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DEVELOPING STOCK ASSESSMENT METHODS FOR THE NEW ENGLAND DEEP SEA RED CRAB FISHERY

Award #04-815

and

EVALUATING BEAM TRAWLS IN STOCK ASSESSMENT OF THE NEW ENGLAND DEEP SEA RED CRAB FISHERY

(Project Development Award)

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Final Report
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Abstract

This final report summarizes the results of our main 3-year red crab project as well as a supplemental development project with an additional objective. The objectives of the main project were to: (1) Employ camera-based and net-trawl sampling methodology established by an earlier NMFS red crab surveys (Wigley et al. 1975) to determine whether abundance, size structure, and sex composition of the population has changed significantly at the same sites sampled in 1974, (2) Conduct sea sampling to better characterize the commercial catch, (3) Conduct tagging to obtain much needed information on red crab growth rates and movement, and (4) Develop three stock assessment modeling approaches of different complexities (size-structured yield-per-recruit model, production model, and size-structured simulation model) to evaluate the dynamics of the red crab stock, estimate current status of the fishery, and evaluate alternative management strategies. The supplemental project compared the efficacy of otter-trawl to net trawl in this application.

The benthic sled system for camera surveys combined with net trawl collection generated the first population density estimates and demographic data of red crab in 30 years. The comparison of the two net trawl methods confirmed that otter trawls were the most efficient approach in these surveys. Results of the main project indicated that the abundance of the largest crabs targeted early in the history of the fishery (males >114 mm, 4.5 inches) is down by approximately 42% since 1974. Based on sea sampling data the fishery now harvests smaller male crabs, and the standing biomass of crabs currently harvested is on a par with 1974 levels. The abundance of smaller males and females is substantially higher than in 1974. Some 9600 crabs were tagged over the course of the study, and of about 300 returns there was little evidence of growth, which is consistent with prior evidence of slow growth for this species. However, the limited growth data curtailed application of the stock assessment models. The full parameterization of these models awaits additional growth data. Models are implemented as Excel spread sheets that and are available from the PI, and will be easy for the user to update as data become available. These results were a key component of the NMFS red crab stock assessment conducted in 2006.

Introduction

Until 2002, the Atlantic deep sea red crab *(Chaceon quinquedens)* had been referred to as the last unmanaged fishery in the Northeast. The fishery is conducted on the Continental Shelf in a narrow band 400-800 m deep. The fresh product is processed and the frozen meat is sold throughout the United States. It is a relatively small fishery developed in response to the collapse of the ground fish industry. In 2000, four 90-120-foot vessels, from Maine, Massachusetts and Rhode Island, participated in the fishery. According to harvester records these vessels collectively harvested about 3.2 metric tons (7 million pounds, a landed value of about $7 million) of red crab annually, approximating NMFS estimates of maximum sustainable yield for this species (Serchuk 1977).

Concerned over the prospect of a rapidly expanding fishery, the New England Red Crab Harvesters Association (NERCHA), pressed NMFS and NEFMC for the implementation of a Fishery Management Plan (FMP). The FMP was implemented in 2002. However, until then the fishery operated with no restrictions. NERCHA was eager to work with researchers to establish a sustainable harvest level. These harvesters provided catch records, access to their vessels as research platforms, and expertise in the red crab fishery.

This project represents a harvester-scientist partnership intended to gather necessary demographic information on red crab toward the development of a stock assessment program with assistance of fisheries managers. In 2002 the Northeast Consortium committed one year of support to the project for a shake-down cruise, with subsequent support contingent on its success. Additional major support was secured from NOAA's Saltonstall-Kennedy (SK) Program and Maine Sea Grant. The study commenced on schedule in April 2002. NMFS and NOAA/NURP provided further in-kind support in the form of equipment.

This project was specifically well suited to the goals of the Northeast Consortium because it: (1) developed a partnership between commercial harvesters, scientists, and fishery managers, (2) engaged commercial fishing vessels as research platforms as a cost-effective way of conducting the research, and (3) drew upon fishermen expertise to develop a workable scientific survey.

Review of Previous Work

The deep-water crabs of the family Geryonidae are widely distributed on the continental slopes of the world, over a depth range of 200-1200 m (reviewed by Hastie 1995). Two species are of commercial importance, *Chaceon (*formerly *Geryon) maritae* off South West Africa, and *Chaceon (*formerly *Geryon) quinquedens* off eastern North America. In New England and Atlantic Canada *C. quinquedens,* the deep sea red crab, is at the northern edge of its geographic range (Fig. 1, Duggan and Lawton 1997). Red crab populations are most dense on mud, sand, and hard bottoms in depths of 300-900 m at temperatures between 5-8° C. Although it is a relatively conspicuous member of the deep sea community on the continental shelf and slope, many aspects of its biology, ecology and behavior remain poorly understood. Males mature at about 75 mm carapace width and can reach a size of 180 mm, a weight of nearly 1.7 kg. Females begin to mature at a somewhat smaller size, and do not grow as large, reaching a maximum carapace width of 136 mm and 0.7 kg. The fishery targets crab ≥114 mm (4.5 inches) carapace width, most of which are males. This is a possible cause for concern if males are only competent to mate when they are larger than mature females. Egg bearing females are found year-round off New England with a peak in November. The large yolky eggs hatch between January and June. Larvae require 23-125 days to develop before they settle to the bottom. 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 cited in Hastie 1995). Juveniles move upslope to warmer water where they are likely to grow faster. On the basis of very limited laboratory-based growth data, red crabs are believed to require 5-6 years to attain the marketable size of 114 mm (Van Heukelem 1983). Prior tagging studies (Lux et al. 1982), while documenting movement, provided almost no information on growth because the tags used were not retained through the molt.

The camera and trawl surveys by Wigley et al. (1975) represent the most comprehensive fishery-independent demographic information available for this species. On the basis of these surveys, Serchuk (1977) provided preliminary estimates of maximum sustainable yield for red crab to be approximately 2700 metric tons (5.9 million lbs.), about $1/10^{th}$ the estimated standing biomass of commercial sized crabs. Annual landings from the late 1990's to 2001 have averaged around 3200 metric tons (7 million lbs.). If Serchuk's estimates are correct, at current fishing effort, the resource is fully exploited. However, the data that these estimates are based on are more than 26 years old. We do not know how current populations compare to those observed by Wigley and coworkers decades ago. However, according to a recent stock assessment of the Canadian red crab fishery, stocks there are close to being overexploited (Duggan and Lawton 1997). Based on a trend of declining catch-per-unit-effort, Canadian fisheries managers further

suspect that current fishing effort is not sustainable. No fishery-independent surveys have been conducted since the NMFS survey of 1974. Moreover, new methods of assessing sustainable yields have been developed and should be applied (e.g., Hilborn and Walters 1992), and see modeling objectives below).

Our limited understanding of geryonid crab biology and population dynamics is captured in quotes from a recent comprehensive review by Hastie (1995)*: "…analysis of population dynamics involves making predictions of birth and death rates, growth and movement processes, and there are insufficient data available on which to make such predictions for most geryonid stocks."*

Most recently, the NEFMC noted the void of data in its draft FMP for red crab: *"The lack of fishery-independent survey data on the red crab resource presents a real challenge to the Council as we have no current estimates of red crab biomass. The NMFS bottom trawl survey only occasionally captures any red crabs and only at the shallowest fringe of their habitat."*

These uncertainties inspired the objectives of our proposal. In keeping with the Sustainable Fisheries Act, it is imperative they are addressed.

Project Objectives

This project is a partnership of researchers with harvesters toward the collection of demographic data that is necessary to estimate sustainable harvest levels and develop a management plan for New England deep sea red crab. The centerpiece of the project is the historical comparison of today's abundance levels to those measured by Wigley et al. (1975), the most comprehensive previous study of red crab to date. Additional analyses were completed to fill the void of information on red crab growth, and to examine the utility of catch data as indices of abundance. Both fishery-dependent and fishery-independent data were used to develop and parameterize stock assessment models.

The objectives of this main three-year project were as follows. Statistical null hypotheses are stated in the Methodology section.

• **Objective 1:** Employ the same trawl- and camera-based sampling methodology established by Wigley et al. (1975) to determine whether abundance, size structure, and sex composition of the red crab population has changed significantly at the same sites since 1974 and over the three years of the proposed project. As a supplement to this objective, additional Project Development funds were used in 2003 to compare the performance of a beam-trawl to otter-trawl over the red crab depth range.

• **Objective 2:** Conduct sea sampling to characterize commercial catch rates and to provide data useful to assess discard rates when compared to landings data.

• **Objective 3:** Conduct tagging to obtain much needed information on red crab growth rates and movement.

• **Objective 4:** Employ three modeling approaches of different complexities (size-structured yield-per-recruit model, production model, and size-structured simulation model) to evaluate the dynamics of the red crab stock, estimate current status of the fishery, and evaluate alternative management strategies.

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Methods

• Objective 1: Trawl and Camera Surveys

The camera and otter trawl surveys originally conducted by NMFS in 1974 and the more recent NEC-supported full surveys in 2003, 2004, and 2005 provide an opportunity to compare the red crab population before and after a period of sustained targeted exploitation for more than two decades. A preliminary shakedown cruise was conducted in 2002, but those data were not used in the stock assessment because relatively few sites were visited. As much as possible an effort was made to pair camera and net tows at each survey site. Camera surveys provided estimates of population density and otter trawls provided data on sex, size, and maturity.

The 1974 surveys were conducted from the R/V *Albatross IV*, a 57 m (187 ft) research vessel operated by the National Marine Fisheries Service, Northeast Science Center. The more recent surveys were conducted from two different fishing vessels, the 96 foot F/V *Hannah Boden* and the 90 foot F/V *Krystle James*, both of which are engaged in the deep sea red crab fishery.

The locations of the camera and net tows conducted in 1974 and in 2003-2005 are shown in Figure 1. The overall sampling effort spanned a segment of the continental shelf break from offshore Maryland to the eastern end of Georges Bank. Survey results are partitioned into seven depth intervals and four geographic sectors originally established by Wigley et al. (1975). The distribution of camera tow and otter trawl sampling effort by depth and sector is tabulated for all years (Table 1).

Specifications of the camera-sled systems and otter trawls employed in the two surveys are summarized in Table 2 and details of the methodology follow.

Camera-Sled System: Photographs were used to determine the density (numbers per unit area) of red crabs and associated fauna. The photographic system in both surveys was mounted on a

benthic sled. The sled used in the more recent survey was somewhat smaller than that used in 1974 primarily because of constraints imposed by the smaller size of the vessels. As a result there were some unavoidable differences in the area of sea bed sampled by the two systems (Table 1). In both cases during preliminary trials in shallow water, a grid with known intervals was placed level on the sea floor in front of the camera to determine the area of illuminated in the image. During image analysis only the best-lighted and unobscured areas of the photograph were used, and crab densities calculated for individual images were thus corrected accordingly.

The camera system used in 1974 consisted of a 70 mm Nikon film camera and stroboscopic light (see Theroux 1976, Wigley et al. 1975 for details). The camera was aimed perpendicular to the sled at a height of 1.75 m and a downward angle of 16 degrees from horizontal. In that position the camera viewed a total area of 148 m^2 although the effective area sampled (illuminated) was 31.8 m^2 (Theroux 1976, Patil et al. 1979). The system was programmed to take photographs every 10 sec; at a speed of 2 knots a photograph would be taken approximately every 10m and a 30 minute tow provided approximately 180 images.

The system used in the 2003-2005 surveys consisted of a Nikon Coolpix 990 digital still camera modified with a programmable intervalometer and computer interface software designed by Engage Technologies. The camera was housed in a deep-sea titanium housing and was coupled to a Benthos model 382 strobe (on loan from the National Undersea Research Center at the University of Connecticut). The camera was aimed perpendicular to the sled at a height of 1m with a downward angle of 35 degrees. In that position the camera viewed a total area of 10 m^2 and an effective illuminated area determined to be 6.6 m^2. This was determined using a grid subdivided into 0.01 m^2 squares placed horizontally on the sea bed in front of the camera. The system was programmed to take photographs every 15 sec; at a speed of 2 knots a photograph was taken approximately every 14m, a 30 minute tow resulting in about 120 images.

For surveys in both 1974 and 2003-2005, it was important to determine if the oblique orientation of the camera relative to the sea bed may have resulted in under-estimates of abundance because of crabs avoiding the sled in the foreground or not being detected in the background. It was only possible to evaluate this question for the 2003-2005 surveys because the photographs from the 1974 were not available. In the case of the 2003-2005 surveys, it was possible to determine if crabs were more abundant in the foreground or background areas of the photograph. A subset of 141 randomly selected photographs from the 2005 surveys was examined, all photographs containing one or more crabs. The 6.6 m^2 illuminated area of each photograph was divided into equal 3.3 m^2 foreground and background sub-areas in which crabs were counted. The null hypothesis that crabs were as likely to be present in the foreground as the background areas was tested with a simple χ^2 statistic. Crabs occurred with significantly greater frequency in the background (79% of the time) than the foreground sub-areas (34% of the time; χ^2 contingency analysis: $\chi^2 = 49.06$, df = 1, $p < 0.0001$). This result suggests crabs may have been avoiding the oncoming sled, and that the resultant density estimates may be too low.

It is possible that population estimates from the 1974 survey would be subject to the same bias, although perhaps to a lesser extent given the larger area photographed. However, it is also possible that the larger area sampled in the 1974 photographs (31.8 m^2 versus 6.6 m^2 in 2003-2005) might cause smaller red crabs to escape detection at the margins, and in turn, result in underestimates of abundance. Unfortunately, materials from the 1974 survey that might be used to evaluate this hypothesis were lost. NEFSC staff searched files and storage facilities for information about calculation of red crab densities during the 1974 camera/bottom trawl survey. Some related materials (originally the property of Roger B.Theroux) were found but no survey photos or information about processing of photo images was recovered.

Otter trawl: Net trawls were used in both surveys to collect crabs for the purpose of determining size, sex and shell condition. The nets used in the two surveys were virtually identical;

specifications are listed in Table 2. Once the net was deployed, it was towed at 1.5- 2.0 knots for 30-45 min. The scope (wire length to depth ratio) used during the 2003-2005 surveys was consistent with that employed during the 1974 surveys (Theroux pers. comm.): it varied between 1.5 and 3 depending on depth and conditions. In the more recent surveys no net tows were conducted at depths greater than 500 fathoms (914 m) because of insufficient wire to tow successfully at those depths.

Catch numbers were standardized to catch-per-30-minute-tow. Catch-per-tow was not found to correlate strongly with the density estimate from the camera tows at the same sites (r^2 = 0.06); therefore catch per tow was not regarded as a reliable indicator of abundance. Otter trawl data, however, were a valuable source of information on crab size and sex composition. The sex and size composition data were used to parse density estimates from the camera survey.

For use in computing recent abundance and fishing mortality, data from surveys during 2003-2005 were combined by averaging the stratum and depth specific estimates available from each individual survey. Standard errors were computed based on the four survey-specific estimates. This approach treats the individual survey estimates (rather than individual camera sled tows) as the experimental unit. Standard errors and CV's for biomass and abundance estimates calculated in this way will be relatively high because the number of observations (4) is lower than the number of camera sled tows.

Otter trawl-Beam trawl comparison: This trawl comparison was incorporated into the sampling plan of the main project. This was a simple comparison of paired trawls conducted at the same sites over a range of depths. Some 25 paired tows were conducted between 150 and 350 fathoms. Nets were towed at a speed of 1.5 to 2 knots for 30 minutes. The scope used for each tow will be optimized for the type of net and depth (usually somewhere between 1:2 and 1:4). Crab numbers, size and sex was determined at the end of the tow. Catch was standardized to crabs caught per 30 min tow. The two nets were statistically compared with respect to catch rates and crab sizes.

The mean size of crabs in the catch in the two nets was identical (87 mm carapace length; $t=1.96$, $df = 494$, $p = 0.976$), but the mean catch per standardized 30 minute tow was more than twice as great with the otter trawl ($t = 2.06$, $df = 23$, $p = 0.036$). We also found that the beam trawl more often filled with mud or became snagged on rocks/boulders on the bottom. Taken together these results lead us to conclude that the otter trawl remains the net of choice for our purposes. All our reported net tow results are from the otter trawl.

Density and Abundance Estimates by Sex and Size: Figure 2 provides an overview of the approach whereby crab densities from camera tows and sex and size composition from net tows enabled estimates of numerical abundance and biomass. Biomass density was determined slightly differently in the two surveys. In Wigley et al. (1975), biomass density was determined by dividing the total weight of the otter trawl catch by the number of crabs in the catch to give an average weight per crab. Biomass density for a given geographic stratum is the product of numerical density and the average weight of crab in the catch.

In the 1974 survey, commercial crabs were defined as crabs of both sexes $\geq$114 mm carapace width, the marketable size at the time. Wigley et al. (1975) did not make a distinction between male and female crabs in estimating standing crop biomass. However, detailed data from otter trawl tows in the 1974 survey were available (Murray 1974) and it was possible to use the otter trawl size and sex data to prorate total abundance and biomass by size and sex.

Sex-specific size-weight relationships (Farlow 1980 cited in Steimle et al. 2001) were used in calculating biomass in the 1974 and 2003-2005 surveys:

Males: $\log W = 3.0997 \log(L) - 0.59763$

Females: $\log W = 2.75225 \log(L) - 0.34986$

where L is carapace width in cm and W is body weight in grams. Using these relationships, it was possible to convert numerical densities for any size group of crabs to biomass density.

To calculate numerical and biomass standing crop, densities were multiplied by estimates of the area of sea floor in each stratum at and depth interval. These areas in hectares (ha) were deduced from Wigley et al. (1975) by dividing the reported abundance estimate by the density estimate for each depth-sector stratum (Table 3).

The depth range over which densities and standing crop are estimated is 125-500 fathoms (229-914m). At greater depths net tows were unreliable and no harvestable crabs were found either in 1974 or in the more recent surveys. In strata where no tow data were available the mean value for that depth was used as a proxy value from which to calculate standing crop.

• Objective 2: Sampling the Commercial Catch

At-sea sampling of the commercial catch was conducted during two commercial trips in 2002 in sector C. Data collected on these occasions provide information on catch per unit effort using different trap types in addition to further information on size, sex, egg composition, and by-catch.

While these initial sea sampling trips provided vast quantities of data on the commercial catch, it quickly became apparent that to send scientific staff on a standard fishing trip was not cost-effective because of the extended time spent on a very small proportion of the fishing area. This led us to recommend to the industry and to the NEFMC Plan Development Team that trained members of the commercial crew may be a more practical solution for sea sampling. Although no funds were available to conduct sea sampling in 2003, our renewed NEC support for 2004 and 2005 included funds for trained members of the commercial crew to conduct sea sampling. This strategy provided a more cost effective and broader geographical sampling of the catch than a dedicated on-board observer.

For each crab in the catch sea samplers recorded the carapace width, sex, shell condition, and presence of eggs. Counts of crabs were made on a per trap basis and the position of the trap was noted by GPS. Sea samplers collected all crabs from the catch and record their data on audiotape to be transcribed later on computer spreadsheets.

In the stock assessment sea sampling data collected by the commercial crew in 2004 and 2005 were used to assess fishing effort and were compared to landings data from the same trips collected by NMFS staff to evaluate the unharvested (discarded) fraction of the catch.

• Objective 3: Tagging Study for Growth Rates & Movement

One of the most glaring gaps in our understanding of the biology of this and other geryonid species is the absence of information on *in situ* growth (Hastie 1995). Growth information is required by apply yield models, and to project landings from knowledge of pre-recruit abundance or year-class strength.

We tagged crabs with T-bar tags (Floy Tag Co., Seattle) that are retained through the molt (e.g., Melville-Smith 1987). Crabs of all available sizes were tagged. Harvesters were asked to report date, location, and body size, and reproductive status at recapture. Because the number of harvesters is relatively small, we expected compliance to be quite high. Tagged crabs were released over the side of the boat in the area where they were collected. Tag loss rates and tag-related mortality were evaluated with crabs held in the laboratory.

Crabs were tagged between 2002 and 2005. We anticipated that the combination of trawl samples and monitoring of the catch by harvesters and processors would provide the greatest sufficient recapture data to assess growth over the course of the project.

• Objective 4: Stock Assessment Models

Three modeling approaches of different complexities were developed to evaluate the dynamics of the red crab stock, estimate current status of the fishery, and evaluate alternative management strategies. They include (1) a size-structured yield-per-recruit model (Chen 1997), (2) a production model (Hilborn and Walters 1992, Chen and Montgomery 1999), and (3) a size-structured simulation model (Quinn and Deriso 1999, Chen et al. 2000).

While all three models have been developed, unfortunately, parameterization and evaluation of these models was limited by two factors: (1) Insufficient funding. The modeling component of the study depended on continued SK funding to support Dr. Chen's participation. The SK program terminated in 2004. (2) Insufficient tag returns. Over the duration of the project tag returns were disappointing, and among some 300 crabs recaptured there was little evidence of growth, underscoring the slow rate of growth in this species.

Alternatives and Limitations to our Approach

Progress on Objective 4 (Modeling) was curtailed by the discontinuation of Saltonstall-Kennedy funding that supported Dr. Chen's time. The SK Program was terminated in 2004. See further comments under Methods and Results sections.

Data Submission

At this writing some of the data have been submitted to NEC and the remainder are being compiled for submission in the near future. These include the following raw data files:

All tow logs giving location, depth, duration of all net and sled tows

Net tow data, including size, sex, shell condition of crabs, and counts of associated fauna.

Camera tow data, includes counts of crabs and associated fauna in each usable image.

List of tagged and recaptured crabs, includes tag number, size, sex, shell condition, date and location of capture and recapture of all tagged crabs.

Results & Conclusions

• Objective 1: Camera and Net tows

Size and Sex Composition: In 1974 a total of 795 female and 641 crabs were collected by otter trawl. Between 2003 and 2005, 4602 female and 2209 male crabs were collected. The overall size composition for the 1974 and 2003-2005 surveys are presented by sex in Figure 3. Size and sex composition differed in the two surveys in important ways. Although the overall size range and catch-per-tow of crabs from the two surveys was similar, the number of large male crabs in the harvestable size range was substantially lower in the more recent surveys than in 1974. The size composition of females differed much less dramatically; with the current size mode of female abundance falling within the same range is it did in 1974. Also apparent in the 2003-2005 size distribution are a greater proportion of crabs of both sexes in the 50 to 80 mm size range. The apparently higher abundance of these small crabs may have been due to good recruitment. It is unlikely the differences in the size composition of crabs between the earlier and more recent

surveys were due to differences in the selectivity of the nets. The nets in the two surveys were virtually identitical and they were towed in the same manner.

Density and Abundance Estimates: Estimates of red crab biomass from the 2003-2005 surveys were compared to estimates from earlier surveys conducted in 1974. Biomass estimates are given for the following groupings of crabs: all crabs, male crabs >114 mm (commercial by 1974 standards), fishable crabs by current standards, as well as sexually mature crabs of both sexes. Tables provided in Appendix D4 of the stock assessment report (ASMFC 2006) summarize the data from which the following analysis was derived; they give numerical density, biomass density, numerical abundance, and total biomass by depth and sector for the different size and sex categories of crabs.

Total red crab biomass is estimated to have increased by two-and-a-half fold since 1974, most likely because of the larger numbers of small crabs (Figure 4). Despite the overall increase in crab abundance, the biomass of crabs of both sexes >114 mm is estimated to be down by 27% (Figure 4), and this decline is primarily the result of a 42% decline in large males >114 mm (Figure 4).

The red crab fishery currently harvests crabs substantially smaller than what was considered marketable in 1974 (114+ mm). Therefore estimates of the biomass of crabs 114+ mm were compared to the estimated biomass of crabs currently vulnerable to the fishery based on fishery selectivity during 2003-2005 (see ASMFC 2006). Despite the estimated decline in very large males, under the current fishery, the biomass of fishable crabs is estimated to be about 5% higher than it was in 1974, although this value falls within 1SE of the 2003-2005 mean (Figure 4).

The depth distribution of red crabs during the 2003-2005 surveys (all sectors combined) was considerably different than in 1974 (Figure 5). In the 2003-2005 surveys, crabs of all sizes were estimated to be somewhat less abundant in the shallow zones, but considerably more abundant in the deeper zones (Figure 5, top). Commercially harvestable males, both by the 1974 standard (114+ mm) and currently fishable standard, were estimated to be considerably less abundant in the shallower zones while their biomass was higher in deeper zones (Figure 5, middle & bottom panels).

Red crab distributions by sector, combining all depths, were also somewhat different than in 1974 (Figure.6). In the recent surveys total crab biomass was estimated to be considerably higher in all sectors except B, relative to 1974 levels (Figure.6 top). The biomass of the larger males (114+ mm) was estimated to be below 1974 levels in all sectors except in D (Figure 6 middle). The biomass of fishable males was about twice 1974 levels in sectors A and D, but fell below 1974 levels in sectors B and C (Figure 6 middle).

The biomass and distribution of reproductive male and female red crabs also appears to have changed since 1974 (Figure 7). For the purposes of this assessment the size of spawning females was defined as females equal to or larger than 70 mm CW based on observations of the smallest ovigerous females. In separate surveys the minimum size of ovigerous females has ranged from 61 to 80 mm (Wigley et al. 1975, Haefner 1977, Elner et al. 1987). Male red crabs may be physiologically mature at sizes less than 40 mm (Haefner 1977), but in camera surveys males observed in copulatory embrace have averaged about 50% larger in carapace width than females. This suggests males must be considerably larger than females to mate successfully. A previous report set the size of reproductive males at 75 mm (McElman & Elner 1982). This size designation seemed reasonable for the purposes of this stock assessment because it balances the uncertainty between physiological and functional maturity and is somewhat larger than the minimum spawning size used here for females.

The depth-wise pattern of spawning male and female red crabs (all sectors combined) has changed from the 1974 pattern in similar ways (Figure 7 top panels). Although the biomass of

spawning female and male red crabs is estimated to have declined from 1974 levels in the 175-225 fathom depth stratum, the biomass of spawning females is currently estimated to be substantially higher at greater depths (Figure 7).

Reproductive crabs were also compared across sectors by combining data from all depths (Figure 7 bottom panels). In all sectors the biomass of spawning females was estimated to be more than twice as high in 2003-2005 as it was in 1974. Differences in mature male biomass among sectors (Figure 7 bottom right) were similar to that for harvestable males (Figure 6 bottom): it was estimated to be lower than in 1974 in sectors B and C, but about twice as high in sectors A and D.

Taken together, while the targeted surveys indicate that the population of red crabs in the entire survey area is substantially greater than it was in 1974, there is evidence of depletion of large commercial size males, especially in the shallow strata and geographic sectors B and C which may be subject to most intensive harvesting.

- **Objective 2: Sampling the Commercial Catch**

Size frequencies of all male red crabs from both sea and port samples were plotted together for comparison (Figure 8, top). Female size composition data were plotted separately (Figure 8, bottom). The data show that proportions of small male red crabs were higher in sea samples than in landings.

Based on visual inspection of the size composition data, male crabs smaller than 90 mm were assumed to be discarded. From 90 mm to 95 mm, half of the males in sea sample size composition data were assumed discarded. All females were assumed discarded. The potentially discarded and kept portions of the sea sample catch were converted from numbers to weight using sex-specific size-weight relationships (Farlow, 1980 cited in Steimle et al. 2001) so that discard ratios could be calculated in terms of numbers and weight. The potential discard ratios were calculated as discard divided by the total catch (males plus females).

- **Objective 3: Tagging**

During the project we tagged some 9600 crabs of which some 280 have been recaptured and reported to date, mostly by the processor in Canada, but also directly by the vessels in the fishery. There has been little evidence of growth among recaptured crabs, suggesting very slow growth rates among the crabs tagged to date. This is consistent with slow growth rates observed in other species of deep sea red crab (Melville-Smith 1987). Laboratory studies we conducted indicate very low rates of tag loss or mortality.

Based on a sample of 87 crabs for which geograophic positions were available at release and recapture, on average, crabs moved 0.03 km per day. Days at large ranged from 18 to 896 days. This limited data set suggests crabs on average do not move much more than tens of meters per day. Because of the great depths (hundreds of meters we have a limited ability to resolve movements at a finer scale. The movement data await a more thorough analysis.

- **Objective 4: Stock Assessment Modeling**

With initial support from Saltonstall-Kennedy Program progress was made in developing three different modeling approaches: (a) a length-structured yield-per-recruit model, (b) a production model, and (c) a length-structured model. The length-structured model has been developed. The model is implemented in an Excel worksheet to facilitate the easy use and understanding. The production model has also been developed. It is also implemented in Excel for easy use. In addition to the above three models defined in the original proposal, we have also developed an egg per recruit model, which has been implemented in an Excel worksheet.

With the termination of S-K Program and no other support, further progress on stock assessment modeling was limited. However, progress and utility of any of these models largely

depends on having accurate growth information. Growth modeling derives from a von Bertalanffy growth function. With that equation we have developed two approaches to estimate the growth transition matrix. One approach is a Monte Carlo simulation; the other is a less straightforward analytic approach. We have developed an approach to estimating a growth transition matrix which describes the probability of a crab in a given size growing into other size classes or staying in the same size class in a given year. The growth transition matrix is essential in a length-structured population model, which is in the advanced state of development. The growth transition matrix can be easily updated as new data arrive from continued tag returns and future projects. All the worksheets that have been developed are available from the PI upon the request.

Conclusions About Stock Status

The following paragraphs are excerpted from the recent red crab stock assessment report (ASMFC 2006) to which this project contributed:

As determined by the Stock Assessment Review Committee, 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 pat 30 yr 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).

Camera/bottom trawl surveys directed at red crab and carried out during 1974 and 2003-2005 are the main source of information about biomass. Biomass of female red crab increased during 1974 to 2003-2005. Total biomass of male and female red crab 114+ mm CW was 25,900 mt during 1974 and declined by 27% to 18,990 $\pm$ 2160 (1SE) mt during 2003-2005. Average biomass of male red crab large enough to contribute to the fishery during 2003-2005 was more than one-half of the level observed in 1974. Biomass of male red crab 114+ mm was 23,794 mt during 1974 and declined by 42% to 13,769 $\pm$ 1334 during 2003-2005. Fishable male biomass (which includes all sizes available to the recent fishery) was 34,264 mt during 1974 and increased by 5% to 36,253 $\pm$ 5459 mt during 2003-2005. Biomass of red crab $\geq$ 114 mm CW decreased while fishable biomass increased because small red crabs which contribute to fishable biomass were abundant during 2003-2005. Small red crabs are abundant suggesting good recruitment, although this may be due to higher probability of detection for small red crabs in the 2003-2005 surveys.

Landings Per Unit Effort (LPUE) and fishing effort were stable during 2001-2005. Landings fluctuated without trend during 1982-2005 and were stable during 2001-2005. Regulations preclude landing female red crabs but discard mortality may occur. Fishery size data show declines in the proportion of large male red crabs which are targeted by the fishery.

The fishery during 2003-2005 targeted smaller red crabs than during the 1970's when most of the landings consisted of red crabs 114+ mm CW. During 2003-2005, median size of male red crabs were fully available to the fishery was 92 mm CW.

Fishing effort (number of vessels and total days fished) is effectively controlled by a limited entry program but latent effort exists because current days at sea allocations (DAS) have

not been fully utilized. The fishery is managed under a target TAC that has not been reached in recent years.

Red crab catches have been fairly stable in bottom trawl surveys directed at groundfish and shrimp. Survey size data show evidence of reductions in the relative abundance of large male red crab.

Based on the ratio of landings and fishable biomass, average ($\pm$ 1SE) fishing mortality is estimated to be 0.055 + 0.008 y^{-1} during 2003-2005. These estimates do not consider potential mortality due to discard of undersized male or female red crabs, which are protected by regulations. Discard of undersized males and females are likely substantial but discard mortality rates are uncertain.

Discards consist of female crabs (which can not be landed by regulation) and male crabs too small to sell. Comparison of port sample data and sea sample data from one vessel during 2004-2005 suggests that discard levels for males and female red crab average about 29% of total catch weight. VTR data are harder to interpret but indicate discard levels of 32 to 35%. Mortality rates for discarded red crab are unknown.

As currently defined in the FMP, overfishing is not occurring because landings of male red crab during 2003-2005 were 2013 mt, which is less than an estimate of MSY (2670 mt) from the last assessment (Serchuk 1977). However, the MSY estimate is based on an assumption that the natural mortality rate M=0.2 y^{-1}, which is probably unrealistic, and a stock assessment method which is more applicable to short-lived productive fish stocks. If red crabs are long-lived, then the estimated MSY level may be misleading and the stock is likely to be less productive than expected.

Stock status relative to biomass thresholds and targets is unknown because biological reference points have not been defined. Biomass during 1974 was probably near virgin biomass. If B_{msy} is one-half of virgin biomass, then current biomass exceeds B_{msy}.

Project Significance

The significance of this project is that co-operative research enabled the collection of the first demographic information of the deep sea red crab in three decades. Data were directly comparable to those collected in earlier NMFS surveys conducted in the 1970s when New England red crab were essentially unexploited. Further, this project informed the stock assessment conducted in spring 2006, and thereby provided current information upon which to base future management decisions and research recommendations.

Partnerships

This was a fisherman initiated project that addressed a problem of keen interest to the fishing industry and NMFS fisheries managers alike. The investigative team included two scientists (Wahle and Chen) and one member of the fishing industry (Williams). The partnership represents complementary skill sets: Wahle's expertise in the design and execution of benthic surveys and experiments, Chen's expertise in population dynamics modeling, and William's expertise in the red crab fishery and vessel operations. Extending beyond the three partners are scientific staff and other members of the fishing industry from boat crew members to processors who have helped with various aspects of the study. Wahle joined the NEFMC Red crab Plan Development Team in 2004. Wahle also led the writing of the red crab stock assessment report (ASMFC 2006). The team worked closely with NMFS and NEFMC staff (Larry Jocobson [NMFS], Jim Weinberg [NMFS], and Deirdre Boelke [NEFMC] to assemble the report.

Impacts and Applications

End users of the project are the red crab fishing industry and fishery managers at NMFS and the New England Fishery Management Council. The primary aim is to establish a stock survey methodology to be carried forward by the industry and managers after this project is completed. The current federal fishery management plan (FMP) implemented prior to these surveys is based on very little biological knowledge of this species. In terms of deliverables, this project contributed substantially to the 2006 Red crab Stock Assessment which should inform future FMPs. The project piloted a sea sampling methodology that can be continued by the crew members contingent on industry and NMFS support. The project has also resulted in the development of three stock assessment models that await further parameterization and testing. The stock assessment committee decided that it would be premature to employ these models in the current stock assessment. These models are available from Dr. Chen. Further research should focus on gathering information needed for model parameterization.

Related Projects

The project was jointly supported by the Northeast Consortium, Saltonstall-Kennedy Program, Maine Sea Grant, Coastal Enterprises, Inc. (CEI) and the red crab industry.

NOAA's National Undersea Research Program (UConn) and NMFS provided in-kind contributions of equipment.

NEC also provided supplemental support in 2003 to evaluate two different trawl designs for sampling red crab.

During several cruises collections of deep sea shrimp, *Pleoticus* sp., were made for Dr. Hans Laufer (U.Conn) for a Sea Grant Development Project (June 2004).

Presentations

Wahle, R.A. Red crab Progress Report to New England Fishery Management Council Red crab Plan Development Team. Aug. 6, 2004.

Wahle, R.A., Y. Chen. Hosted initial meeting of red crab Stock Assessment Team at Bigelow Lab to organize for the 2006 stock assessment, April 2005

Williams, J. Participated in panel on cooperative research at the Maine Fishermen's Forum, March 2005

Wahle, R.A. Presentations at several red crab SARC meetings, March, April, June 2006.

Bergeron, C., R.A. Wahle, J. Williams, M. Dunnington, Y. Chen. "New England Deep-sea Red Crabs after a decade of harvesting" (poster), NEC Participant Meeting, 2005, Portsmouth, New Hampshire.

Bergeron, C., R.A. Wahle, J. Williams, M. Dunnington, Y. Chen. "New England Deep-sea Red Crabs after a decade of harvesting: Consequences to reproduction?" (oral presentation), Benthic Ecology Meeting, March 9-11, 2006, Quebec City, Quebec, Canada.

Wahle, R.A., J. Williams, Y. Chen. Developing stock assessment methods for the New England deep sea red crab. NEC Participants Meeting. Portsmouth, NH. Dec. 2006.

Student Participation

Participating Graduate Students:

Shelly Tallack, University of the Shetland Islands, UK (April-Sept, 2002)
Curtis Brown, Univ. Maine (June 2004)
Hua Bai, Univ. Connecticut (June 2004)

Participating Undergraduates

Elizabeth Perry, U. Mass. Dartmouth (May – Sept, 2002)
Lindsay Routt, Oregon State Univ. (May – Oct, 2003)
Tom Langley, Rutgers (May 2004 – Dec. 2004, May 2005 – Nov. 2005)
Rich Crowley – Colby College (May 2005 – Oct.2005)

Published Reports and Papers

Wahle, R.A., J. Williams, Y. Chen. 2004. Saltonstall-Kennedy completion report, submitted in Feb. 2004.

Atlantic States Marine Fisheries Commission (ASMFC). 2006. Assessment of deep sea red crab, *Chaceon quinquedens*. 43rd Stock Assessment Workshop. May 22, 2006.

Wahle, R.A., C. Bergeron, Y. Chen. In prep. "New England Deep-sea Red Crabs after a decade of harvesting: Consequences to reproduction?" to be submitted to *Fisheries Research*

Images

A selection of digital photos will be provided.

Future Research

Below is an abbreviated list of research recommendations identified during the red crab stock assessment (ASMFC 2006).

- Develop a better understanding of the reproductive cycle, maturity schedule, fecundity of the deep sea red crab, and particularly the reproductive consequences of depleting large males.
- Develop a better understanding of the growth rate and molt cycle of red crab.
- Examine red crab sex ratios: can they be standardized by depth so that comparisons can be made from year to year and changes in the ratio tracked?
- Information on larval supply, transport, settlement and early juvenile distributions and abundance would contribute to an understanding of recruitment processes.
- More detailed bathymetry of the continental slope would be beneficial to an understanding of this and other deepwater species.

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Table 1. Distribution of camera (a) and otter trawl (b) sampling effort by Wigley et al. in 1974, and by Wahle et al. in 2003, 2004, and 2005. Strata as defined by Wigley et al. (1975).

A. Camera Survey - Number of tows

1974 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	1		3	2	6
175-225	320-412	3		2	2	7
225-275	412-503	1	2	3	2	8
275-350	503-640	1	1	4	0	6
350-500	640-914	1		2		3
500-700	914-1280	1		1		2
700-900	1280-1646			1		1
2003 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	1	1	1	1	4
175-225	320-412			1		1
225-275	412-503	1	2	1		4
275-350	503-640		1		2	3
350-500	640-914	2	2	3	1	8
2003 August						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320			1	1	2
175-225	320-412	1	1	1		3
225-275	412-503	2	2	1	1	6
275-350	503-640		1	2		3
350-500	640-914	4	2	1	2	9
2004 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	3	3	3		9
175-225	320-412	1		1	2	4
225-275	412-503	2	3	2	2	9
275-350	503-640	2			1	3
350-500	640-914	5	5	6	3	19
500-700	914-1280	3	3	3	2	11
2005 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	2	2	2	1	7
175-225	320-412	1	2			3
225-275	412-503		1	2		3
275-350	503-640	3	2	2	1	8
350-500	640-914	6	4	2	2	14
500-700	914-1280	3	3	2	1	9

B. Net Survey - Number of tows

1974 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	2	1	4	3	10
175-225	320-412	1	1	1	2	5
225-275	412-503	2	2	3	4	11
275-350	503-640		1	2	1	4
350-500	640-914	1	1	3	2	7
500-700	914-1280	1		2		3
700-900	1280-1646	1		2		3
2003 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	1		1	1	3
175-225	320-412		1			1
225-275	412-503	1	2	2		5
275-350	503-640		2	1	2	5
350-500	640-914	1		1		2
2003 August						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320			1	1	2
175-225	320-412	1	1	2		4
225-275	412-503	2	1		1	4
275-350	503-640	1	2	1		4
350-500	640-914	3	2	2	2	9
2004 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	3	3	3	2	11
175-225	320-412			1	1	2
225-275	412-503	2	2	2	2	8
275-350	503-640	2	2	2	3	9
350-500	640-914	5	5	4	3	17

2005 June						
Depth(fath)	Depth (m)	A	B	C	D	All
125-175	229-320	2	1		1	4
175-225	320-412	1	2	2		5
225-275	412-503	3	1	2	2	8
275-350	503-640	1	3	2		6
350-500	640-914	4	4	4	2	14

Table 2. Specifications for sleds, cameras and nets used in the surveys conducted in 1974 and in 2003-2005.

	Wigley et al.	Wahle et al.
Sled		
Length	2.7 m	2.1 m
Width	2.1 m	1.2 m
Height	1.9 m	1.5 m
Material	6.4 cm steel tubing	10, 5, & 2.5 cm steel tubing
Weight	1225 kg	363 kg
Camera System		
Camera		
Type	Film	Digital
Manufacturer	Hydroproducts	Engage Technologies
Make	DeepSea Photo Cam	SeaSnap
Model	Model PC705	Nikon CoolPix 995, DigiSnap 2000
Strobe		
Manufacturer	Hydroproducts	Benthos
Make	DeepSea Strobe	DeepSea Strobe
Model	Model PF730	Model 382
Medium	Kodak Ectachrome EF	Digital 2048x1536 pixel
Camera Setup		
Height off bottom	1.7 m	0.92 m
Angle of camera	16 deg	35 deg
Shot interval	10 sec	15 sec.
Tow Duration	30-75 min	30-45 min
Approx. number photos	400	120-260
Total area covered by photo	148 m^2	10 m^2
Effective (illuminated) area sampled	31.8 m^2	6.6 m^2
Trawl Net		
Type	semi-balloon otter trawl	semi-balloon otter trawl
Length	4.9 m	6.2 m
ground rope	5.8 m	7.3 m
wire extension pieces	4 m	3.7 m
mesh of wings	No. 9 thread, 3.8 cm stretched measure	No. 7 thread, 3.8 cm stretched measure
mesh of body	No. 9 thread, 3.8 cm stretched measure	No. 7 thread, 3.8 cm stretched measure
mesh of cod end	No. 15 thread, 3.2 cm stretched measure	No. 15 thread, 3.2 cm stretched measure
codend liner	NA	12 mm
tow speed	1.5 - 2 knots	1.5 - 2 knots
tow duration	15 or 30 min	27 - 45 min

Table 3. Survey stratum areas in hectares (ha) by depth as calculated from Wigley et al. (1975).

Area by Depth (ha)					
Depth (fath)	A	B	C	D	All
125-175	30310	17803	55000	39109	142,222
175-225	43800	26996	75300	64100	210,196
225-275	23401	17200	37300	26501	104,402
275-350	44502	28301	62600	28901	164,304
350-500	65599	47827	63703	56836	213,491
500-700	121704	60442	77995	90025	350,166
700-900	124037	54679	67523	113028	359,266

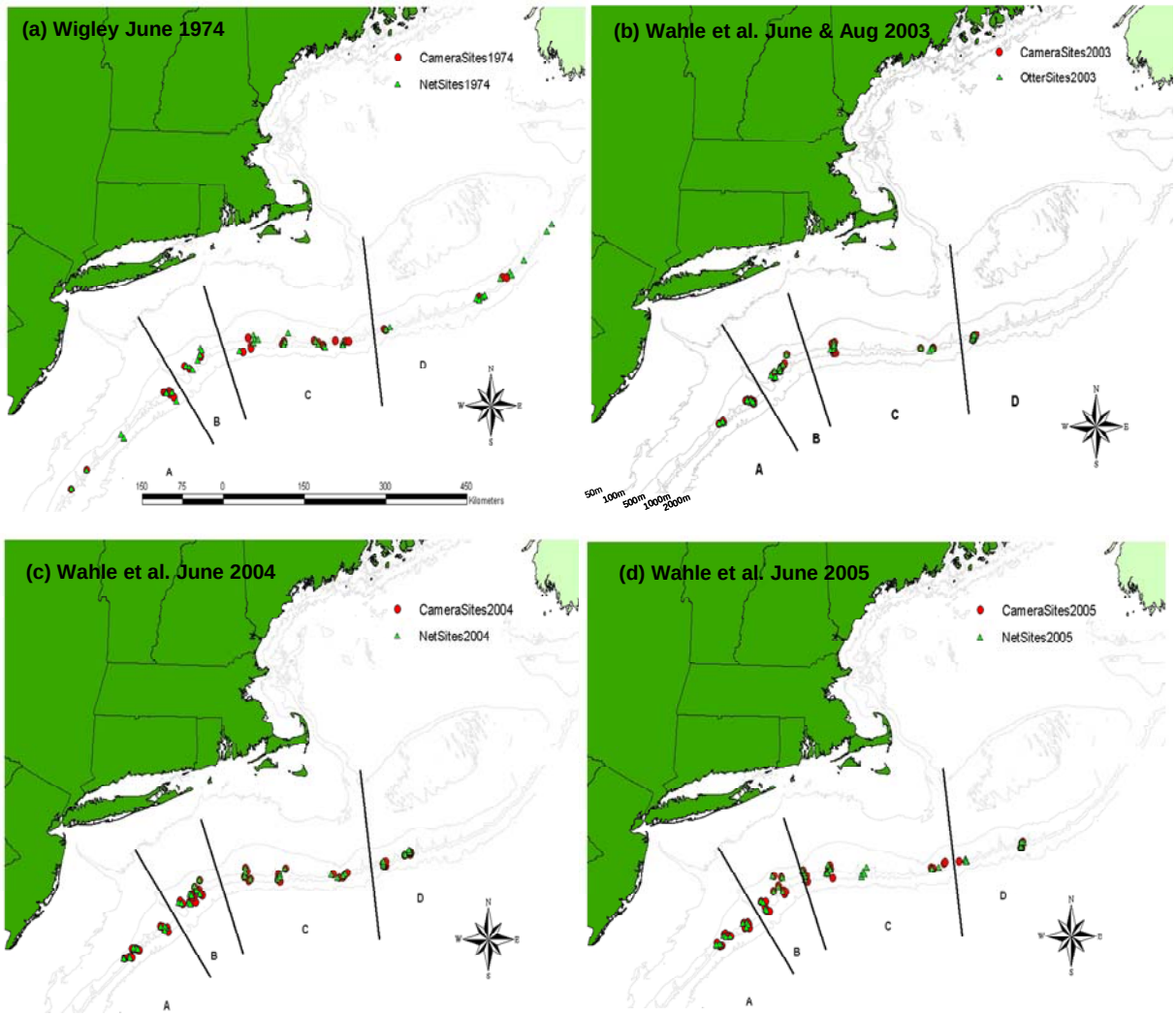

Figure 1. Locations of net and camera tows during the (a) Wigley et al. surveys conducted in 1974 and (b-d) Wahle et al. surveys conducted in 2003-2005.

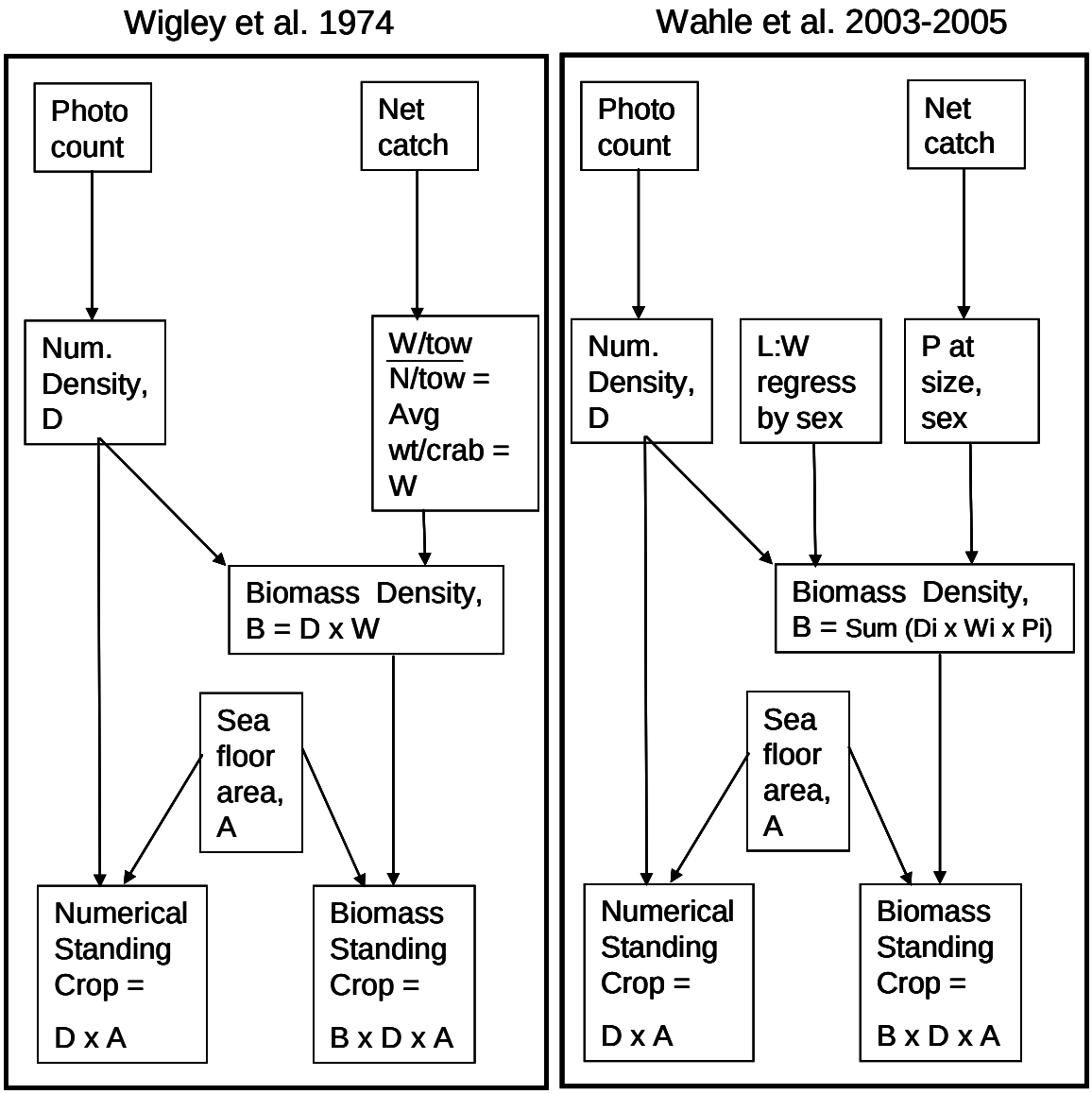

Figure 2. Comparative overview of 1974 (Wigley et al.) and 2003-05 (Wahle et al.) camera and net survey method to estimate standing crop.

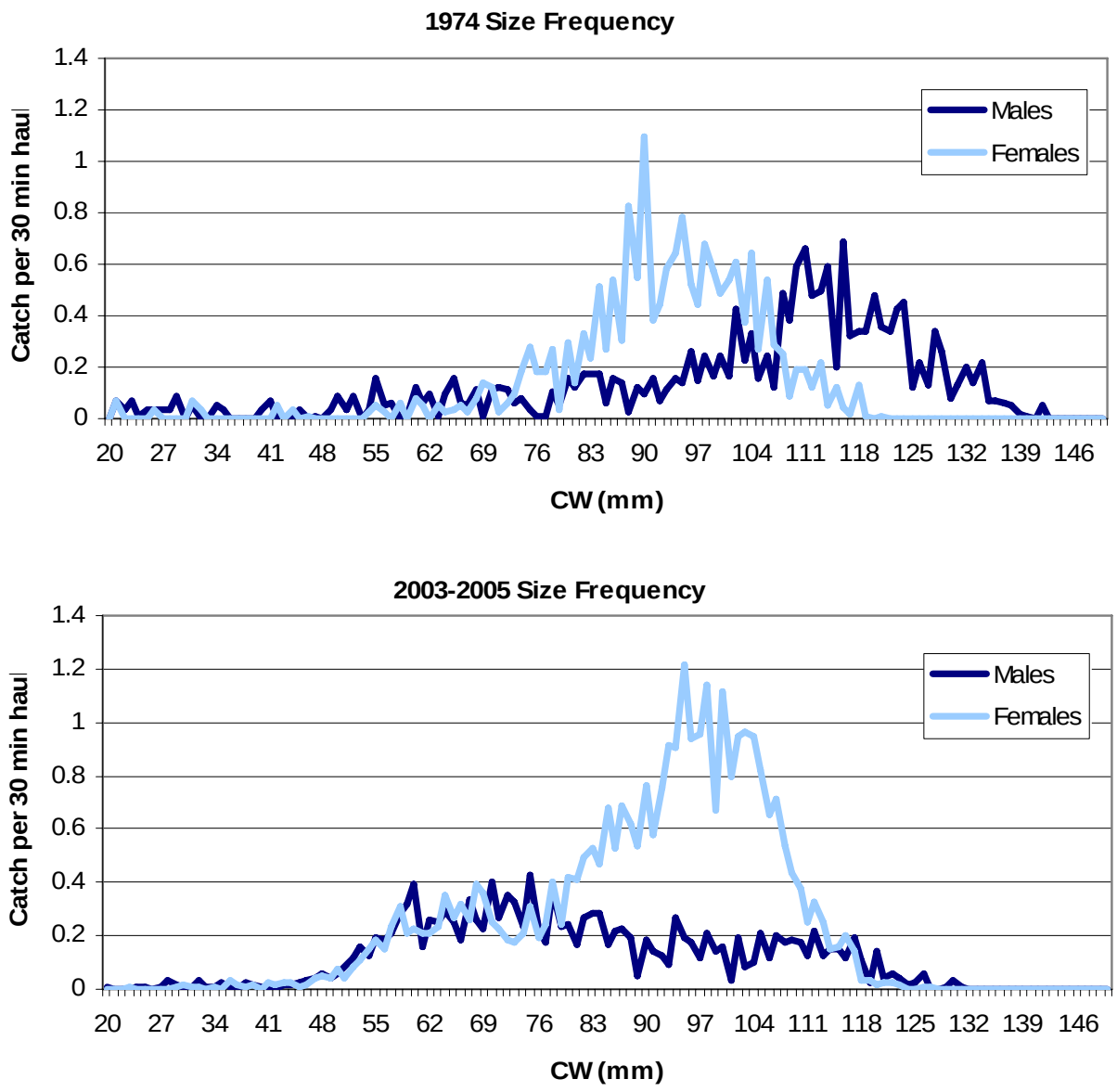

Figure 3. Red crab size and sex composition in the 1974 and 2003-2005 otter trawl samples during camera/trawl surveys standardized to catch-per-30-minute-tow, tows from all depths and sectors combined. Vertical line indicates "commercial" size as defined in Wigley et al. (1975): crabs ≥114 mm carapace width. The 1974 size distribution is represented by 641 male and 795 female crabs; the 2003-2005 distribution, 2209 male and 4602 female crabs. Complete size-sex composition by depth and sector is tabulated in Appendix D3 of the Stock Assessment Report (ASMFC 2006).

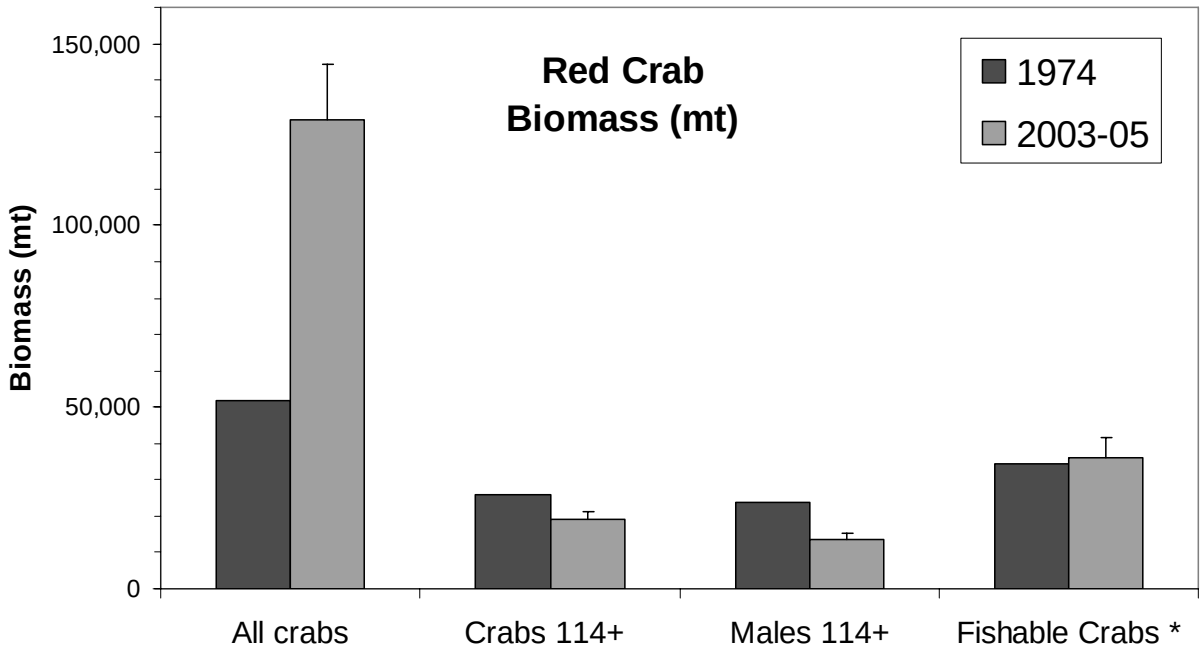

Figure 4. Red crab standing biomass (mt) estimates for 1974 and the mean (+1SE) of four surveys conducted between 2003 and 2005. Estimates for 2003-2005 represent the mean (+1SE) of four surveys conducted over that period. No error term is available for the 1974 estimates. * Biomass of fishable crabs determined from fishery selectivity analysis (section 7.1 of the Stock Assessment Report (ASMFC 2006).

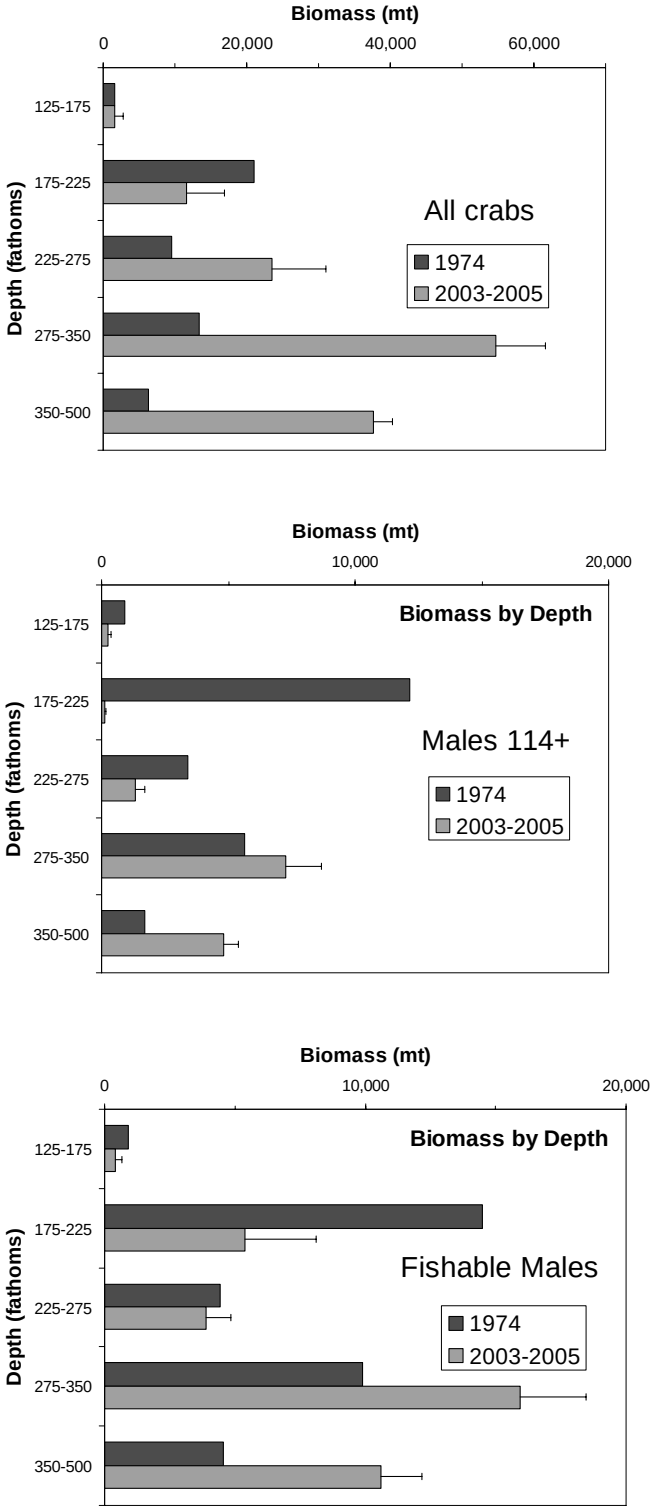

Figure 5. Red crab biomass by depth in 1974 and 2003-2005. All crabs (top), males 114+ mm (middle), and currently fishable males (bottom). Estimates for 2003-2005 represent the mean (+1SE) of four surveys conducted over that period. No error term is available for the 1974 estimates.

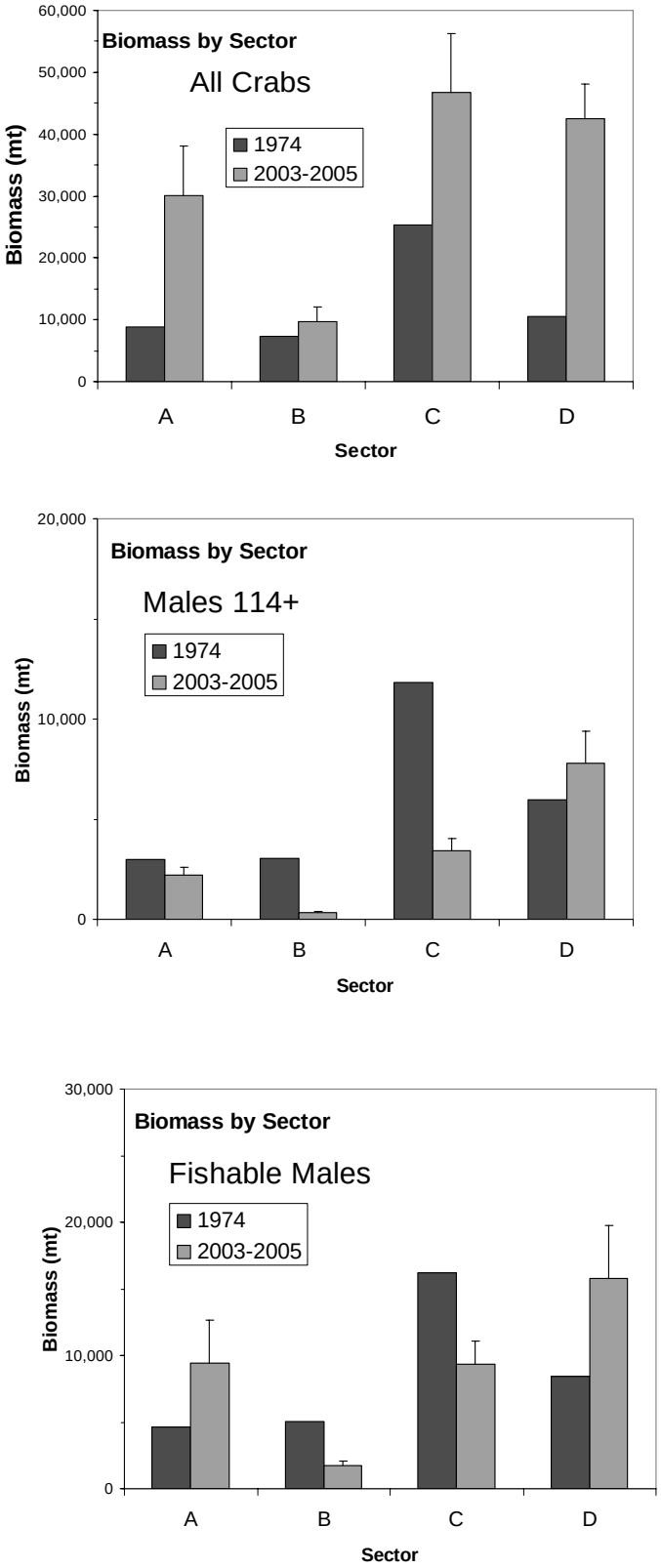

Figure 6. Red crab biomass by sector in 1974 and 2003-2005. All crabs (top), males over 114+ mm (middle), and currently fishable males (bottom). Estimates for 2003-2005 represent the mean (+1 SE) of four surveys conducted over that period. No error term is available for the 1974 estimates.

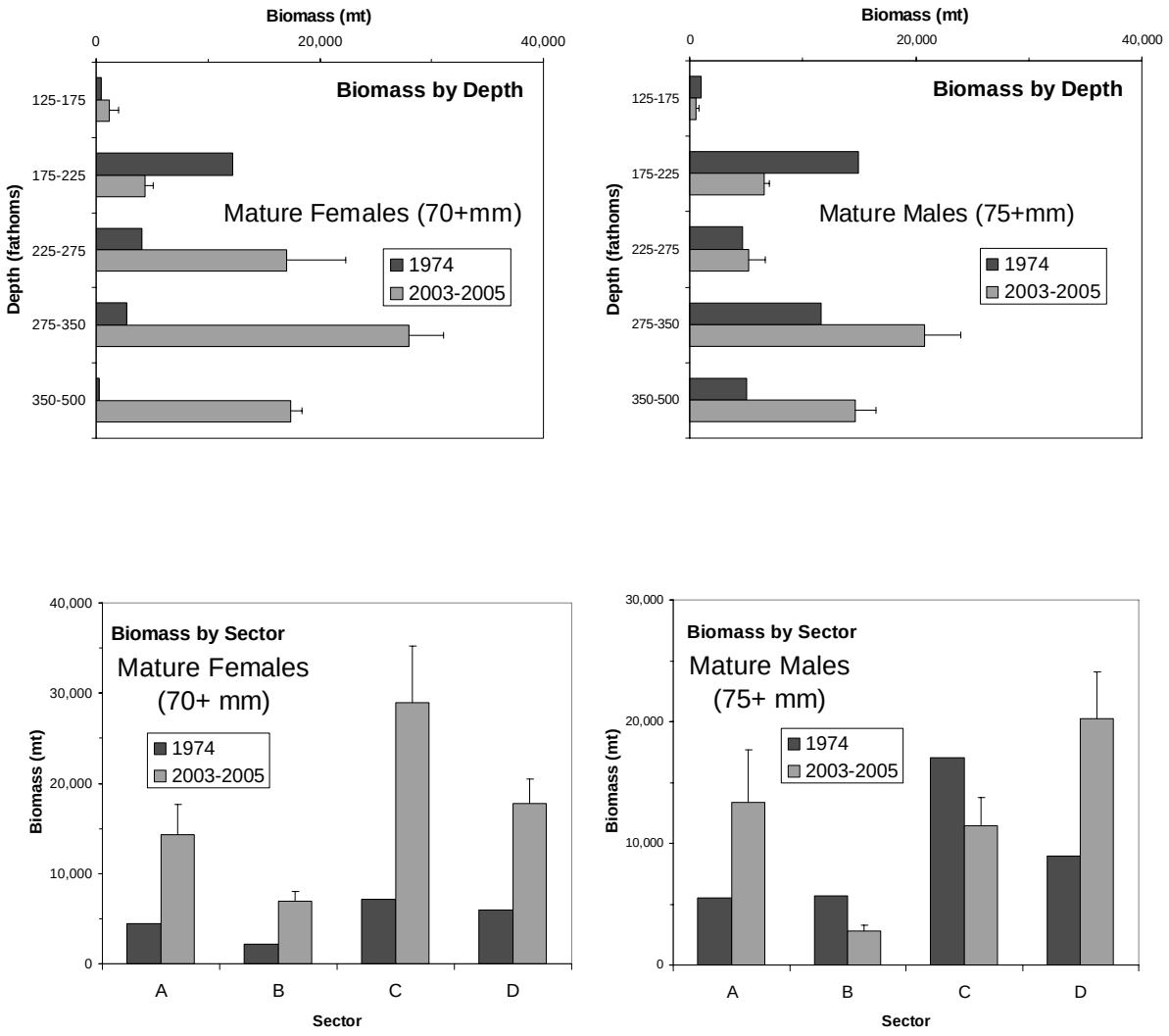

Figure 7. Biomass estimates of reproductive males (75+ mm) and females (70+ mm) in 1974 and 2003-2005 by depth stratum and geographic sector. Estimates for 2003-2005 represent the mean (+1 SE) of four surveys conducted over that period. No error term is available for the 1974 estimates.

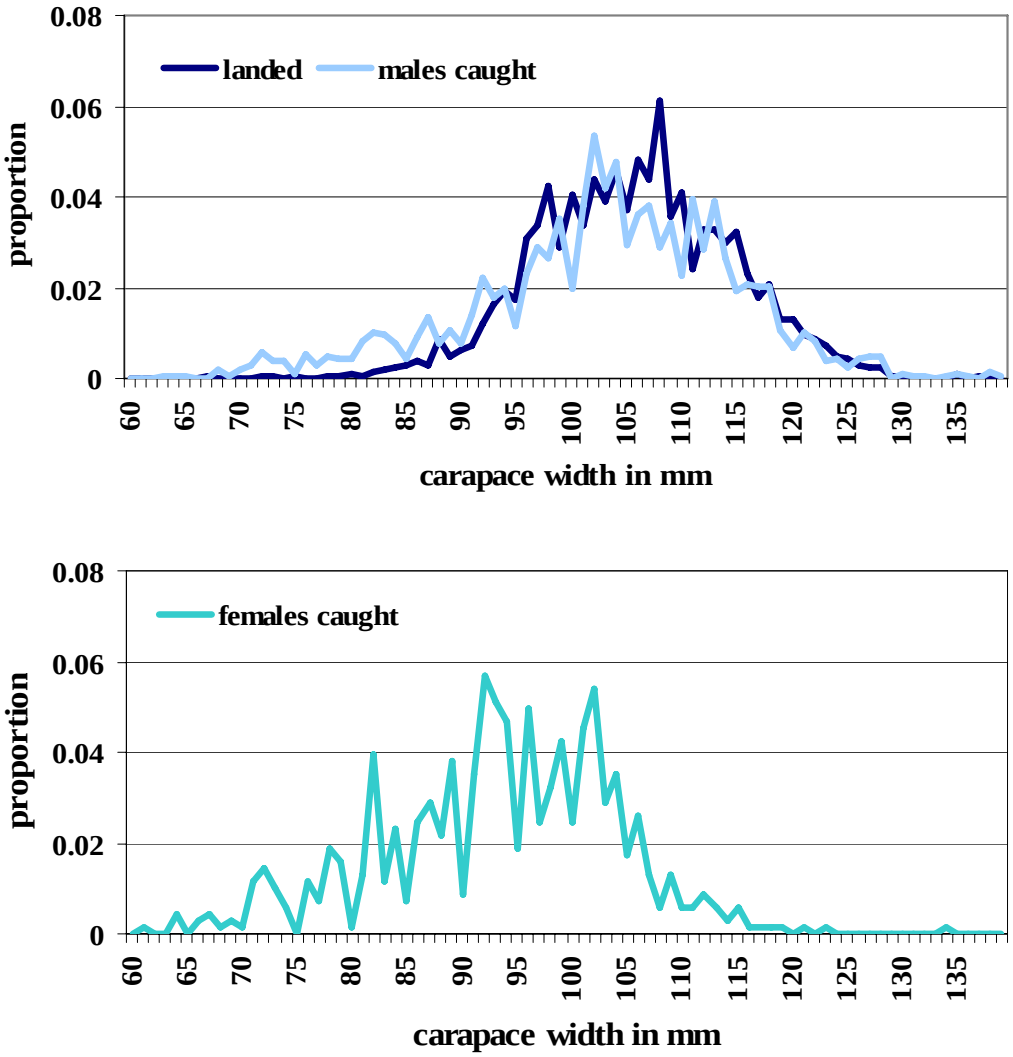

Figure 8. (A) Red crab length composition data from port samples (only males are landed) and sea samples (males only). (B) Length composition data from sea samples, females only. All crabs were caught during 2004-2005 in survey strata A, C and D over a range of seasons.