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# ESTIMATION OF MINIMUM TAIL WIDTH SIZE FOR LEGAL SPINY LOBSTER IN THE NORTHWESTERN HAWAIIAN ISLANDS FISHERY

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## ABSTRACT

Changing the minimum size regulation in the spiny lobster fishery in the Northwestern Hawaiian Islands from carapace length to tail width required a statistical relationship to be determined, but this was complicated with problems in finding an acceptable tail width measurement site. Data were collected on both government research cruises and by observers on commercial vessels. Functional regression equations were fit to tail width and carapace length for females, males, and both sexes combined. The relationship for females was estimated to be

$$TW3 = 3.40228 + 0.6361 * CL$$

where the former minimum size of 77 mm CL is equal to 52 mm TW3.

## INTRODUCTION

During the development of the fishery management plan for the Northwestern Hawaiian Islands (NWHI) lobster fishery, the Western Pacific Regional Fishery Management Council (Council) decided that the fishery would be managed using a minimum size regulation for the spiny lobster, *Panulirus marginatus*, which was based on the reproductive biology of females and designed to protect egg production. Initially the minimum size was set at 7.7 cm carapace length (CL), but this limit was augmented before the fishery management plan was actually put into effect to include a tail width measurement for use by the National Marine Fisheries Service (NMFS), Southwest Region (SWR) enforcement officers. This change was made because the fishers began landing frozen tails in addition to live lobsters. This new tail width (TW1) was defined as "the straight line distance between the lateral notches on the first tail segment." The TW1 equivalent to 7.7 cm CL was estimated as 5.0 cm through linear regression techniques. However, discriminate analysis of typical landings of legal lobsters showed that 15% could have a TW1 <5.0 cm and >4.5 cm.[1] Thus, the minimum size regulation was defined as 7.7 cm CL, but allowed use of a minimum TW1 of 5.0 cm with a tolerance of 15% of the landing between 5.0 and 4.5 cm.

The SWR enforcement officers experienced a number of problems in enforcing this minimum size regulation. First, the lateral notch is sometimes broken making it impossible to take the measurement. Second, ice tends to form at this location, and tail meat occasionally becomes folded over the lateral notches and frozen. Thus, to measure tail width, the product must either be defrosted or the ice or frozen meat must be broken away from the lateral notches; neither alternative is practical. Third, it has proven difficult if not impossible to determine whether 15% of the landed tails fall between a TW1 of 5.0 and 4.5 cm because of sampling problems. Specifically, it has proven very difficult to take a random sample from a large catch stored in several holds, and the occurrence of nonrandom capture and storage (sorting) of the product relative to tail size further complicates the problem.

Therefore, the SWR requested that the NMFS Southwest Fisheries Center (SWFC) recommend a new tail width measurement and a minimum size based only on the new tail width. Based on discussions with the SWR enforcement officers, a new site (TW2) for measuring the tail width was selected, namely the straight line distance across the tail at two orange-colored pits located between the first and second abdominal segments. This measurement is essentially across the narrowest spot between the first and second tail segments.

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[1]Polovina, J. J., and D. T. Tagami. 1981. A procedure to classify spiny lobsters as legal or sublegal based on tail widths. Natl. Mar. Fish. Serv., NOAA, Honolulu, Hawaii. Southwest Fish. Cent. Admin. Rep H-81-3.

Samples were collected on the NOAA ship Townsend Cromwell in conjunction with spiny lobster escape vent research being conducted at Necker Island and Maro Reef in October 1984. Results of the analysis of these data were reported to the SWR by the SWFC Honolulu Laboratory in November 1984. Since the legal minimum carapace length for spiny lobster (7.7 cm CL) was based on the reproductive biology of female lobster, a linear functional relationship was established between the new tail width measurement (TW2) and the carapace length for females. This relationship was the basis for a new spiny lobster minimum legal size, TW2 = 5.0 cm, recommended by the SWFC Honolulu Laboratory.

During the next meeting of the Council in December 1984, the SWR recommended the adoption of the TW2 at 5.0 cm as the sole definition of legal size and the rescinding of the 15% tolerance factor for undersized lobsters. Industry representatives argued that adoption of the 5.0 cm TW2, based on female lobster, would result in reduced landings because males have thinner tails which would not be fair. In addition, industry representatives argued that the length-width regression was based on a relatively small sample (348 lobsters) from only two islands. Based on a functional regression for combined male and female samples from Necker Island and Maro Reef (SWFC November 1984 report to the SWR), a minimum TW2 size of 4.8 cm with no tolerance factor was agreed upon for a 90-day (emergency) trial period, and industry representatives agreed to carry SWFC observers aboard their boats to collect additional samples to improve the estimate. This regression was based on 849 data points and yielded a TW2 estimate of 48.6 mm as equal to 77.0 mm CL.

After additional consultation with the SWR enforcement officers, a slight modification was made for a new site for tail width measurement to allow use of measurement templates cut from aluminum stock rather than calipers. This new measurement, TW3, is now defined as "the straight line distance across the tail measured at the widest spot between the first and second abdominal spines." The owners of the FV Alaska Gulf and the FV Kona Kai agreed to carry an SWFC observer, but the owners of the FV Lusty and the FV Bounty indicated they had insufficient bunk space, and the owner of the FV Magic Dragon said the boat could not carry an observer on the upcoming cruise because of a complete change in crew. Roy L. Bendell, SWFC observer, departed on 30 April on the Alaska Gulf and returned, due to equipment failure, on 29 May 1985; the vessel fished off Maro Reef. He departed again on 18 June, but returned on 11 July 1985 because the vessel returned to Maro Reef, rather than other fishing grounds, as planned. Because of the limited data from the second cruise and because data from only the first cruise were used in providing information to the Council, data from the second cruise have not been included in the analyses presented in this report. Victor A. Honda, SWFC observer, departed on 20 April 1985 on the Kona Kai and spent 67 days collecting data at Gardner Pinnacles, Raita Bank, and Pearl and Hermes Reef.

## METHODS

The SWFC observers on the commercial vessels collected data on carapace length and the new tail width measurement (TW3) by sex and by species of lobster every other day. The alternate days were spent collecting counts of the catches of spiny and slipper lobsters.

"Functional," rather than the usual "predictive" regressions, were fit to TW2 (for Cromwell data) or TW3 (for data collected by the observers on the commercial vessels) on CL for males, females, and both sexes combined for each island fished. Functional regression is appropriate when the variability of two variates is completely natural and there is no logical causal effect between the variates (Ricker 1973). Predictive regression is appropriate, of course, when changes in one of the variates (the independent) causes changes in the other variate (the dependent) and the variability of the independent variable is due solely or primarily to sampling, and that for the dependent variable is primarily natural with small sampling or measurement error. For instance, there is a cause and effect relationship between a classical treatment factor and response factor in an experiment.

The model fit to the data is

$$TW = U + V * CL,$$

where U is the functional intercept and V is the functional slope. V is sometimes called the "initial growth constant" although its biological meaning is not well defined. U has no biological meaning. This model is a special case of the generalized allometric model,

$$TW = V * CL^{\alpha} ,$$

where $\alpha$, the coefficient of allometry, equals one. This implies that the geometric growth rates of tail weight and carapace length are equal and constant. The intercept, U, is included because plots of the data indicated that a regression line would not pass through the origin. Although this clashes with intuition, it is in fact common when fitting the model to data collected from animals in the last of several growth stages (Simpson et al. 1960).

Although the design of the experiment called for combining all of the island and vessel data for a pooled estimate, we calculated an analysis of covariance and Bartlett's test of homogeneity of variance to determine whether there would be any statistical qualifications in doing so. The analysis of covariance is not strictly valid, since it pertains to predictive regressions. Although statistical differences found may not be real, the analysis provides guidance in interpretation of the results. To assist interpretation, 95% symmetrical confidence intervals about the functional regressions were calculated for selected results. This too is not completely valid because the calculated confidence intervals are symmetrical, whereas, they should be asymmetrical as viewed from either the x or y axes.

Statistics from the October 1984 Cromwell cruise (TC-84-06) are presented for comparative purposes, but not included in the final, island-pooled results which consist only of the observer data. Since tail width was measured at different sites on the Cromwell and commercial vessel cruises, the functional regression intercepts should be different; this would indicate in turn that the regression lines are statistically different, whether the slopes are the same or not.

## RESULTS AND DISCUSSION

Since a single curve for the relationship between TW3 and CL for the NWHI fishery is needed for management purposes, the data collected on the Alaska Gulf and the Kona Kai at Gardner Pinnacles, Raita Bank, Maro Reef, and Pearl and Hermes Reef were combined. Then, the allometric coefficients were computed for females, males, and both sexes combined (Table 1-I). For comparative purposes, the computed values for TW2 on CL for Cromwell data collected at Necker Island and Maro Reef are presented in Table 1-II. The plots of the data for males, females, and both sexes combined (Figs. 1A, 2A, and 3A) show what appears to be linear relationships between TW3 and CL. Although the outliers noted on these figures appear to be merely transpositions of the TW3 and CL measurements, they were eliminated from the statistical analysis. The plots of the residuals from the fitted functional regressions (Figs. 1B, 2B, and 3B) show reasonably even bands about the zero lines, which implies normality of the residuals which in turn indicates that the model fits the data. The worst fit occurred for the combined sexes where the smallest lobsters (CL) had mostly positive residuals whereas the largest had only negative residuals. Since all of the largest lobsters were males, this result suggests that it may not be statistically valid to combine male and female data in the analysis; but of course this must be done for operational purposes and was included in the design of the experiment. The square of the correlation coefficients showed that the linear model accounted for more than 90% of the variability in the data except for both sexes combined for TW3 on CL where the value fell to 86.6%.

During a meeting of the Council's plan development team, it was suggested that a log-log relationship was more commonly used in such situations and might reduce the interisland variability in the preliminary allometric parameter estimates that were presented to them. This is equivalent to using the generalized allometric model linearized by taking logarithms on both sides of the equation. Results from fitting this log-linear model are presented in Table 1-III and plotted in Figures 4-6. The scatter plots of the log transformed variables, which appear in the "A" panels of the figures, appear also to be linear just as the arithmetic plots in Figures 1-3 did. Plots of the deviations from the functional log-log regressions, which appear in the "B" panels of the figures, appear much the same as those for the linear relationships and do not show any obvious improvement. The square of the correlation coefficients are higher than those for the linear models (Table 1), but only marginally so. Note that the estimates for V in the log-linear model (Table 1-III) differ from those for the linear model (Table 1-I), and that is because they were estimated in different parameter spaces. The estimates of $\alpha$ vary about unity, especially for both sexes combined, which lends credence to the assumption in the linear model that $\alpha$ equals one. Since the log-linear model does not seem to perform significantly better than the linear model, the simpler, linear model was chosen as the more statistically appropriate.

Using the linear model on data collected on the commercial vessel, the estimated minimum tail width (TW3) equivalent to 7.7 cm CL for females is 52.4 mm or 5.2 cm (Table 1-I), compared to a TW2 of 50.4 mm or 5.0 cm for the combined Necker and Maro measurements from the Cromwell (Table 1-II). The TW2 statistics were those initially recommended by the SWFC and presented to the Council by the SWR. The estimated minimum TW3 for male and female lobster combined is 51.1 mm or 5.1 cm, compared to a TW2 of 48.6 mm or 4.9 cm (the millimeter figure was rounded to 4.8 cm in the discussions at the Council meeting when the 90-day trial size was agreed upon). The relationship among the three linear curves for TW3 on Cl is shown in Figure 7. Comparable estimates using the log-linear model (Table 1-III) differ from those of the linear model by no more than a tenth of a millimeter; hence, any uncertainty about the correct model is mostly academic rather than practical, at least over the size range in this study.

Results from fitting functional regressions to TW3 on CL for the data collected by the observers by each of the islands, by vessel, and by sex are presented in Table 2. Comparable data for TW2 on CL for Cromwell data from Necker and Maro by sex are presented in Table 3. All of the regressions fit the data well at least from the viewpoint of correlation. The highest square of the correlation coefficient shows 98.5% of the variation accounted for by the regression and the lowest shows 81.3%. The "A" panels of Figures 8-11 show the relationship between TW3 and CL, and the "B" panels show the residuals from the linear functional regressions. The "A" panel plots appear to be linear, although there seems to be some heteroscedasticity present as well as a few outliers (as noted above these all appear to be recording errors where tail widths and CL's were reversed; these values were excluded from the analysis). The "B" panel plots of deviations from the regressions show that the deviations are distributed in relatively uniform bands about the zero line, suggesting that the data do not deviate significantly from the linear model.

For each sex category plotted in Figures 12-14, the functional regressions for each island form a family of curves with similar slopes and intercepts. The curves for females form a tighter, more consistent group than do those for males and, as a consequence, for both sexes combined as well. The relationships determined for males on Pearl and Hermes Reef and on Raita Bank are aberrant. Also, the regression lines for the samples taken on the Cromwell always fell on the lower side of the family of curves, as would be expected, since TW2 is measured along a narrower part of the tail than TW3. Only two of the samples came from the same island, namely from the Cromwell and the Alaska Gulf at Maro Reef. Based on these regression lines for TW2 and TW3, respectively, on CL, it would appear that the estimates of the slopes differ more so than the intercepts. This result was not expected.

The analyses of covariance for the Necker and Maro samples collected on the Cromwell are shown in Tables 4A, 4B, and 4C for females, males, and both sexes combined. The slopes of the relationships are not different, except for some indication for both sexes combined, whereas the adjusted means are statistically different. The variances are homogeneous for females and both sexes combined, but not for males; an explanation for this in not apparent.

These results suggest that the relative growth of TW2 and CL is the same on the two islands, but that the initial size of the tail width relative to CL is larger on Maro.

The analyses of covariance for the two Maro Reef samples (from the Cromwell using TW2 and the Alaska Gulf using TW3) indicate that the slopes are not different for females, both sexes combined, and males, but that the adjusted means are statistically different (Tables 5A, 5B, and 5C). This result conflicts with that suggested above based on the 95% confidence interval plots in Figures 12-14. The variances are heterogeneous as would be expected since different measurement sites were used. Thus, results from the analysis of covariance indicate that statistically the relationships for the Cromwell (TW2) and the Alaska Gulf (TW3) samples are not the same because of differing intercepts and variances. Intuition leads to the same conclusion.

Turning to an examination of all the island-vessel data collected on commercial vessels, there is heterogeneity of variance for females, both sexes, and males (Tables 6A, 6B, and 6C). The measurements collected at Maro Reef on the Alaska Gulf had the largest variance, and it might be noted that the variance for the Cromwell data was nearly as large (see Tables 5A, 5B, and 5C). The smallest variance by a factor of around five was found for the sample from Raita Bank. With heterogeneity of variance, it is not technically (statistically) correct to continue with an analysis of covariance; however, if continued, the levels of significance are probably much lower than indicated.

The analysis of covariance indicates that the slopes of the functional regressions among islands are statistically different for females, both sexes combined, and males. However, since the "F" values are 3.53, 8.90, and 5.79, respectively, there is a chance that these levels are not in fact significant due to the heterogeneity of variance among the samples. The adjusted means are also statistically significant, and since the "F" values are larger (39.96, 15.82, and 21.29), it is likely that these are significant even given the heterogeneity of variance.

Although there are obvious statistical problems in interpreting these results because of heterogeneity of variance, it would seem that the slope of the relationship between TW3 and CL is the same or nearly so among the islands sampled, whereas the intercepts are not the same. In other words, there seems to be a family of curves representing each island that has the same slope, but a different starting point relative to the horizontal or x-axis. Whereas the proportional growth of TW3 and CL seems to be the same, the lobsters on some islands start out having proportionally smaller tails.

Based on a suggestion made at a Council plan development team meeting, 95% confidence intervals about the linear functional regression lines have been calculated for sex categories with the data pooled across all islands sampled by the observers and for each island using only female data. The relationships were plotted only for the central part of the distribution, namely from 65 to 85 mm CL. For the relationships among the sexes (Fig. 15), the functional regression lines lie close together and each of the regression lines falls within the 95% confidence interval of the other two relationships. For the island relationships (Fig. 16), the regression lines again fall close together. Also, each of the regression lines also falls within the 95% confidence interval of any of the other relationships. These results could be interpreted to mean that in practical terms the estimates within the size range of interest would not differ sufficiently to warrant separate relationships by sex or by island.

During the émergency regulation period in 1985, the SWR enforcement officers were enforcing the TW2 of 4.8 cm as a TW3 measurement. Since the TW3 measurement was used, the equivalent size to be enforced should have been 5.1 cm.

At the 50th Council meeting held in Kailua-Kona, Hawaii in August 1985, the Council voted to adopt a TW3 of 4.8 cm as the minimum size for legal lobsters in the NWHI fishery. This size is equivalent to 7.0 cm CL for females or 7.2 cm CL for both sexes combined. This was included in amendment 3 to the FMP that was subsequently submitted to the Department of Commerce for approval. That amendment was partially disapproved resulting in TW3 being accepted as the new measurement site, but at a 5.0 cm minimum size. Thus since a minimum size for management was first discussed, the size has gone from 8.25 cm to 7.7 cm CL, then temporarily to 7.1 cm CL (a TW3 of 4.8 cm) and finally to 7.5 cm CL (a TW3 of 5.0 cm).

## SUMMARY

Data to determine the relationship between tail width and carapace length were collected on the NOAA ship <u>Townsend</u> <u>Cromwell</u> and by SWFC observers on two commercial vessels. The relationship between TW3 and CL for males, females, and both sexes combined, was determined using a linear allometric model and was fitted using a functional regression. The TW3 size equivalent to the original legal minimum size, 7.7 cm CL, was estimated to be 5.2, 5.0, and 5.1 cm for females, males, and both sexes combined, respectively. The validity of the simple linear model was investigated as was that of the log-linear model.

In addition, the relationship between TW3 and CL among the different island area sampled was investigated. Although there were problems with heterogeneity of variances among the samples, it appears that the slope of the relationship (V) is the same or nearly so among the islands whereas the intercepts (U) are different. Thus, it appears that the relative growth of TW and CL is about the same on the various islands, but lobsters on some islands start out with relatively narrower tails than on other islands.

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Table 1.--Functional regression estimates of TW on CL for spiny lobster by different island and vessel combinations.

I. TW3 on CL for Gardner Pinnacles, Raita Bank, Maro Reef, and Pearl and Hermes Reef; Alaska Gulf and Kona Kai

| Sex | Intercept U | Slope V | $r^2$ | N | $TW3_{77}$ |
|---|---|---|---|---|---|
| Female | 3.4028 | 0.6361 | 0.927 | 734 | 52.4 |
| Male | 8.1324 | 0.5404 | 0.905 | 619 | 49.7 |
| Both | 5.6238 | 0.5910 | 0.866 | 1,354 | 51.1 |

II. TW2 on CL for Necker and Maro Reef; Townsend Cromwell

| Sex | Intercept U | Slope V | $r^2$ | N | $TW2_{77}$ |
|---|---|---|---|---|---|
| Female | 4.8789 | 0.5917 | 0.954 | 348 | 50.4 |
| Male | 9.3766 | 0.4955 | 0.945 | 500 | 47.6 |
| Both | 8.7449 | 0.5185 | 0.906 | 849 | 48.7 |

III. Ln TW3 on ln CL for Gardner Pinnacles, Raita Bank, Maro Reef, and Pearl and Hermes Reef; Alaska Gulf and Kona Kai

| Sex | Coefficient V | Coefficient $\alpha$ | $r^2$ | N | $TW3_{77}$ |
|---|---|---|---|---|---|
| Female | 0.9065 | 0.9341 | 0.935 | 734 | 52.4 |
| Male | 0.8505 | 1.2383 | 0.917 | 619 | 49.8 |
| Both | 0.8981 | 1.0345 | 0.885 | 1,354 | 51.2 |

Table 2.--Functional regression estimates for TW3 on CL of spiny lobster, by sex, island, and vessel.

| Sex | Island | Vessel | Intercept U | Slope V | $r^2$ | N | $TW3_{77}$ |
|---|---|---|---|---|---|---|---|
| Female | Pearl and Hermes Reef | Kona Kai | 4.1554 | 0.6224 | 0.952 | 217 | 52.1 |
| Female | Raita Bank | Kona Kai | 2.3200 | 0.6473 | 0.985 | 115 | 52.7 |
| Female | Maro Reef | Alaska G. | 5.4941 | 0.6236 | 0.919 | 248 | 53.5 |
| Female | Gardner Pinnacles | Kona Kai | 4.3626 | 0.6129 | 0.888 | 154 | 51.6 |
| Male | Pearl and Hermes Reef | Kona Kai | 1.7950 | 0.6073 | 0.902 | 135 | 48.6 |
| Male | Raita Bank | Kona Kai | 5.8170 | 0.5724 | 0.963 | 111 | 49.9 |
| Male | Maro Reef | Alaska G. | 10.9990 | 0.5141 | 0.909 | 280 | 50.6 |
| Male | Gardner Pinnacles | Kona Kai | 7.5785 | 0.5325 | 0.892 | 93 | 48.6 |
| Both | Pearl and Hermes Reef | Kona Kai | 3.5846 | 0.6124 | 0.857 | 352 | 50.7 |
| Both | Raita Bank | Kona Kai | 2.5751 | 0.6274 | 0.938 | 226 | 50.9 |
| Both | Maro Reef | Alaska G. | 8.4007 | 0.5649 | 0.861 | 528 | 51.9 |
| Both | Gardner Pinnacles | Kona Kai | 3.7013 | 0.6048 | 0.813 | 248 | 50.3 |

Table 3.--Parameters for functional regression of TW2 on CL for spiny lobster, by island; data collected on the Townsend Cromwell, TC-84-06.

| Sex | Island | Intercept U | Slope V | $r^2$ | N | $TW2_{77}$ |
|---|---|---|---|---|---|---|
| Female | Maro | 4.9375 | 0.5925 | 0.966 | 221 | 50.6 |
| Female | Necker | 4.5761 | 0.5892 | 0.912 | 127 | 49.9 |
| Male | Maro | 11.3663 | 0.4831 | 0.964 | 243 | 48.6 |
| Male | Necker | 7.3781 | 0.5113 | 0.923 | 257 | 46.8 |
| Both | Maro | 9.2026 | 0.5236 | 0.921 | 464 | 49.5 |
| Both | Necker | 8.2861 | 0.5100 | 0.881 | 385 | 47.6 |

Table 4A.--Analysis of covariance of functional regression of TW2 on CL for female spiny lobster using Townsend Cromwell samples from Necker and Maro ($df_2 = df_1 - 1$).

| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|
| Necker, TC-84-06 | 126 | 12,030 | 6,770 | 4,176 | 0.5892 | 125 | 366 | 2.9280 |
| Maro, TC-84-06 | 220 | 40,404 | 23,531 | 14,183 | 0.5925 | 219 | 479 | 2.1872 |
| Within | -- | -- | -- | -- | -- | 344 | 845 | 2.4564 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 3 | 3.0 |
| Common | 346 | 52,434 | 30,301 | 18,359 | 0.5917 | 345 | 848 | 2.4591 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 2,823 | 2,823.0 |
| Total | 347 | 60,528 | 32,130 | 20,727 | -- | 346 | 3,671 | -- |

$F_{1,\ 344}$ for regression coefficient = 3.0/2.4564 = 1.22 NS.

$F_{1,\ 345}$ for adjusted means = 2,823.0/2.4591 = 1,147.98 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| Necker | 366 | 125 | 2.9280 | 1.0743 | 134.2899 |
| Maro | 479 | 219 | 2.1872 | 0.7826 | 171.3957 |
| a = 2 | 845 | 344 | -- | -- | 305.6857 |

$\bar{s}^2$ = 845/344 = 2.4564; $\ln \bar{s}^2$ = 0.8987; $df \cdot \ln \bar{s}^2$ = 309.1511.

$\chi^2$ = 2.3026 (309.1511 - 305.5924) = 3.4654 NS.

Table 4B.--Analysis of covariance of functional regression of TW2 on CL for male and female spiny lobster from Townsend Cromwell samples, for Necker and Maro ($df_2 = df_1 - 1$).

| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|
| Necker, TC-84-06 | 384 | 66,088 | 31,629 | 17,189 | 0.5100 | 383 | 2,052 | 5.3577 |
| Maro, TC-84-06 | 463 | 107,512 | 54,027 | 29,474 | 0.5236 | 462 | 2,324 | 5.0303 |
| Within | -- | -- | -- | -- | -- | 845 | 4,376 | 5.1787 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 23 | 23.0 |
| Common | 847 | 173,600 | 85,656 | 46,663 | 0.5185 | 846 | 4,399 | 5.2003 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 931 | 931.0 |
| Total | 848 | 211,159 | 110,710 | 63,375 | -- | 847 | 5,330 | -- |

$F_{1,\ 845}$ for regression coefficient = 23.0/5.1787 = 4.44 *.

$F_{1,\ 846}$ for adjusted means = 931.0/5.2003 = 179.03 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| Necker | 2,052 | 383 | 5.3577 | 1.6785 | 642.8790 |
| Maro | 2,324 | 462 | 5.0303 | 1.6155 | 746.3519 |
| a = 2 | 4,376 | 845 | -- | -- | 1,389.2309 |

$\bar{s}^2$ = 4376/845 = 5.1787; $\ln \bar{s}^2$ = 1.6446; $df \cdot \ln \bar{s}^2$ = 1389.6479.

$\chi^2$ = 2.3026 (1,389.6479 - 1,389.2309) = 0.9603 NS.

Table 4C.--Analysis of covariance of functional regression of TW2 on CL for male spiny lobster using Townsend Cromwell samples from Necker and Maro ($df_2 = df_1 - 1$).

| | | | | | | Deviations from regression | | |
|---|---|---|---|---|---|---|---|---|
| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
| Necker, TC-84-06 | 256 | 49,397 | 24,262 | 12,913 | 0.5113 | 255 | 996 | 3.9059 |
| Maro, TC-84-06 | 242 | 65,147 | 30,903 | 15,205 | 0.4831 | 241 | 546 | 2.2656 |
| Within | -- | -- | -- | -- | -- | 496 | 1,542 | 3.1089 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 8 | 8.0 |
| Common | 498 | 114,544 | 55,165 | 28,118 | 0.4955 | 497 | 1,550 | 3.1192 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 369 | 369.0 |
| Total | 499 | 135,758 | 68,428 | 36,410 | -- | 498 | 1,919 | -- |

$F_{1,\ 496}$ for regression coefficient = 8.0/3.1089 = 2.57 NS.

$F_{1,\ 497}$ for adjusted means = 369.0/3.1192 = 118.30 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | ln $s^2$ | df · ln $s^2$ |
|---|---|---|---|---|---|
| Necker | 996 | 255 | 3.9059 | 1.3625 | 347.4333 |
| Maro | 546 | 241 | 2.2656 | 0.8178 | 197.0951 |
| a = 2 | 1,542 | 496 | -- | -- | 544.5285 |

$\bar{s}^2$ = 1,542/496 = 3.1089; ln $\bar{s}^2$ = 1.1343; df · ln $\bar{s}^2$ = 562.5928.

$\chi^2$ = 2.3026 (562.5928 - 544.5285) = 41.5949 **.

Table 5A.--Analysis of covariance of functional regression of TW2 and TW3 on CL for female lobster data on Maro ($df_2 = df_1 - 1$).

| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|
| TC-84-06 | 220 | 40,404 | 23,531 | 14,183 | 0.5925 | 219 | 479 | 2.1872 |
| Alaska Gulf | 247 | 57,030 | 34,101 | 22,177 | 0.6236 | 246 | 1,786 | 7.2616 |
| Within | -- | -- | -- | -- | -- | 465 | 2,265 | 4.8710 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 5 | 5.0 |
| Common | 467 | 97,434 | 57,632 | 36,360 | 0.6109 | 466 | 2,270 | 4.8730 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 1,235 | 1,235.0 |
| Total | 468 | 97,907 | 58,680 | 38,675 | -- | 467 | 3,505 | -- |

$F_{1,\ 465}$ for regression coefficient = 5.0/4.9290 = 1.026 NS.

$F_{1,\ 466}$ for adjusted means = 1,235/4.8730 = 253.44 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| TC-84-06 | 479 | 219 | 2.1872 | 0.7826 | 171.3957 |
| Alaska Gulf | 1,786 | 246 | 7.2602 | 1.9824 | 487.6709 |
| a = 2 | 2,265 | 465 | -- | -- | 659.0667 |

$\bar{s}^2$ = 2,265/465 = 4.8710; $\ln \bar{s}^2$ = 1.5833; $df \cdot \ln \bar{s}^2$ = 736.2311.

$\chi^2$ = 2.3026 (736.2311 - 659.0667) = 177.6788 **.

Table 5B.--Analysis of covariance of functional regression of TW2 and TW3 on CL for male and female data combined at Maro ($df_2 = df_1 - 1$).

| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|
| TC-84-06 | 463 | 107,512 | 54,027 | 29,473 | 0.5236 | 462 | 2,324 | 5.0303 |
| Alaska Gulf | 527 | 144,353 | 75,656 | 46,071 | 0.5644 | 526 | 6,419 | 12.2034 |
| Within | -- | -- | -- | -- | -- | 988 | 8,743 | 8.8492 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 28 | 28.0 |
| Common | 990 | 251,865 | 129,683 | 75,544 | 0.5477 | 989 | 8,771 | 8.8690 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 2,004 | 2,004.0 |
| Total | 991 | 252,176 | 130,633 | 78,446 | -- | 990 | 10,775 | -- |

$F_{1,\ 988}$ for regression coefficient = 28/8.8492 = 3.16 NS.

$F_{1,\ 989}$ for adjusted means = 2,004/8.8690 = 225.96 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| TC-84-06 | 2,324 | 462 | 5.0303 | 1.6155 | 746.3519 |
| Alaska Gulf | 6,419 | 527 | 12.2034 | 2.5017 | 1,315.9028 |
| a = 2 | 8,743 | 988 | -- | -- | 2,062.2547 |

$\bar{s}^2$ = 8,743/988 = 8.8492; $\ln \bar{s}^2$ = 2.1803; $df \cdot \ln \bar{s}^2$ = 2,154.1620.

$\chi^2$ = 2.3026 (2,154.1620 - 2,062.2547) = 211.6259 **.

Table 5C.--Analysis of covariance of functional regression of TW2 and TW3 on CL for males at Maro Reef ($df_2 = df_1 - 1$).

| | | | | | | Deviations from regression | | |
|---|---|---|---|---|---|---|---|---|
| Line | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
| TC-84-06 | 242 | 65,147 | 30,903 | 15,205 | 0.4831 | 241 | 546 | 2.2656 |
| Alaska Gulf | 279 | 86,575 | 42,424 | 22,882 | 0.5141 | 278 | 2,093 | 7.5293 |
| Within | -- | -- | -- | -- | -- | 519 | 2,639 | 5.0848 |
| Regression coefficient | -- | -- | -- | -- | -- | 1 | 9 | 9.0 |
| Common | 521 | 151,722 | 73,327 | 38,087 | 0.5010 | 520 | 2,648 | 5.0927 |
| Adjusted means | -- | -- | -- | -- | -- | 1 | 746 | 746.0 |
| Total | 522 | 151,733 | 73,421 | 38,921 | -- | 521 | 3,394 | -- |

$F_{1, 519}$ for regression coefficient 9/5.0848 = 1.77 NS.

$F_{1, 520}$ for adjusted means 746/5.0927 = 146.48 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | ln $s^2$ | df · ln $s^2$ |
|---|---|---|---|---|---|
| TC-84-06 | 546 | 241 | 2.2656 | 0.8178 | 197.0951 |
| Alaska Gulf | 2,093 | 278 | 7.5288 | 2.0187 | 561.2077 |
| a = 2 | 2,639 | 519 | -- | -- | 758.3028 |

$\bar{s}^2$ = 2,639/519 = 5.0848; ln $\bar{s}^2$ = 1.6263; df · ln $\bar{s}^2$ = 844.0245.

$\chi^2$ = 2.3026 (844.0245 - 758.3028) = 197.3828 **.

Table 6A.--Analysis of covariance of functional regression of TW3 on CL for female spiny lobster data collected on commercial vessels ($df_2 = df_1 - 1$).

| Line | | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression: $df_2$ | Deviations from regression: $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Deviations from regression: Mean square |
|---|---|---|---|---|---|---|---|---|---|
| Gardner | *Kona Kai* | 153 | 13,430 | 7,755 | 5,045 | 0.6129 | 152 | 567 | 3.7303 |
| Raita | *Kona Kai* | 114 | 20,473 | 13,155 | 8,579 | 0.6473 | 113 | 126 | 1.1150 |
| Maro | *Alaska G* | 247 | 57,030 | 34,101 | 22,177 | 0.6236 | 246 | 1,786 | 7.2602 |
| Pearl and Hermes Reef | *Kona Kai* | 216 | 21,781 | 13,227 | 8,436 | 0.6224 | 215 | 404 | 1.8791 |
| Within | | -- | -- | -- | -- | -- | 726 | 2,883 | 3.9711 |
| Regression coefficient | | -- | -- | -- | -- | -- | 3 | 42 | 14.0000 |
| Common | | 730 | 112,714 | 68,238 | 44,237 | 0.6265 | 729 | 2,925 | 4.0125 |
| Adjusted means | | -- | -- | -- | -- | -- | 3 | 481 | 160.3333 |
| Total | | 733 | 115,446 | 70,707 | 46,712 | -- | 732 | 3,406 | -- |

$F_{3,\ 726}$ for regression coefficient = 14/3.9711 = 3.53 *.

$F_{3,\ 729}$ for adjusted means = 160.3333/4.0125 = 39.96 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| Gardner | 567 | 152 | 3.7303 | 1.3165 | 200.1048 |
| Raita | 126 | 113 | 1.1150 | 0.1089 | 12.3050 |
| Maro | 1,786 | 246 | 7.2602 | 1.9824 | 487.6709 |
| Pearl and Hermes Reef | 404 | 215 | 1.8791 | 0.6308 | 135.6170 |
| a = 4 | 2,883 | 726 | -- | -- | 835.6978 |

$\bar{s}^2$ = 2,883/726 = 3.9711; $\ln \bar{s}^2$ = 1.3790; $df \cdot \ln \bar{s}^2$ = 1,001.1806.

$\chi^2$ = 2.3026 (1,001.1806 - 835.6978) = 381.0408 **.

Table 6B.--Analysis of covariance of functional regression of TW3 on CL for male and female spiny lobster from on commercial vessels ($df_2 = df_1 - 1$).

| Line | | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|---|
| Gardner | Kona Kai | 247 | 24,701 | 13,468 | 9,035 | 0.6048 | 246 | 1,692 | 6.8780 |
| Raita | Kona Kai | 225 | 34,438 | 20,924 | 13,557 | 0.6274 | 224 | 844 | 3.7679 |
| Maro | Alaska G | 527 | 144,353 | 75,656 | 46,071 | 0.5649 | 526 | 6,419 | 12.2034 |
| Pearl and Hermes Reef | Kona Kai | 351 | 35,134 | 19,919 | 13,177 | 0.6124 | 350 | 1,884 | 5.3830 |
| Within | | -- | -- | -- | -- | -- | 1,346 | 10,839 | 8.0527 |
| Regression coefficient | | -- | -- | -- | -- | -- | 3 | 215 | 71.6667 |
| Common | | 1,350 | 238,626 | 129,967 | 81,840 | 0.5856 | 1,349 | 11,054 | 8.1941 |
| Adjusted means | | -- | -- | -- | -- | -- | 3 | 389 | 129.6667 |
| Total | | 1,353 | 243,707 | 133,997 | 85,118 | -- | 1,352 | 11,443 | -- |

$F_{3,\ 1346}$ for regression coefficient = 71.6667/8.0527 = 8.90 **.

$F_{3,\ 1349}$ for adjusted means = 129.6667/8.1941 = 15.82 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| Gardner | 1,692 | 246 | 6.8780 | 1.9283 | 474.3704 |
| Raita | 844 | 224 | 3.7679 | 1.3265 | 297.1374 |
| Maro | 6,419 | 526 | 12.2034 | 2.5017 | 1,315.9028 |
| Pearl and Hermes Reef | 1,884 | 350 | 5.3829 | 1.6832 | 589.1268 |
| a = 4 | 10,839 | 1,346 | -- | -- | 2,676.5374 |

$\bar{s}^2$ = 10,839/1,346 = 8.0527; $\ln \bar{s}^2$ = 2.0860; $df \cdot \ln \bar{s}^2$ = 2,807.7742

$\chi^2$ = 2.3026 (2,807.7742 - 2,676.5374) = 302.1857 **.

Table 6C.--Analysis of covariance of functional regression of TW3 on CL for male spiny lobster on commercial vessels ($df_2 = df_1 - 1$).

| Line | | $df_1$ | $\Sigma x^2$ | $\Sigma xy$ | $\Sigma y^2$ | Functional regression coefficient | Deviations from regression $df_2$ | $\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}$ | Mean square |
|---|---|---|---|---|---|---|---|---|---|
| Gardner | Kona Kai | 92 | 11,254 | 5,659 | 3,191 | 0.5325 | 91 | 345 | 3.9712 |
| Raita | Kona Kai | 110 | 13,953 | 7,839 | 4,572 | 0.5724 | 109 | 168 | 1.5413 |
| Maro | Alaska G | 279 | 86,576 | 42,424 | 22,882 | 0.5141 | 278 | 2,093 | 7.5388 |
| Pearl and Hermes Reef | Kona Kai | 134 | 12,351 | 7,122 | 4,555 | 0.6073 | 133 | 488 | 3.6692 |
| Within | | -- | -- | -- | -- | -- | 611 | 3,094 | 5.0638 |
| Regression coefficient | | -- | -- | -- | -- | -- | 3 | 88 | 29.3333 |
| Common | | 615 | 124,134 | 63,044 | 35,200 | 0.5325 | 614 | 3,182 | 5.1821 |
| Adjusted means | | -- | -- | -- | -- | -- | 3 | 331 | 110.3333 |
| Total | | 618 | 126,383 | 64,964 | 36,906 | -- | 617 | 3,513 | -- |

$F_{3,\ 611}$ for regression coefficient = 29.3333/5.0638 = 5.79 **.

$F_{3,\ 614}$ for adjusted means = 110.3333/5.1821 = 21.29 **.

Bartlett's test for homogeneity of variance

| Sample | $\Sigma x^2$ | df | $s^2$ | $\ln s^2$ | $df \cdot \ln s^2$ |
|---|---|---|---|---|---|
| Gardner | 345 | 91 | 3.7912 | 1.3327 | 121.2743 |
| Raita | 168 | 109 | 1.5413 | 0.4326 | 47.1552 |
| Maro | 2,093 | 278 | 7.5288 | 2.0187 | 561.2077 |
| Pearl and Hermes Reef | 488 | 133 | 3.6692 | 1.3000 | 172.8955 |
| a = 4 | 3,094 | 611 | -- | -- | 902.5327 |

$\bar{s}^2 = 3{,}094/611 = 5.0638$; $\ln \bar{s}^2 = 1.6221$; $df \cdot \ln \bar{s}^2 = 991.1172$.

$\chi^2 = 2.3026\ (991.1172 - 902.5327) = 203.9748$ **.

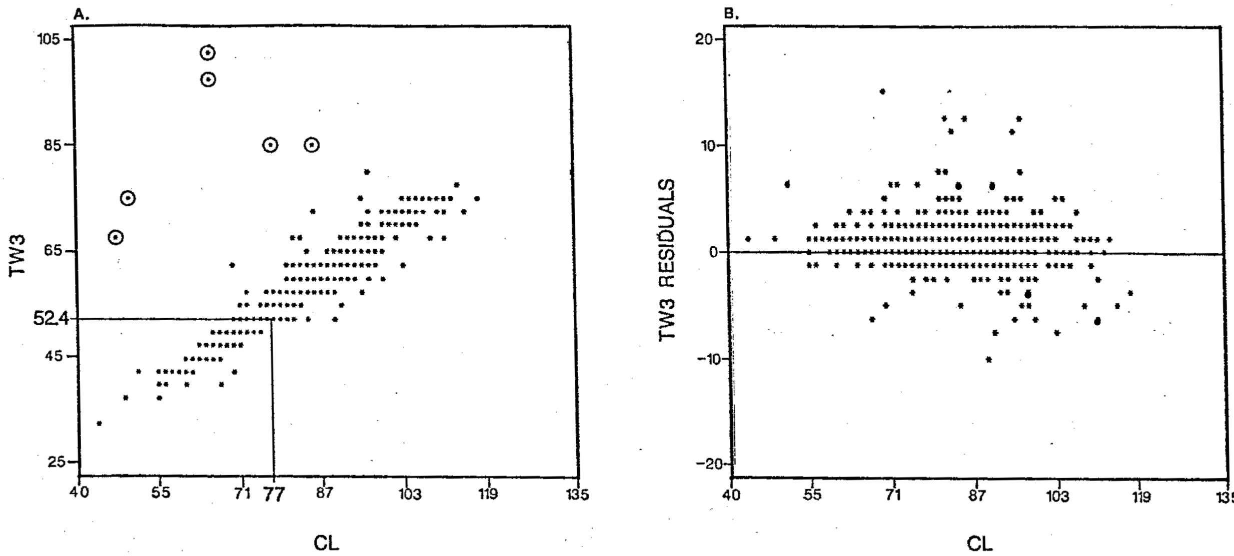


Figure 1.--Linear allometric model for female spiny lobster from both commercial vessels and all islands. A) Scatter plot of TW3 versus CL. The circled data are outliers, and the solid lines indicate equivalent minimum legal sizes. N = 740. B) Deviations from the linear functional regression.

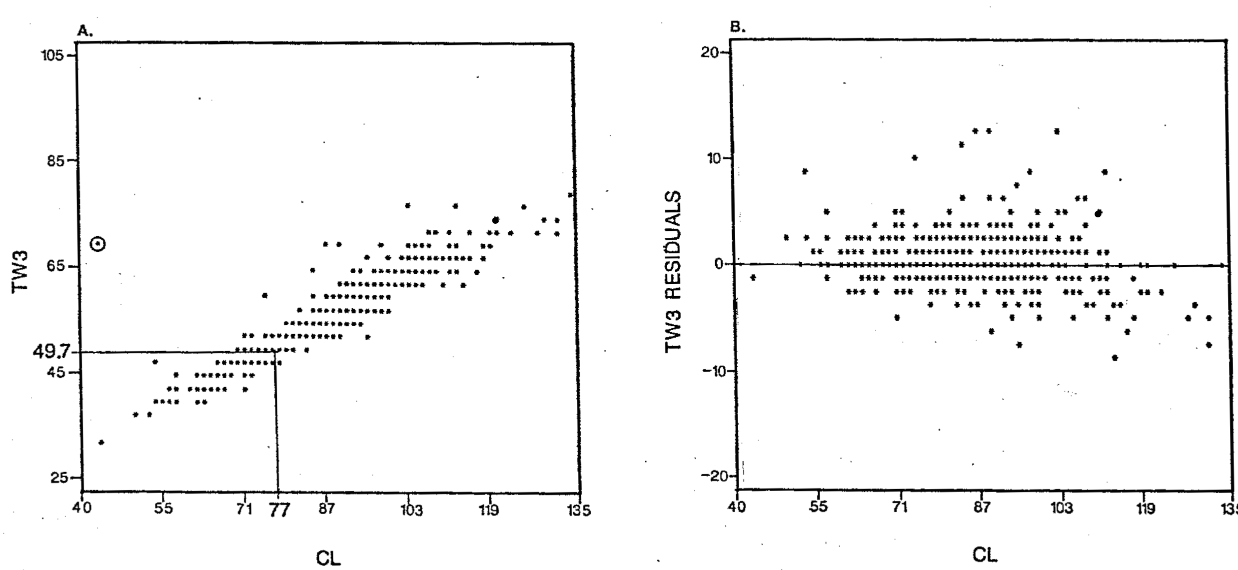


Figure 2.--Linear allometric model for male spiny lobster from both commercial vessels and all islands. A) Scatter plot of TW3 versus CL. The circled datum is an outlier, and the solid lines indicate equivalent minimum legal sizes. N = 620. B) Deviations from the linear functional regression.

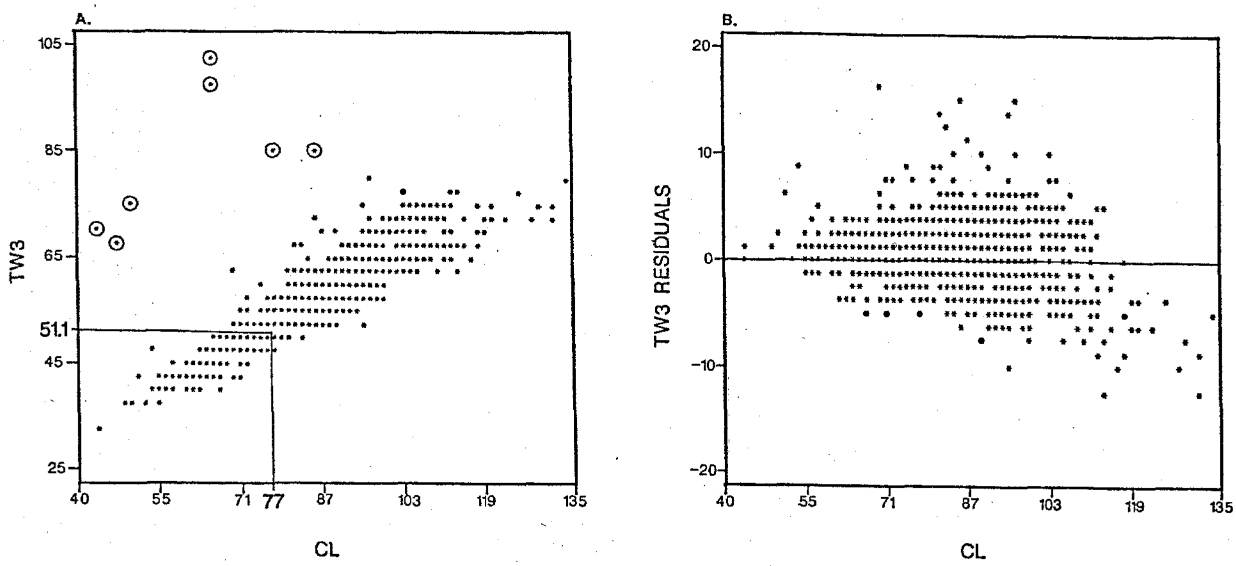


Figure 3.--Linear allometric model for male and female lobster combined from both commercial vessels and all islands. A) Scatter plot of TW3 versus CL. The circled data are outliers, and the solid lines indicate equivalent minimum legal sizes. N = 1,354. B) Deviations from the linear functional regression.

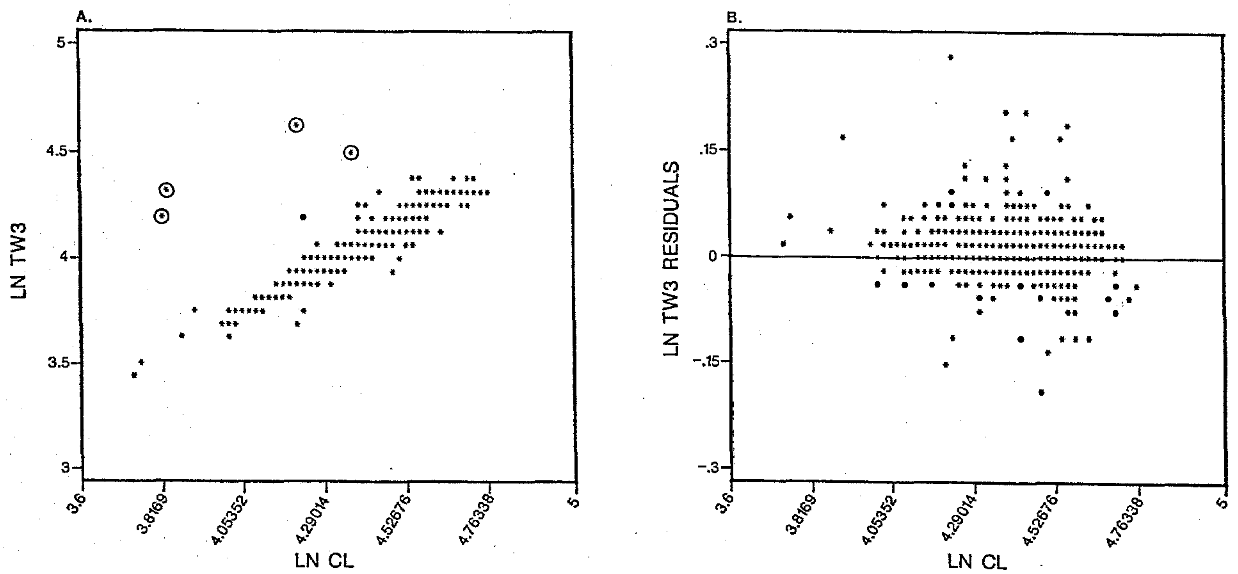


Figure 4.--Log-linear allometric model for female spiny lobster from both commercial vessels and all islands. A) Scatter plot of ln TW3 versus ln CL. The circled data are outliers. N = 740. B) Deviations from the log-linear functional regression.

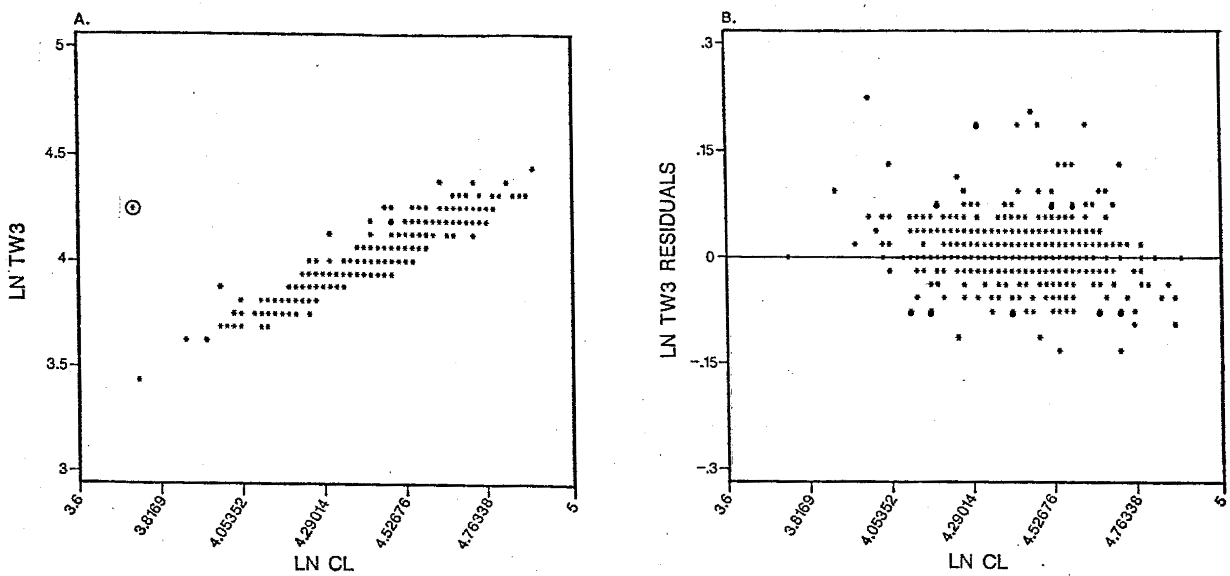


Figure 5.--Log-linear allometric model for male spiny lobster from both commercial vessels and all islands. A) Scatter plot of ln TW3 versus ln CL. The circled datum is an outlier. N = 620. B) Deviations from the log-linear functional regression.

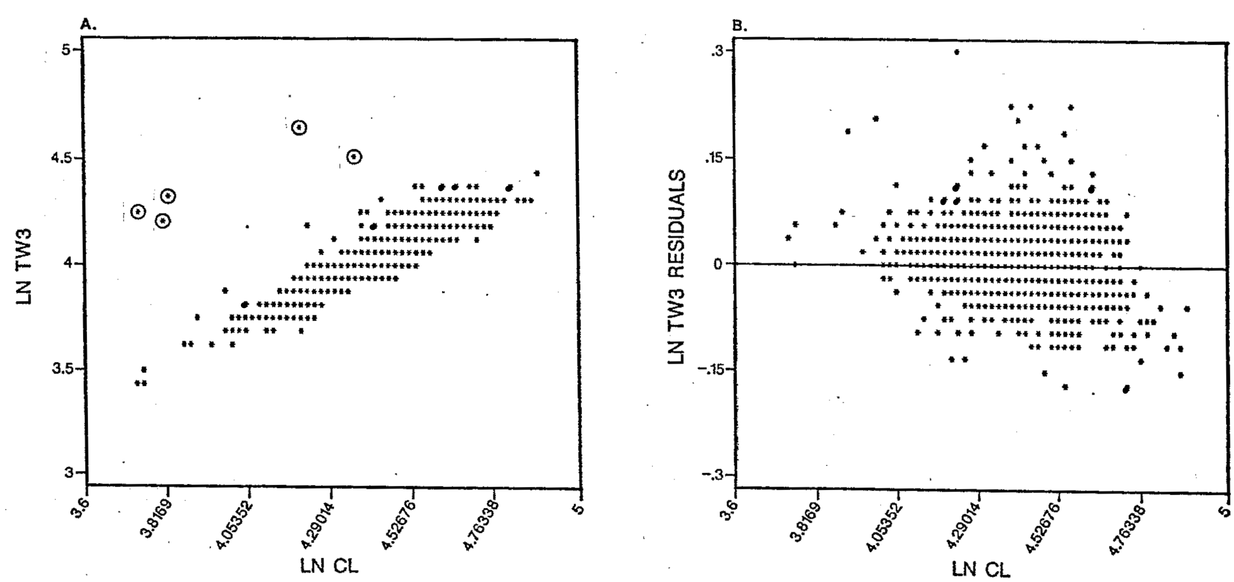


Figure 6.--Log-linear allometric model for male and female spiny lobster from both commercial vessels and all islands. A) Scatter plot of ln TW3 versus ln CL. The circled data are outliers, N = 1,354. B) Deviations from the log-linear functional regression.

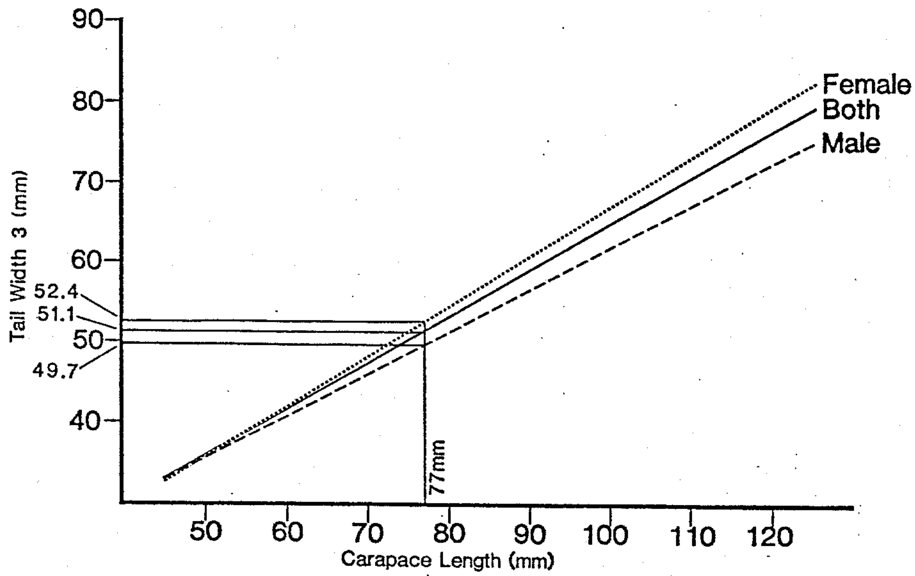


Figure 7.--Functional regression of TW3 on CL by sex category for observer data pooled across all islands. Estimated TW3 values that are equivalent to 77 mm CL minimum legal size are given.

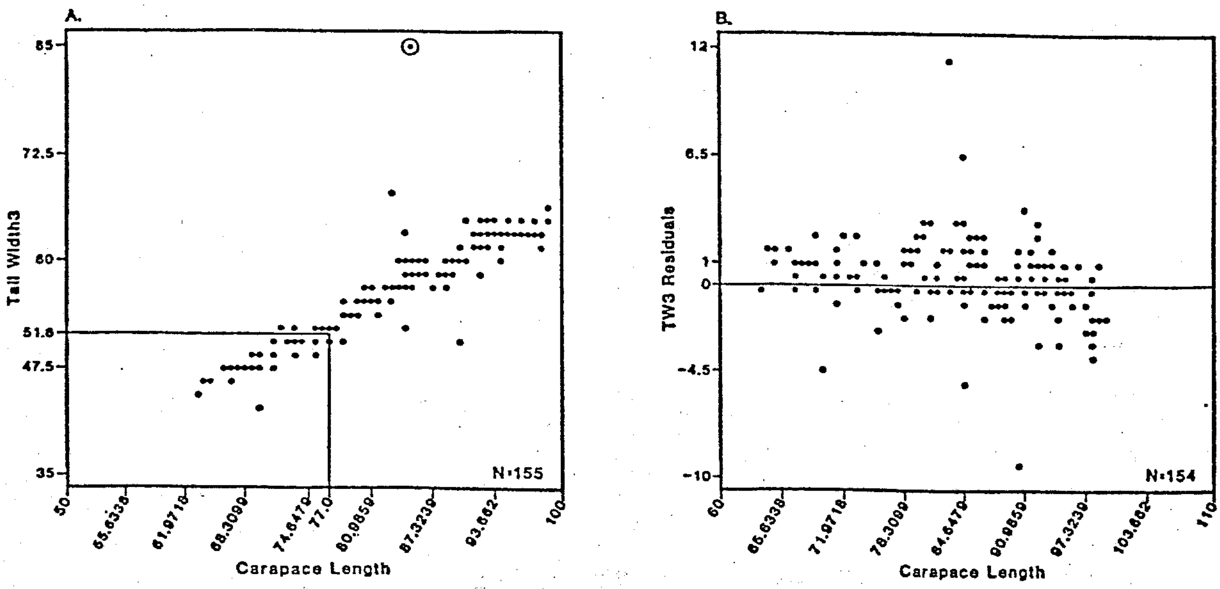


Figure 8.--Female spiny lobster at Gardner Pinnacles. A. Scatter plot of TW3 and CL. The circled data point indicates an outlier, and the solid lines indicate equivalent minimum legal sizes. B. Deviations from the linear functional regression.

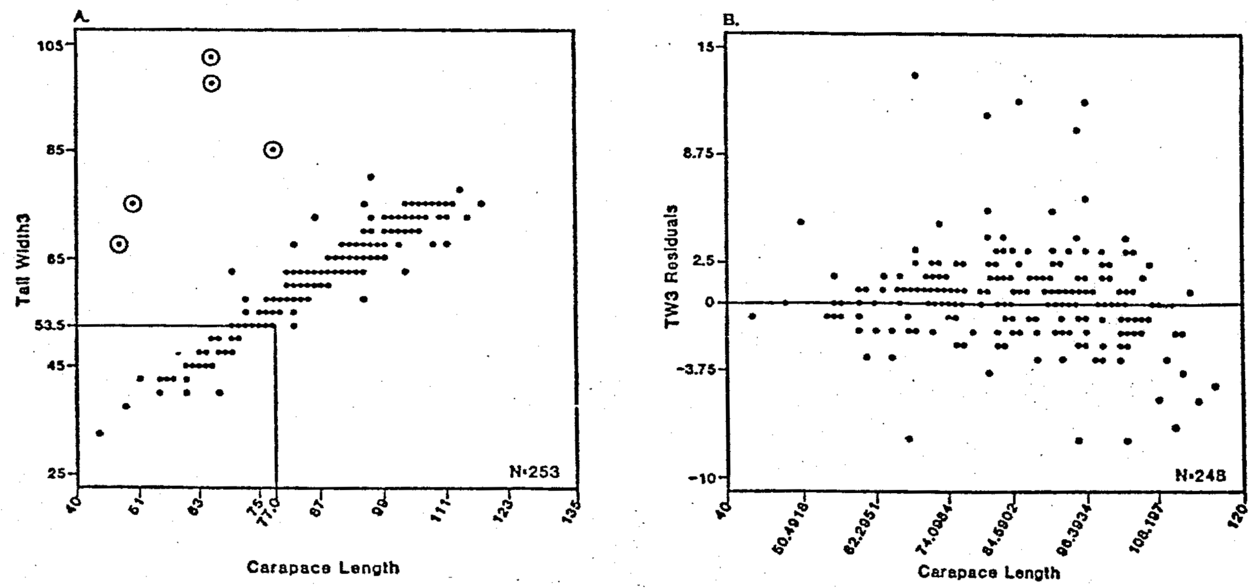


Figure 9.—Female spiny lobster at Maro Reef. A. Scatter plot of TW3 and CL. The circled data points indicate outliers, and the solid lines indicate equivalent minimum legal sizes. B. Deviations from the linear functional regression.

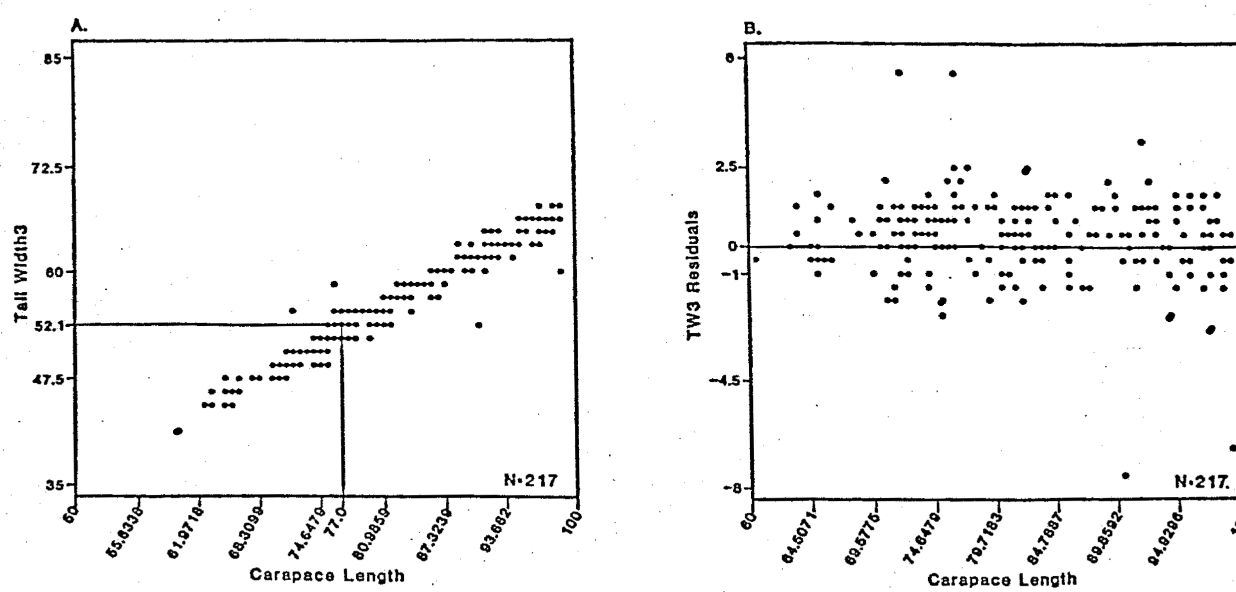


Figure 10.—Female spiny lobster at Pearl and Hermes Reef. A. Scatter plot of TW3 and CL. The solid lines indicate equivalent minimum legal sizes. B. Deviations from the linear functional regression.

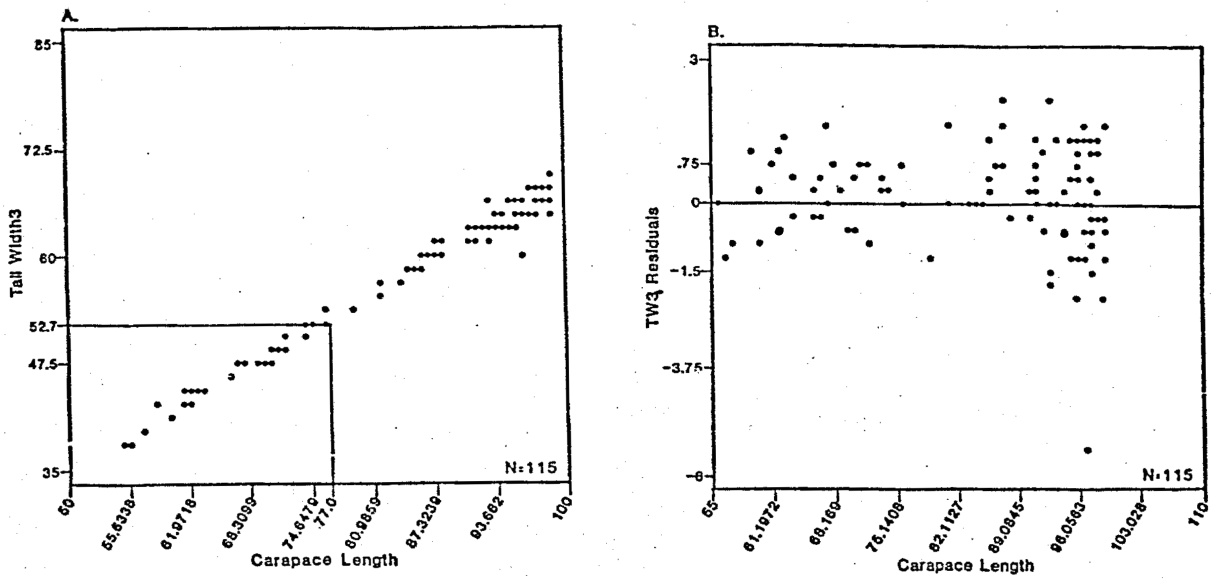


Figure 11.--Female spiny lobster at Raita Bank. A. Scatter plot of TW3 and CL. The solid lines represent equivalent minimum legal sizes. B. Deviations from the linear functional regression.

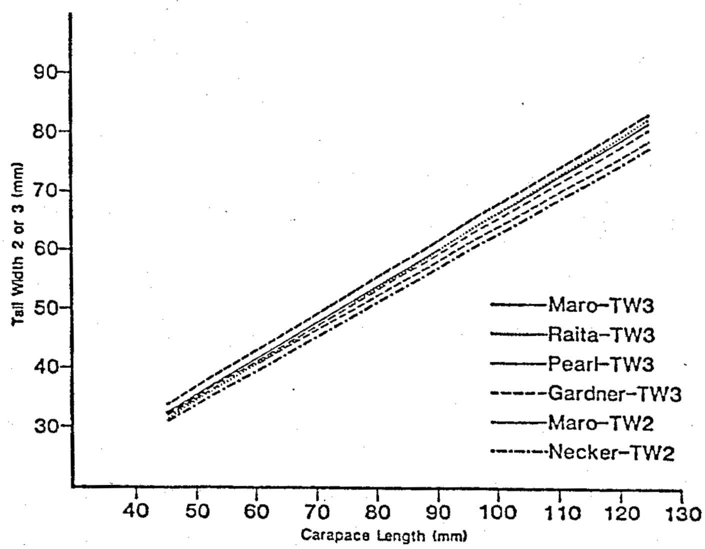


Figure 12.--Functional regression of TW on CL for female spiny lobster, by island.

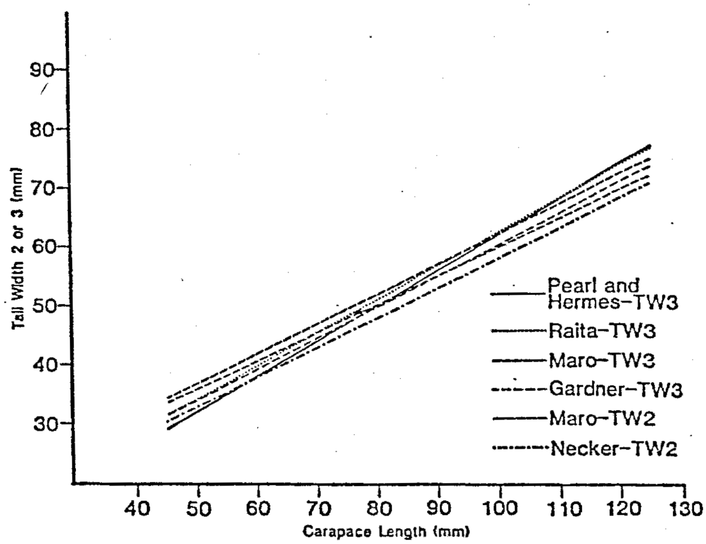


Figure 13.--Functional regression of TW on CL for male spiny lobster, by island.

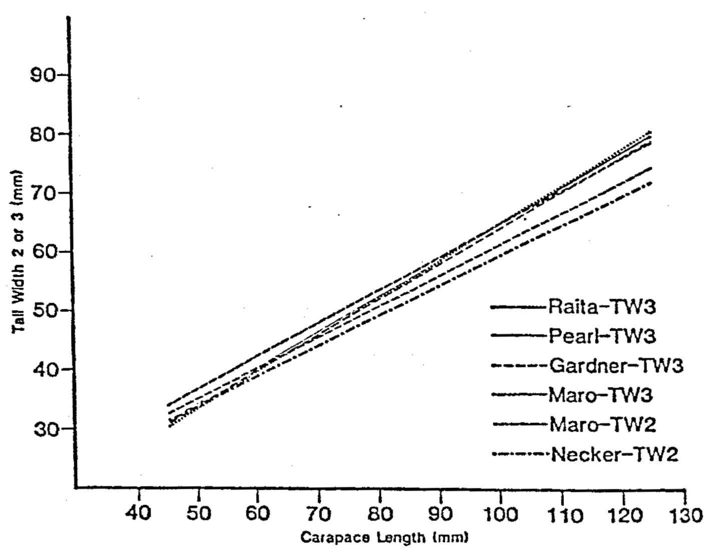


Figure 14.--Functional regression of TW on CL for spiny lobster with both sexes combined, by island.

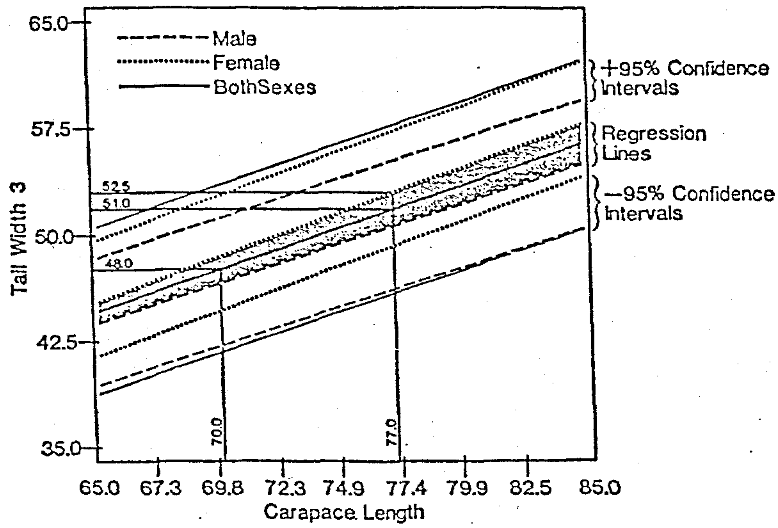


Figure 15.--Relationship between TW3 and CL by sex for all islands sampled by observers and the 95% confidence interval about the functional regression line. The horizontal and vertical lines show estimates of TW3 and CL for sizes proposed for enforcement purposes.

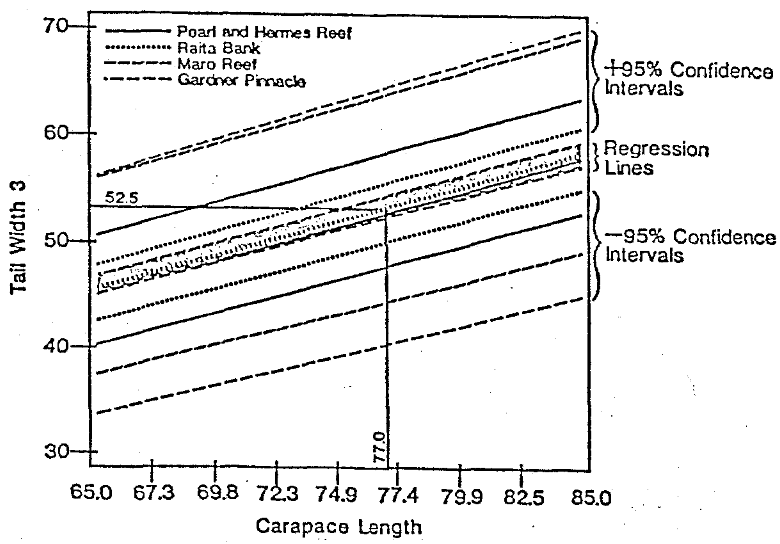


Figure 16.--Relationship between TW3 and CL for female spiny lobster by area sampled by observers and the 95% confidence interval about the functional regression line. The horizontal and vertical lines show estimates of TW3 for 77 mm CL based on a regression pooled over all islands.