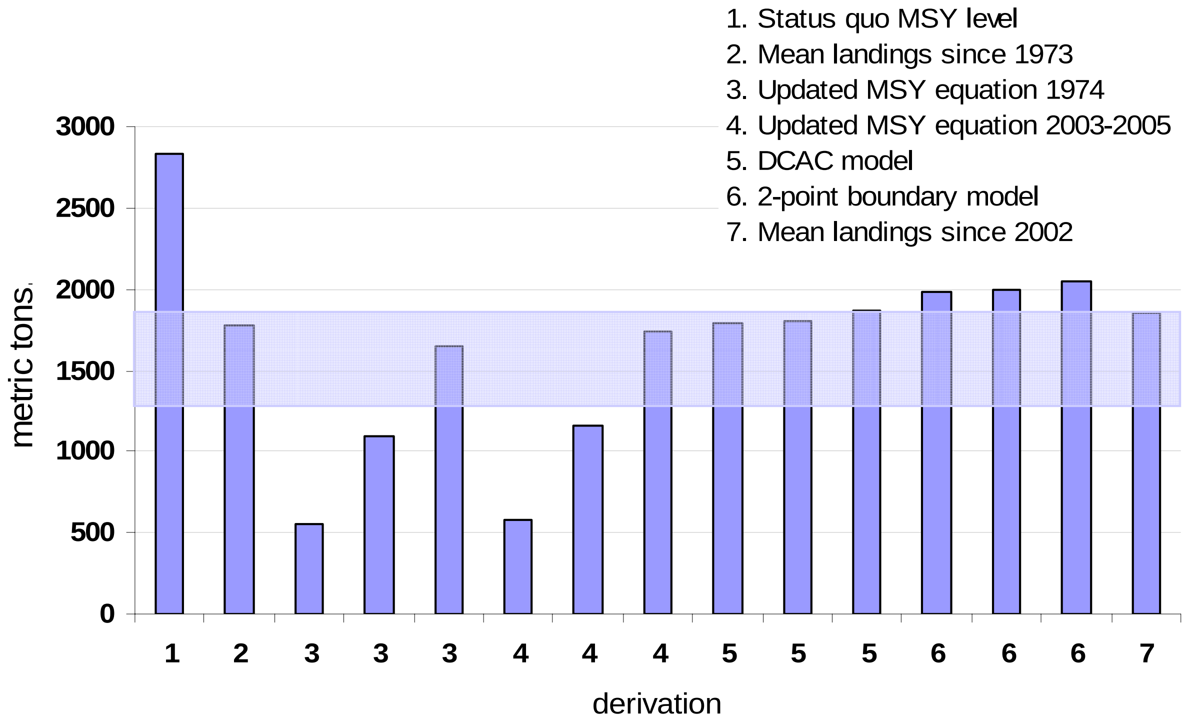


Figure 4. Summary of estimates of sustainable yield for red crab estimated using various methods. The upper boundary of the shaded area is the mean annual landings of red crab since 2002 and the lower boundary represents landings during 2007.

11. Scientific risks and uncertainties

Risks and uncertainties regarding BRPs for deep-sea red crabs are described below that are important in the context of choosing among BRP options and setting ACLs once BRPs are chosen. Risks to the stock due to overharvest and to the fishery due to foregone harvest are described in general terms but have not been quantified (no formal risk analyses were carried out).

Biomass based BRPs are difficult to evaluate for red crabs 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, and reproductive biology. There is also uncertainty about whether red crabs have a terminal molt and the extent to which females can store sperm.
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.
c) Minimum marketable sizes and fishery size selectivity have changes since the early 1970s and processors now accept smaller male red crabs. There are no management measures regulating minimum size. Thus future fishery 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+ CW) probably due to fishing. There is little uncertainty about reductions in occurrence of large males. There are questions about the potential importance of large males in spawning. In particular, 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.
e) Discards of undersize males and females are thought to be about 30% of total catch but the estimates are uncertain. Mortality of discarded crabs was relatively low in a recent study (~5%) but is uncertain and may be higher during routine fishing.
f) 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 landings 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 landings.
g) Some of the methods used to calculate biological reference points in this report involved equilibrium assumptions that may not be justified for red crab. The potential effects of the equilibrium assumptions are uncertain.
h) As noted above, biomass estimates from the camera/trawl survey during 1974 are uncertain because of questions about the effective area searched by 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 or near-virgin stock levels.
i) Recent red crab biomass estimates from surveys during 2003-2005 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 crabs. Available data from comparative fishing experiments provide little evidence one way or the other in this regard.
k) Changes in fishing locations have occurred during recent years, presumably due to localized depletion.

12. Research recommendations

a) Establish a regular schedule for surveys that provide useful information about deep-sea red crab. This is the most important research recommendation for red crabs.
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 that the same equipment and approaches would be useful for deep-sea red crab.
c) Evaluate the importance of large male red crabs 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) Place scientific observers on board fishing vessels during routine fishing trips to collect data about discards.

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14. Appendixes

Appendix 1.

Red crab size composition analysis

Based on the ratio of minimum mature size, and ratio of mean size in 1974, we assume that males must be at least 25% larger than females to mate successfully (alternative assumptions could be explored). This analysis examines the impact of the fishery on the size structure of the population, specifically with regard to the ratio of 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 the sex ratio in terms of observed densities of crabs, but lacks 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 crabs from the 1974 and 2003-2005 surveys. Females are assumed to mature at 70mm, and males at 90mm. The densities of mature male crabs per 30-minute tow declined slightly, 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 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 relatively low observed value of 15 is presumably due to exploitation effects. 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. In order to maintain a similar level of fertilization, the average male in 2003-2005 must mate with 2.33 times the number of females that it did in 1974. If the1974 size composition already showed exploitation effects, the population impact is greater than is shown in table 1a.

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 (mm)	113.8	94.1	105.7	95.1
mean ratio of size-dependent				
available females to males	25.3		58.9	

Appendix 2.

Alec MacCall, NMFS/SWFSC/FED (draft 9/6/07)

Depletion-Adjusted Average Catch Model

Unlike the classic fishery problem of estimating MSY, data-poor fishery analysis must be content simply 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 tend to overestimate the 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 Ypot = 0.5*M*Bunfished (Alverson and Pereyra,1969; Gulland,
1970) is based on combining two approximations: 1) that Bmsy occurs at 0.5*Bunfished, and 2) that Fmsy = M. In this and the following calculations fishing mortality rate (F) and exploitation rate are treated as roughly equivalent.

However, it is possible to take the potential yield rationale one step farther, and calculate the ratio of the one-time “windfall” harvest (W) due to reducing the abundance from Bunfished to the assumed Bmsy 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*Bunfished, and

W = 0.5*Bunfished.

Under the potential yield assumptions, the ratio of one-time windfall yield to sustainable yield is the windfall/sustainable yield ratio (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 of fishes occurs somewhat below the level of 0.5*Bunfished. We replace the value of 0.5 with a value of 0.4 as a better approximation of common stock-recruitment relationships.

The Fmsy = M assumption also requires revision, as fishery experience has shown it tends to be too high, and should be replaced by a Fmsy = c*M assumption (Deriso, 1982; Walters and Martell, 2004). Walters and Martell suggest that coefficient c is commonly around 0.8, but may be 0.6 or less for vulnerable stocks. Figure 1 shows the distribution of c values for West Coast groundfish stocks assessed in 2005. The average of c for those West Coast 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 yield that is potentially sustainable under these revised assumptions is

Y = 0.4* Bunfished *c*M,

or for c = 0.5,

Y = 0.2* Bunfished *M.

The windfall is based on the reduction in abundance from the beginning of the catch time series to the end of the series,

W = Bbegin - Bend = DELTA*Bunfished,

where DELTA 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 Bbegin = Bunfished, and Bend = 0.4*Bunfished, in which case DELTA = 0.6. In practice, Bbegin is rarely Bunfished, and DELTA is unlikely to be known explicitly. Although data may be insufficient for use of conventional stock assessment methods, an estimate (or range) of DELTA 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 Bunfished to near Bmsy where DELTA=0.6, if c = 0.5, 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 units 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 annual 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 (Ysust) is
Ysust = sum(C)/(n + W/Y).

In the special case of no change in biomass, DELTA = 0, W/Y = 0, and Ysust is the historical
average catch. If abundance increases, DELTA is negative, W/Y is negative, and Ysust 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 ca. 5000 mtons, with indications that abundance had fallen to 20-33% of Bunfished.

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 Bmsy 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 Bunfished).

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 Bmsy. If the resource has fallen below Bmsy, the currently sustainable yield (Ycurrent) is necessarily smaller. A possible approximation would be based on the ratio of Bcurrent to Bmsy,

Ycurrent = Ysust*(Bcurrent/Bmsy) if Bcurrent<Bmsy

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 Fmsy 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 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

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

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 or $S=e^{-(G-M)}$. For this application it was assumed that increments to population biomass via growth are included in the Rt term; therefore $S=e^{-M}$ No information is available to estimate the annual recruitment to the population but Eq. 1 can be simplified by let R_t equal a constant, say R.

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

Substituting Eq. 1 into 2 recursively leads to

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

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

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

….

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

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.

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

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

$$\hat{F}_t \approx \frac{C_t}{B_t + R} \qquad (5)$$

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 estimated as

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

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

$$\begin{aligned} B_T &= \left(B_T - \overline{C}_{EQ} + R\right)S \\ \overline{C}_{EQ} &= R - \frac{B_T(1-S)}{S} \end{aligned} \qquad (7)$$

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 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 $B_t \sim N(\mu_t\ \sigma_t^2)$, $B_{t+T} \sim N(\mu_{t+T}\ \sigma_{t+T}^2)$ and $\Phi(.)$ define the cdf of the normal distribution. The inverse of the normal cdf, say $\Phi^{-1}(.)$, can be used to define population estimates for equal probability intervals

$$\begin{aligned} B_{t,\alpha} &= \Phi^{-1}\left(\mu_t, \sigma_t^2, \alpha\right), \quad \alpha = \alpha_{\min}, \ldots \alpha_{\max} \\ B_{T,\beta} &= \Phi^{-1}\left(\mu_T, \sigma_T^2, \beta\right), \quad \beta = \beta_{\min}, \ldots \beta_{\max} \end{aligned} \qquad (8)$$

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 a small step size, say δ and evaluate $R_{\alpha,\beta}$ for equal increments between the minimum and maximum values of the cdf. The sampling distribution of

R, Fbar, and Ceq is just the collection of discrete estimates since all 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 and 2004 fishery independent surveys (Table xx) and landings from 1974 to 2003 (Table zz). The distributions of R, Fbar and CEQ 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 2601 (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 8500 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 the females was essentially zero, the estimated median recruitment was 9837 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 sexes. For example, assuming an M=0.13 for females results in a median R of 7,810 mt that is about the same 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 xx. 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 ZZ. Summary of annual landings (mt) of red crab in US.

Year	Landings (mt)
73	112.5
74	503.1
75	307.3
76	637.9
77	1244.6
78	1247.6
79	1210.8
80	2481.2
81	3031.8
82	2445.6
83	3252.4
84	3875.0
85	2236.7
86	1248.7
87	2110.3
88	3592.7
89	2393.2
90	1526.7
91	1791.0
92	1061.2
93	1439.9
94	0.3
95	572.0
96	465.6
97	1725.2
98	1501.1
99	1869.2
00	3129.4
01	4002.7
02	2142.5
03	1920.0
04	2040.3
05	2013.2
06	1716.0
07	1284.0

Table yy. Estimated median recruitment, average F, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality 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 Biomass (>90 mm CW)	9,044 (7,408, 10,785)	0	72 (52, 93)

Table yy1. Estimated median recruitment, average F, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality 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 yy2. Estimated median recruitment, average F, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality is assumed to be 0.1 (S=0.905)

Category	Recruitment	Fishing Mortality	Equilibrium Catch
Fishable Biomass of Males	5,819 (5,095, 6587)	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 yy3. Estimated median recruitment, average F, and equilibrium catch based on 2-point boundary value method. Values in parentheses represent 90% confidence interval. Natural mortality 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)

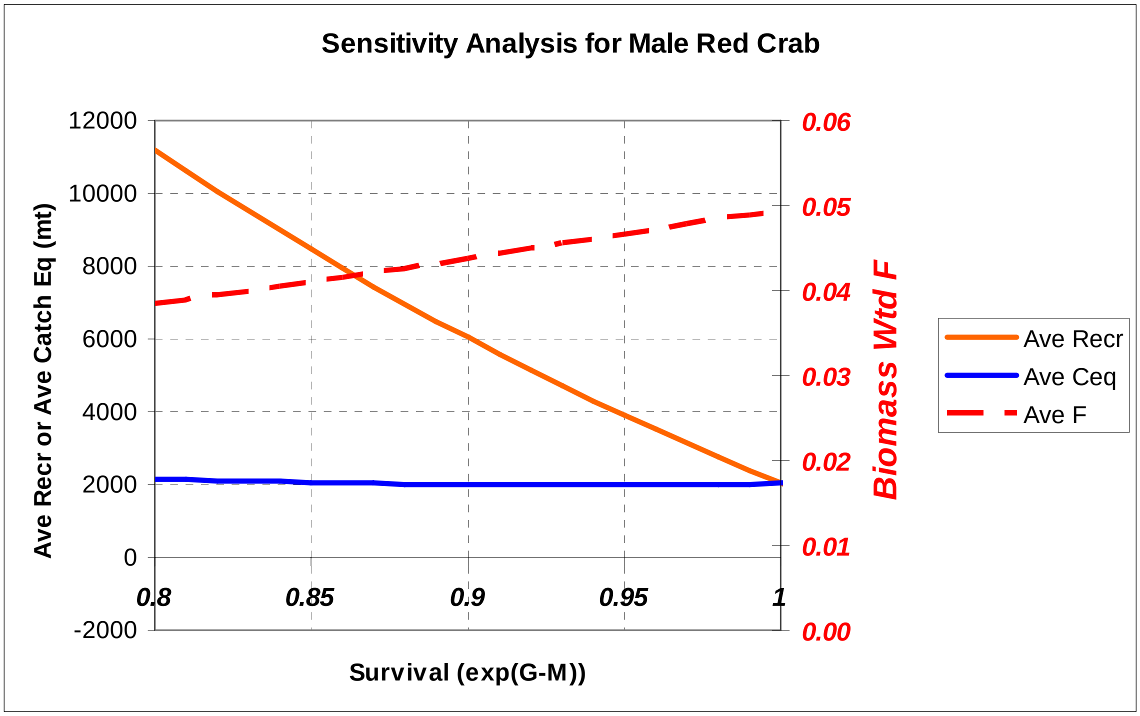

Fig 1. Sensitivity analysis of recruitment, average F and equilibrium catch for male red crab to varying levels of survival rate.

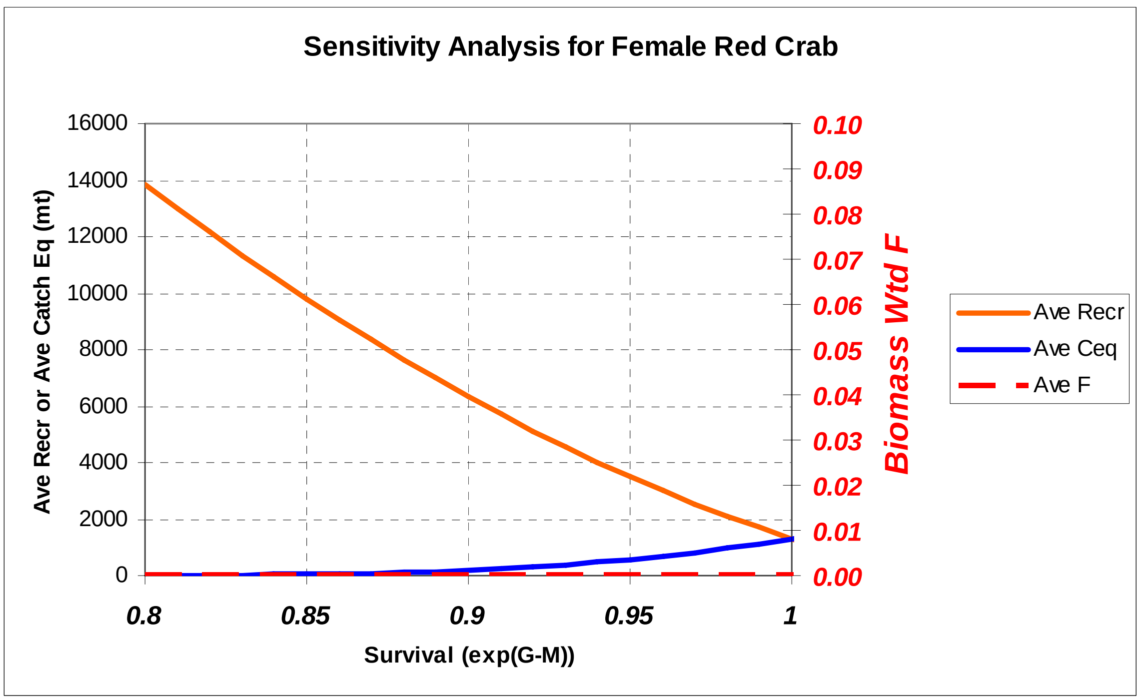

Fig. 2. Sensitivity analysis of recruitment, average F and equilibrium catch for female red crab to varying levels of survival rate.