Conclusions

There will always be uncertainty regarding abundance estimates from the 1974 deep-sea red crab survey because technical details are not available in Wigley, Theroux, and Murray (1975; hereafter Wigley et al., a paper with results and analysis of the 1974 red crab survey) and because data from only three stations were analyzed statistically by Patil, Taillie, and Wigley (1979; hereafter Patil et al., a book chapter entitled “Transect sampling methods and their application to the deep-sea red crab”). However, we conclude that the exponential visibility function and area compression effects described in Patil et al. were probably accounted for in the adjustments made by Wigley et al. when converting the number of crabs visible in a photograph to an estimate of crabs present in the theoretical searched area. This conclusion is based on facts including the consistency of expansion factors for counts in Wigley et al. and Patil et al., and our estimates of illuminated area.

Patil and Wigley collaborated on the Patil et al. paper, so they knew each other and worked together in the 1970s. Wigley and his co-authors were well respected and skilled field biologists, but probably did not have the mathematical and statistical training to carry out calculations like those in Patil et al. Therefore it is possible that Wigley et al. discussed transect sampling methods they could use for their survey with Patil, as they were likely thinking about their respective projects about the same time. Patil et al. was published in 1979, four years after Wigley et al., but this is not unusual as survey results need to be published quickly for management purposes, and an academic paper using results from that survey might be expected to take longer.

From Wigley et al. (p. 4), “Standard coefficients of diminished visibility of organisms, based on the square of the distance from the camera, were derived from a random sample” suggests that a mathematical approach based on relative light intensity (which attenuates as a function of distance squared) was used to adjust raw counts from the 1974 red crab survey. However, there is no mention of area compression, evidence of experiments to calculate the probability of detecting red crabs as a function of light intensity, nor experiments to measure light intensity under field conditions. We therefore interpret the quote above as a general statement about the role of diminishing light intensity in detecting red crabs during the survey.

There are several sources of potential bias in Wigley et al.’s camera sled estimates that were not quantified, including potential red crab avoidance behavior and changing angles of the sled – therefore the source of illumination – due to uneven bottom. The precision of the adjustment factors used in Wigley et al. is unknown. The use of a random sample implies that one set of adjustment factors was used for all tows, but the number of randomly sampled stations or images used to estimate the adjustment is not recorded in Wigley et al. It is possible that the sample of three stations used in Patil et al. is all of the data used to estimate the adjustments.

Sensitivity analysis suggests that avoidance behavior may have biased Wigley et al.’s density estimates. However, results of the analysis show the direction of the potential bias depends on how the crabs respond to the passing sled based on their distance from it.

Introduction

In the early 1970s, as the fishery for deep sea red crab (*Chaceon quinquedens*) was developing off the east coast of the United States, there was a need to determine the size and condition of the stock (Serchuk 1977). To address this need, the Northeast Fisheries Science Center conducted the first survey to estimate abundance of red crabs by photographing and counting them *in situ*. The apparatus housing the underwater camera, called the Towed Underwater Benthic Sled (TUBS) IV, was towed over the ocean floor on large runners that allowed it to ride over bumps and sand waves (Figure 1). A camera and strobe were mounted facing out from the side of the sled, and non-overlapping photographs of the bottom were every taken every ten seconds (Figure 2). Between camera sled tows, an otter trawl was deployed to catch red crabs for determination of size composition and sex ratio. The crabs in the photographs were assumed to have the same characteristics as the crabs caught in the nearest trawl.

The otter trawl and camera tow stations were distributed randomly within the narrow band (229-1,280 meters in depth) of red crab habitat at the edge of the continental shelf, where the bottom drops off steeply (Figure 3). The survey area was divided into four latitudinal regions with seven depth classes within each latitudinal zone, for a total of 28 subareas or strata. Overall density estimates were means of individual strata weighted by stratum area. Overall, 33 successful camera sled tows and 43 otter trawl tows were made during the survey (Table 1). From the number of crabs counted in the photographs, Wigley et al. estimated there were 59 million pounds of commercial-sized (in 1974, this was considered >114 mm carapace width) male red crabs in the surveyed area.

According to Wigley et al. (p. 4):

> "To maximize the accuracy of information acquired from the photographic enumeration, only the best-lighted area nearest the camera in individual photographs, which represented a bottom area of 31.8m^2, was examined and the faunal components counted. All areas darkened or obscured by sediment clouds and other factors that obscured the view were deducted in determining crab density. Standard coefficients of diminished visibility of organisms, based on the square of the distance from the camera, were derived from a random sample."

Details concerning the 31.8 m^2 figure (used to convert counts to density and abundance) were not provided by Wigley et al. In addition, the coefficients of visibility and the manner in which they were used were also not discussed. Thus, the steps taken to convert the number of crabs counted in the photographs to a biomass estimate were not known well enough to check or completely understand Wigley et al.'s results. It was important for us to try and reduce the uncertainty because Wigley et al.'s biomass estimates for 1974 have been, and will be in the future, a central part of the assessment of deep sea red crab (NEFSC 2006).

We wanted to gain a more complete understanding of how the 1974 density estimates were derived and reduce uncertainty about the 1974 survey for future users of these important assessment data. This brief report details our effort to clarify how the numbers of crabs seen in the images from the 1974 survey were transformed into density estimates based on data obtained from the original photographs, handwritten notes by the authors, and related papers.

Materials and methods

In 2008, after the death of Roger Theroux (one of Wigley et al.'s co-authors), the original photographs from the 1974 camera survey and a folder of notes and drawings by the authors (which he had stored at his house) were donated to the Northeast Fisheries Science Center (NEFSC). The NEFSC received 48 film canisters each containing a spool of film from a single tow during the 1974 survey. For the majority of the tows the camera on TUBS IV used color transparency film, which when developed yielded a strip of positive 70mm images. In 1974, the images on these strips were projected one by one onto a white background so red crabs could be counted for abundance estimates (Roger Theroux, pers. comm.). We scanned each individual 70 mm image at a resolution of 800 pixels per inch, which allowed us to enlarge each digital image to about 21 x 24 cm while maintaining the clarity of the original photograph. These images would allow us to determine the number of crabs visible in the photographs upon which the density estimates in Wigley et al. were based.

Wigley et al. used only 33 out of the 48 tows to estimate the density of red crabs; the other tows were not useful because the sled was apparently not upright on the bottom (Table 2). Most of the tows used for the density estimates had a few images that were considered unacceptable for analysis due to plumes of silt or extreme angles of the sled. Each useful image was darkest in the distance at the top of the photograph with a pool of light (illuminated area) from the strobe front and center (Figure 2).

The Patil et al. paper was another important source of information, as it describes a transect survey method appropriate for partially illuminated habitats and uses some of the red crab camera sled survey data to provide examples. Patil et al. describe methods for adjusting density estimates to account for diminished visibility with distance and the compression of area viewed with distance, using the data from three red crab survey tows (stations 16, 21, and 67) as an example. In particular, Patil et al. demonstrate methods for calculating the area covered by a photograph of the bottom, and the visibility function which incorporates all the properties of the photograph when used to adjust numbers of targets seen in only the illuminated area. The area of the bottom covered by each photograph (effective area) and visibility function are closely related, because a raw density estimate *D*=number counted/area searched can be corrected for both trapezoidal area effects and diminishing visibility by adjusting either the number of red crabs counted (visibility function) or area (effective area). Patil et al. discuss both types of adjustments from a mathematical and statistical perspective with more emphasis on effective area. We don't know if Patil et al.'s methods were exactly the same as used by Wigley et al., but the two analyses appear closely related. The last sentence in Patil et al.'s summary states that "Some of the basic mathematical concepts on which this [Wigley et al.'s] survey was based are analyzed and show the utility and limitations of the line transect method."

Patil et al. tested several model variants for visibility-distance effects, and concluded that an exponential model was the best overall approach for the red crab data from the three survey tows that they analyzed. Area compression effects are based on geometry and were modeled in the same manner for all cases. The exponential visibility function is $g(-\lambda; x) = e^{-\lambda x}$, where x is distance of the target from the sled and λ is an estimated parameter.

We checked the density estimates for the three survey tows in Patil et al. by recalculating them based on the published parameter values, and then by fitting the exponential model to re-estimate parameter values (Table 3). We were able to replicate Patil et al.'s density and other estimates using the published parameter estimates. However, when re-estimating parameters we found that Patil et al.'s estimates for Station 21 were incorrect because a different visibility parameter had a lower negative log likelihood. It is probable that the likelihood surface is relatively flat near the best solution and Patil's software stopped iterating before reaching the best estimate. We used the original published estimates when calculating an average adjustment factor below, since we wanted to attempt to reproduce the factor that was actually used, and not one that was technically correct based on current software capabilities.

The camera mounted on TUBS IV had three different "views" described in Wigley et al., Patil et al. and Theroux (1984). The "maximum area" is the area of the bottom of the ocean that would be visible to the camera (with its specific lens diameter and angle of view) under ideal conditions of illumination and clear water. Theroux (1984) states that the maximum "area viewed by the lens [of TUBS IV] was 147.3m^2 as determined by mock-up tests photographing grid patterns in the Benthos, Inc. testing pool, and by tests in Vineyard Sound." In Wigley et al., the "camera view" is a portion of this maximum area (determined by Wigley et al. to be 31.8 m^2) adjacent to the sled that more accurately describes the area the lens could view under field conditions. The "illuminated area" is the portion of the camera view where the strobe provides a pool of light within which red crabs can be seen. Wigley et al. calculated the number of crabs that would be expected to be in the camera view based on the number of crabs visible in the illuminated area. The illuminated area varied somewhat from image to image based on the angle of the sled, silt, sessile animals, topography, and other factors. In principle, crabs within the camera view not seen due to lack of light were accounted for on average using adjustment factors much like those found in Patil et al.

The camera view appears rectangular in photographs but actually covers a trapezoidal area of the bottom, because bottom area covered in photographs increases with distance from the camera (Figure 4). Regions of the ocean floor with equal area appear smaller in photographs as distance from the sled increases. Patil et al. divided the camera view into five zones of equal height but differing width. The zones appear compressed in photographs as distance from the lens increases (Figure 4). Patil et al. estimated different adjustment factors for each zone to predict the number of crabs within it based on the number of crabs that were visible and counted. The adjustment factors got larger with distance of the zone from the sled to account for both the increasing area covered and decreasing visibility. Zone one (the zone nearest the sled) was reduced to half the height of the other zones, as the plume of silt stirred up by the sled's runners obscured the bottom very close to the sled (Patil et al.).

Among the items in the folder of notes we acquired was a grid drawn on a 27 x 31 cm piece of cardboard depicting a view from a certain height and angle, presumably the height and angle of the TUBS IV camera (Figure 5). There were also transparencies of this grid which may have been used in conjunction with the images projected for counting. Five zones of decreasing apparent size were colored in on the grid adjacent to the sled. These zones were likely the same as those in of Patil et al., each representing a zone of the photograph that has the same height and a larger width but appears to be of diminishing size with distance from the camera, as in Figure 4. The annotation "31.8 m^2" on the drawing appears to be the camera view area covered by these five zones adjacent to the sled (after removing half of the area in zone 1). The five zones do not cover the whole grid, and the annotation "147.3m^2" further away from the camera corresponds to the "area viewed by the lens [of TUBS IV]" during testing. The fact that Wigley et al. apparently used the same method of compressing the trapezoidal camera view into a rectangle as Patil et al. supports the idea that they used the same methods of adjusting the number of crabs as well.

We wanted to estimate the size of the illuminated area in each image to determine its relationship to the camera view, and to get an idea of the scale of adjustment that was made to transform the numbers of crabs seen in the illuminated area to an estimate of abundance for the whole camera view. Our grid, divided up into five zones of equal height, represented 31.8 m^2. At this point, we were working independently and not taking Patil's estimations of area for each of the five zones (Table 4) into account, as we were not sure they would be the same. Since we needed something to provide scale, we found 42 digitized images with an apparently medium-sized red crab near the front of the image and used the crab as a ruler. Depending on the skewness of the frequency distribution, we used either the mean or median carapace width (CW) of the red crabs caught at the nearest otter trawl station (Murray 1974) and assumed the CW of the crab in the image was that size. We then drew a digital line around the area determined to be illuminated enough to see red crabs (see the pool of light thrown by the strobe in Figure 2), then overlaid a transparency of the camera view grid onto the image. The assigned CW of the crab was then used to estimate the width of the illuminated area which fell into the nearest zone. For example, if the average crab from the trawl was 100mm CW, and the illuminated area within the first zone measured 15 crab widths, then the illuminated area was 1.5m wide nearest the camera and the size of a square in the grid could be estimated. Areas of illumination in subsequent zones were calculated using the grid squares, and all the areas were summed. The 42 estimates of illuminated area made using this rough method were 2 to 30 m^2 with a median of 10 m^2 (Figure 6). Thus, the illuminated area averaged about one third of the 31.8m^2 camera view.

To approximate the number of visible crabs Wigley et al. started with before applying conversion factors for density estimates, we counted all of the red crabs in the images for seven tows. The notes from 1974 included a table listing total number of frames (images), number of frames analyzed, area analyzed in hectares, and number of crabs per hectare for each camera sled tow (Table 5). Total number of frames was essentially the length of the film strip including both good and bad photos. Number of frames analyzed excluded those frames where the sled was not upright or plumes of silt obscured the majority of the bottom. Area analyzed in hectares was the number of frames analyzed multiplied by 31.8m^2, minus a small amount due to silt obscuring parts of images but leaving the rest usable. Number of red crabs seen per hectare was the total number of crabs visible and counted in all the images from the tow divided by the area analyzed. After some practice, we felt confident that we were seeing a large percentage of the visible crabs. We divided the total number of red crabs we had seen with the total area analyzed from the notes and obtained numbers that were usually only slightly different from the crabs per hectare written in the notes in 1974.

We used several approaches to understand the "coefficients of diminishing visibility" and adjustments for area compression in Wigley et al. Our red crab recounts did not include information about zone, but we could estimate an average coefficient for all zones combined by comparing raw density estimates from our counts (assuming 31.8m^2 search area) and the overall density estimate from Wigley et al. Wigley et al. reported abundance and biomass by subarea (combination of depth stratum and geographical zone with 1-3 tows in each, Figure 3). We calculated the mean number of crabs per hectare (weighted by area analyzed) from the tows within a subarea and computed area-weighted means for larger areas using Wigley et al.'s estimates of the number of hectares within each subarea. We found the published density estimates were 2.77 to 3.02 (mean 2.82, n = 18 subareas) times what they would be using only the number of crabs visible in the illuminated areas. These results indicate that Wigley et al.'s raw counts were adjusted upwards on average by about 2.8 to account for diminished visibility and increased area with distance (Figure 7). These conversion factors are plausible in view of the size of the illuminated area, which was about 1/3 as large as the camera view in our small sample of 42 images, implying an adjustment factor of at least three. The weighted visibility functions from Patil et al. for stations 16, 21, and 67 that include visibility and area effects were 5.48, 3.23, and 1.61, indicating that counts would be adjusted up by about 3.44 times on average. If the coefficients used in Wigley et al. were based only on the analysis of the three stations by Patil et al., the mean adjustment factor might have been slightly higher, but the numbers are close enough to indicate Wigley et al. were taking the same features into account when determining adjustment factors.

Discussion

The images from the red crab survey are of interest for other reasons than enumerating red crabs. We also observed cod, hagfish, monkfish, hake, skates, lobsters, anemones, cancer crabs, and sea stars when analyzing the images. The photographs also clearly show bottom type and structure, including burrows and craters made by various animals, and marks which look like those made by a bottom trawl. Both the original photographs and the digitized images are now part of the collection of the National Archives and Records Administration (www.archives.gov).

An enlightening aspect of reviewing the images from the 1974 survey was recognizing that the variation in size and shape of the illuminated area depended on the tilt of the camera sled, and realizing how often the TUBS IV was not upright. Several film canisters were marked "water shots only" or "tow entirely on side." The tilt factor would contribute to variation in raw counts of crabs and could even lead to overestimation. The illuminated area would be increased proportionally more if the sled was tilting away from the camera than it would be decreased if the sled were tilting the same amount in the other direction, due to the geometry of an oblique ellipse (illumination) contacting a plane (the ocean bottom).

It is also possible that crab abundance was underestimated if crabs moved away as the camera sled approached. Wigley et al.'s adjustments for diminishing visibility would have helped mitigate some of the effects of avoidance, but crabs are known to respond to light and vibration, although some individuals may have escaped detection entirely before the sled arrived at their location.

We were able to test the sensitivity of Patil et al.'s density estimates for stations 16, 21, and 67 to avoidance behavior under six assumed scenarios. We refit Patil et al.'s models and used the estimates as baselines for this analysis, rather than using Patil's original figures, for the sake of consistency and as a check on our own work. In the first four scenarios, the original red crab count data in Patil et al. were changed by increasing percentages of the observations originally in Zone 1 to Zone 2, originally in Zone 2 to Zone 3, etc., but without moving any red crabs out of the camera view area (zero crabs lost entirely). In Scenarios 5 and 6, we moved crabs as in Scenario 4 but with some crabs from Zone 5 moved completely out of the camera view area. The first four scenarios tested effects of movements entirely within the camera view area, while the last two tested effects of movements within the camera view area together with loss of crabs from the experiment (Table 3).

Sensitivity analysis showed that bias in Patil's model estimates is complicated and dependent on the behavior of the crabs. The magnitude of the bias depended on how quickly the raw red crab counts declined with distance from the sled in each scenario. Density estimates were biased low in Scenarios 1-4 by -1% to -24%. In these scenarios, avoidance behavior made crab counts in outer zones higher and counts in inner zones lower, indicating that visibility declined relatively slowly so that fewer crabs (lower density) were required to explain the observed data. In scenarios 4 and 5, density estimates for stations 16 and 67 were biased high by 4% to 26% respectively, while estimates for station 21 were biased low by about -18%. The positive bias for stations 16 and 67 occurred because the loss of crabs from Zone 5 exaggerated the effect of distance on visibility. Reduced visibility with distance translates into higher density estimates because more crabs are required to predict the observed data. For Station 21, the trends in counts for each zone indicated that visibility effects were weaker than they actually were.

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