Incorporation of between-haul variation using bootstrapping and nonparametric estimation of selection curves.

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The most frequently used parametric description of trawl selectivity is the logistic curve. If $r(l)$ denotes the retention probability of a length l individual, the logistic selection curve is specified as

$$r(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)}, \qquad (1)$$

where a and b are parameters to be estimated. Under this formulation it can be seen that $b>0$, because this is a requirement for $r(l)$ to increase with l. Also, $a<0$ because we require the retention probability of a length-0 individual to be (effectively) zero. A similar curve is provided by the probit function (the cumulative distribution function of the Normal distribution) which has slightly shorter tails than the logistic curve (McCullagh and Nelder, 1989). Both of these curves are symmetric about the length at which retention is 50%, which will be denoted by l_{50}. More generally, l_x will denote the length at which retention is x%.

Some selectivity data suggest an asymmetric selection curve. The log-log curve (also known as the Gompertz curve) and complimentary log-log curve are two parameter asymmetric curves that can be used in the analysis of count data (McCullagh and Nelder, 1989). Although Pope et al. (1975) mention the log-log curve as a potential selection curve, neither of these asymmetric curves appears to have been used in published selectivity studies prior to this current study.

Richards curves (Richards, 1959) are three parameter curves that generalize the logistic in the form

$$r(l) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)}\right)^{1/\delta}. \qquad (2)$$

Parameter δ controls the amount of asymmetry with $\delta>1$ or $0<\delta<1$ giving longer tail to the left or right of l_{50} respectively, and $\delta=1$ giving the symmetric logistic curve. The author (Millar, 1991) has found that the Richards curve will often provide an adequate fit to data in cases where the logistic curve is clearly inappropriate.

Selectivity data are count data, and in fitting selection curves to these data it is usual to assume that the counts are binomially distributed (McCullagh and Nelder 1989). Within a single selectivity haul, the binomial assumption is appropriate if the fish encountering the gear behave independently. It is common practice to fit a selection curve to the data combined over all successful hauls, and for the binomial assumption to remain valid it is then also necessary to assume that selectivity does not vary between hauls. This assumption is not valid in general, owing in part to variables such as catch size and haul duration. Gear saturation may occur for high catch sizes because of reduced selectivity in the latter part of the tow caused by meshes becoming clogged with fish (e.g., Suuronen and Millar, 1992) or distorted by the strain upon the gear. Hauls of longer duration may increase selectivity (e.g., Clark 1957) by allowing fish more time to escape, notwithstanding that the effect will be confounded with catch size.

If between-haul variation is not of primary interest, then fitting a selection curve to the combined hauls data remains a reasonable approach because the estimated selection curve parameters are quite insensitive to violation of the binomial assumption (McCullagh and Nelder, 1989). The combined hauls approach can be viewed as modelling the "average" $r(l)$, where the average is over the population of all hauls that could be made on that fishery. The selectivity hauls must therefore be a representative sample from this hypothetical population.

Between-haul variation does, however, invalidate the estimates of variability for the parameters of the combined hauls fit. To correct for this it is common to apply a goodness-of-fit based correction to the estimated standard errors (McCullagh and Nelder, 1989), but Fryer (1991) has demonstrated that this can underestimate the effect of between-haul variation. Suuronen and Millar (1992) corrected the standard errors by using the replication estimator of dispersion (McCullagh and Nelder, 1989, p. 127). This is a nonparametric estimator that is analogous to the pure error sums of squares estimator of linear regression analysis (Myers, 1990). The replication estimate of dispersion has an approximate chi-squared distribution when there is no between-haul variation and within-haul

Manuscript accepted 27 April 1993.
Fishery Bulletin: 91:564–572 (1993).

variation is binomial. When between-haul variation is present the approximate chi-square distribution no longer holds because the replicates across different size classes are then not independent. Nonetheless, the estimator provides a correction to the standard errors that incorporates both between-haul variation and within-haul variation.

If between-haul variation is of specific interest then fits to individual haul data are required. Fryer (1991) and Reeves et al. (1992) modelled between-haul variability by permitting parameters a and b of the logistic curve (1) to vary between hauls according to a bivariate normal distribution which can be estimated from the individual haul fits. Suuronen et al. (1991) and Suuronen and Millar (1992) regressed the estimated l_{50}'s for individual hauls against their catch sizes, and in four of five separate selectivity trials a decrease in l_{50} with catch size was indicated, though only one of these was statistically significant at the 5% level. These regressions used weights given by the inverse of the estimated variance of the individual haul l_{50}'s.

In the next section it is shown that neither the individual haul or combined hauls data from a scallop dredge selectivity study could be adequately modelled by any of the above mentioned approaches and that extreme between haul variation was present. A nonparametric analysis of the combined hauls data was implemented and between-haul variability was incorporated into the estimates of reliability through bootstrapping. The approach assumed

A1) the selection curve $r(l)$ is a nondecreasing function of l.

In addition, being a combined hauls approach, it was also assumed that

A2) the selectivity tows were representative of tows on the fishery.

Material and methods

Selectivity trials

Selectivity trials were performed onboard the 82-m stern trawler *Gadus Atlantica* during the last week of August 1991 as part of an Iceland scallop (*Chlamys islandica*) biomass survey for the St Pierre Bank (off the South coast of Newfoundland). The objectives of the study were 1) to summarize the retention properties of the survey dredge by estimating the shell heights l_{25}, l_{50} and l_{75} corresponding to 25%, 50% and 75% retention, and 2) to estimate the survey dredge's percent retention (by meat weight) of commercial sized (≥60 mm shell height) scallops.

The survey dredge was a 3.66-m (12-ft) wide offshore scallop dredge with belly constructed from 3 inch (inside-diameter) metal rings joined together with metal links. One selectivity tow was performed at each of ten locations randomly chosen within the survey area. For these tows, shrimp netting covers (35 mm inside mesh opening) were attached behind the dredge, and chafing gear was used under the bottom cover. The covered dredge was towed over the distance (1.0 nautical mile) and at the speed (3.0 kn) used in regular biomass survey tows. The contents of the dredge and covers were separately dumped, carefully picked over, and all Iceland scallops were removed. The scallop catch was weighed and a representative sample of between 20 and 40 kg (200–400 scallops), or the entire scallop catch if less than 20 kg, was taken for measurement. Each scallop in the sample was measured to the nearest millimetre in shell height. The catch weights were then used to estimate the size frequencies for the entire catch in the dredge and covers.

Selectivity analysis

We had planned to perform parametric analyses of the individual haul and combined hauls data using the standard maximum likelihood (McCullagh and Nelder, 1989) theory of the binomial model to choose the most appropriate form of the selection curve from those discussed above. However, as seen in the Results section, neither the individual haul nor combined haul data were amenable to parametric analysis.

Although it may not be possible to specify a parsimonious parametric form for the selection curves, it is at least reasonable to insist that they be nondecreasing. That is, the larger a scallop, the greater its chances of being retained in the dredge. The nonparametric statistical technique of isotonic regression fits nondecreasing curves to data. When the data are binomially distributed then the isotonic regression curve is the maximum likelihood fit to the data (Barlow et al., 1972, p. 38).

Isotonic regression curves are piecewise linear and can be fitted in an intuitive way using the PAV (pool adjacent violators) algorithm (Barlow et al. 1972, p. 13). In this application, the essence of the PAV algorithm is to pool adjacent size classes whenever their observed retention proportions violate the nondecreasing constraint. Isotonic regression views this violation as an artifact due to insufficient numbers in the "offending" size classes and so the pooling results in a block of size classes having a common observed retention proportion.

Barlow et al. (1972) show that the isotonic regression curve is unique and does not depend on the order in which violators are pooled. The PAV algorithm can be implemented on computer as follows: Initially, treat all size classes as blocks of size 1. At each step of the algorithm there is an active block which is compared with the adjacent block in the active direction. The latter will be denoted L or R for active directions left and right, respectively. The initial active block and active direction are the smallest size class and R, respectively. The smallest size class is deemed to satisfy the nondecreasing constraint in active direction L. The PAV algorithm proceeds as follows:

B1) If comparison in the active direction results in violation of the nondecreasing constraint, then the two blocks are pooled to form a larger active block and the active direction becomes (or remains) L.

B2) If comparison in the active direction does not violate the nondecreasing constraint then the active direction becomes (or remains) R. In addition,

- if the active direction was L then the active block remains the active block.
- if the active direction was R then the active block becomes the next block on the right.

After a finite number of steps, the algorithm terminates when the rightmost block is active and R is the active direction.

If the observed retention proportions are nondecreasing for increasing l, then the isotonic regression curve is simply given by connecting all the proportions together with straight line segments. If the isotonic regression curve fitted to the observed retention proportions is flat (corresponding to a pooled block) at 0.25, 0.50 or 0.75, then the estimated l_{25}, l_{50}, or l_{75} is given by the shell size that is the midpoint of that pooled block.

For this study, published FORTRAN code (Cran, 1980) for implementation of the PAV algorithm (Barlow et al., 1972) was interfaced to the *Splus* statistical package.

Isotonic regression does not provide an estimate of the standard errors of the estimated l_{25}, l_{50}, and l_{75}. These were obtained by bootstrapping the data (Efron, 1982). To this end, the individual selectivity hauls were used to define a "population" of hauls. To include between-haul variability, the bootstrap resamples (with replacement) from this population. Within each resampled haul the retention proportions were also bootstrapped to include within-haul variability. That is, for each size class, the bootstrapped retention proportion was the proportion of dredge caught scallops in a sample taken with replacement from the captured (in dredge and covers) scallops of that size. The bootstrap samples were the same size as those represented in the data. For example, in haul 1 there were 48 scallops of 70-mm shell height, of which 28 were caught in the dredge. For this size class, a bootstrap sample of 48 scallops was taken by sampling with replacement from the 48 scallops whenever haul 1 was selected for the bootstrapped combined hauls.

The above resampling scheme was performed 200 times and on each occasion l_{25}, l_{50}, and l_{75} were estimated from isotonic regression fits to the combined hauls data, and percent retention (by meat weight) of commercial sized scallops was calculated by using the shell height to meat weight relationship given in Naidu (1991).

Results

The first four tows were taken over a relatively smooth bottom consisting mainly of small stones and pebbles. The remaining six tows were taken over a rougher bottom consisting of larger stones, rocks and boulders. The data from tow 5 were discarded owing to a torn cover. The proportion of commercial-sized scallops was lower in hauls 1–4 (58%) than in hauls 6–10 (81%). The weight of trash (rocks, sea cucumbers, starfish, etc.) exceeded the weight of scallops in every haul, particularly so in hauls 6–10. A complete summary of the hauls can be found in Millar and Naidu (1991).

The replication estimate of dispersion, calculated over size classes with a total combined catch of at least 10 scallops, was 828 on 480 degrees of freedom. Under the null hypothesis, H_0: {No between-haul variation and binomial within-haul variation} the estimator has an approximate chi-square distribution, hence H_0 is rejected with P-value $<10^{-6}$. Binomial variation within hauls should be a reasonable assumption for scallops, so rejection of H_0 suggests significant between-haul variation.

Results of parametric analysis

Figure 1 shows, for each successful haul and combined-over hauls, the proportions of the covered dredge's catch of scallops that were in the dredge. These retention proportions can be extremely variable, especially for the smaller scallops, because of the low numbers encountered. Logistic curves fitted to these retention proportions are shown as dashed lines. The residual plots show that the fitted logistic curves are inadequate. This is particularly true for the combined hauls data. (The residuals plotted in Fig. 1 are deviance residuals, as defined by McCullagh and Nelder [1989, p.39].)

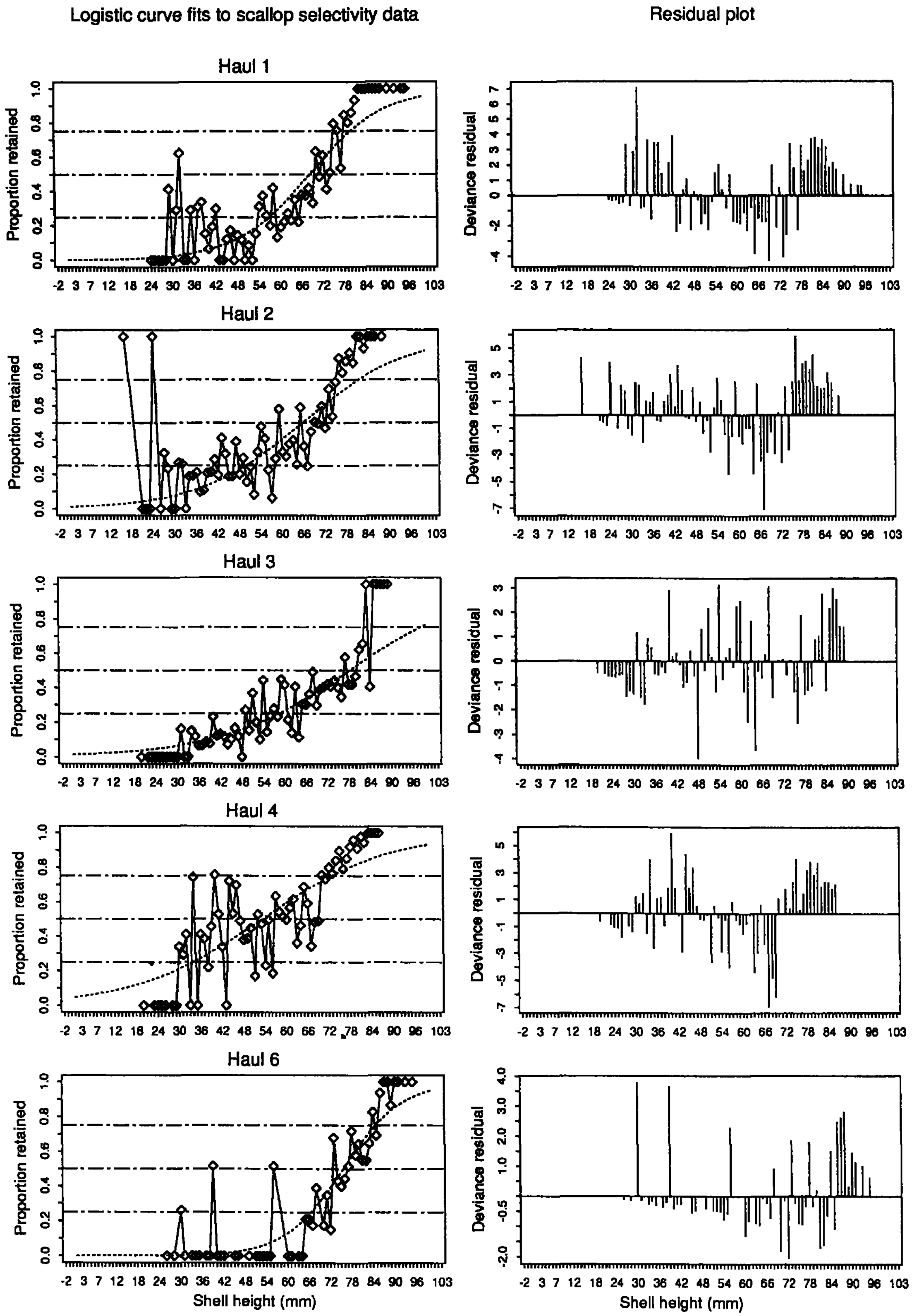

Figure 1
Logistic selection curves fitted to the individual haul and combined hauls data, and the deviance residuals from the fits.

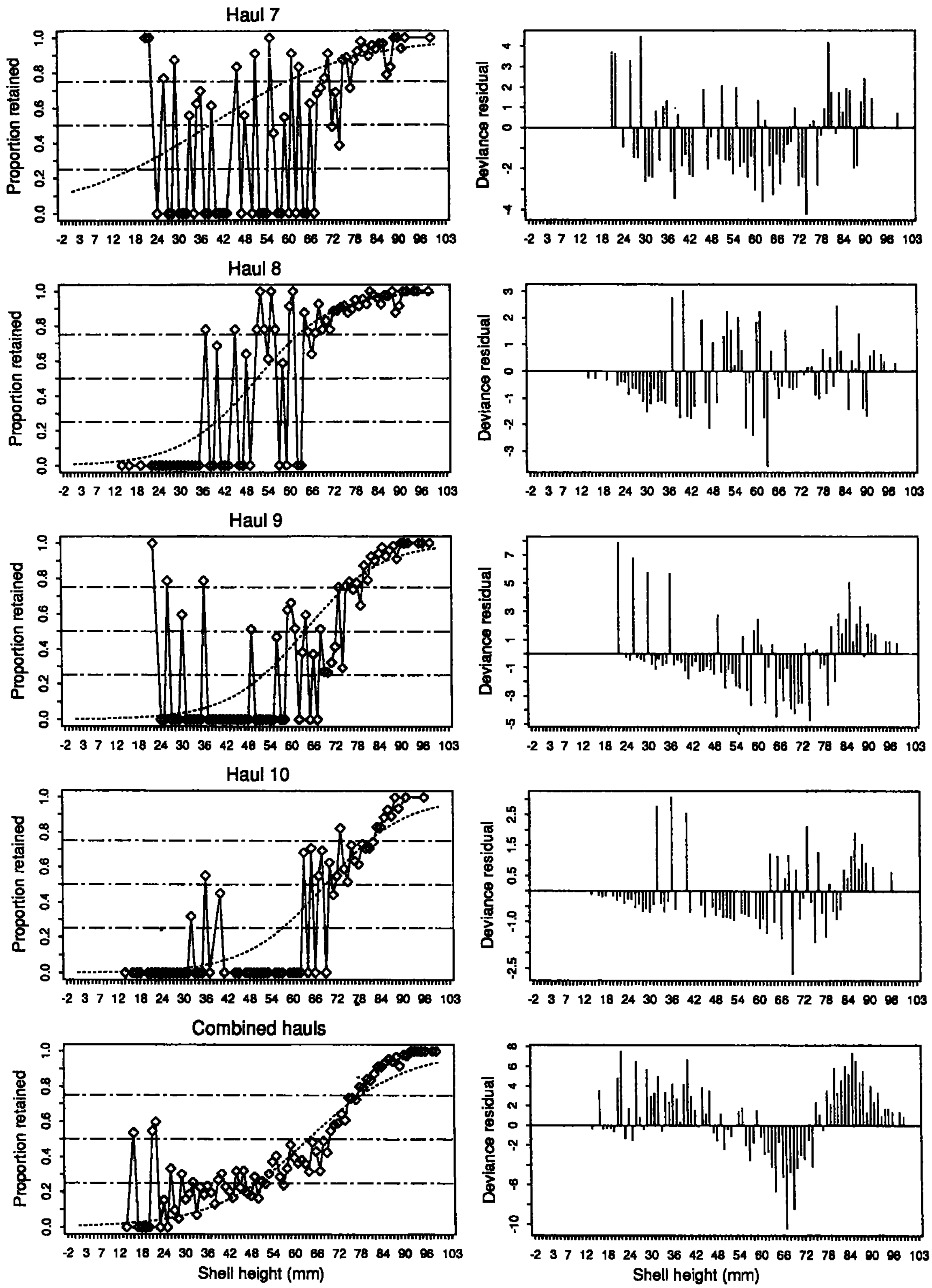

Figure 1 (Continued)
Logistic selection curves fitted to the individual haul and combined hauls data, and the deviance residuals from the fits.

Fits of the complimentary log-log, log-log, and Richards curve were also used on the individual haul data. The complimentary log-log curve fits were marginally better than the logistic fits but were still clearly inadequate. The log-log curve fits displayed worse residual structure than the logistic fits. This is because the log-log curve has a longer tail to the right of l_{50}, whereas the data suggest a longer tail to the left. The three parameter Richards curve fits provided a big improvement and, though very hard to judge, fits to about half of the individual hauls appeared to be adequate.

Figure 2 shows the combined hauls data fits of the logistic, complimentary log-log, log-log, and Richards curves. The Richards curve fit is the only one that could possibly be considered adequate, though there is an obvious clustering of negative residuals for shell heights between 61 mm and 71 mm. Since this group of residuals contains the estimated value of l_{50} (66.8 mm) it is of some concern, and the fit was deemed to be inadequate. (One might consider performing a run's test (say) for independence of the residuals. However, the run's test would be very approximate since it assumes that residuals will be positive or negative with equal probability 0.5. This is not the case for these data, especially for the very small and very large size classes, even when the model is correct.)

Nonparametric analysis

The nonparametric selection curve fits to the individual haul and combined hauls data are overlaid on proportion-retained plots in Figure 3 and the corresponding estimated sizes of 25%, 50%, and 75% retention are given in Table 1. Note that the flat portions of the curves (Fig. 3) correspond to size classes that were pooled. Considerable variability in the estimated l_{50}'s is evident, the smallest being 45.3 mm (haul 7) and the largest 80.1 mm (haul 3). Figure 3 suggests that the estimated l_{50} for haul 7 may be very unreliable—there were relatively few scallops less than 70 mm in this haul and the observed retention proportions of the smaller scallops are extremely variable because of the low numbers caught.

The estimates of l_{25}, l_{50}, and l_{75} from the combined hauls fit were 50.5, 69.4, and 77.3 mm, respectively. The percentile method (Efron 1982, p. 78), was used to determine approximate confidence intervals from the bootstrap. This gave 95% confidence intervals for l_{25}, l_{50}, and l_{75} of 21.0–53.8 mm, 66.1–72.5 mm and 73.6–80.5 mm, respectively. The extremely large confidence interval on l_{25} reflects the paucity of data for the smaller scallops. Retention by meat weight of commercial sized scallops was estimated to be 73% with a 95% confidence interval of 63%–82%.

Discussion

Bootstrapping (resampling) the experimental units (selectivity tows) is a natural way to emulate the effect of between-haul variability. In doing so, one requires an automated procedure for fitting a selectivity curve to the bootstrapped combined hauls data. Isotonic regression is well suited to this task because the selection curve for the bootstrapped combined hauls will always satisfy assumption A1. In contrast, parametric selection curves may not be sufficiently flexible to adequately fit all the possible bootstrapped combined hauls data sets.

One Referee of this paper made the interesting suggestion that it may not matter that parametric fits to the combined hauls data or bootstrapped combined hauls could be inadequate, because the bootstrap procedure should nonetheless be applicable and any problems with the fits would be indicated by wide confidence intervals or indications of bias (e.g., Efron, 1982, p.33). To investigate this, Richards curves were fitted to the same bootstrapped combined hauls used in the nonparametric analysis. The combined hauls fit had l_{25}, l_{50}, and l_{75} of 48.5 mm, 66.8 mm, and 77.6 mm, respectively, and the 95% confidence intervals obtained from the bootstrap were 33.3–56.6 mm, 59.4–71.5 mm and 74.1–80.3 mm, respectively. These confidence intervals have widths of 23.3, 12.1, and 6.2 mm, respectively, compared with 32.8, 6.4, and 6.9 mm from the nonparametric fits. The percent retention value and its confidence interval were the same as for the nonparametric analysis. However, the more subtle and possibly more relevant consequence of bootstrapping with a parametric curve is that the bootstrap indicates the ability of the combined hauls parametric fit as an estimator of the parametric fit to the entire hypothetical population of tows on the fishery. The latter may not be adequately modelled by a parametric curve—but the bootstrap will not consider this. The isotonic curve can not suffer this deficiency since the selection curve for the entire hypothetical fishery will be nondecreasing.

It was assumed that the selectivity tows were representative of survey tows on the scallop fishery (assumption A2). The selectivity gear used here was a covered survey dredge and it was deployed under survey conditions on a random subsample of survey locations. Assumption A2 will therefore by reasonable provided that the covers on the dredge did not have significant impact on its selectivity. To address this question Millar and Naidu (1991) compared the catch in the covered dredge with that in an uncovered dredge that was towed simultaneously. There was evidence to suggest a possible cover effect for scallops below about 58-mm shell height. This is unlikely to affect the

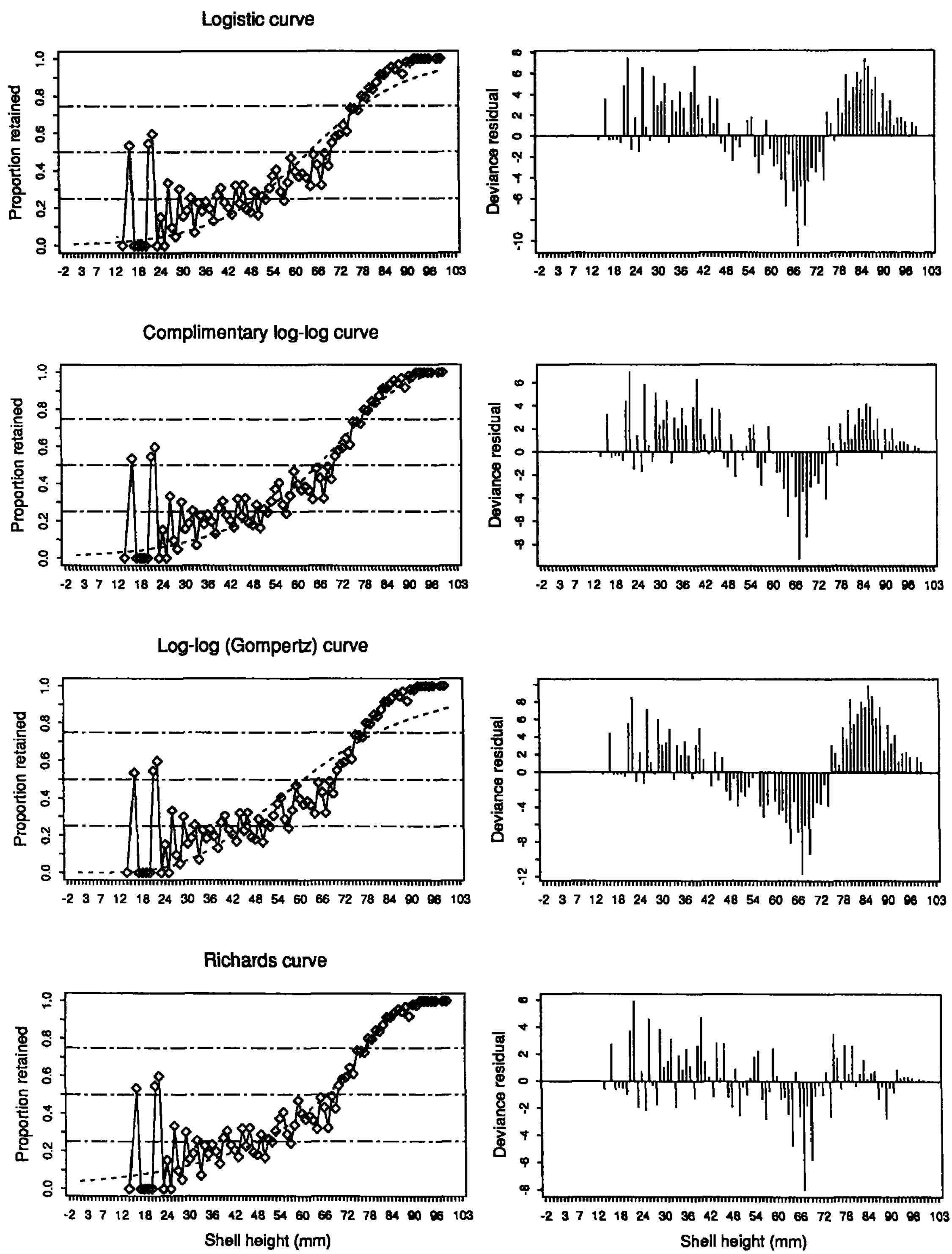

Figure 2

Logistic, log-log, complimentary log-log, and Richards curves fitted to the combined hauls data.

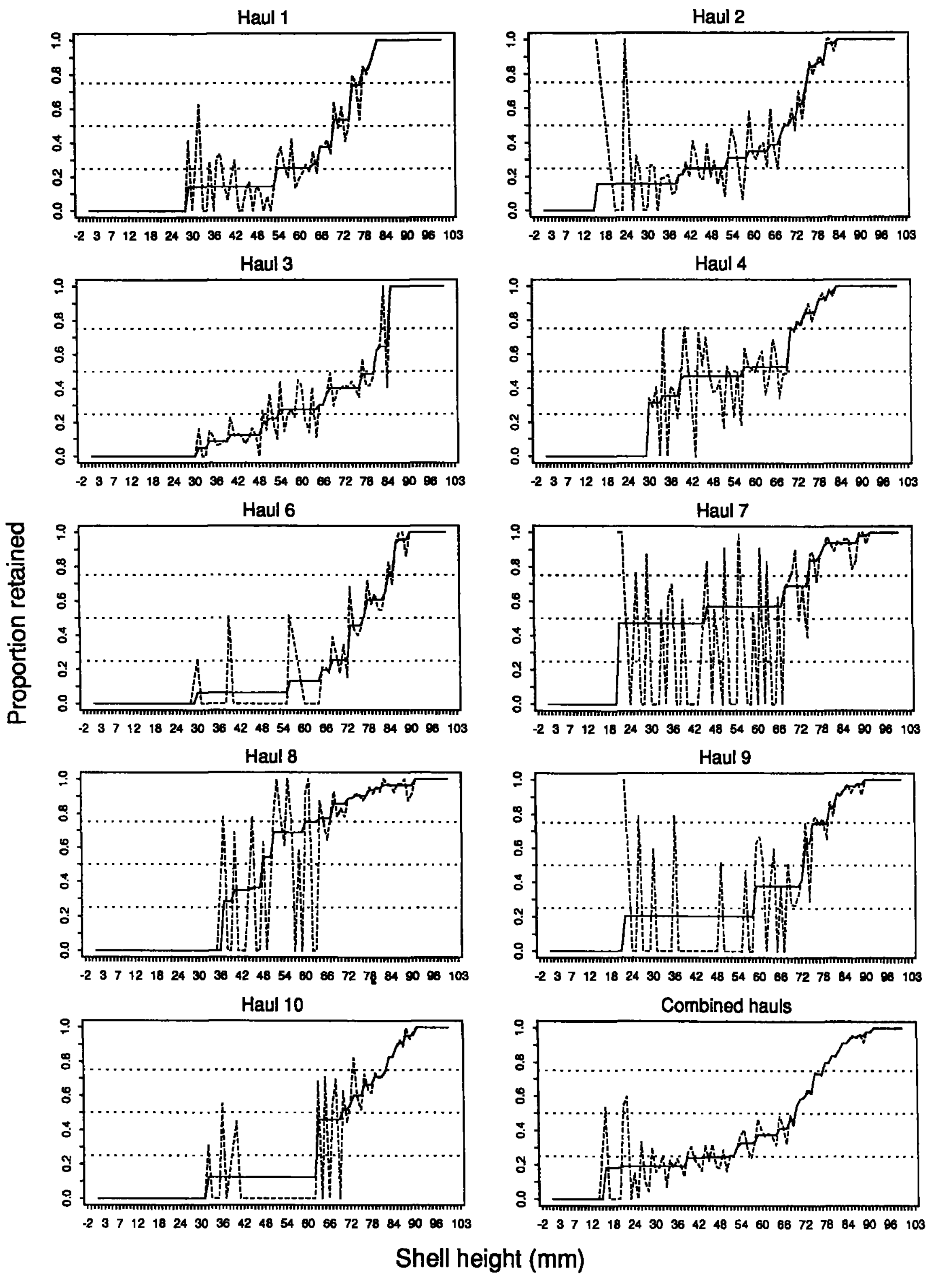

Figure 3

Isotonic selection curves (solid lines) fitted to the individual haul and combined hauls data (dashed lines).

Table 1
The estimated shell heights of 25%, 50%, and 75% retention for hauls 1–4, 6–10, and the combined hauls data, obtained by isotonic regression.

Haul	l_{25}	l_{50}	l_{75}
1	54.0	69.8	77.1
2	52.0	70.0	75.1
3	53.5	80.1	84.3
4	29.8	56.5	71.2
6	67.9	76.7	83.9
7	20.5	45.3	74.4
8	36.9	47.8	63.1
9	58.3	72.4	79.1
10	62.4	69.7	82.1
Combined	50.5	69.4	77.3

isotonic fit estimates of l_{50}, l_{75} or percent meat weight retention because bad data for small sizes will not affect the fit to large sizes. The same may not be true of parametric fits.

Acknowledgements

This work would not have been possible without the logistical support provided by K.S. Naidu and the programing assistance of Noel Cadigan, both of the Department of Fisheries and Oceans, St. John's, Newfoundland, Canada.

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