Northeast Fisheries Science Center Reference Document 13-22

Clarification of Methods Used to Determine Deep Sea Red Crab (*Chaceon quinquedens*) Abundance from Data Collected during the 1974 Photographic Survey

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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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Table 1. Depth and location information for camera sled stations analyzed for red crab densities in 1974 and digitized in 2011. The beginning depth for station 67 is apparently an estimate.

Station	No. images digitized	Depth (m)	Start lat.	Start lon.	Comments
2	192	357-366	39°58.0	-70°59.0	
5	0	823-841	39°51.5	-70°59.0	B&W negative
6	218	1079-1097	39°49.0	-70°56.0	
7	0	1463-1463	39°46.0	-71°04.0	B&W negative
8	0	256-256	39°35.0	-72°02.0	B&W negative
10	358	454-476	39°33.0	-71°57.5	B&W negative
11	351	549-549	39°33.0	-71°57.0	
13	423	311-326	39°14.0	-72°23.0	
14	442	366-384	39°14.0	-72°21.0	
15	416	457-466	39°15.0	-72°18.0	
16	430	530-530	39°14.0	-72°16.0	
17	364	713-732	39°12.0	-72°16.5	
18	230	1051-1079	39°10.0	-72°13.0	
21	420	393-412	38°12.0	-73°39.5	
22	400	274-274	37°56.3	-73°55.5	
27	418	439-494	39°55.0	-70°23.0	
28	440	585-640	39°53.0	-70°25.0	
29	110	521-732	39°53.0	-70°23.5	
30	330	274-284	39°55.5	-69°32.0	
31	438	366-457	39°55.0	-69°22.0	
32	38	457-503	39°55.2	-69°22.0	
33	400	603-622	39°55.0	-69°18.5	
38	427	348-439	40°05.2	-68°43.5	
39	420	430-448	40°04.0	-68°41.5	
40	368	284-293	40°30.0	-68°08.5	
41	364	357-512	40°29.0	-67°08.5	
45	306	210-293	40°45.5	-66°45.5	
46	378	357-366	40°46.0	-66°41.0	
59	340	256-265	39°55.5	-69°53.0	
60	433	402-421	39°54.0	-69°48.5	60 and 60A combined
62	420	558-576	39°52.5	-69°44.0	62 and 62A combined
63	116	750-768	39°51.0	-69°44.0	
67	440	~412-960	39°43.0	-71°46.0	

Table 2. Digital scan of comments on each individual tow. The column "type" refers to the size of the film; either 35 or 70 mm. All the images used for estimating red crab density were 70 mm. "R.C." stands for red crab, "L" is for lobster and "J.C." is for Jonah crab.

1

Films Analyzed
Alb. IV - 74-7

STA.	Tow	Type	No. of frames	Comments
2	1	70		
3	1	35		Only 6 good shots in middle - no crabs.
3		70		Data card says 2A - No shots
3A	2	70		1 u.w. shot - no crabs - rest blank (side tow)
4	1	70		No shots - upside down?
6	1	70		OK
11	1	70		OK
12	1	35		No. shots
13	1	70		Good shots - Red crab - Lobster - Jonah crabs etc.
14	1	70		Very int. bottom disturbance
15	1	70		Good shots - R.C. - J.C. etc.
16	1	70		Good R.C. - Anemones (feeding of R.C.?)
17	1	70		Not too many crabs.
18	1	70		Begins on side. ends on side, Good in bet.
19	1	70		Towed entirely on side - some found!
21	1	70		Many red crabs - fuzzy tho.
22	1	70		Many Hyalinoecia - J.C. - Lobster - No R.C.
23	1	70		Only 8 frames @ end - Upside down?
26	1	70		No shots - only fouled polyprop. line - on side!
27	1	70		Good R.C. area. - fishes etc.
28A	1	70		Good R.C. area - " "
29	1	70		Few frames but good R.C. - 1 fr. c̄ 4.
30	1	70		Very Fuzzy R.C - L - J.C.
31	1	70		Very good for R.C. - L - J.C.
32	1	70		Few frames c̄ R.C. - mostly on side or back

Table 2 continued.

Film Analyzed

STA.	TOW	Type	No. of frames	Comment
33	1	70		Very good for R.C. @ begin. - reasonably sharp. does much rolling gets very fuzzy. (good underp with loose focus)
34	1	35		Short length, only water shots except 10 at end, but all of same area.
37	1	70		All water shots. - side or top tow?
38	1	70		Excellent for R.C. - J.C - Rocks - boulders, pebbles cobbles etc, Anemones.
39	1	70		Good evidence of tumbling - Good R.C. - Fuzzy
40	1	70		Very fuzzy - some R.C. - Rocks.
41	1	70		Very fuzzy - Some R.C.
45	1	70		" " Very few R.C.
46	1	70		Very fuzzy to sharp. - Few R.C.
59	1	70		Very boring bottom - Few of anything. Some R.C.
60	1	70		Good for R.C. but fuzzy
60A.	1	70		V. Good for R.C. - fuzzy.
61	1	70		No shots - all side or top.
61A	2	70		No shot - all side or top
62	1	70		Some obscuration but v.g. for R.C.
62A	2	70		Many 2-3-4-5 dbl etc. exposures but good R.C. data
63	1	70		Short roll - good focus. + R.C, + fishes
64	1	35		a Very few good shots - mostly water - 1 RC. no data on area yet.
65	1	70		Only 8 poor exps. No. R.C.
66	1	70		No shots. - Fouled old wire - all watershots
67	1	70		Very fuzzy - Good for R.C.
68	1	70		Useless - all on side + short length -

Table 3. Exponential visibility model estimates for deep-sea red crab counts by zone for three stations from the 1974 survey with sensitivity analyses to measure bias in density estimates due to escape behavior. Patil et al.'s estimates are in column 2. Column 3 shows recalculated density, predicted counts and negative log liklelihoods (NLL) based on Patil et al.'s estimates. Column 4 shows estimates when the model was refit using Patil et al.'s methodology. Columns 5-10 are sensitivity analyses in which the indicated proportions of original counts were moved from one zone to the next to simulate escape behavior.

Statistic or zone	Original figures from Patil et al.	Recalculate using original parameters	Refit original models	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Avoidance parameters (% moving to next zone)									
Zone 1 to 2	0%	0%	0%	5%	10%	15%	20%	20%	20%
Zone 2 to 3	0%	0%	0%	0%	5%	10%	15%	15%	15%
Zone 3 to 4	0%	0%	0%	0%	0%	5%	10%	10%	10%
Zone 4 to 5	0%	0%	0%	0%	0%	0%	5%	5%	5%
Zone 5 to outside (lost)	0%	0%	0%	0%	0%	0%	0%	50%	100%
Station 16									
Lambda	0.208	0.208	0.207	0.203	0.198	0.183	0.167	0.271	0.390
Density (n/hectare)	150.0	149.7	149.5	146.3	142.7	132.7	122.8	158.2	189.1
Percent bias in density relative to reestimated models				**-2%**	**-5%**	**-11%**	**-18%**	**6%**	**26%**
Predicted N by zone									
1	10.7	10.7	10.7	10.6	10.4	10.1	9.7	11.1	12.8
2	22.5	22.6	22.5	22.4	22.2	21.7	21.2	22.1	22.8
3	22.6	22.6	22.6	22.6	22.5	22.4	22.3	20.5	18.3
4	21.5	21.5	21.5	21.6	21.7	22.0	22.3	18.0	13.9
5	19.7	19.7	19.7	19.9	20.1	20.8	21.5	15.3	10.2
NLL	na	153.39	153.39	152.64	152.63	151.87	151.89	135.75	118.88
Station 21									
Lambda	0.425	0.425	0.836	0.820	0.770	0.717	0.662	0.756	0.813
Density (n/hectare)	307.0	306.6	642.8	628.1	582.1	534.6	487.6	526.3	533.7
Percent bias in density relative to reestimated models				**-2%**	**-9%**	**-17%**	**-24%**	**-18%**	**-17%**
Predicted N by zone									
1	21.0	21.0	38.8	38.1	35.9	33.5	31.0	32.6	32.4
2	36.3	36.4	46.2	46.0	45.3	44.4	43.3	41.7	39.4
3	28.0	27.9	21.5	21.8	22.8	23.9	24.9	21.4	18.8
4	20.4	20.4	9.5	9.8	10.9	12.2	13.6	10.4	8.6
5	14.4	14.4	4.1	4.3	5.1	6.0	7.2	4.9	3.8
NLL	na	-27.08	-28.50	-28.55	-28.22	-27.77	-27.33	-26.85	-26.53
Station 67									
Log lambda		-1.109	-1.112	-1.124	-1.158	-1.209	-1.279	-0.935	-0.626
Lambda	0.330	0.330	0.329	0.325	0.314	0.299	0.278	0.393	0.535
Density (n/hectare)	192.0	192.2	191.7	190.0	185.0	178.0	169.3	199.7	242.2
Percent bias in density relative to reestimated models				**-1%**	**-3%**	**-7%**	**-12%**	**4%**	**26%**
Predicted N by zone									
1	14.2	14.2	14.1	14.0	13.7	13.3	12.7	14.5	16.8
2	26.7	26.8	26.8	26.6	26.3	25.8	25.1	25.8	26.3
3	23.1	23.1	23.1	23.1	23.1	23.1	23.1	20.6	17.7
4	19.0	18.9	19.0	19.0	19.3	19.7	20.1	15.6	11.3
5	15.0	15.0	15.0	15.2	15.6	16.2	17.0	11.5	7.0
NLL	na	158.15	158.15	157.58	157.17	156.89	156.70	137.67	117.69
Total NLL		284.46	283.04	281.66	281.58	280.99	281.25	246.56	210.03

Table 4. Dimensions and calculations for the area of each zone used by Patil et al. to analyze data from the 1974 deep-sea red crab survey. The near border of a zone is the edge parallel and nearest to the sled. The far border parallel and furthest from the sled. Distances to borders are measured perpendicular to sled runners from the near border of Zone 1. Widths are distances measured parallel to sled runners along the border of zones.

Parameters used to calculate area of zones (Patil et al., p. 54 and Fig.2 on p. 55)

a	2.868	
b	0.961	
H	5.490	<- For documentation only, not used here.

Zone dimensions and areas

		Dimensions						
Zone	Height	Distance to near border	Distance to far border	Distance to middle	Width near border	Width far border	Width middle	Area
1	0.61	0.00	0.61	0.31	2.87	3.45	3.16	1.93
2	1.22	0.61	1.83	1.22	3.45	4.63	4.04	4.93
3	1.22	1.83	3.05	2.44	4.63	5.80	5.21	6.36
4	1.22	3.05	4.27	3.66	5.80	6.97	6.39	7.79
5	1.22	4.27	5.49	4.88	6.97	8.14	7.56	9.22
							Total	30.23

Formula for area of a trapezoid (Wikipedia)

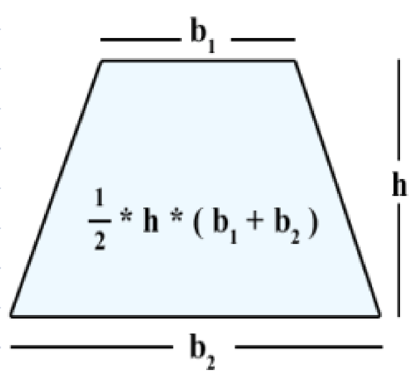

Table 5. This table allowed us to compare the number of crabs we counted in the digital scans of the images with the number of crabs counted by Wigley et al. in 1974. Also, the number of images analyzed vs. the number of original images allowed us to determine what constituted an acceptable image for analysis.

Table 2

Alb. IV Cruise 74-7

Photo Frame: Counts, Analysed, Area covered + Analysed.

Station/Film Number	Original frames	Analysed frames	Area covered m²/film	Total area analysed m²	Acres m² ÷ 4047	Hectares	Distance covered Meters	Number/Ha. Geryon	Cancer	Homarus
2	262	173	8331.6	5,463.5		.55 (.546)		67.8		
3	All (500)	0	15,900.0	–		1.59		–		
3	" (400)	0	12,720.0	–		1.27		–		
3A	" (400)	0	12,720.0	–		1.27		–		
4	" (400)	0	12,720.0	–		1.27		–		
5	368	176	11,170.2	5,173.6		.52 (.517)		15.5		
6	270	210	6679.0	6489.7		.65 (.649)		31 (30.8)		
7	116	89	3698.8	2,759.5		.28 (.276)		4 (3.6)		
8	81	74	2575.8	2,267.5		.23 (.227)		4.4		
~~9~~										
10	391	340	14,812.1	9,839.2		.98 (.984)		71.1		
11	395	286	9094.8	8403.1		.84 (.840)		95.2	.1	
12	All (500)	0	15,900.0	–		1.59		–		
13	442	435	13,833.0	13316.1		1.33 (1.332)		14 (13.5)	3.7	.1
14	448	258	8204.4	7427.6		.74 (.743)		~~92~~ 90.2	1.0	
15	396	393	12,497.4	11909.9		1.19 (1.191)		92 (91.5)	.2	
16	448	408	12,974.4	12338.7		1.23 (1.234)		70 (70.5)		
17	364	293	9,317.4	8749.4		.88 (0.875)		25 (25.1)		
18	190	181	5755.8	5579.8		.56 (0.558)		12 (12.5)		
19	All (400)	0	12,720.0	–		12.7		–		
21	431	397	12,624.6	12139.8		1.21 (1.214)		100 (100.5)		
22	401	280	8,904.0	8826.5		.88 (0.883)		0	4.4	.1
~~23~~	~~8~~	~~8~~	~~254.4~~	~~244.4~~		~~.02~~		~~100~~		
26	All (400)	0	12,720.0	–		12.7		–		
27	428	329	10,462.2	10219.0		1.02 (1.022)		66 (65)		
27A	440	338	10,743.4	10,483.9		1.05 (1.048)		46 (45.6)		
29	105	84	2,671.2	2664.7		.27 (0.266)		79 (79.0)		
30	338	221	7,027.8	6874.3		.69 (0.687)		13 (13.1)	4.6	.1
31	361	203	6,455.4	6069.9		.61 (0.607)		194 (194.4)	.5	.2
32	32	24	763.2	738.2		.07 (0.074)		~~47~~ (67.6)		
33	460	172	5469.6	5000.1		.50 (0.500)		68 (68.0)		
34	Short (100)	0	3,180.0	–		3.2		–		
37	All (400)	0	12,720.0	–		12.7		–		
38	397	210	6678.0	6450.0		.64 (0.645)		~~94~~ (91.6)	5.9	
39	155	82	2,607.6	2589.6		.26 (0.259)		127 (127.4)		
40	364	178	5660.4	5402.9		.54 (0.540)		17 (16.7)		
41	317	116	3688.8	3636.3		.36 (0.364)		30 ~~31~~ (30.2)	.8	
45	316	316	10048.8	9937.3		.99 (0.994)		2 (2.0)	1	
46	367	320	10176.0	9485.4		.95 (0.948)		18 (17.9)	.1	
59	337	337	10716.6	10716.6		1.07 (1.072)		8 (8.4)	.7	
60	267	241 353	7663.8	7218.5 10768.1		.72 1.077		140 136		
60A	113	112	3561.6	3549.6		.36		125 (135.6)		
61	All (400)	0	12,720.0	–		12.7		–		
61A	" (400)	0	12,720.0	–		12.7		–		
62	425	348 528	11,866.4	10665.9		1.07 1.35		262 215		
62A	200	180	5,724.0	5686.0		.57		126 (215.3)		
63	60	60	1908.0	1908.0		.19 (0.191)		52 ~~53~~ (52.4)		
~~64~~	~~55~~	~~55~~	~~1749.0~~	~~1749.0~~		~~.18 (0.175)~~		~~6 (5.9)~~		
65	All (400)	0	12,720.0	–		12.7		–		
66	" (400)	0	12,720.0	–		12.7		–		
67	450	398	12,656.4	12086.6		1.27 (1.269)		71 (71.1)		
68	Short (200)	0	6,360.0	–		.64		–		
Totals	~~17,274~~	~~7,638~~	~~414,208.6~~	~~233,775.9~~						
Stns 5, 38, 10+	956	679	28296.9	20038.8				1,998.2		
	18230	8317	442505.5	253814.7						
	− 55	− 55	−1749.0	1749.0						
	18175	8,262	440756.5	252,065.7						

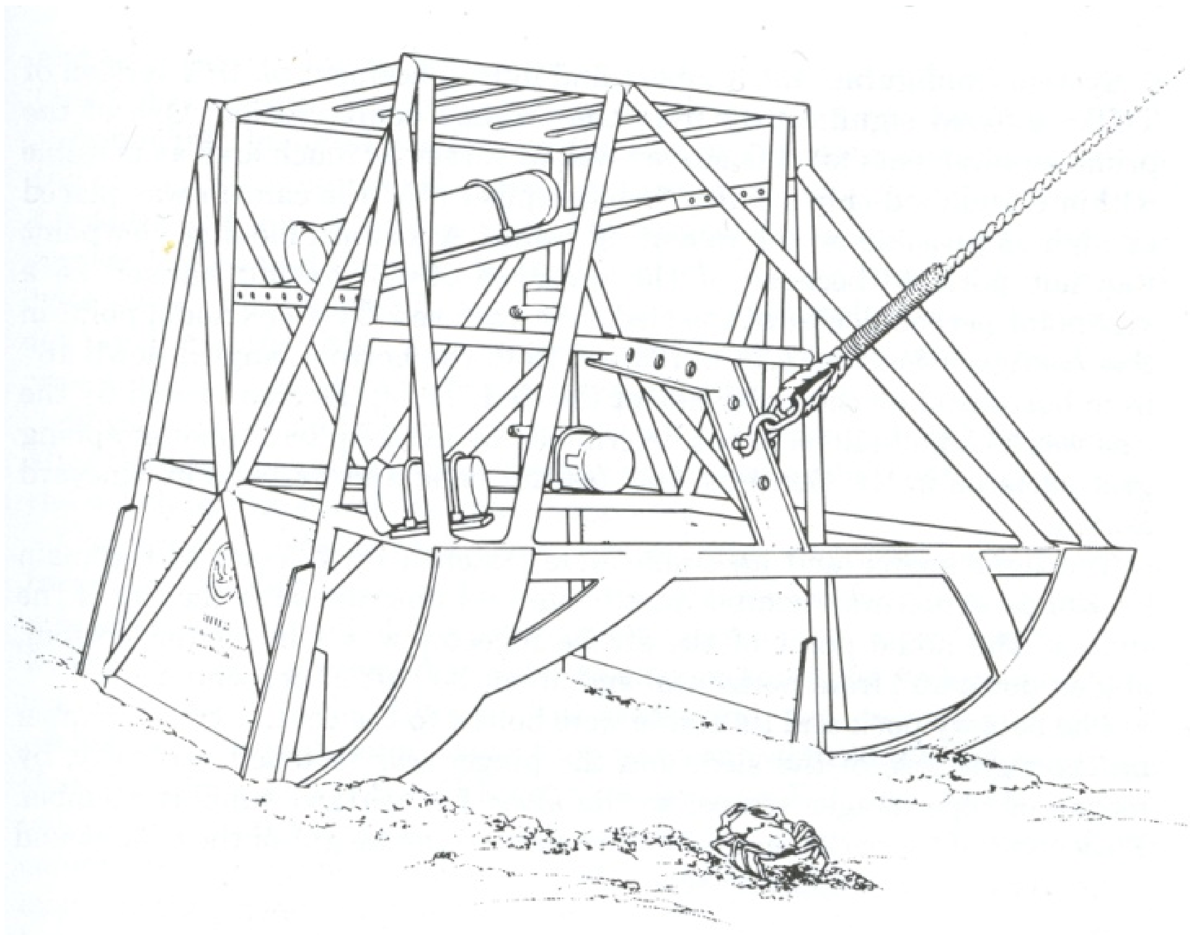

Figure 1. Towed Underwater Benthic Sled (TUBS) version IV with side-facing camera and strobe used during the 1974 red crab survey. TUBS IV was 2.7 m long, 1.9 m high and weighed 1,225 kg.

Figure 2. Example of an image from the 1974 red crab survey showing a red crab, silt disturbed by the sled, the watch, the card reading the station number and the depth indicator. The illuminated area of the image is the portion of the image within the pool of light from the strobe. The watch, the station number and the fathometer readout that are captured next to each image were inside the camera housing. It is impossible to say exactly what the setup was, but the method of including information from other instruments with each exposure was widely employed at that time (Tom Kleindinst, WHOI Graphics, pers. comm.). The camera was programmed to expose the film through the main lens looking out onto the ocean floor every ten seconds, and then wind the film a certain distance, which left a space in between the exposed areas. As the film wound away from the main camera aperture, it was exposed to the watch, card and meter which were in their own independently lit chamber and separated from the film by glass and a piece of black material with cutouts for each. The film was exposed to the watch, card and meter in the space between the exposures of the ocean floor. Since the film was exposed first to the main camera lens which took the big picture and then had to wind some distance before being exposed again to the inside chamber, the information next to each image is offset by one or more exposures.

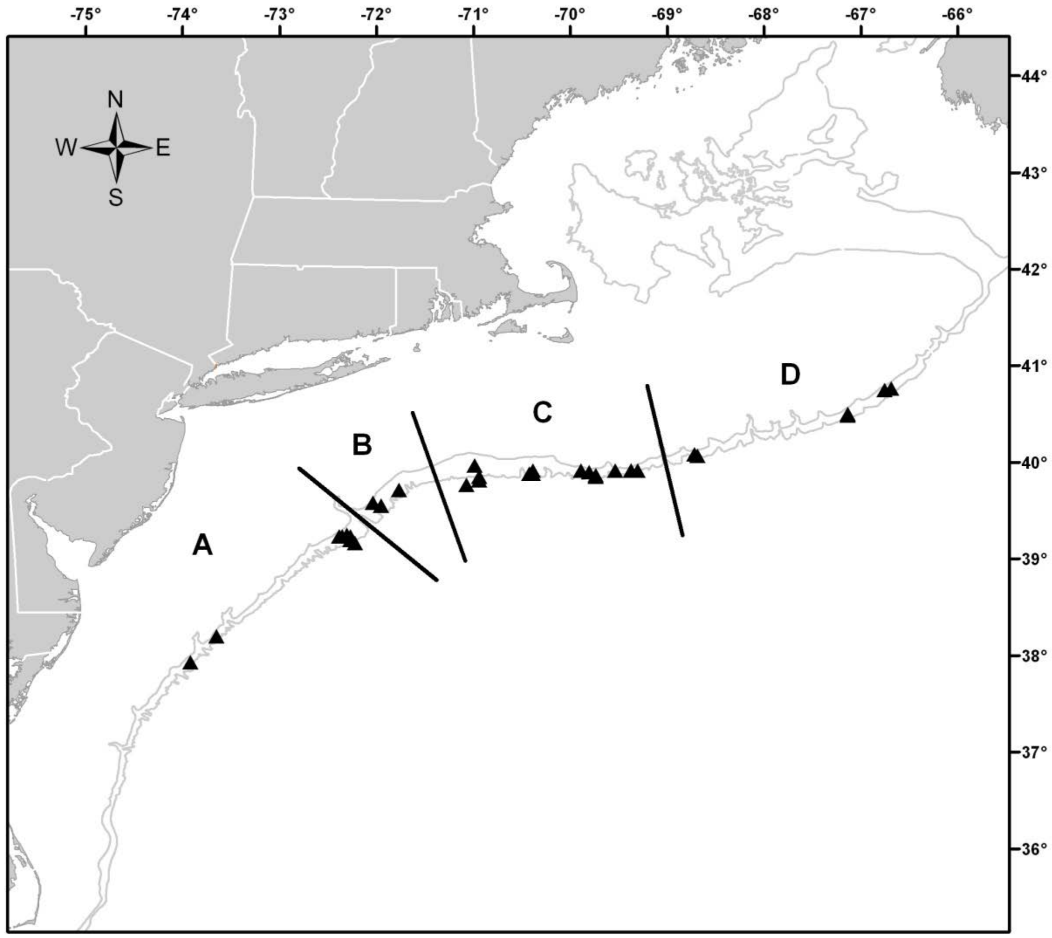

Figure 3. Locations of all the camera tows from the 1974 red crab survey, divided into the four geographic zones.

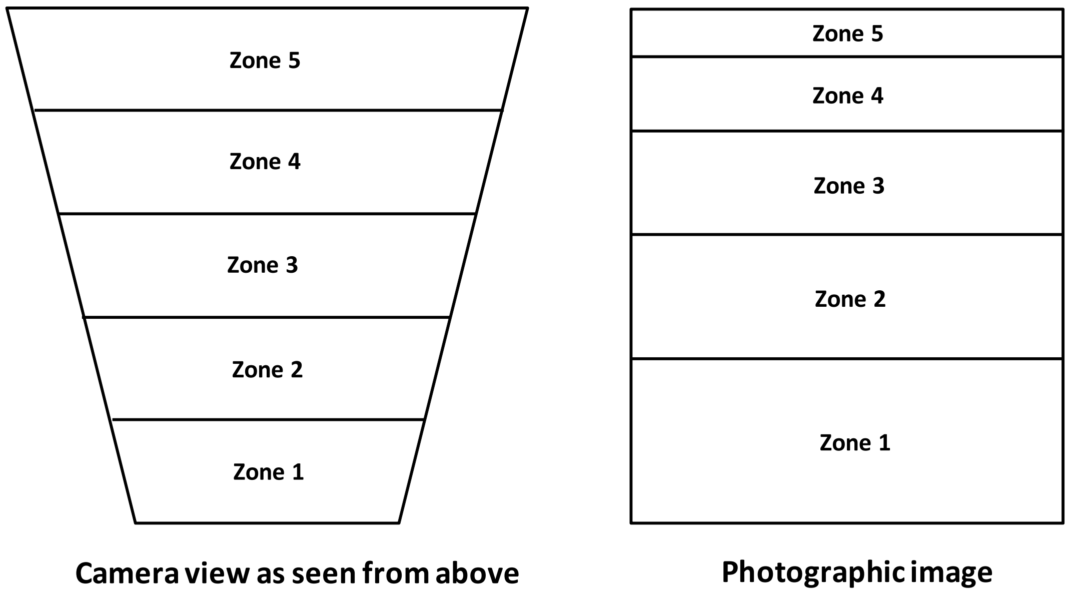

Figure 4. After Patil, et al. (1979). Diagrams of the camera view (left) and its photographic image (right), showing zones of equal height as they would look in both views. These zones are much like those used to subdivide the 1974 images.

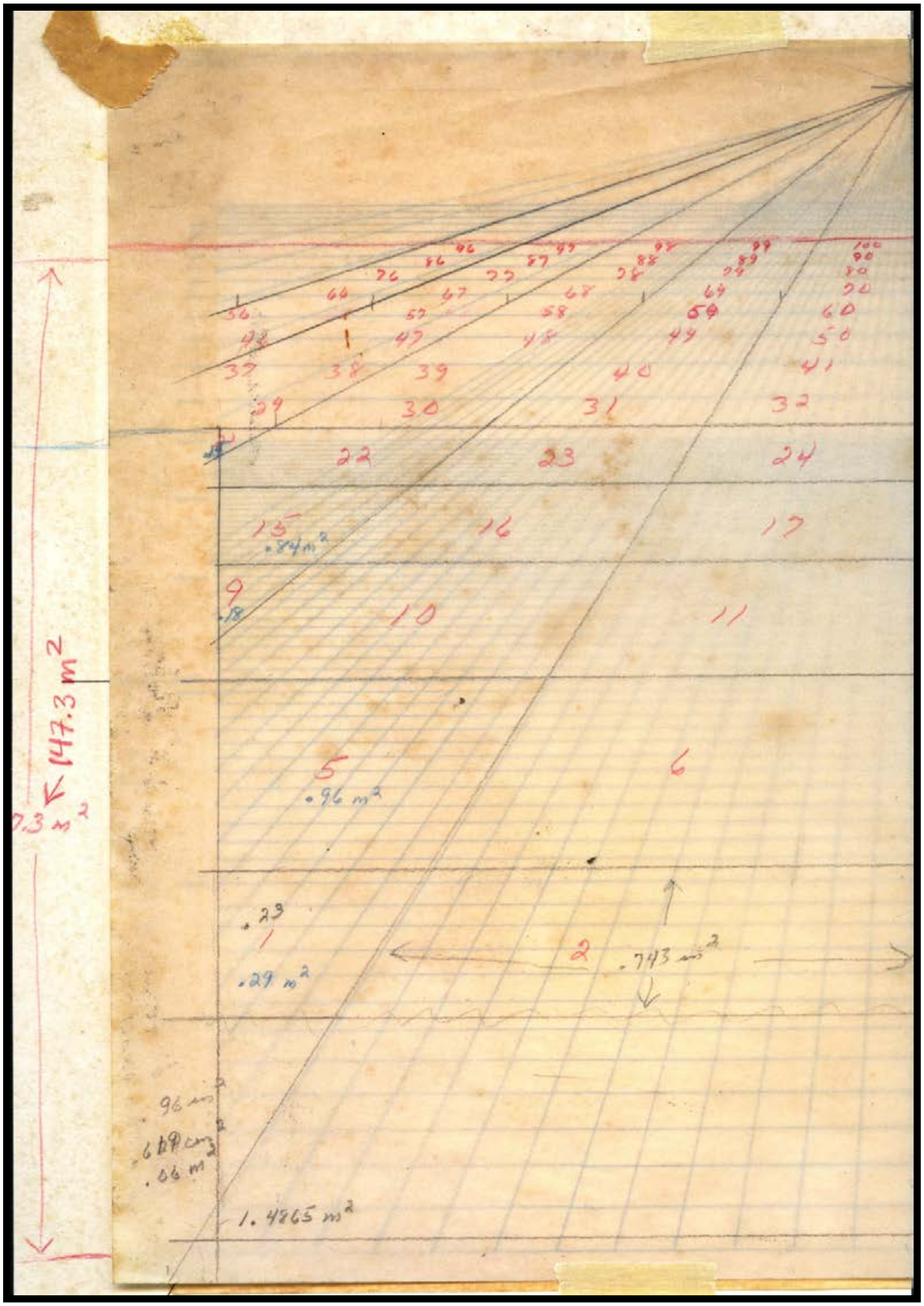

Figure 5. The left half of the grid used to determine the area of the ocean floor covered in each image. Each rectangle represents the same area but becomes more distorted as the distance from the camera increases. The areas of the rectangles only partially covered by the camera's view have been determined and written in or near the rectangle in question. The grid is 10 inches wide by 7 inches high.

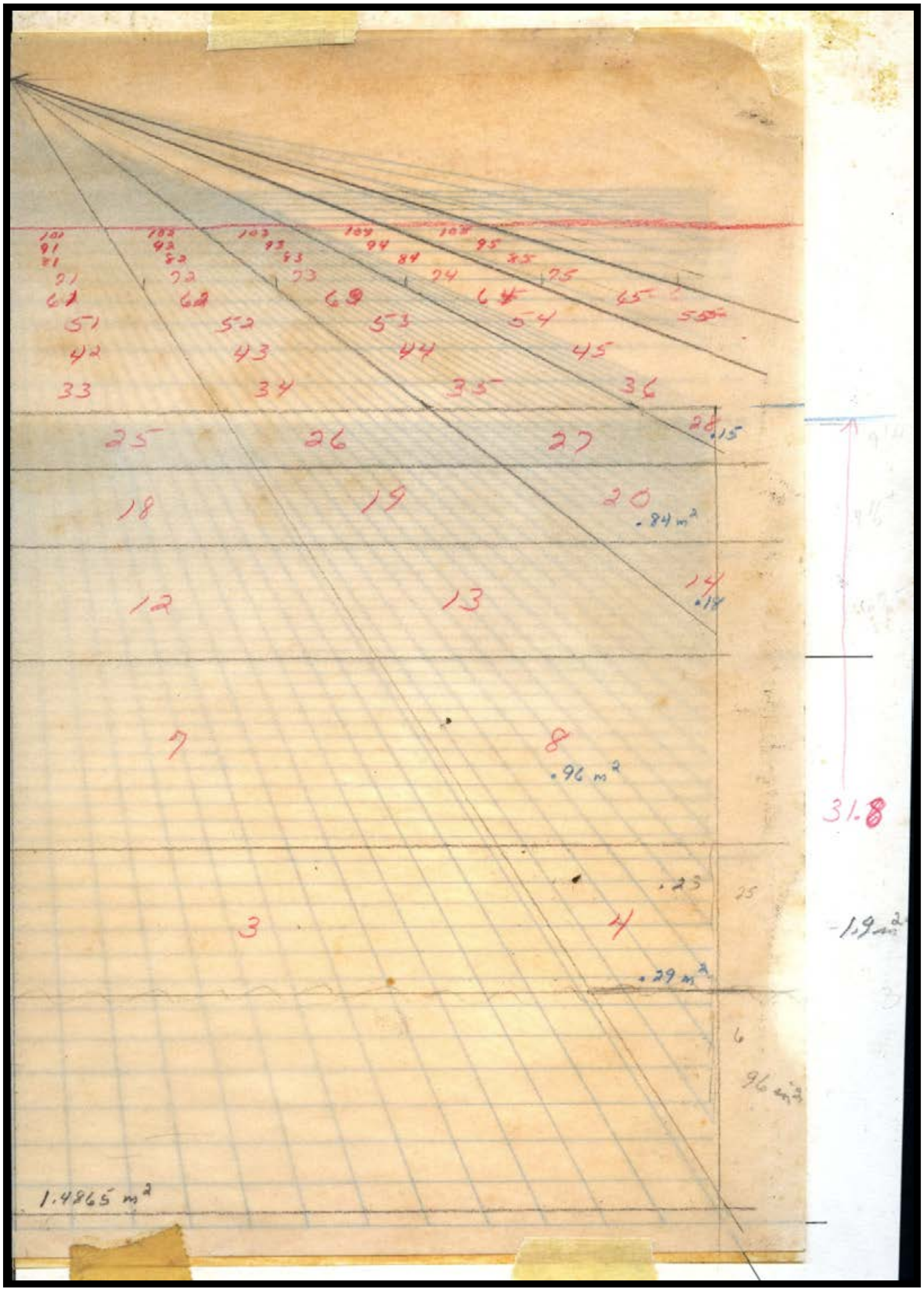

Figure 5 continued.

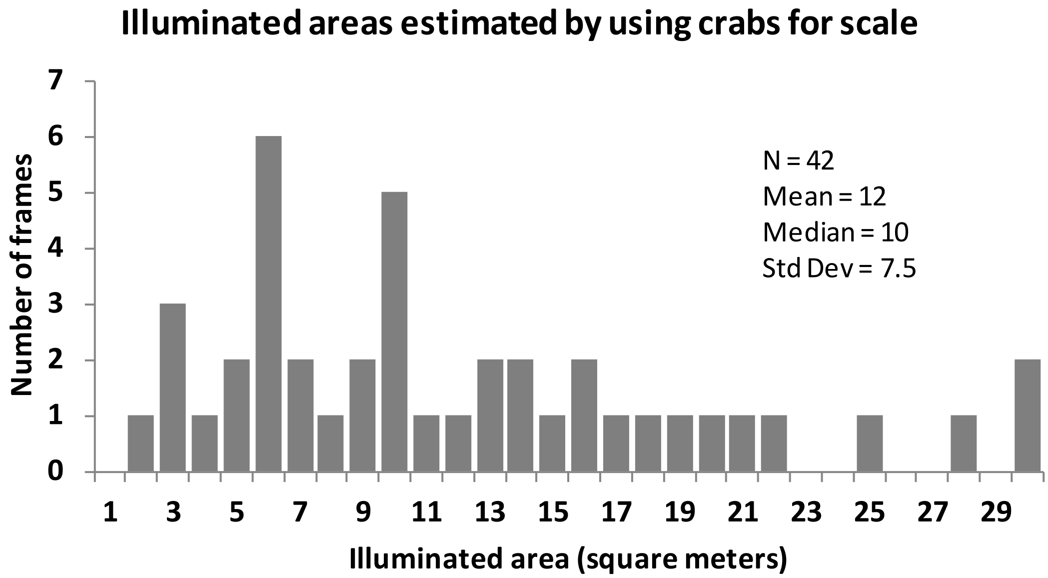

Figure 6. Estimated illuminated area of 42 bottom photographs from 1974. Each photo featured a red crab near the front of the image which was used for scale.

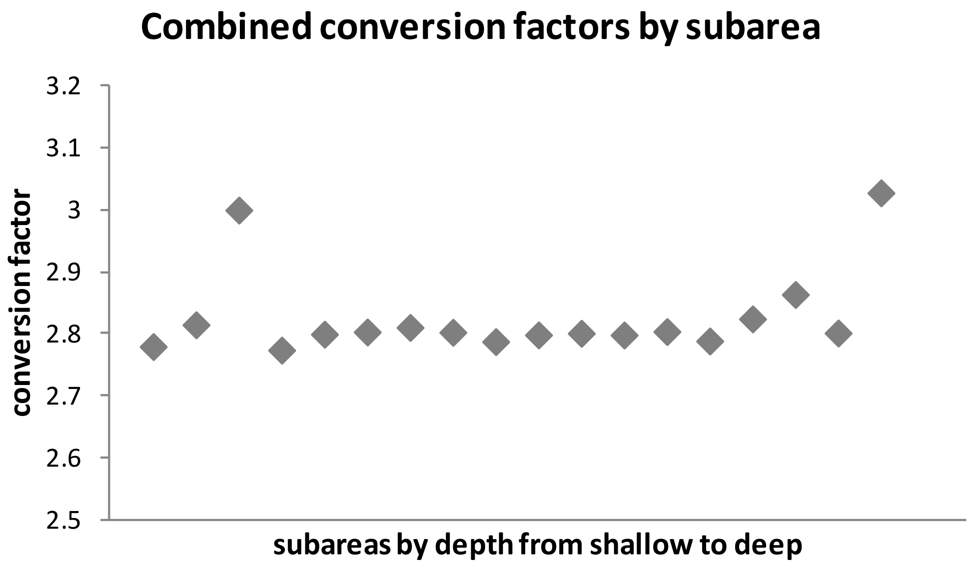

Figure 7. The conversion factors applied to the total number of crabs (zones not differentiated) seen in the illuminated area to extrapolate from the illuminated area to the camera view.

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