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Estimation of Halibut Body Size from Otolith Size

by

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ABSTRACT

From 1962 through 1990, the International Pacific Halibut Commission estimated the sizes of fish in the commercial catch from the sizes of their otoliths, using a series of statistical predictors developed over the years. It was recognized that the relationship between otolith size and body size depended on growth rate and therefore could vary among regions and over time, but this was not regarded as a serious problem. Over the last ten years, however, there has been a major change in the relationship in the central and western Gulf of Alaska, a smaller change in Southeast Alaska, and very little change in British Columbia. Because of these variations over time, it now appears that otolith size is not a sufficiently reliable predictor of body size for routine use in estimating mean size in the catch or monitoring changes in growth schedule. For both purposes, the Commission in 1991 resumed its earlier practice of measuring the lengths of fish in the commercial catch sample when collecting otoliths.

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BACKGROUND

Since 1933, the International Pacific Halibut Commission has sampled commercial halibut landings to estimate the age and size composition of the catch. In conjunction with reports of total landings in weight, the mean weight of fish in the sample has also been used to estimate the numbers of fish in the catch by age. In recent years, catch-at-age analysis based on these estimates has been the primary source of staff advice on stock size and catch limits.

Hardman and Southward (1965) give a history of the development of sampling techniques. Before 1962, the catch was sampled by measuring the lengths of a large number of fish from every sampled landing and collecting a sample of otoliths from each length interval in the landing. The age composition of the landing was estimated by keying out the sample length distribution, and the net (i.e., headed and gutted) weight of the fish was estimated by applying the Commission's standard length-weight relationship to the sample lengths:

$$W_N = 6.92 \times 10^{-6} \times L_F^{3.24}$$

where L_F is fork length in centimeters and W_N is net weight in pounds.

Thanks to the large number of length measurements, this procedure provided good estimates of size and age composition, but it required a crew of three to perform the sampling: one cutting otoliths, one measuring, and one recording.

Southward (1962) estimated a linear (log-log) relationship between otolith radius and body length that allowed the Commission to calculate a length corresponding to each sampled otolith. It was then possible for one person to sample a landing, cutting a large number of otoliths but not having to measure lengths or record any specimen data. Back at the office, an estimated length distribution was calculated from the otolith radii, and otoliths from each length interval were chosen for aging to construct a key that was applied to the estimated length distribution to estimate the age composition. Net weights of the fish in the sample were calculated from the estimated lengths using the Commission's length-weight relationship.

This procedure would provide good estimates of age composition even if the lengths estimated from otolith radii were biased, since it amounted to obtaining a good estimate of the otolith radius distribution and subsampling it for age, which is just as effective as estimating and subsampling the body length distribution, as had been done before. However, if the estimated lengths were biased, the procedure would not provide good estimates of mean weight in the catch, and therefore the estimates of numbers caught at each age would be biased.

When estimating the relationship between otolith radius and body length, Southward (1962) used a very diverse set of data from Commission tagging cruises, covering years from 1926 through 1957, areas from central British Columbia to the Bering Sea, and trawl as well as longline catches. He tested for differences in the relationship between early data (1925-1934) and later data (1935-1957), and between "southern" data (presumably the present Area 2, British Columbia and Southeast Alaska) and "western" data (presumably the present Areas 3 and 4, central and western Gulf of Alaska and Bering Sea). He found statistically significant differences among the regressions, the early fish being smaller than the later fish at a given otolith radius, and the southern fish being smaller than the western fish. At the time, however, he argued that the differences were not large enough to be of any practical importance, and advocated the use of a single predictive equation for all areas and years. He applied this equation to data from the Portlock-Albatross grounds (off Kodiak Island) to estimate changes in growth schedule during the period 1935-1957, and the Commission applied the equation to commercial catch data during the years 1962-1967.

Because it was easier to measure, otolith length was adopted in place of otolith radius in 1968, and a single (log-log) regression of body length on otolith length was used to estimate lengths in the commercial catch in the years 1968-1970 (Southward and Hardman 1973). Further analysis of "current data" (presumably data from around 1970) showed that, at least in some areas, a cubic equation in (log) otolith length fitted the observations of (log) body length significantly better than a linear equation. The analysis also showed, again, that there were significant differences among areas in the relationship, and this time an equation was fitted for each of four regions: British Columbia, Southeast Alaska, Gulf of Alaska, and Bering Sea. No tests were done to check for a difference over time in the relationship, but Southward and Hardman noted that halibut growth rates differed among regions and had increased coastwide since the beginning of the fishery early in the century. They therefore cautioned:

> "The determination that separate regression lines are needed for current data from regions where the growth rates differ implies that the relationship between otolith and fish length is dependent on the growth rate. Further, this indicates that the regressions described in this report must be validated from time to time and that these regressions cannot be used to estimate fish length from otoliths collected during earlier periods of the fishery."

The four regional log-log cubic equations were used to estimate body lengths from otolith lengths during the years 1971-1977. In 1978, otolith weight was adopted in place of otolith length as the measure of otolith size, partly for convenience but also because it gave a more precise estimate of body length (Quinn et al. 1983).

Because of the earlier finding that the otolith length-body length relationship had changed since the beginning of the fishery, only data from the years 1954-1978 were used to estimate the current otolith weight-body length relationship (R.J. Myhre, former IPHC staff, pers. comm.). As before, the data included fish from all regions, research as well as commercial catches, and trawl as well as longline catches. A cubic equation of otolith weight was found to predict fork length well, without the need for a logarithmic transformation. At first five separate regional equations were fitted, but in 1980 it was decided that two regional equations were adequate, and these constituted the standard predictor of fork length from otolith weight throughout the 1980s. For the area south of Cape St. Elias, the standard predictor is (Quinn et al. 1983):

$$L_F = 16.3 + 0.499 \times W_O - 0.528 \times 10^{-3} \times W_O^2 + 0.242 \times 10^{-6} \times W_O^3$$

where L_F is fork length in centimeters and W_O is otolith weight in milligrams. For the area west of Cape St. Elias, the standard predictor is:

$$L_F = 21.0 + 0.409 \times W_O - 0.373 \times 10^{-3} \times W_O^2 + 0.153 \times 10^{-6} \times W_O^3$$

These two equations will be referred to collectively as "the standard predictor" throughout this paper.

In the early 1980s, IPHC staff compared the actual and predicted weights of fish in a number of commercial landings, mostly in Prince Rupert, and found that the predictions were low by about 10% on average. To compensate for this bias, the estimated weights of fish in the catch in years after 1978 were adjusted upward by 10% when catch-at-age analysis was performed in the course of doing the annual stock assessment during the 1980s (Quinn et al. 1985; Ian McGregor, pers. comm.). (More precisely, weights and numbers in the catch were estimated, and published in some tables, without any corrections. But for the purpose of doing the annual stock assessment, the uncorrected estimates of catch at age in number were scaled down by 10%. These numbers were used to estimate stock size in number, and exploitable biomass was computed as the product of these numbers and the corrected weight estimates. As regards the stock assessment, this procedure had the same effect as adjusting the weight estimates upward in the first place and then estimating the numbers accordingly.)

In 1988, the Commission chartered the longliner *Polaris* to conduct experimental fishing near Kodiak. All the fish landed from this trip were weighed individually, and this time a comparison of the predicted and actual weights showed that the predictions were *high* by about 10% on average. Also, the stock assessment done at the end of 1988 showed a decline in exploitable biomass due in part to a steady decrease after 1986 in mean weight at age, inferred from a decrease in the mean weight of otoliths at each age. The apparent decrease in mean weight was more pronounced among older fish and therefore suggested a change in the sex ratio, since among older fish females (and their otoliths) are considerably larger than males.

Both the *Polaris* data and the mysterious drop in estimated mean weight at age prompted the Commission to conduct a series of charter collections in 1989 on commercial halibut grounds from British Columbia to the Aleutians. All fish caught on these trips were sexed, measured, and weighed, and the otoliths were aged and weighed. The aim of this project was to collect a large synoptic data set to investigate differences in the otolith weight-body weight relationship due to sex, age, area of capture, and time of year (i.e., early summer versus late summer).

This paper presents an analysis of the data collected in 1989 and a review of historical data from the 1970s and 1980s. The conclusions of the study are:

(i) There are differences due to age and sex in the otolith size-body size relationship, but the differences are not of much practical importance for the purpose of estimating mean weight at age in the commercial catch, which always consists of a mixture of females and males of a range of ages.

(ii) There are differences among areas and years in the otolith size-body size relationship, and these differences can obviously cause a considerable bias in the estimate of mean weight in any given area and year if a single predictor is used year after year.

(iii) There are no differences due to age, sex, area, or year in the length-weight relationship; the standard length-weight predictor always produces an estimate of the mean weight of any group of fish that is close to the actual mean weight.

(iv) Therefore, in order to get a good estimate of mean weight in the catch, the fish chosen for the otolith sample should also be measured so that their body weights can be estimated from their body lengths rather than from their otolith weights.

MATERIALS AND METHODS

Data Available

All of the data used in this study came from longline catches taken on Commission charter trips during the years 1976-1989. The distribution of data (specimens) by year and area is shown in Table 1.

Table 1. Distribution of specimen data (numbers of fish) by regulatory area and year. (See Figure 1 for location of regulatory areas.)

	IPHC regulatory area			
Year	2B	2C	3A	3B
1976	198			117
1977	212		810	
1978	229		600	
1979			872	
1980	468	987	1368	
1981	424		1755	912
1982	445	769	1577	822
1983	361	1818	1523	
1984	1313	2179	1196	
1985	891	2132	1193	
1986	792	2044	1174	
1987				
1988			927	
1989	706	914	2738	877

In 1976-1986, each of these trips was a systematic survey of part of the coast, with stations located at regular intervals along regularly spaced inshore-offshore transects. About half of the fish caught on these surveys were tagged and released; specimen data is available for the other half, which were not suitable for tagging (Hoag et al. 1980).

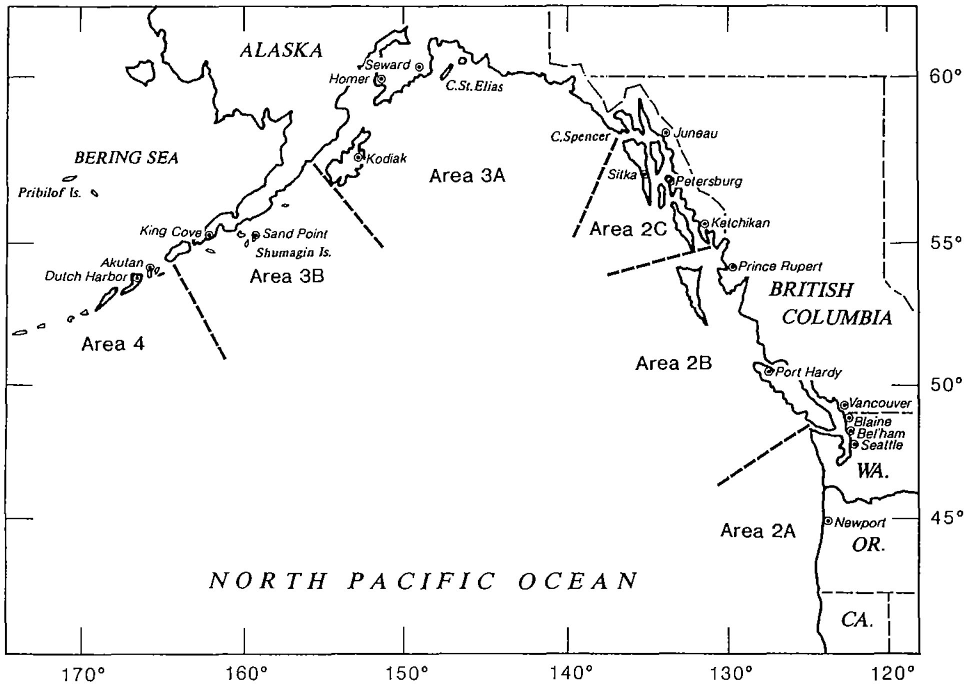

Figure 1. **IPHC regulatory areas.**

Length distributions do not indicate any important difference between the tagged and untagged groups, and there is no other reason to suppose that they might differ in respect of the otolith size-body size relationship. The specimen data collected on the surveys includes fork length, sex, age, and otolith weight, but not body weight. On the 1988 and 1989 charters, described above, individual (net) body weights were taken.

Equivalence of Body Length and Body Weight

As an example of the relationship between otolith weight and body weight, Figure 2 shows a scatterplot of data from all fish caught on the 1989 charters (Panel A). It is clear that body weight increases as a power function of otolith weight, so on a log-log scale the relationship is approximately linear, with a great deal of variation about the trend (Panel B). Plotting the otolith weight-body weight relationship and the body length-body weight relationship together (Panel C) shows that body length gives a much more precise prediction of body weight than does otolith weight. (The standard deviation of log body weight is about 0.30 at any given otolith weight, but it is only about 0.11 at a given body length).

In addition to being very close, the length-weight relationship is very consistent. When applied to the lengths of fish caught in 1988 and 1989, the standard length-weight equation — fitted long ago to historical data — gives a very good estimate of their mean weight. Nor is there any practical difference due to region or sex in the length-weight relationship; it gives a very good estimate of mean weight whether the lengths refer to females in Area 3A or males in Area 2B or any other definable subgroup.

For both reasons, to estimate the mean weight of any group of fish it is sufficient to know their lengths. Similarly, to investigate historical changes in the relationship

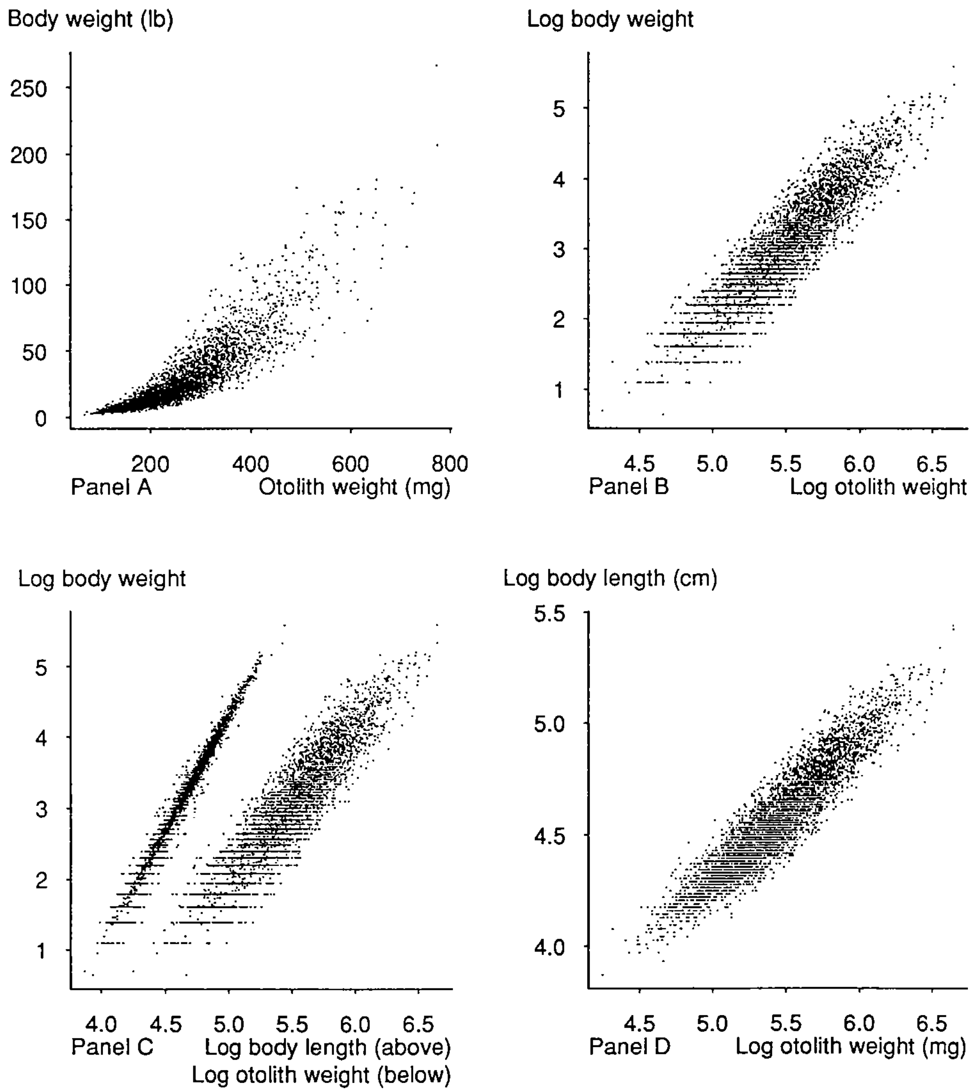

Figure 2. **Relationships among body measurements in fish caught in 1989. (Outlying 1% of points removed from every plot.)**

between otolith weight and body weight, it is sufficient to investigate historical changes in the relationship between otolith weight and body *length*, which is fortunate because only length is available in most of the specimen data. The remainder of this analysis will therefore deal with the latter relationship, shown for the 1989 data in Panel D of Figure 2. Not surprisingly, the log-log scatterplot of body length against otolith weight looks very similar to the plot of body weight against otolith weight (Panel B).

Form of the Relationship and Effect of the Size Limit

When all of the 1989 data are plotted on a log-log scale, the scatterplot of body length against otolith weight appears to be approximately linear (Figure 3, Panel A), and this is confirmed by running a scatterplot smoother through the data (Panel C).

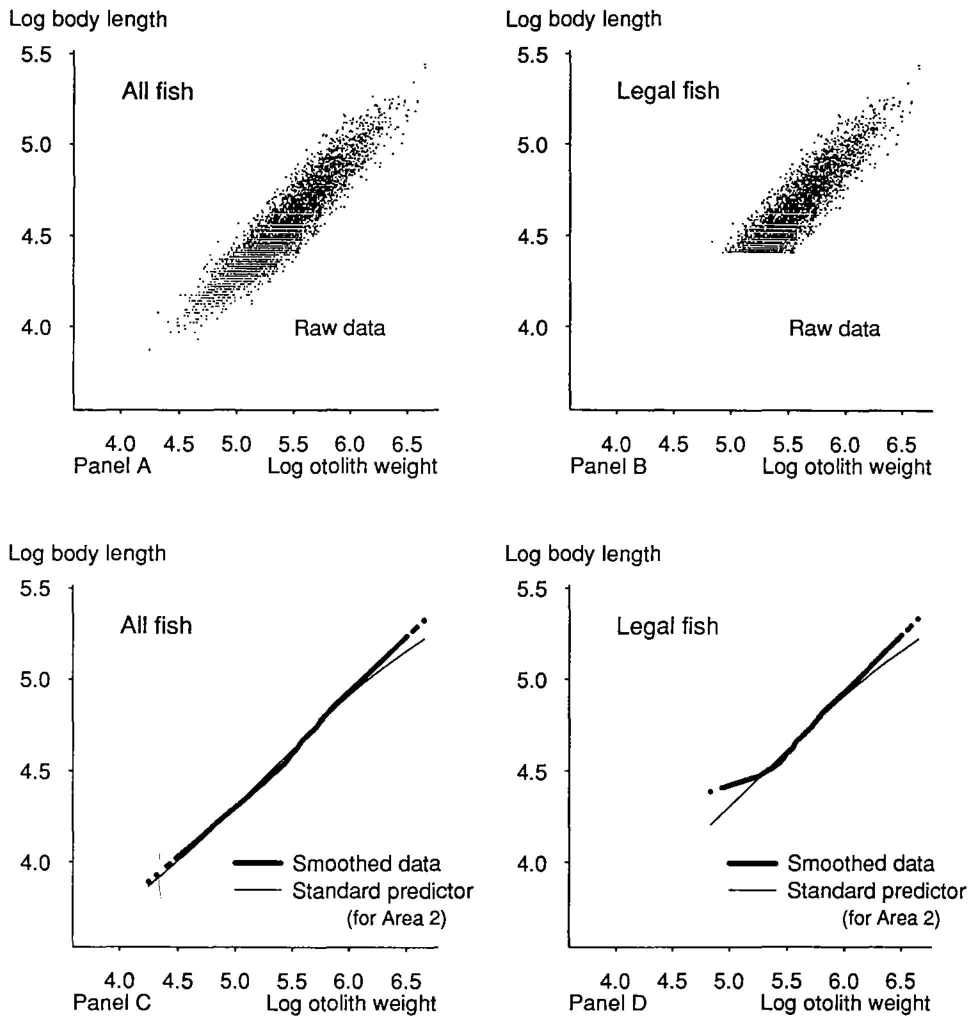

Figure 3. **Otolith weight-body length relationship for all fish and for legal fish. (Data refer to fish caught in 1989. Legal fish are those > 81 cm.)**

Also, the standard predictor for Area 2 (which is south of Cape St.Elias) tracks the trend of the data very closely.

The picture is quite different when only the data on legal fish (greater than 81 cm) are plotted. The effect of the size limit is to truncate the distribution of body length abruptly across a range of otolith weights, running from about 5 to 5.5 on the log scale (Panel B). This range of otolith weights accounts for about a third of the legal fish caught on the 1989 charters. Within this range, the mean body length among legal fish will obviously be greater than among all fish, since the sublegals are excluded. This is clearly shown by the upturn in the scatterplot smoother below a log otolith weight of about 5.4 (Panel D). Note that the standard predictor does not track this upturn; it was fitted to data on sublegal as well as legal fish (including trawl-caught fish), and as a result it substantially underestimates the body lengths of *legal* fish with small otoliths. This feature of the otolith weight-body length relationship among legal fish doubtless contributed to the underestimation of mean weights of fish in commercial landings that was detected in the early 1980s.

The Commission's interest is in estimating the sizes of fish in commercial landings from the weights of their otoliths. The form of the otolith weight-body length relationship for this purpose is the one observed among legal fish: above a log otolith weight of about 5.4, log body length increases almost linearly with log otolith weight, while below a log otolith weight of 5.4, the relationship is nonlinear and weak. (Because all legal fish are at least 81 cm, average body length cannot vary much with otolith weight at the lower end of the otolith weight range observed in commercial landings.)

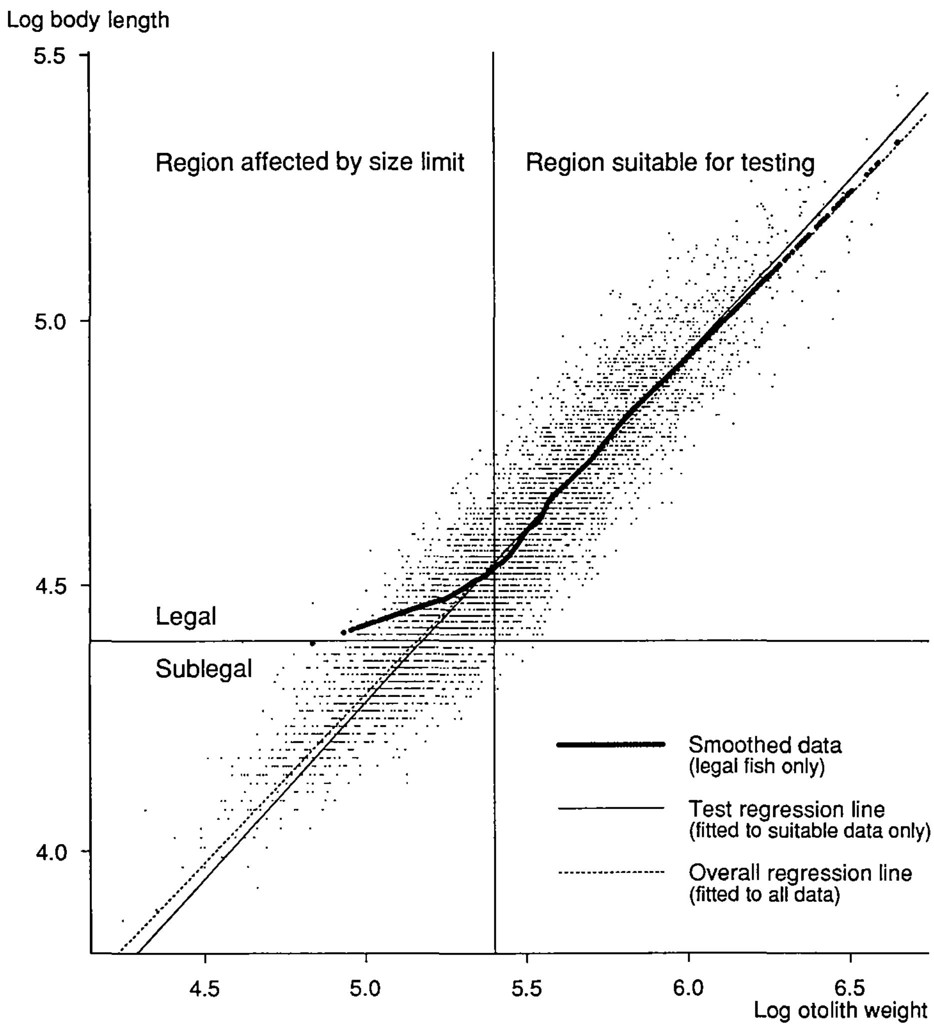

Figure 4. **Data suitable for testing differences in the relationship (i.e., legal fish with otolith weights beyond the region affected by the size limit. 1989 data shown.)**

Method of Testing for Differences

A straightforward test for differences in the otolith weight-body length relationship – e.g., between females and males, or among areas or years – can be performed by comparing regression lines fitted to that part of the data lying above a log otolith weight of 5.4. In this region, the relationship is approximately linear and there is a reasonably symmetric distribution of data points above and below the trend line. For both reasons, the data in this region are suitable for fitting regressions and testing differences between regressions. Below a log otolith weight of 5.4, the trend turns upward for legal fish, and the distribution of log body lengths is cut off abruptly by the size limit (Figure 4). Note that when, as in Figure 4, the data cover a wide range of otolith weights, the regression fitted to only the upper part of the otolith weight range is quite close to the regression fitted to all of the data.

The comparison between groups will be made by fitting regressions to the data for each group separately, estimating the mean log body length according to each regression at the overall mean log otolith weight, and testing for a statistically significant difference between the estimates. If the two estimates of mean body length at the mean log otolith weight do not differ, then either regression would give the same estimate of mean length when applied to the entire set of otolith weights, which is to say that there is no difference between the regressions as regards estimating body length from otolith weight.

An alternative approach would be to test for a significant difference between the regressions themselves, or between the regression coefficients. The shortcoming of this approach is that two groups can have significantly different regression lines but still produce the same estimate of mean log body length (e.g., because the regressions cross in the vicinity of the mean log otolith weight). Thus even when a test of this kind showed a difference, it would still be necessary to compute the two estimates of mean log body length and see whether they were significantly different, because that is the practical issue. Rather than carry out an inconclusive test for a difference between the regressions, therefore, the method used here will be to proceed directly to a conclusive test for a difference between the estimates obtained from the regressions.

A direct comparison of the estimates has the added advantage of showing the size of any significant difference. In many cases there are enough data to detect very small significant differences, which are not of any practical importance.

As an example, Figure 5 shows regressions fitted to fish caught in Area 3A early and late during the 1989 field season to determine whether there was any seasonal difference in the relationship. There is a significant difference between the regressions ($F = 4.27$ with 2 and 1472 df; $\alpha = 0.014$), but the regression lines cross and the two lines are nearly coincident through the great bulk of the data, so it is not clear that these two data sets would provide different estimates of mean log length. Those two estimates and their standard deviations are given at the bottom of the table. The early data imply an estimate of mean log body length ("ym" in the figure) of 4.76 at the overall mean log otolith weight (given as 5.73 in the figure legend). At the same value of log otolith weight, the late data imply an estimate of 4.77, or about 1% greater. The standard deviations of these estimates of mean body length ("sm" in the figure) are nearly zero owing to the large number of data points, so the standard deviation of the difference between the estimates is also very small and the difference of 1% is therefore significant in the usual statistical sense of exceeding two standard deviations (corresponding to a confidence level of 95%.) But while statistically significant, a 1% difference is of no practical importance, so this comparison shows that the seasonal effect is negligible.

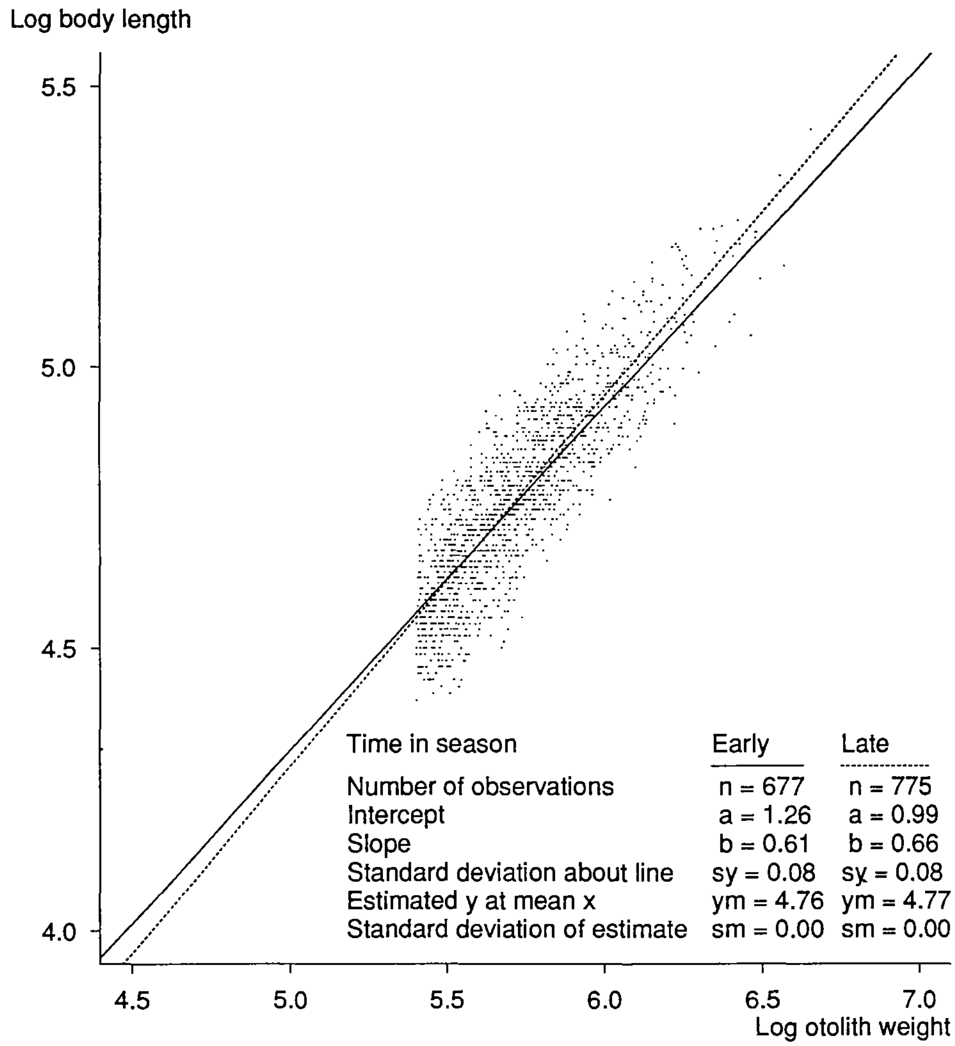

Figure 5. **Regressions and estimates for 3A fish caught early and late in 1989. (Mean log otolith weight for all fish = 5.73.)**

In all of the comparisons reported below, the estimates of mean log body length at an overall mean log otolith weight, and the standard deviations of those estimates, are shown in the relevant figure in the same format as in Figure 5. The standard deviation of the difference between the two estimates, while not shown, can be obtained in each case as the square root of the sum of squares of the standard deviations of the estimates. If the absolute difference between two estimates exceeds two standard deviations of the difference, the two groups in question are reported in the text to be significantly different (in the statistical sense) as regards the otolith weight-body length relationship. If the difference is less than two standard deviations, the two groups are reported as not being different. In some of these cases there may in fact be a difference in regression coefficients, but the important point is that there is no difference in the prediction of overall mean log body length between the two groups.

Method of Fitting Predictive Equations

It is convenient to fit regressions to a part of the data to test for differences in the otolith weight-body length relationship, but for making actual predictions of body length corresponding to various otolith weights, a computing formula is needed that provides a good approximation to the data over the entire range of otolith weights observed among fish of legal size. A "good approximation to the data" for this purpose means reproducing the average value of body length observed in the data at each otolith weight. This is exactly what the scatterplot smoother does, so a good predictive equation is any curve of convenience that closely approximates the smoothed data on which the predictions are to be based. (The smoother used for this purpose estimates the mean value of the dependent variable at each point from a local least-squares

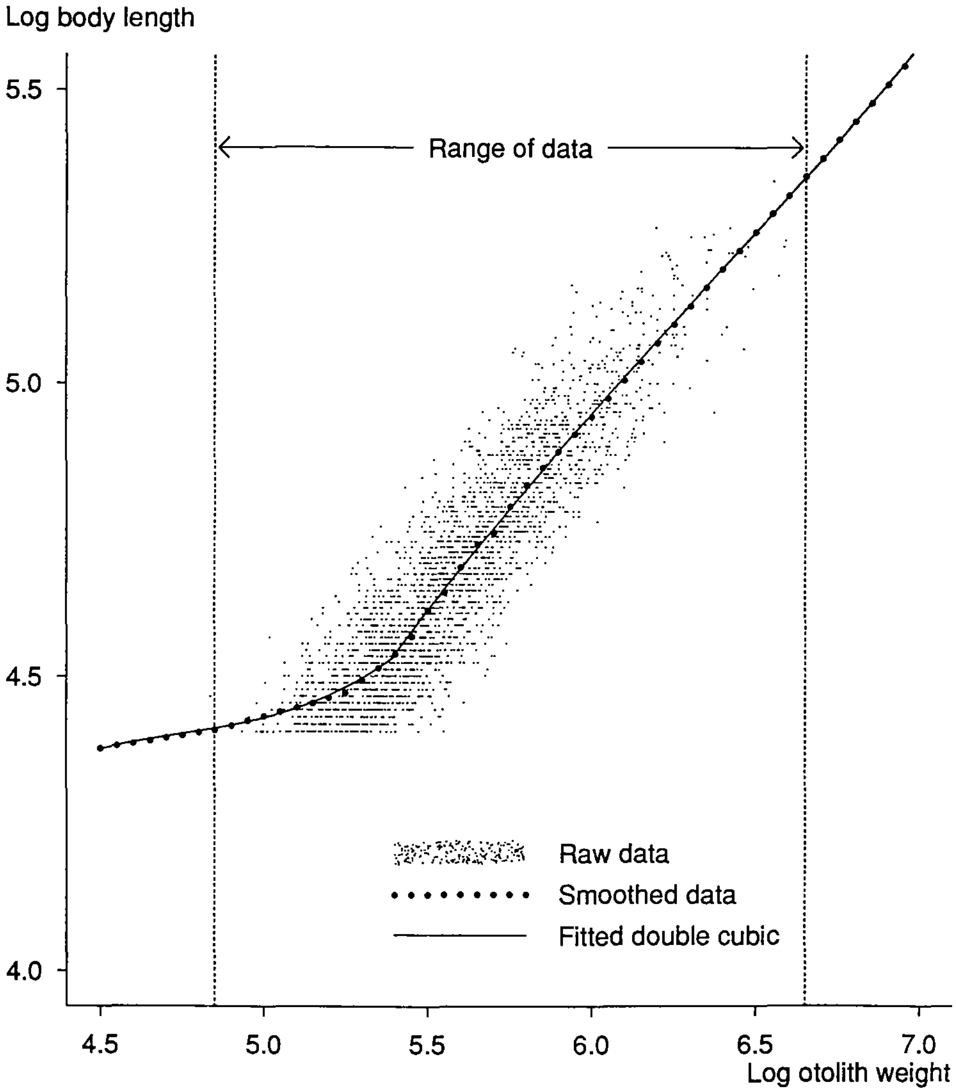

Figure 6. **Area 3 data from 1989, with fitted double cubic (break at x = 5.4).**

regression at each point. The size of the interval used for the regression is adjusted so as to minimize the variance of the estimate.)

As explained above, the effect of the size limit is to divide the otolith weight-body length relationship for legal fish into two parts at a log otolith weight of about 5.4. On the lower (left-hand) section, the graph is flatter and curved upward (Figure 4). On the upper (right-hand) section, the graph is steeper and nearly linear, but there is a very slight downward curvature. Both sections can be fitted very closely by running a separate cubic equation through the path of the data smoother on each side of the break at 5.4, as shown in Figure 6. (The two cubics were fitted separately by ordinary least squares to 50 data points equally spaced along the path of the data smoother, as shown in the figure. This was not a cubic spline regression, and no attempt was made to

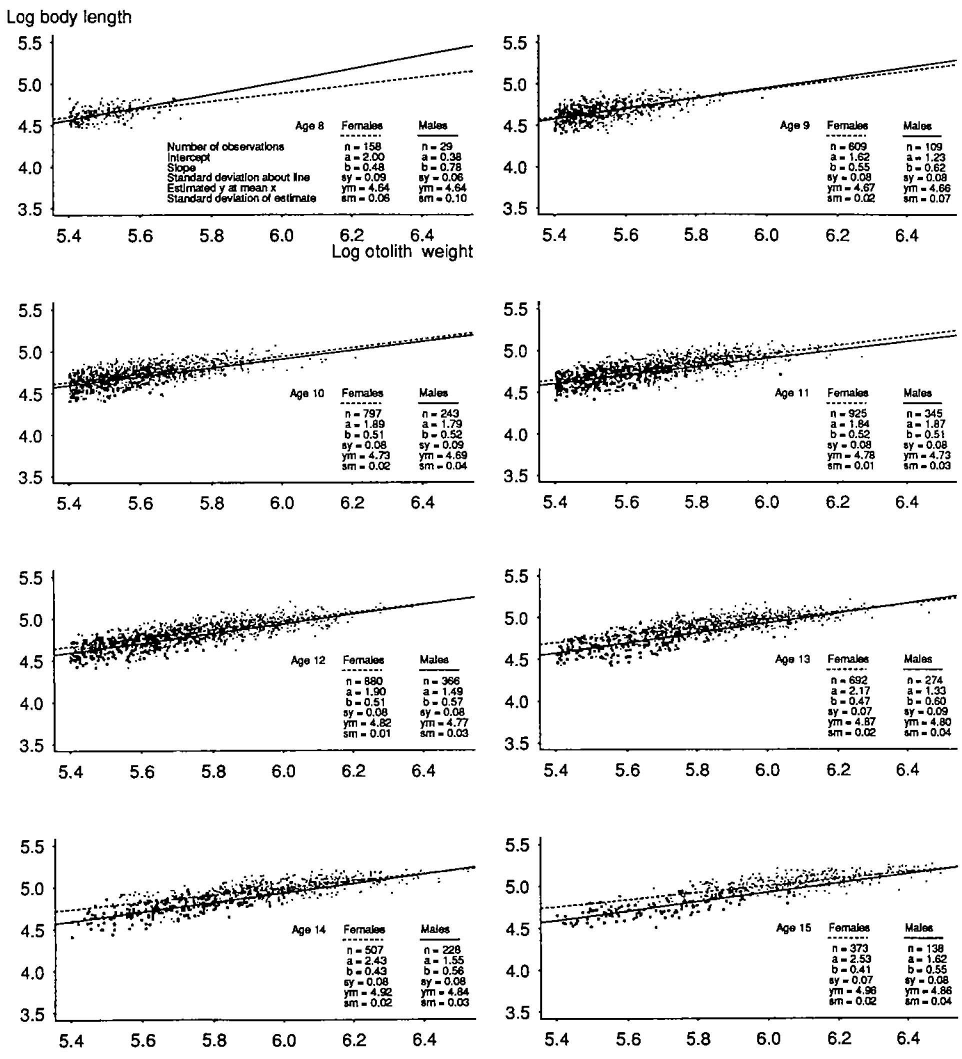

Figure 7. Otolith-body size relationship for Area 3A fish by sex within age. (All years combined; groups with n > 25; female data plotted in light points, male in heavy.)

choose the most parsimonious polynomial model, as the aim was simply to obtain a computing formula that would mimic the data smoother.)

Note that the predictive equations are extended to a standard range (log otolith weight of 4.5-7.0, corresponding to an otolith weight of 90-1100 mg) that considerably exceeds the range of the reference data in order that the equations can at need be used at any extreme values in any data set to which they are applied. On the low end, the graph is extended by assuming that the smallest otolith (90 mg) would correspond to a body length of 80 cm. On the upper end, the graph is simply continued at the slope observed over the uppermost third of the range of the data. Typically the slope is nearly constant on this section of the graph.

The double cubic equations themselves provide a means of predicting average log body length from (log) otolith weight, so a first estimate of corresponding body weight can be obtained by applying the length-weight relationship to the antilog of the

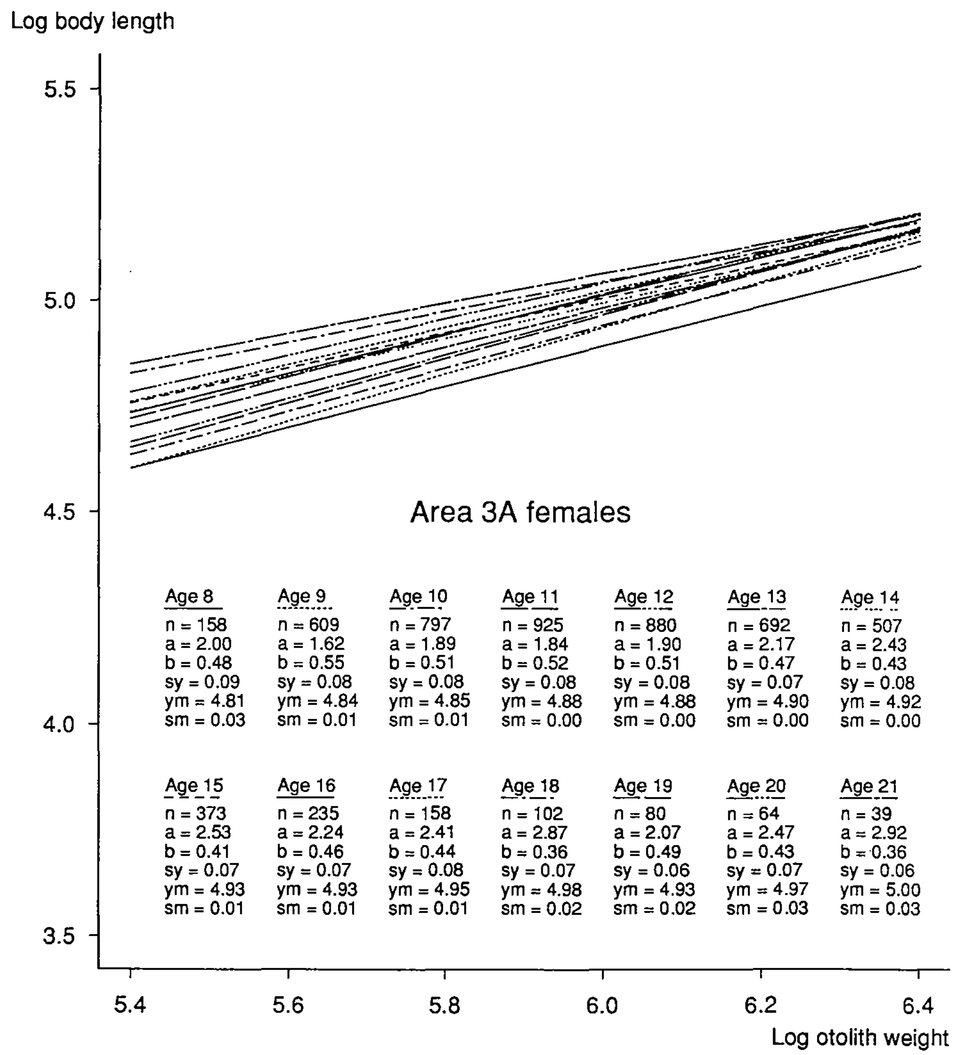

Figure 8. **Area 3A females age by age (overall mean log otolith weight = 5.83).**

predicted mean log length. This would underestimate the mean weight, however, because the mean weight of a group of animals depends on the variance as well as on the mean of their lengths, and there is a sizable variance of log body length about the mean at each value of log otolith weight. To account for the effect of variance in the otolith weight-body length relationship, the straightforward estimate of mean weight has to be increased by about 3.5%. (This correction factor was derived empirically by simply computing the straightforward estimate of mean weight based on otolith weights and comparing it to the estimate based on actual lengths, for each regulatory area. The area-specific correction factors varied between 2.5% and 4.5%. The midpoint of the range – 3.5% – gives adequate results in all areas.)

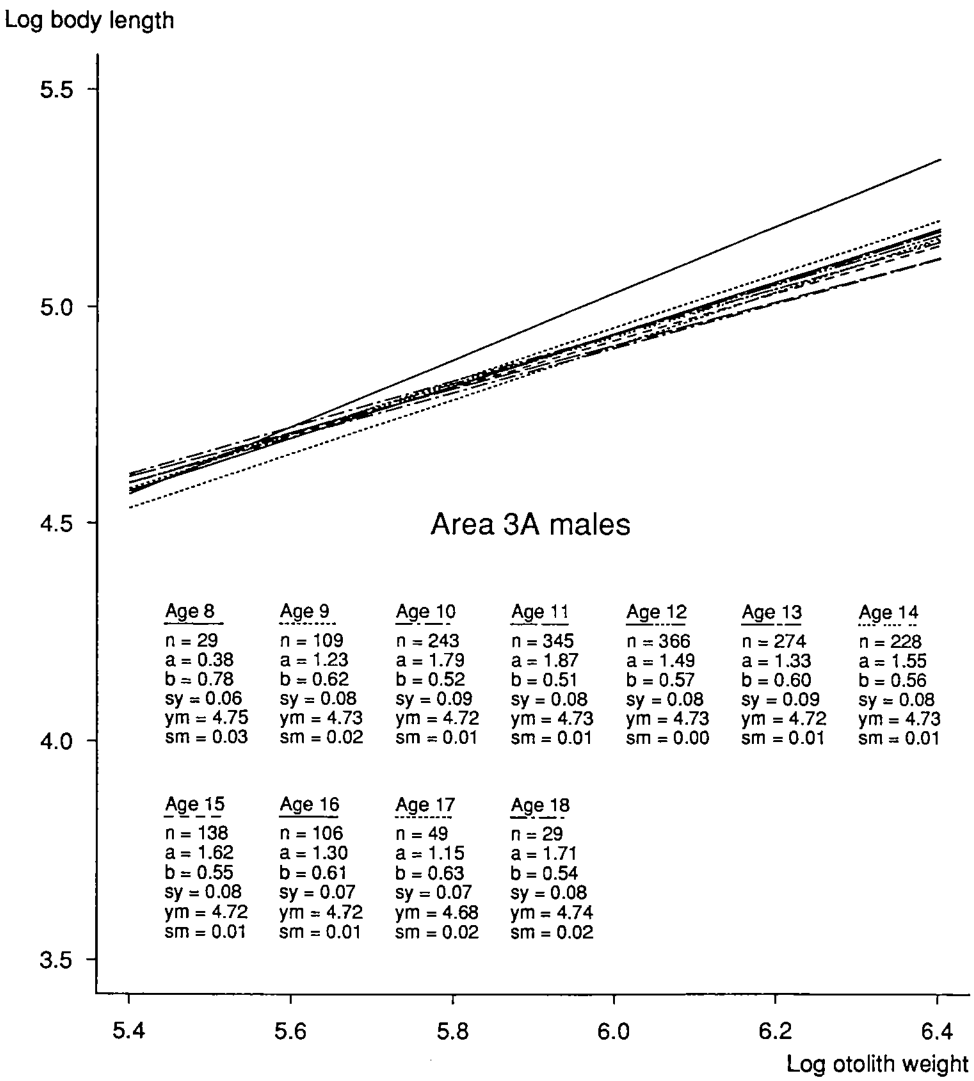

Figure 9. **Area 3A males age by age (overall mean log otolith weight = 5.64).**

RESULTS OF TESTS

Differences Due to Sex and Age

Since all years of data include a mixture of ages and sexes, all years of data from an area can be combined for the purpose of testing for differences between females and males, and among ages. In these tests, any differences among years will add to the variance about the regression lines, but the increase in sample size more than compensates for that.

There is a difference between females and males in the otolith weight-body length relationship, and the difference increases with age. As an example, Figure 7 shows the tests for sex differences by age among fish from Area 3A. In the recruiting age groups (ages 8 and 9), there is little difference between the sexes in mean length at the mean otolith weight. In the most common age groups in the catch (ages 10-12), females are about 5% longer than males at the average otolith weight, and among the older fish (ages 13-15) about 10% longer. The corresponding differences in mean body weight are magnified by the roughly cubic length-weight relationship; a difference of 5-10% in mean length implies a difference of 17-36% in mean weight. The same progression of differences by sex, increasing with age, is seen in fish from Areas 2B and 2C.

The relationship also varies with age, at least among females. In Area 3A, for example, females show a steady increase with age in the predicted average length at the overall average otolith weight (Figure 8). For the oldest fish (age 21), the predicted mean log length is about 20% higher than for the youngest (age 8), which is a very large difference. Males, on the other hand, show hardly any variation with age in the prediction (Figure 9). This is probably due in part to the simple fact that males as a group have smaller otoliths and there is less variation in otolith size among males than among females, especially when the fish with smaller otoliths have been excluded.

When the relationship is fitted for each age with males and females combined (Figure 10), there appears to be a difference of about 10% between the youngest and oldest age groups – the predicted mean log length at the overall mean log otolith weight increases from about 4.80 at age 8 to about 4.90 at age 20. But there is little change from about age 10 through age 17. This range of ages accounts for the great bulk of the data, so for practical purposes the variation with age observed among females disappears when females and males are combined at each age in tests. And lacking variation with age, all age groups can be combined as well, so that all the data from a given region and year can be combined when testing for differences among years or regions.

The reason that pooling the data by sex removes the variation with age, is that at any age the female and male data tend to fall into overlapping clusters. The common regression line is strongly attracted by the means of the two clusters, and less strongly by the trend within each cluster. It is the similarity of this common regression line among ages that allows pooling. When the data are pooled for both sexes and all ages, the points fall into many overlapping clusters, and the common regression line approximates what is often called the functional regression, which is the trend line of the cluster means.

Strictly speaking, the combination of all data for purposes of comparison among regions and years would not be legitimate if in fact there were large differences among years or regions in the age or sex composition of the catch. If, for example, one region contained only old females and another only young males, a comparison of the two regions would certainly be affected by the differences between sexes and ages described above. But by the nature of the fishery, the catch will always contain a mixture of ages

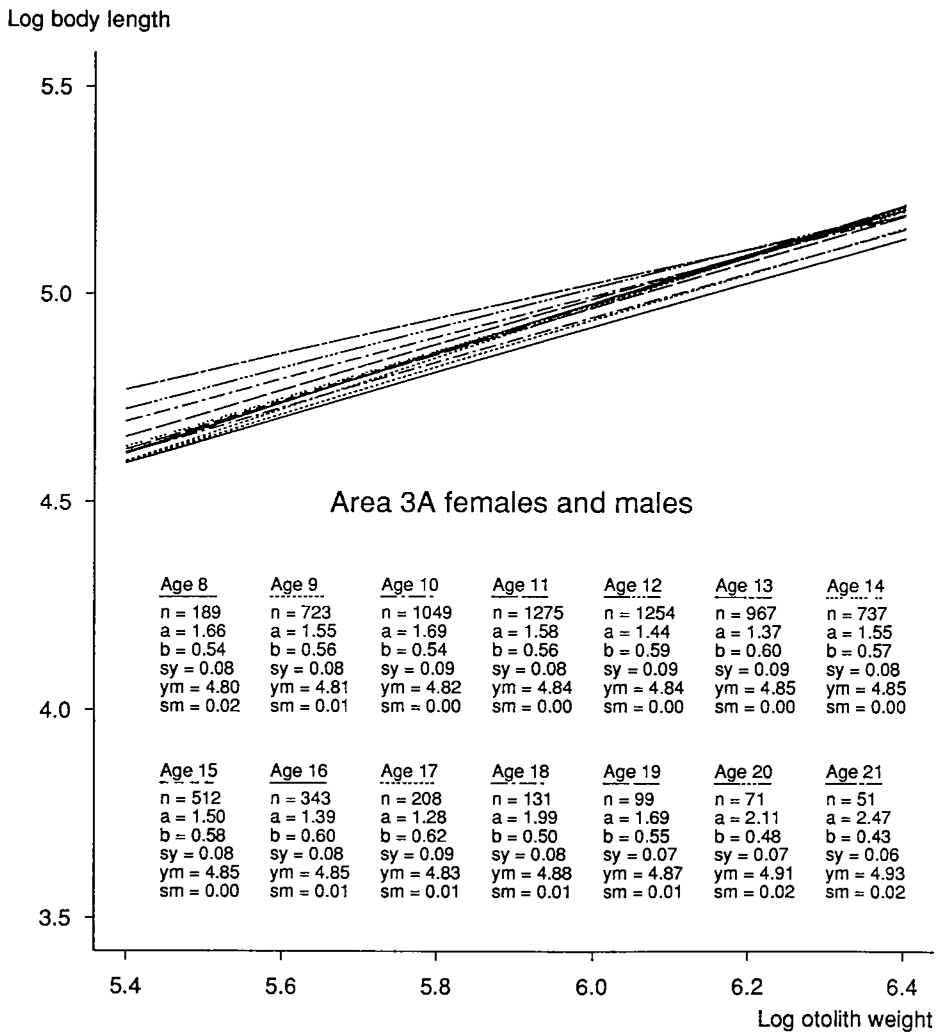

Figure 10. Area 3A females and males age by age (mean log otolith weight = 5.78).

of both sexes, and as a consequence the same collection of clusters of data points will always be present in every region, although not always in the same proportions. So long as the clusters are present, however, the regression lines will be determined largely by the trend of the cluster means in each region (and year), and not greatly affected by the sizes of the clusters, so any differences among regressions can confidently be taken to indicate real differences among regions (or years) in the otolith weight-body length relationship rather than mere differences in sex or age composition.

As regards testing, the working argument here is that over the range of age and sex composition encountered in halibut survey and commercial catches, the overall otolith size-body length relationship for a region and year is not much affected by the precise age or sex composition of the fish. In fact the age composition of halibut catches is quite similar from year to year, and the sex composition of the survey catches does not show any large systematic variations (Table 2).

Table 2. Proportion of female fish in survey catches, by IPHC regulatory area and year. (Figures refer to legal fish only.)

	IPHC regulatory area			
Year	**2B**	**2C**	**3A**	**3B**
1976	0.80		0.64	
1977	0.61		0.71	
1978	0.60		0.67	
1979			0.65	
1980	0.64	0.78	0.71	
1981	0.72		0.72	0.88
1982	0.62	0.63	0.71	0.84
1983	0.76	0.63	0.74	
1984	0.66	0.56	0.57	
1985	0.68	0.63	0.57	
1986	0.68	0.61	0.58	
1987				
1988			0.80	
1989	0.74	0.56	0.72	0.69

Differences Due to Region and Year

There are important differences among regions, and in Area 3 a major change over time. For most of the period 1977-1989, fish in Area 3 were about 10% longer at the average otolith weight than fish in Area 2B, with fish in Area 2C falling about midway between them (Figure 11). During this period, there was no change in the relationship in Area 2B, and after 1980 only a very small decrease in length at mean otolith weight in Area 2C. In Area 3, however, mean length at the average otolith weight began to decrease in 1984, and by 1989 was about 7% below the 1977 value. As a consequence of the decrease in Area 3, the differences among regions were much smaller in 1989 than in 1977. (Note that Areas 3A and 3B are combined for testing regional differences, on the basis of other tests that showed the two to be nearly identical in otolith weight-body length relationship in all years.)

All of these differences are significant in the statistical sense, because the number of data points is large in every case and as a result the standard deviation of the predicted mean log length at the mean log otolith weight is small in every case – 0.01 or less. Many of the differences are of practical significance as well. The 7% decline in mean length at average otolith weight in Area 3 translates to about a 25% decrease in mean body weight at average otolith weight.

Recall that these tests apply only to legal fish with log otolith weights greater than 5.4. As explained earlier, it is not possible to run regression tests on legal fish with smaller otoliths because of the effect of the size limit on the distribution of lengths at each otolith weight, but the change in the relationship over time among fish in this group is informative. Generally the pattern of differences is the same as among fish with larger otoliths, but the differences among regions are smaller throughout and by

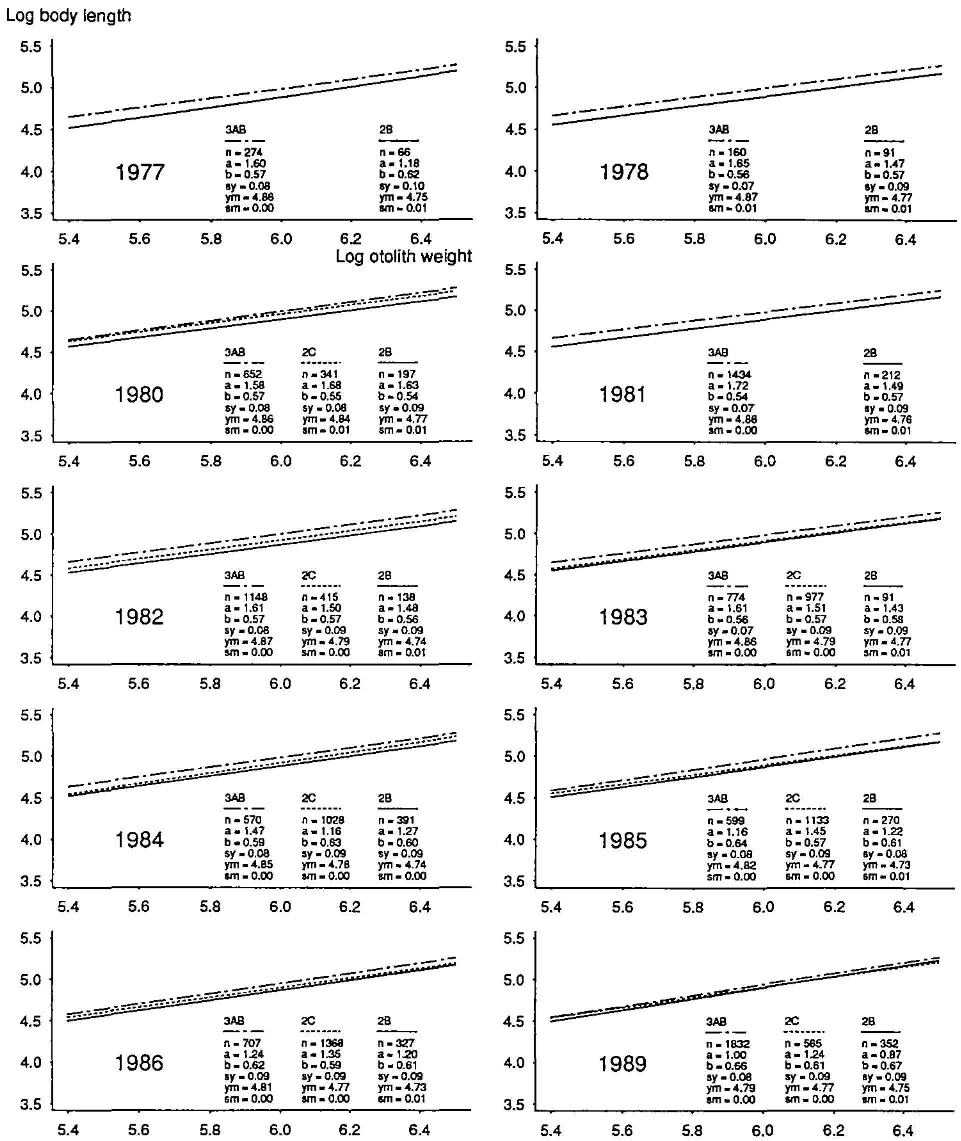

Figure 11. Regional comparisons within years (mean log otolith weight = 5.77).

1989 there is no difference among regions. Mean length at average otolith weight declines most in Area 3, but even in Area 2B there is a small decline (2-3%).

CONCLUSION OF TESTS

As regards the problem of predicting halibut body length from otolith weight, the results above show that there are statistically significant differences due to sex and age, but these differences are not of practical importance so long as predictive equations are always estimated from, and applied to, catches that include a mixture of ages of both sexes, which is the normal case.

The differences among regions and years are of considerable practical importance because the main use of any predictive equation is to estimate the mean weight of fish in the catch in a particular region and year. An equation based on data from some other time or place will not generally provide an accurate estimate.

Grouping by Years

It is clear from Figure 11 that separate predictive equations are needed for Areas 2B, 2C, and 3, and that at least in Area 3 different predictors are needed for the early and recent years during the period 1977-1989. Figure 12 shows annual fits of double cubic predictors to the data from each area. Generally the graphs shift downward over time in all areas, and the predictors for the most recent years (after 1984) are the lowest in the series in all areas. Note that these graphs cover the entire range of otolith weights

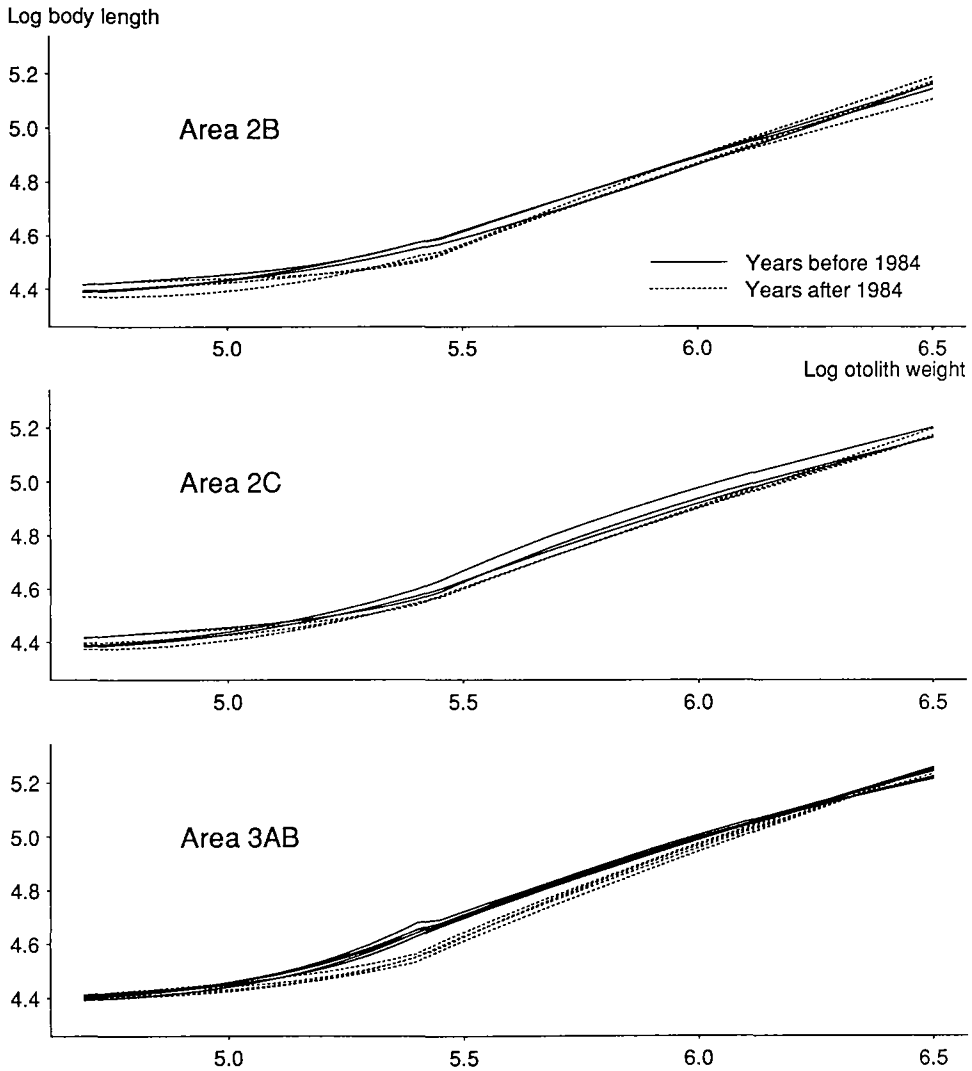

Figure 12. **Annual fits of double cubic predictive equations in each region.**

(rather than just the larger ones), and that in Area 2B the impression of lower values in recent years comes entirely from the low end of the otolith weight range.

While there is a general downward shift over time in all areas, the periods before and after 1984 appear as quite distinct clusters, at least in Areas 2B and 3. (The graph for 1984 itself, which is not shown in Figure 12, is intermediate between the clusters but closer to the earlier data, especially in Area 3). In Area 2C there is little change over time after 1980, which appears as the highest line on the graph. The high 1980 line may be an anomaly; the fish caught in that year's survey were very large (averaging over 60 pounds among legal fish), so the data may be biased somehow toward larger fish at each otolith size. At any rate, even in Area 2C the graphs for years after 1984 fall below the graphs for earlier years.

It appears from Figure 12 that most of the variation over time in the otolith weight-body length relationship can be accounted for by fitting early and late predictive equations, the former covering years through 1984 and the latter years since 1984.

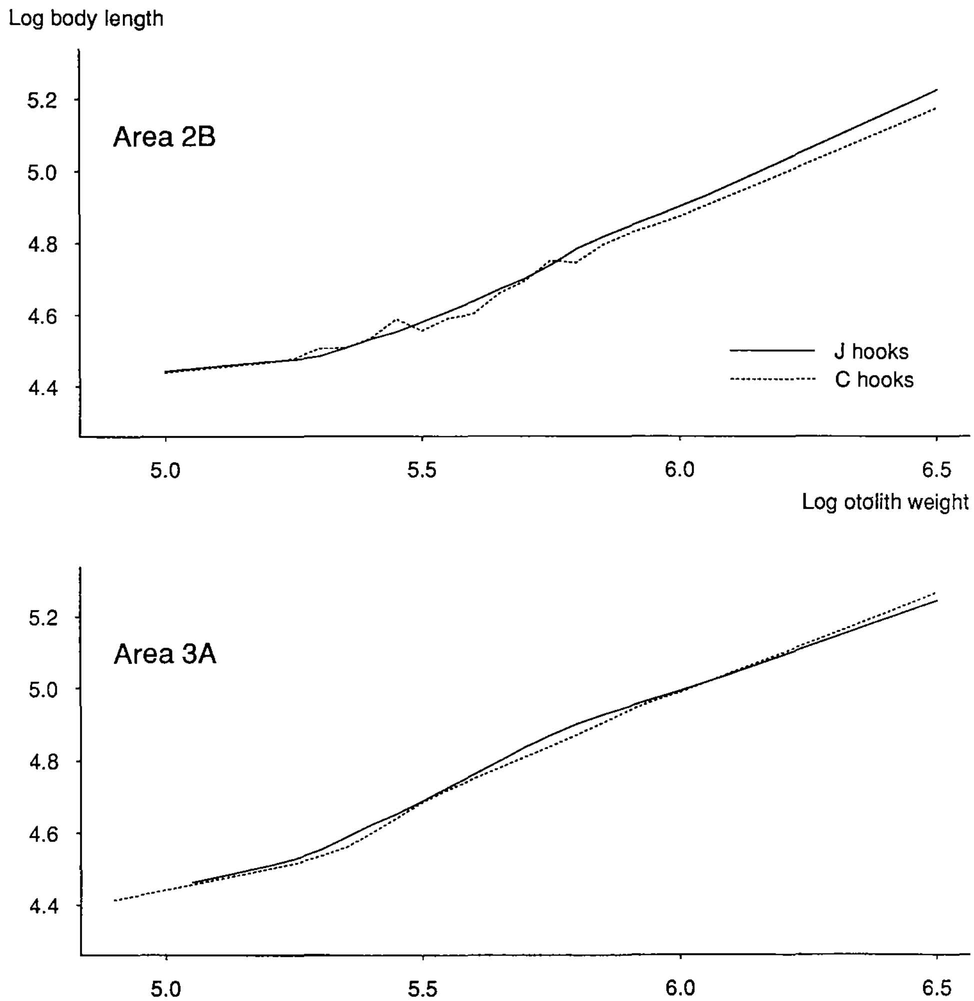

Figure 13. Comparison of J-hook and C-hook data from 1984 surveys.

Effect of Hook Type

The large shift in the otolith weight-body length relationship between 1983 and 1985 coincides exactly with a change from J (J-shaped) hooks to C (circle) hooks in the data series: before 1984 all surveys were conducted with J hooks, and after 1984 with C hooks. During the 1984 surveys in Areas 2B and 3A, strings of J hooks and C hooks were fished alternately to provide comparative data, so the 1984 data are mixed.

The (smoothed) comparative data from 1984 are shown in Figure 13. It is clear from the figure that when fished side by side, J hooks and C hooks showed no practical difference in the otolith weight-body length relationship. Nor was there a large shift in Area 2C, where the same conversion was made even though there was no comparative fishing. It therefore appears that the coincidence of the change in hook type and the change in the relationship was no more than a coincidence.

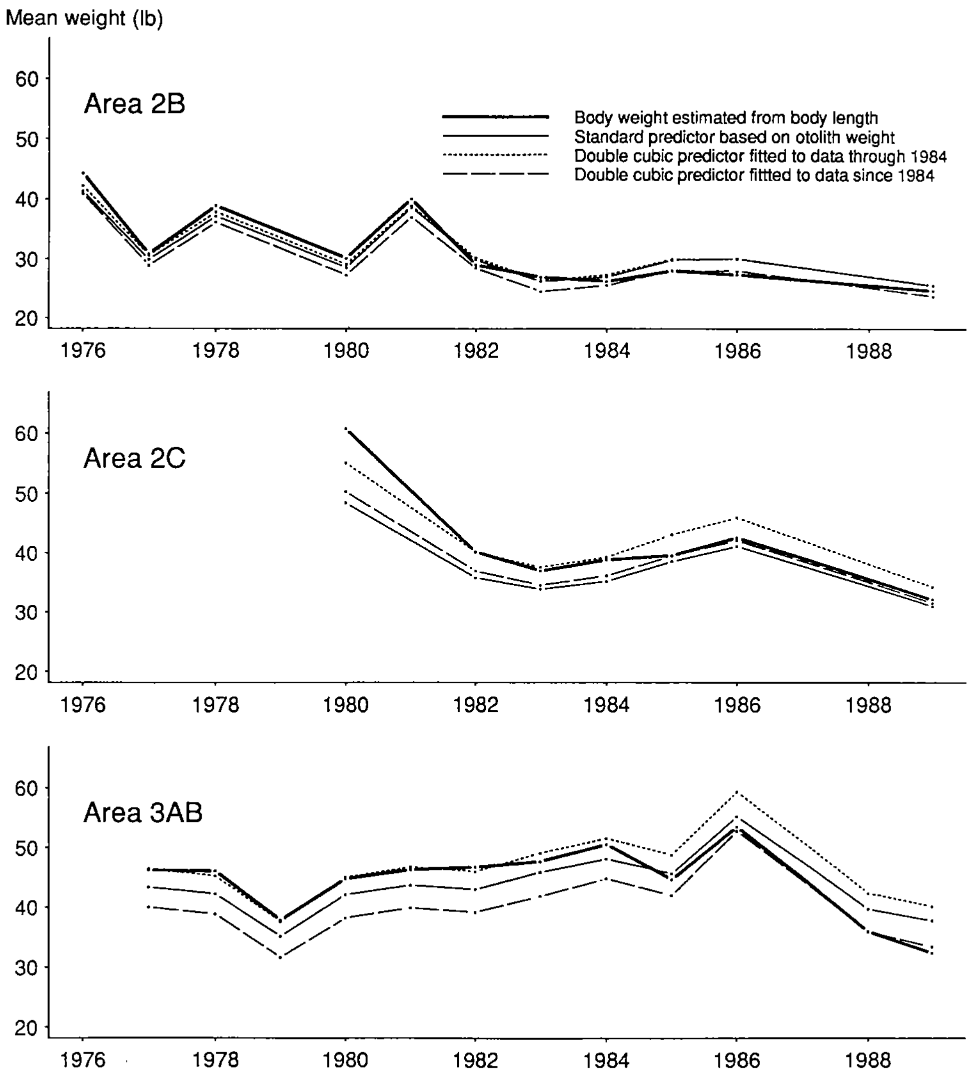

Figure 14. **"True" mean weights (based on lengths) and various predictions based on otolith weights, by year within region.**

Performance of Predictors

Figure 14 shows estimated mean weight by area and year. The estimate based on the length of the fish and the body length-body weight relationship is shown as a heavy line and treated as the correct value. As mentioned earlier, in data sets that include both length and weight, the estimate of mean weight based on the length-weight relationship is always within one or two percent of the measured value. Also shown are the standard predictor based on otolith weight that was in routine use during 1978-1990, and the early and recent double cubic predictors (also based on otolith weight) proposed above, the early predictor based on data through 1984 and the recent one on data from years since 1984.

While the relative positions of the various predictors in Figure 14 are as expected,

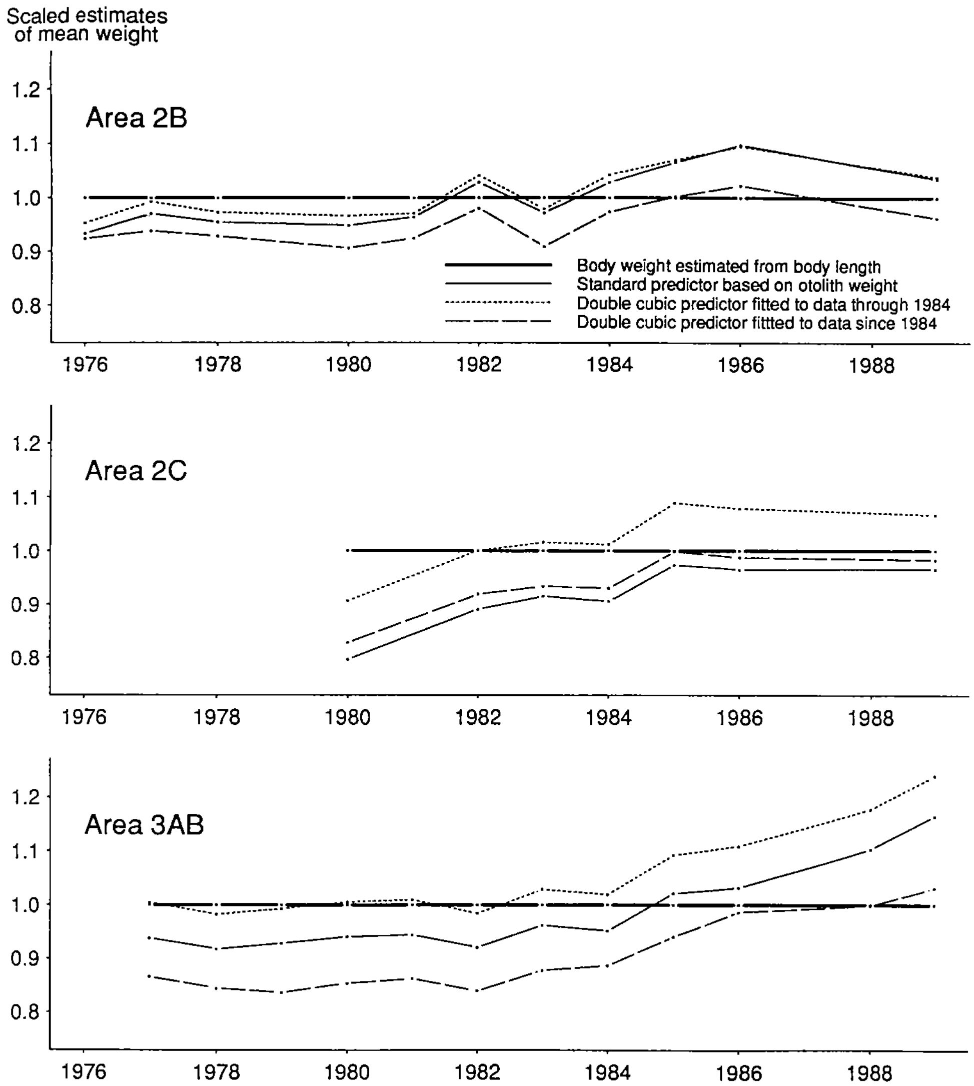

Figure 15. **Scaled estimates of mean weight. In each region and year, the estimate based on lengths is equal to one, and the other estimates are shown as proportions of that value.**

it is not clear from the figure what relative error is associated with each of the predictors based on otolith weight. To bring that out, Figure 15 shows the same values rescaled so that the estimate of mean weight based on length is equal to one in each region and year. The other estimates are shown as proportions of the length-weight estimate in each year. A value of 0.90 for the standard predictor, for example, means that in that region and year the standard predictor's estimate of mean weight was 90% of the value obtained from the length-weight relationship.

Figure 15 shows that in Area 2B the standard predictor has not performed badly: it was low in the late 1970s and high in the mid-1980s, but it has always stayed within 10% of the correct value and almost always within 5%. In Area 2C the standard predictor was 10-20% low in the early 1980s but in recent years has been only a few percent low. In Area 3 the standard predictor was about 5% low through the mid-1980s and in the last few years has shifted to the point where it was nearly 20% high in 1989. Within their periods of reference, the early and late double cubic predictors are, of course, always close to the correct value.

The early and late double cubic predictors are appropriate for estimating body length and weight from otolith weight for longline catches taken subject to the 32 inch (81 cm) size limit, imposed in 1973. The equations can be applied to commercial catches or to longline survey catches from which sublegal fish are excluded, but not to trawl catches and never to fish less than 32 in. Coefficients and computing formulas are given in Table 3.

DISCUSSION

Cause of Variation in the Otolith Size-Body Size Relationship

There are a number of things that could conceivably produce a shift in the otolith size-body size relationship in the commercial catch, including large changes in age or sex composition, or changes in regulations, gear, or fishing strategies. Fortunately, all of the data examined in this study came from IPHC research charters, and most of the possible causes of the observed shift can be eliminated. The only good suspect, aside from a real change in the stock, is the conversion to C hooks in 1984, and the evidence is against that explanation.

The conclusion is that a real change in the relationship did occur, meaning that the relationship between otolith growth and body growth changed. Secor and Dean (1989) suggested that otolith growth is not simply proportional to body growth but consists of time-dependent and growth-dependent components. This model is consistent with the finding of Southward and Hardman (1973) that the otolith size-body size relationship in halibut depends on growth rate. Further support is provided by careful field studies (Pawson 1990) and laboratory experiments (Reznick et al. 1989).

In the case at hand, the nature of the change can be seen by examining the apparent otolith and body growth rates in Area 3 during the early years in the data series and during recent years (Figure 16). Among the dominant age groups (ages 8-14), mean otolith size at each age is virtually unchanged from the early years, while there has been a considerable decrease in mean length at age. The pattern is the same for females and males. Hence the change in the relationship.

General Consideration of the Effect of Size Selection

Given the large variation in halibut body length that is observed at any given otolith weight, the otolith weight-body length relationship must be determined in part

Table 3. Predictive equations.

These equations are valid only for longline-caught fish subject to the 32" size limit, not for trawl-caught or sublegal fish. The table gives the coefficients of the cubi c equation for predicting the *natural logarithm* of body length from the *natural logarithm* of otolith weight, according to the area and year of capture and the weight of the otolith. Do not round the coefficients. The estimate of log length is calculated as:

$$\log(\hat{L}_F) = b_O + b_1 \times \log(W_O)) + b_2 \times (\log(W_O))^2 + b_3 \times (\log(W_O))^3$$

where W_O is otolith weight in milligrams and L_F is fork length in centimeters. The corresponding estimate of net (headed and gutted) body weight $\hat{W}$ in pounds is then calculated as:

$$\hat{W}_N = 1.035 \times (6.92 \times 10^{-6} \times \hat{L}_F^{3.24})$$

In this formula, $\hat{L}_F = \exp(\log(\hat{L}_F))$. The parenthesized expression on the right is the Commission's standard length-weight relationship; 1.035 is a correction factor that adjusts for variance in the otolith weight-body length relationship.

Area, period, otolith size	Coefficients of cubic equations			
	b_0	b_1	b_2	b_3
Area 2B				
Years through 1984				
Log otolith weight ≤ 5.4	-15.0707	12.34151	-2.629206	0.1882495
Log otolith weight > 5.4	-3.6945	2.73082	-0.287576	0.0118329
Years since 1984				
Log otolith weight ≤ 5.4	0.4582	2.93323	-0.727035	0.0597732
Log otolith weight > 5.4	-8.9696	5.37091	-0.733519	0.0371692
Area 2C				
Years through 1984				
Log otolith weight ≤ 5.4	-34.0833	23.75398	-4.907418	0.3395591
Log otolith weight > 5.4	-6.3112	3.90882	-0.460517	0.0202322
Years since 1984				
Log otolith weight ≤ 5.4	-0.0131	3.16525	-0.768035	0.0625734
Log otolith weight > 5.4	-6.2872	4.01283	-0.498157	0.0233662
Areas 3 and 4				
Years through 1984				
Log otolith weight ≤ 5.4	-42.7746	29.84937	-6.319273	0.4476836
Log otolith weight > 5.4	-14.6536	8.14374	-1.163776	0.0587255
Years since 1984				
Log otolith weight ≤ 5.4	-22.3516	16.85752	-3.559328	0.2518227
Log otolith weight > 5.4	-15.9456	8.609370	-1.228230	0.0623204

by the size selectivity of the fishery. The commercial size limit is simply an extreme form of size selection: at any otolith weight, it totally excludes all fish below the minimum legal length from the catch. The usual size selectivity of fishing gear produces the same effect, however, by making the capture of larger (or smaller) fish more *likely* at any otolith weight. More subtly, *any* change in fishing strategies or regulations that affects the size selectivity of the fishery will in turn alter the apparent otolith weight-body length relationship in the catch.

Implications for Catch Sampling

Because the otolith size-body size relationship is clearly subject to significant changes due to changes in halibut growth rates or size selection by the fishery, its

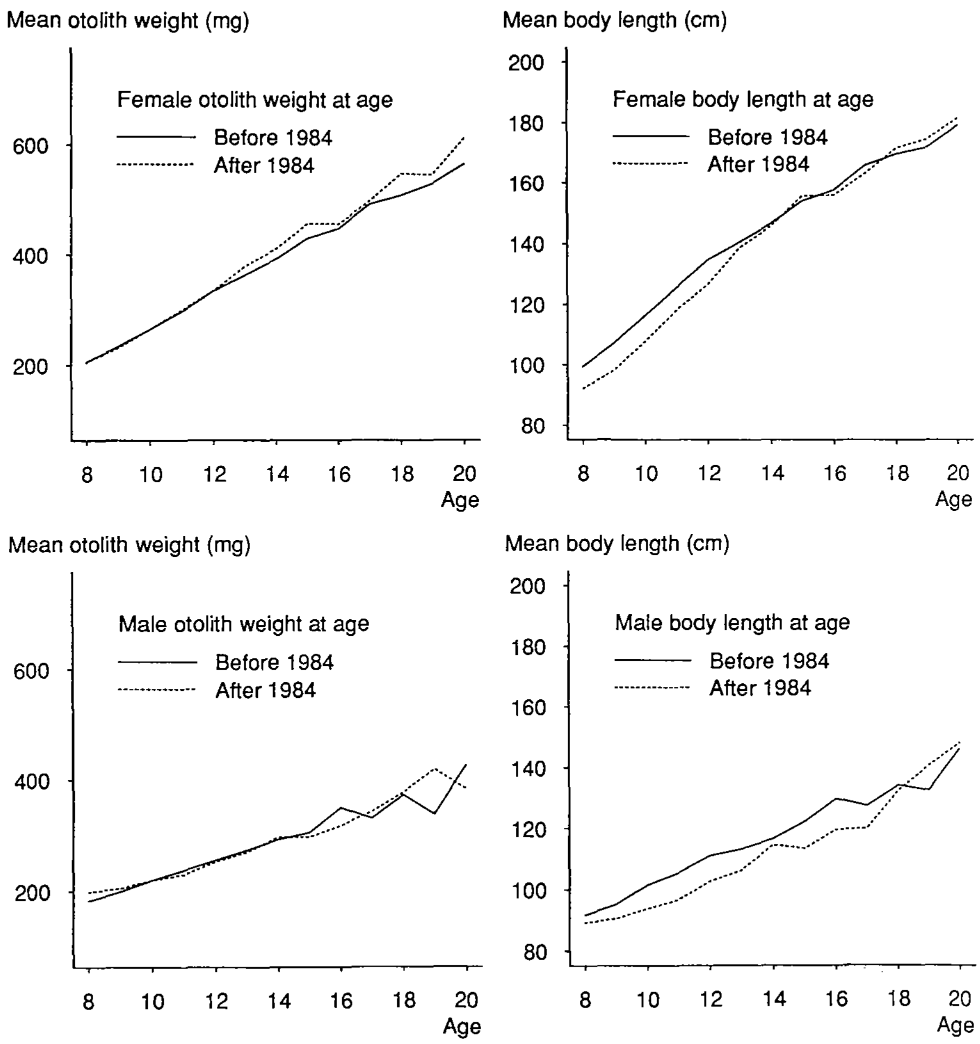

Figure 16. Otolith weight at age and body length at age in Area 3AB before and after 1984, by sex.

continued use would require annual calibration in each region. And owing to the large variance of body size at each otolith weight, calibrating the relationship would require measuring a sample of about the same size and distribution as the present market sample (which is 2000 fish per regulatory area per year, distributed proportionally over ports and fishery openings). The simplest solution to the problem of estimating mean weight in the catch is therefore simply to measure the fish in the market sample, estimate their weights from their lengths, and use the otoliths only for age determination.

Importance of Body Weight Estimates in Stock Assessment

Southward and Hardman (1973) noted that the otolith size-body size relationship would have changed over time as a result of changes in halibut growth rates during the first half of the century. The size of the change can be inferred from the previous paper by Southward (1962), which includes regressions fitted to early data (1925-1934) and later data (1935-1957) in Area 2 and Area 3. In both areas, the average body length at same typical otolith radius was about 7% greater in the later data than in the earlier data – a change identical to the change reported above to have occurred in Area 3 during the 1980's.

In the 1960s and 1970s a difference of this size was regarded as unimportant for practical purposes, because the main purpose of estimating body length from otolith radius (later otolith length, later otolith weight) was only to stratify the market sample in order to obtain a more precise estimate of the age compostion of the landings. As mentioned above, this stratification could just as well have been based on otolith size itself, but the estimated lengths were also used to estimate mean weight and numbers at age in the catch. In that period, however, the estimates of numbers at age in the catch were not of great practical importance because they were not used in stock assessment.

During the 1980s, the Commission staff has come to rely heavily on stock size estimates derived from catch-at-age analysis (Quinn et al. 1985, Deriso et al. 1985).These methods require accurate estimates of numbers at age in the landings and therefore accurate estimates of mean weight in the market sample. A 7% bias in estimated length (corresponding to a 25% bias in estimated weight) that was unimportant in 1970 is therefore a serious matter now.

Value of Survey Data

For many years the Commission conducted setline surveys at stations located on a grid pattern to obtain a fishery-independent index of halibut abundance. At present commercial catch-per-effort is preferred for use in stock assessments because it is based on vastly more effort and is therefore less variable than the survey index. Survey data are still valuable, however, in providing a fishery-independent measure of changes in stock composition, as demonstrated by their use in this study in showing that a real change in size at age had occurred in the stock. If survey data had not been available, the change in size at age observed in the landings could well have been ascribed to a change in selectivity by the fishery. It would therefore be worthwhile to resume the systematic surveys in order to continue the series of fishery-independent data on such things as size and maturity at age, sex composition, and patchiness of halibut distribution.

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