A Comparison of Driftnet Fishery Bycatch Estimation Methods Based on Empirical Bootstrap Distributions

by
Jerry A. Wetherall and Marian Y.Y. Yong
Honolulu Laboratory
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2570 Dole Street
Honolulu, HI 96822
U.S.A.

I. ABSTRACT

Two methods were compared for estimating the total bycatch of albacore (*Thunnus alalunga*), skipjack tuna (*Katsuwonus pelamis*), and blue shark (*Prionace glauca*) in the 1990 Japanese driftnet fishery for neon flying squid (*Ommastrephes bartrami*): (1) a standard method that expands the arithmetic mean of sample bycatch rates, and (2) the Pennington method which expands the delta-lognormal estimator of the mean bycatch rate. Bootstrap distributions of the two estimators consistently showed that the Pennington method estimated higher total bycatch and wider approximate confidence intervals for total bycatch. The results agree with other findings published recently, indicating that the Pennington estimator is not robust with respect to the key assumption of lognormality in the positive bycatch rates.

II. INTRODUCTION

Estimates of bycatch levels in the high-seas driftnet fisheries may vary substantially depending on the statistical method used. Whether the statistical method is applicable and the resulting estimates useful depends on the validity of critical underlying assumptions. Using data from the 1990 Japanese fishery for neon flying squid (*Ommastrephes bartrami*), we compared bycatch estimates from two procedures: (1) a standard method that expands the arithmetic mean of sample bycatch rates, and (2) a method which expands the delta-lognormal estimator of mean bycatch rate. The latter method is derived from ideas first developed by Aitchison (1955) and introduced to fishery surveys by Pennington (1983). Empirical bootstrap distributions of each estimator were computed. In both cases, total bycatch was estimated for specified time-area strata and then summed over the strata.

III. BYCATCH RATE AND FISHING EFFORT DATA

The data for bycatch estimation consist of observations of bycatch rates for a sample of fishing operations by selected Japanese commercial squid driftnet vessels, and statistics on fishing effort by the total squid driftnet fleet. The fleet effort data were provided by the Japan Fisheries Agency (JFA). The bycatch data were collected by Canadian, Japanese, and U.S. scientific observers deployed on squid driftnet vessels in 1990. Observers were deployed on selected squid driftnet vessels at the discretion of the JFA with a view to achieving representative coverage of the fleet's total effort.

A fishing operation on a Japanese squid driftnet vessel involves the deployment of several independent driftnet sections. A section consists of about 100 net panels or "tans", each 35-50 m long and about 8 m deep, joined together. In a typical operation the setting of the net sections begins around dusk, and retrieval commences before dawn the following day. Although retrieval usually takes 8-12 hours, it may be slower if squid catch rates are extremely high or other difficulties occur. Then, some driftnet sections may be left in the water one or two additional nights. Such extended retrievals occurred in 4.6% of the operations monitored by observers in 1990.

Observers collected bycatch data from a subset of the driftnet sections that were set and retrieved during each monitored fishing operation. Observers usually monitored 6-7 sections out of the 7-10 sections typically deployed. Observers decided which sections to monitor at the beginning of the operation based on tables of random numbers. The sampling tables and all other bycatch observation procedures were developed and standardized jointly by the three countries. For the purposes of this analysis, bycatch data from all monitored sections of a fishing operation were pooled.

Bycatch rate statistics for each species caught in the operation were computed by dividing the pooled bycatch by the pooled fishing effort (standardized as the number of 50-m tan equivalents). The bycatch rate for each species, expressed as the number of animals decked per 1,000 standardized tans of monitored fishing effort, was associated with the exact position and date of the operation. Statistics on the fleet's fishing effort, expressed as the number of standardized tans deployed, were available only in summarized form for each 10-day period and 1° latitude x 1° longitude cell within the regulated squid driftnet fishing area.

IV. STRATIFICATION

Bycatch rate data and fleet effort statistics were stratified by month (May through December) and longitude (145°W-160°W, 160°W-175°W, and 175°W-170°E). The fleet did not operate in some time-area strata. Further, some strata had low effort and no observer coverage, particularly late in the year. Fleet effort and bycatch rate statistics from such strata were pooled with data from adjacent strata. As a result, there were 19 time-area strata overall (Table 1).

In addition, each time-area stratum was divided into two substrata, one consisting of all 1° latitude x 1° longitude cells in which observer data were available (substratum A) and the other consisting of the remaining cells with no observer coverage (substratum B).

V. BYCATCH ESTIMATORS

Two bycatch estimators were compared. The first is the standard method employing the arithmetic mean bycatch. In this simple approach bycatch in each time-area stratum is estimated by calculating the arithmetic mean of the bycatch rates over all monitored operations within the stratum, then multiplying the mean bycatch rate by the total fleet effort (see below) in the stratum. Total bycatch is estimated as the sum of the individual stratum bycatch estimates. Under the usual assumptions regarding random sampling within each stratum, the standard estimator is unbiased.

Table 1. Summary of 1990 fishing effort, by month and area, for the entire Japanese squid driftnet fleet and for the subset of driftnet vessels on which observers were deployed.

			Total fleet		Monitored vessels	
Stratum	Month	Area[1]	Operations	1,000 tans	Operations	1,000 tans
1	May	C	12	14	14	12
2		E	67	84	62	59
3		W	31	35	36	31
4	June	C	2,422	2,709	357	310
5		E	730	832	163	143
6		W	1,640	1,542	237	186
7	July	C	4,317	4,255	704	568
8		E	862	868	171	140
9		W	2,833	2,410	214	139
10	August	C	434	413	58	44
11		E	1,204	1,186	273	220
12		W	3,356	2,874	310	220
13	September	C	393	390	49	39
14		E	94	94	18	16
15		W	2,176	2,123	153	115
16	October	C	317	317	14	12
17		W	1,988	1,902	111	91
18	November	W	683	638	29	23
19	December	W	84	74	7	6
Total			23,643	22,759	2,980	2,374

[1]E = 145W-160°W, C = 160W-175°W, W = 175W°-170°E

The second method is known as the Pennington estimator (Pennington 1983). It assumes that the time-space distribution of the species of interest is patchy: The species either does not occur in the bycatch (zero bycatch rate) or does occur at some variable frequency such that the positive bycatch rates follow a lognormal distribution. Accordingly, the distribution of the bycatch rates is described by the delta-lognormal mixture distribution (Aitchison and Brown 1957). The mean bycatch rate is estimated under this assumption, then expanded by total effort as in the standard method.

More explicitly, within a given time-area stratum let n represent the total number of sampled operations, and let m denote the number of operations with positive bycatch. Let x_i be the bycatch rate for the i^{th} operation within the stratum, and for operations with positive bycatch, let $y_i = \log(x_i)$. Let x_{bar} denote the arithmetic mean of all the x_i; y_{bar}, the arithmetic mean of the y_i; and s, the standard deviation among the y_i. In the standard estimation method, the mean bycatch in the time-area stratum, u, is estimated by the arithmetic mean bycatch, $u_s = x_{bar}$. In the Pennington method, u is estimated by the statistic u_p, where

$$u_p = \begin{cases} (m/n)*\exp(y_{bar})*H(m-1)/2; & \\ \quad (s/4)*(m-1)/m & m>1 \\ x_1/n & m=1 \\ 0 & m=0 \end{cases}$$

is the minimum variance unbiased estimator of u under the delta-lognormal assumption (Crow and Shimizu 1988). The symbol H{.} denotes the hypergeometric function defined as

$$H\{a;z\} = 1 + z/f_1(a) + z^2/[2*f_2(a)] + \ldots + z^j/[j!*f_j(a)] + \ldots$$

where

$$f_j(a) = \begin{cases} a*(a+1)*(a+2)*\ldots*(a+j-1) & j\geq1 \\ 1 & j=0 \end{cases}$$

As in the standard method, overall bycatch is estimated by summing the bycatch estimates for individual strata. If sampling is random and the positive bycatch rates are truly lognormal, the Pennington estimator is unbiased, and more efficient than the standard estimator based on the arithmetic mean bycatch.

In computing bycatch within each time-area stratum, two options were explored to expand the mean bycatch rate. In the first option, the bycatch rate in substratum A was assumed to be applicable to substratum B, so the total bycatch for the time-area stratum was computed by multiplying the mean bycatch rate by the total fleet effort in the two substrata:

Option 1: $C = u*(E_A + E_B)$
(effort) $\quad = u*E_A*(1 + (E_B/E_A)) \qquad E_A > 0,$

where C is the total bycatch and E_A and E_B are the respective fleet effort levels.

In the second option, the fleet effort in substratum B was ignored, and information on the fleet's decked catches within the substrata were used to expand the bycatch rate:

Option 2: $C = u*E_A*(1 + (W_B/W_A)) \qquad W_A > 0,$
(weight)

where W_B and W_A are the reported decked catches in the A and B substrata. The second option makes no assumptions about the relative bycatch rates in the two substrata, but assumes that discard rates, average weights of decked animals, and reporting rates for the species in question are the same in both substrata.

We demonstrate the two methods by applying them to bycatch data for albacore (*Thunnus alalunga*), skipjack tuna (*Katsuwonus pelamis*), and blue shark (*Prionace glauca*). Overall frequency distributions of bycatch rates for albacore, skipjack tuna, and blue shark were skewed strongly to the right (Figs. 1-3). When aggregated over time-area strata, the distributions of the log-transformed positive bycatch rates were not particularly normal. But they appeared to be nearly normal in many individual strata, suggesting that the Pennington estimator would be appropriate and provide estimates of total bycatch with greater precision than the standard estimator.

VI. BOOTSTRAP SAMPLING

We compared the performance of the two estimators by generating their "bootstrap distributions" from the following Monte Carlo algorithm:

(1) Within each time-area stratum, the observed bycatch rate distribution was taken to be the non-parametric maximum likelihood estimator of the true bycatch rate frequency distribution. Data from all of the monitored fishing operations within the stratum were included, whether or not they involved extended retrievals.

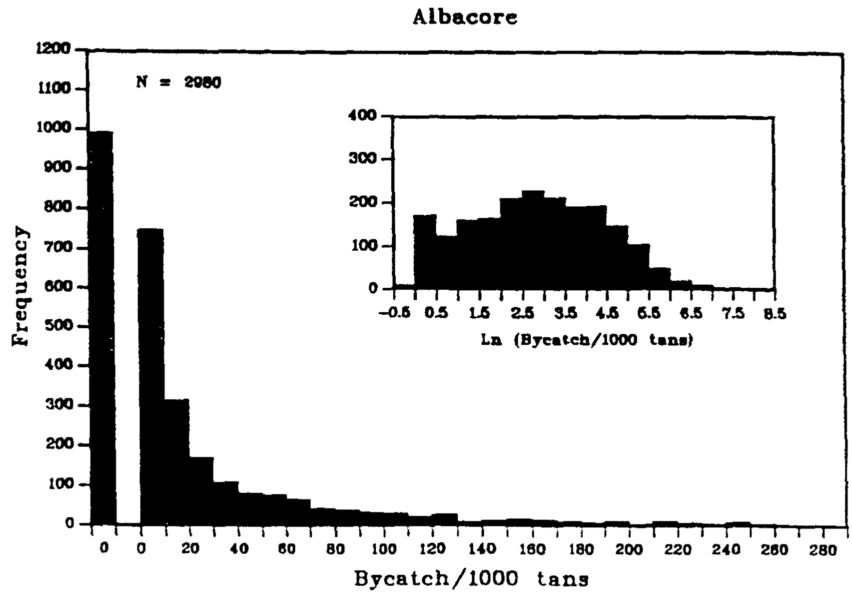

Figure 1. Bycatch rate frequency distribution for albacore in the 1990 Japanese squid driftnet fishery. Inset shows corresponding frequency distribution for log-transformed positive bycatch rates.

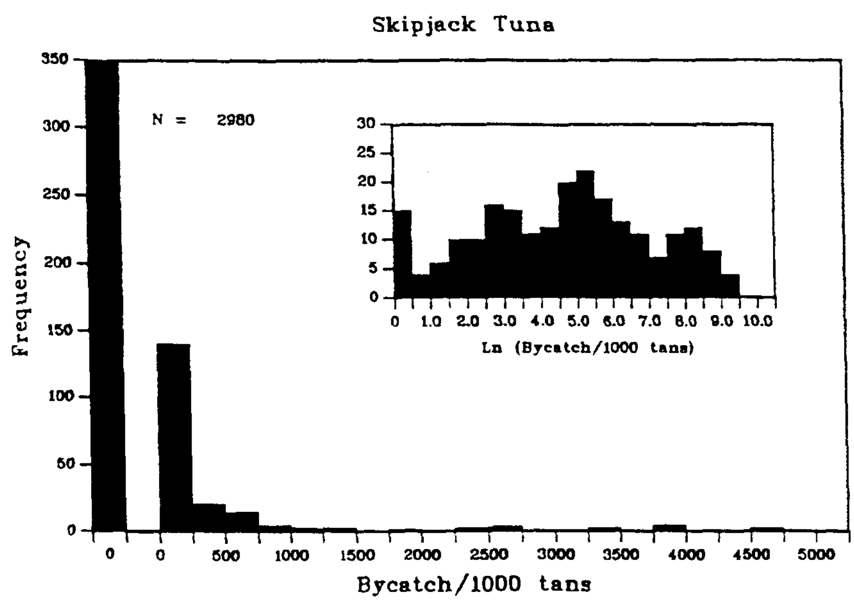

Figure 2. Bycatch rate frequency distribution for skipjack tuna in the 1990 Japanese squid driftnet fishery. Inset shows corresponding frequency distribution for log-transformed positive bycatch rates. For ease in plotting the frequency of operations with zero bycatch rate was truncated at 350; the actual frequency was 2,771 operations.

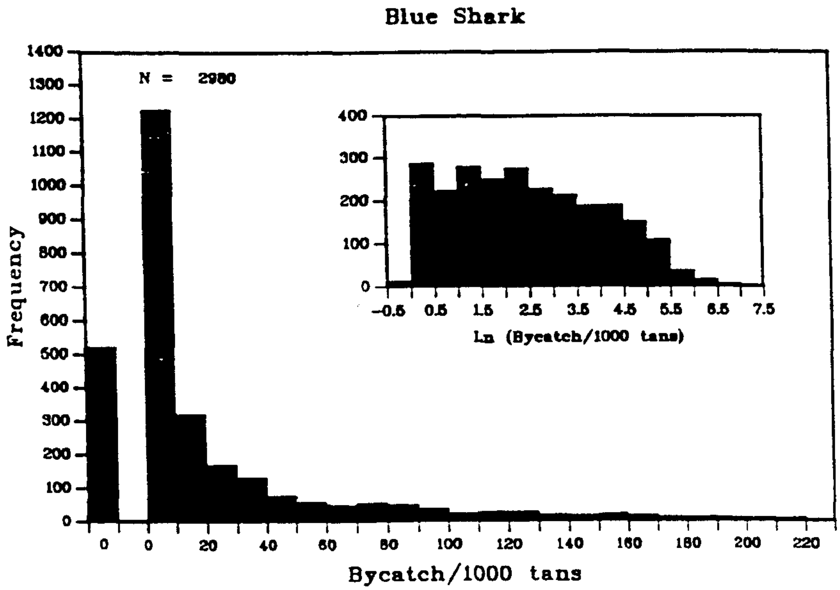

Figure 3. Bycatch rate frequency distribution for blue shark in the 1990 Japanese squid driftnet fishery. Inset shows corresponding frequency distribution for log-transformed positive bycatch rates.

(2) A random "bootstrap" sample was taken (with replacement) from the empirical bycatch rate distribution in each time-area stratum. Sample sizes in each stratum were equal to the number of fishing operations monitored by observers.

(3) The two bycatch estimators were applied to each set of bootstrap sample values, producing a corresponding bootstrap "replicate" pair of total bycatch estimates.

(4) Steps (2) and (3) were repeated 1,000 times (1,000 replicates), generating empirical frequency distributions of total bycatch estimates under the two estimation procedures.

In the Monte Carlo procedure, random bycatch rates were computed by the inverse transformation method (Naylor *et al.* 1966). The required uniformly distributed pseudorandom variates were generated using the *ran1* algorithm described by Press *et al.* (1988).

The bootstrap bycatch distributions are Monte Carlo approximations to the non-parametric maximum likelihood estimators of the true frequency distributions (Efron 1982). As such, they provide an empirical basis for comparing the estimation methods. We evaluated the estimators on the basis of their relative bias and precision. To examine relative bias, we compared the expected values of the estimators, as indicated by their bootstrap distribution means. Specifically, we computed the relative bias of the Pennington estimator as the amount by which its bootstrap distribution mean exceeded the standard estimator bootstrap mean, expressed as a percentage of the latter. Assuming random sampling within strata, this measure is sensitive to violations of the critical assumptions of the Pennington method. To examine estimator precision, we computed the coefficients of variation and the 5th and 95th percentiles of the bootstrap distributions. The percentiles are bootstrap approximations of the upper and lower 90% confidence limits for total bycatch.

VII. RESULTS

A comparison of the bootstrap distribution means (Table 2) for albacore, skipjack tuna, and blue shark shows that, on average, the Pennington method estimated higher bycatches than did the standard method. The comparisons are based on the Option 1 expansion. The difference was smallest for blue shark (+6.1%), intermediate for albacore (+14.2%), and largest for skipjack tuna (+205%).

Table 2. Characteristics of bootstrap distributions of total bycatch (number of fish) for two bycatch estimators, based on 1,000 replicates. Data are for the 1990 Japanese squid driftnet fishery.

SPECIES	ESTIMATOR	5^{th} PERCENTILE ($X10^3$)	MEAN ($X10^3$)	95^{th} PERCENTILE ($X10^3$)	COEFFICIENT OF VARIATION
Albacore	Standard	7.203	8.077	9.095	0.0699
	Pennington	8.189	9.221	10.426	0.0736
	Relative bias	13.7%	14.2%	14.6%	5.3%
Skipjack tuna	Standard	21.987	29.193	36.752	0.1536
	Pennington	50.037	88.922	148.022	0.3708
	Relative bias	128%	205%	303%	141%
Blue shark	Standard	6.259	6.656	7.080	0.0380
	Pennington	6.554	7.060	7.586	0.0444
	Relative bias	4.7%	6.1%	7.1%	16.8%

These results are consistent with the apparent differences among species in distribution patchiness, at least at the scale measured in a fishing operation. In particular, the differences between the standard and Pennington estimates are directly related to the proportion of zero-bycatch operations in the data.

In estimating total bycatch, the Option 1 expansion gave results differing only slightly from results under the Option 2 approach (Table 3). The similarity between the estimates indicates that observer placement was geographically well-balanced in 1990. (By contrast, observer coverage in the 1989 pilot observer program on Japanese squid vessels was relatively poor in the southern extremity of the fishing area. Consequently, when we estimated the 1989 bycatch of skipjack tuna, which are more abundant in the lower latitudes, Option 2 produced a better estimate than did Option 1.)

As expected, differences between the standard arithmetic mean method and the Pennington method in regard to the 5^{th} and 95^{th} percentiles followed the same pattern as seen in distribution means (Table 2). The differences were smallest in blue shark (+4.7% in the 5^{th} percentile, +7.1% in the 95^{th} percentile), intermediate in albacore (+13.7%, +14.6%), and largest in skipjack tuna (+128%, +303%).

The Pennington estimator is unbiased (and equivalent to the standard arithmetic mean estimator) when the data are truly delta-lognormal. Differences between Pennington estimates and simple arithmetic mean estimates of bycatch would not necessarily be of concern if we were comparing single instances of the statistics calculated from all the bycatch data. The large differences between the bootstrap distribution means, however, indicate a systematic bias in the Pennington estimator. We suspect that the bias is due to failure of the key assumption of the Pennington method. In recent computer simulation experiments, Myers and Pepin (1990) showed that slight departures from lognormality in the positive data values can lead to serious upward bias in the Pennington estimator of the distribution mean.

When the positive bycatch rates are truly lognormal, the Pennington estimator of total bycatch, besides being unbiased, is more precise than the simple arithmetic mean estimator. Indeed, this is the chief motivation for using the Pennington method. But our data show that the coefficients of variation of the bootstrap distributions were consistently higher for the Pennington estimator than for the standard arithmetic mean estimator: albacore, +5.3%; blue shark, +16.8%; skipjack tuna, +141% (Table 2). These results confirm the simulation studies by Myers and Pepin (1990), which showed a steady loss of efficiency, relative to the arithmetic mean estimator, when the lognormal assumption was violated.

Our experience adds to a growing body of results, indicating that the Pennington estimator, despite its theoretical attractions, is not very robust and may often be inappropriate. This seems to be the case for driftnet bycatch estimation. In most instances, non-parametric estimates based on bootstrap distributions of the simple arithmetic mean bycatch rate would be preferable.

Table 3. Bootstrap estimates of total bycatch (number of fish) for two expansion options, based on 1,000 replicates. The standard arithmetic mean estimator was used. Data are for the 1990 Japanese squid driftnet fishery.

SPECIES	EXPANSION OPTION	BYCATCH ESTIMATE ($x10^5$)	COEFFICIENT OF VARIATION
Albacore	1 - effort	8.077	0.0699
	2 - weight	8.019	0.0697
Skipjack tuna	1 - effort	29.193	0.1536
	2 - weight	30.724	0.1510
Blue shark	1 - effort	6.656	0.0380
	2 - weight	6.551	0.0360

VIII. REFERENCES

AITCHISON, J. 1955. On the distribution of a positive random variable having a discrete probability mass at the origin. J. Am. Stat. Assoc. 50:901-908.

AITCHISON, J., and J.A.C. BROWN. 1957. The lognormal distribution. Cambridge University Press.

CROW, E.L., and K. SHIMIZU (eds.). 1988. Lognormal distributions: theory and applications. Marcel Dekker, New York.

EFRON, B. 1982. The jackknife, the bootstrap and other resampling plans. Soc. Ind. Appl. Math. CBMS-NSF Conference Series in Applied Mathematics, 92 p.

MYERS, R.A., and P. PEPIN. 1990. The robustness of lognormal-based estimators of abundance. Biometrics 46:1185-1192.

NAYLOR, T.H., J.L. BALINTFY, D.S. BURDICK, and K. CHU. 1966. Computer simulation techniques. John Wiley & Sons, New York, 352 p.

PENNINGTON, M. 1983. Efficient estimators of abundance, for fish and plankton surveys. Biometrics 39:281-286.

PRESS, W.H., B.P. FLANNERY, S.A. TEUKOLSKY, and W.T. VETTERLING. 1988. Numerical recipes in C: the art of scientific computing. Cambridge University Press, 735 p.