Assessing the precision of frequency distributions estimated from trawl-survey samples

Abstract—In trawl surveys a cluster of fish are caught at each station, and fish caught together tend to have more similar characteristics, such as length, age, stomach contents etc., than those in the entire population. When this is the case, the effective sample size for estimates of the frequency distribution of a population characteristic can, therefore, be much smaller than the number of fish sampled during a survey. As examples, it is shown that the effective sample size for estimates of length-frequency distributions generated by trawl surveys conducted in the Barents Sea, off Namibia, and off South Africa is on average approximately one fish per tow. Thus many more fish than necessary are measured at each station (location). One way to increase the effective sample size for these surveys and, hence, increase the precision of the length-frequency estimates, is to reduce tow duration and use the time saved to collect samples at more stations.

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Survey-based assessments often appear to provide a more accurate prognosis of the status of a fish stock than catch-based assessments (Nakken, 1998; Pennington and Strømme, 1998; Korsbrekke et al., 2001). An advantage that survey-based assessments have over those based on commercial catch statistics is that the uncertainties associated with survey estimates can be studied and quantified, and based on such research, survey methods, and ultimately stock assessments, can be improved (Godø, 1994). In contrast, it is generally difficult to determine either the accuracy or the precision of estimates based on commercial catch data, and it is not clear how to improve, at a reasonable cost, the collection of catch data so that these data would more accurately reflect the mortality caused by fishing (Christensen, 1996).

Trawl surveys provide estimates of the abundance or relative abundance of a fish stock and estimates of the relative frequency of various population characteristics, such as length, age, and stomach contents. In our study we examined the precision of survey-based estimates of the length-frequency distributions of cod and haddock in the Barents Sea, hake off South Africa, and hake off Namibia. The focus was on length, but the results are relevant for estimating the frequency distribution of other population characteristics.

Materials and methods

Survey length data

Bottom trawl survey length data for Northeast Artic cod (*Gadus mohua*) and Northeast Arctic haddock (*Melanogrammus aeglefinus*)[1] were collected during the Institute of Marine Research (Norway) winter and summer surveys in the Barents Sea. The surveys were stratified systematic surveys and at each station the trawl was towed for 30 minutes.[2]

[1] Also known as "Atlantic cod" and "haddock," respectively, according to *Common and scientific names of fishes from the United States and Canada*. 1991. Am. Fish. Soc. Spec. publ. 20, Besthesda, MD, 183 p.

[2] Aglen, A. 1999. Report on the demersal fish surveys in the Barents Sea and Svalbard area during summer/autumn 1996 and 1997. Unpubl. manuscr., Fisket og Havet NR. 7-1999. Institute of Marine Research, PO Box 1870 Nordnes, N-5817 Bergen, Norway.

The data for the Namibian deepwater hake (*Meluccius paradoxus*) were collected during bottom trawl surveys off Namibia conducted by the Ministry of Fisheries and Marine Resources of Namibia in conjunction with the Norwegian Agency for Foreign Aid (NORAD). For these surveys, tows of 30-minute duration were made at stations along transects perpendicular to the coast.[3]

The data for the deepwater hake for South Africa, were collected from during bottom trawl surveys off the west coast of South Africa. The surveys were conducted by the Marine and Coastal Management Centre, South Africa, by using a stratified random design. Tows of 30-minute duration were made at each station (see Payne et al., 1985).

Assessing the precision of length-frequency estimates

The sample of fish of a particular species measured during a survey is not a random sample of individual fish from the entire population but a sample of n clusters, one cluster from each station. Because fish caught together are usually more similar than those in the general population, a total of M fish collected in n clusters will contain less information about the population length distribution than M fish sampled randomly. One way to measure the information contained in a sample of length measurements is to estimate the number of fish that one would need to sample at random (the effective sample size) to obtain the same information on length contained in the cluster samples.

The effective sample size for cluster sampling can be defined and calculated as follows (Pennington and Vølstad, 1994; Folmer and Pennington, 2000). First estimate the population mean fish length and its variance based on the clusters of fish caught at n stations. Because both the lengths and the number of fish at a station are random variables, a ratio estimator is appropriate (Cochran, 1977). The ratio estimator, $\hat{R}$, of the mean length is given by

$$\hat{R} = \frac{\sum_{i=1}^{n} M_i \hat{\mu}_i}{\sum_{i=1}^{n} M_i}, \tag{1}$$

where M_i = the number of fish caught (either actual or estimated) at station i; and

$\hat{\mu}_i$ = an estimate of the average length of fish at station i.

For example, if the catch at a station is divided into strata and a random sample of fish are chosen in each stratum, then for that station $\hat{\mu}_i$ would be the stratified estimate of mean length. The estimated variance of $\hat{R}$ is approximately given by

$$\operatorname{var}(\hat{R}) = \sum_{i=1}^{n} \frac{(M_i/\overline{M})^2 (\hat{\mu}_i - \hat{R})^2}{n(n-1)}, \tag{2}$$

where $\overline{M} = \sum_{i=1}^{n} M_i / n$.

Next estimate the variance, σ_x^2, of the population length distribution. If m_i fish are randomly selected at each station (or if all fish are measured), then

$$\hat{\sigma}_x^2 = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m_i} (M_i/m_i)(x_{i,j} - \hat{R})^2}{M-1} \tag{3}$$

is an estimator of σ_x^2,

where $M = \sum_{i=1}^{n} M_i$ is the total number of fish caught during the survey; and

$x_{i,j}$ = the length of the j^{th} fish at station i.

For other sampling schemes at a station, first estimate the number of fish caught during the survey in each of L length bins, then (e.g. Bhattacharyya and Johnson, 1977)

$$\hat{\sigma}_x^2 = \frac{\sum_{k=1}^{L} f_k (y_k' - \hat{R})^2}{M-1} \tag{4}$$

is an estimator of σ_x^2,

where f_k = the frequency of fish in the k^{th} length bin; and

y_k' = the bin's midpoint.

Now if it were possible to sample m fish at random from the population, then the variance of the sample mean would be equal to σ_x^2/m. The effective sample, m_{eff}, is defined as the number of fish that would need to be sampled at random so that the sample mean would have the same precision as an estimate based on a sample of n clusters. An estimate of the effective sample size for a particular cluster sample can be derived by substituting the estimates from Equation 2 and either Equation 3 or 4 into the equation

$$\frac{\hat{\sigma}_x^2}{\hat{m}_{eff}} = \operatorname{var}(\hat{R}). \tag{5}$$

The effective sample size is related to Kish's design effect (*deff*), which for estimating the mean from cluster sampling is defined by (Cochran, 1977)

$$deff = \frac{\operatorname{var}(\hat{R})}{\sigma_x^2 / m}$$

[3] Anonymous. 1999. Survey of fish resources of Namibia. Preliminary cruise report 1/99. NORAD-FAO/UNDP Project GLO92/013, 52. Unpubl. manuscr. NatMIRC, PO Box 912, Swakopmund, Namibia.

Table 1

Summary statistics for assessing the precision of the estimated length distributions of Northeast Arctic cod based on the winter and summer bottom trawl surveys in the Barents Sea. The estimated effective sample size is denoted by $\hat{m}_{eff}$, n is the number of stations at which cod were caught, M is the total number of cod caught, m is the number measured, $\hat{R}$ is the estimate of mean length, and var($\hat{R}$) is its variance.

Year	n	M	m	$\hat{R}$(cm)	var($\hat{R}$)	$\hat{m}_{eff}$	$\hat{m}_{eff}/n$	$(\hat{m}_{eff}/m) \times 100\%$
Winter								
1995	296	175006	47286	20.0	0.7	313	1.1	0.7
1996	314	209114	44021	18.0	0.3	511	1.6	1.1
1997	177	71418	25689	19.0	2.1	119	0.7	0.7
1998	197	60746	32536	22.1	0.7	394	2.0	1.2
1999	223	50192	21760	25.0	1.9	107	0.5	0.5
	Avg.	113295	34258			289	1.2	0.8
Summer								
1995	329	66643	46161	31.2	1.4	252	0.8	0.6
1996	341	115834	45286	24.4	0.6	478	1.4	1.1
1997	266	72093	26947	23.1	0.8	266	1.0	1.0
1998	218	72360	23461	25.1	1.1	184	0.8	0.8
1999	217	46593	23253	30.8	0.9	211	0.9	0.9
	Avg.	74705	33022			278	1.0	0.9

and, therefore, $m_{eff} = m/deff$. Some statistical software packages for the analysis of complex survey data, such as SUDAAN (Research Triangle Institute, 2001), generate estimates of the design effect.

Simulation techniques were used to examine the effect that reducing the total number of fish measured during a particular survey would have on the estimates of the mean length and the effective sample size. Length measurements consist of one or more subsamples from the fish caught at each station. The simulated estimates of the distributions of $\hat{m}_{eff}$ and $\hat{R}$ (given the actual fish measured during the survey) were generated by randomly selecting from every haul a maximum of k fish without replacement from each subsample. If fewer than k fish were in a subsample, then all were chosen. This was done 500 times for k = 10, 30, and 100, and each run produced values of $\hat{m}_{eff}$ and $\hat{R}$.

To assess the precision of an estimated length distribution, bootstrapping (Efron, 1982) was used to generate 95% confidence intervals for the proportion of fish in each 5-cm length bin. For each of 500 runs, n stations (the number of tows made during the survey) were randomly sampled with replacement and the confidence interval for each 5-cm length bin was based on the resulting 500 estimates of the proportion of fish in that bin. Finally, bootstrapping was used to examine how much the length of the 95% confidence intervals would increase if a maximum of 10 fish were selected from each subsample.

Results

Estimates of the effective sample size and associated statistics for survey-based estimates of the length composition of cod in the Barents Sea are presented in Table 1. The results indicate that for cod the estimated effective sample size is small compared with the number of fish measured. For example during the 1995 winter survey, 175,006 cod were caught, 47,286 were measured, and the effective sample size was 313 fish or 0.7% of the total number measured (Table 1). The average effective sample size for the winter surveys was 1.2 cod per tow and for the summer surveys, 1.0 cod per tow. The estimated effective sample sizes for the Northeast Arctic haddock survey data were, on average, approximately one fish per tow (Table 2).

The effective sample sizes for the survey estimates of the length distribution of deepwater hake off Namibia and off South Africa (Tables 3 and 4) followed the same pattern as for cod and haddock in the Barents Sea. In particular, the average effective sample size was 0.5 hake per tow for the Namibian surveys and 1.3 hake per tow for the South African surveys.

The simulated distributions of $\hat{m}_{eff}$ and $\hat{R}$, which demonstrate the effects of reducing the total number of measured fish on estimates of mean length, for the 1995 and 1999 winter surveys of cod in the Barents Sea are shown in Figures 1 and 2. For example, if a maximum of 30 fish were selected from each subsample at each station, then a total of 11,123 fish would have been measured during the 1995 survey compared with 47,286 fish that were actually measured. For 1995, $\hat{R}$ = 19.96 and the 95% confidence interval for $\hat{R}$ was (18.29, 21.63). As can be seen from Figure 1, all 500 simulated estimates of the mean based on the reduced sample size were well within the 95% confidence limits for $\hat{R}$. When the number of fish measured was reduced to a maximum of 10 fish per subsample for a total sample of 2597 fish, the simulated estimates were also

Table 2

Summary statistics for assessing the precision of the estimated length distributions of Northeast Arctic haddock generated by the winter and summer bottom trawl surveys in the Barents Sea. The notation is the same as that shown in Table 1.

Year	n	M	m	$\hat{R}$(cm)	var($\hat{R}$)	$\hat{m}_{\text{eff}}$	$\hat{m}_{eff}/n$	$(\hat{m}_{eff}/m) \times 100\%$
Winter								
1995	199	66009	22938	25.0	1.0	168	0.8	0.7
1996	235	54892	25525	32.0	2.9	69	0.3	0.3
1997	140	37441	13273	22.0	0.8	185	0.8	1.4
1998	144	12704	9620	23.9	1.0	169	1.2	1.8
1999	182	41612	12152	13.4	0.4	188	1.0	1.6
	Avg.	42532	16702			155	0.8	1.2
Summer								
1995	208	25771	15763	27.0	0.95	147	0.7	0.9
1996	163	14139	7338	31.1	3.65	51	0.3	0.7
1997	114	13560	4314	23.1	1.72	56	0.5	1.3
1998	89	7432	2699	21.3	0.34	170	1.9	6.3
1999	140	11922	5489	20.1	0.36	197	1.4	3.6
	Avg.	14565	7536			124	1.0	2.6

Table 3

Summary statistics for assessing the precision of the estimated length distribution of deepwater hake off Namibia based on bottom trawl surveys. The notation is the same as that shown in Table 1.

Year	n	M	m	$\hat{R}$(cm)	var($\hat{R}$)	$\hat{m}_{\text{eff}}$	$\hat{m}_{eff}/n$	$(\hat{m}_{eff}/m) \times 100\%$
Sep 1990	37	6671	1837	24.6	1.8	35	1.0	1.9
Jan 1991	19	3887	1329	29.2	3.3	19	1.0	1.4
Oct 1992	53	22369	5090	30.1	2.1	30	0.6	0.6
Apr 1992	63	33107	5411	34.0	2.8	30	0.5	0.6
Oct 1993	88	36814	8480	30.3	2.6	41	0.5	0.5
Jan 1993	70	36247	8208	37.3	2.9	33	0.5	0.4
Apr 1993	84	25746	7023	32.7	4.2	35	0.4	0.5
Jan 1994	60	30134	7997	28.4	10.0	13	0.2	0.2
Apr 1994	103	72012	17694	35.3	1.4	63	0.6	0.4
Oct 1994	105	70817	17216	28.1	1.9	44	0.4	0.3
Apr 1995	79	47585	14661	26.0	7.0	20	0.3	0.2
Jan 1996	105	57540	27834	30.3	2.9	45	0.4	0.2
Sep 1996	105	78562	24975	28.7	1.6	50	0.5	0.2
Jan 1997	122	54995	27648	28.5	4.6	29	0.2	0.1
Jan 1998	104	52573	15717	34.5	2.3	44	0.4	0.4
Jan 1999	104	68419	19305	28.4	4.1	30	0.3	0.2
	Avg.	43592	13152			35	0.5	0.5

well within the 95% confidence interval for $\hat{R}$ (Fig. 1). The results of the simulations for the winter survey in 1999 were similar to those for 1995 (Fig. 2).

Bootstrapped estimates of the 95% confidence intervals for the estimated proportion of fish in each 5-cm length bin for the 1995 and 1999 Barents Sea winter survey of cod are shown in Figure 3. The inner brackets denote the confidence interval based on the total number of fish actually measured and the outer brackets denote the confidence intervals if a maximum of 10 fish were measured per subsample.

Discussion and conclusions

For all the surveys examined, the effective sample size for the survey length data was much smaller than the total number of fish measured. The average effective sample size

Table 4

Summary statistics for assessing the precision of the estimated length distribution of deepwater hake off South Africa based on bottom trawl surveys. The notation is the same as that shown in Table 1.

Year	n	M	m	$\hat{R}$(cm)	var($\hat{R}$)	$\hat{m}_{\text{eff}}$	$\hat{m}_{eff}/n$	$(\hat{m}_{eff}/m) \times 100\%$
Jan 1985	75	75883	13863	29.3	0.7	70	0.9	0.5
Jul 1985	65	55704	10786	29.9	0.9	52	0.8	0.5
Jan 1986	86	82720	16216	28.2	0.3	132	1.5	0.8
Jan 1987	91	140685	18317	26.7	0.3	122	1.3	0.7
Jul 1987	76	80476	14774	27.0	0.8	68	0.9	0.5
Feb 1988	88	91828	17187	24.3	0.5	98	1.1	0.6
Feb 1989	33	234796	10115	25.7	0.1	207	6.3	2.0
Jan 1990	75	150814	23093	26.0	1.6	43	0.6	0.2
Jan 1991	73	226234	17115	27.2	0.9	38	0.5	0.2
Feb 1992	83	174364	24334	25.2	0.8	58	0.7	0.2
Jan 1993	81	102395	24922	26.0	0.6	89	1.1	0.4
Jan 1994	63	139268	28621	27.1	0.7	68	1.1	0.2
Jan 1995	81	137225	37481	26.4	0.5	97	1.2	0.3
Jan 1996	77	167765	31538	25.2	1.1	46	0.6	0.1
Jan 1997	88	219218	33537	24.2	0.7	70	0.8	0.2
Jan 1998	76	251050	26328	25.9	0.3	116	1.5	0.4
Jan 1999	74	218438	26144	25.4	0.5	91	1.2	0.3
	Avg.	149933	22022			86	1.3	0.5

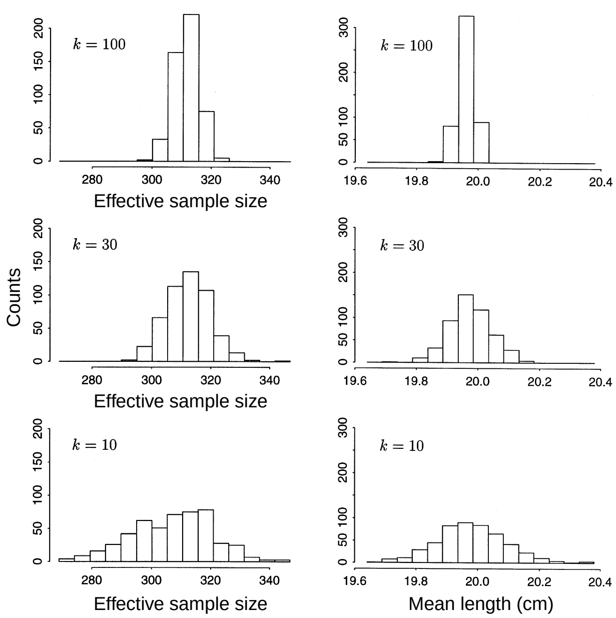

Figure 1

Simulated estimates of the distribution of the effective sample size, $\hat{m}_{eff}$, and of the mean length, $\hat{R}$, when the total number of fish measured is reduced for the 1995 winter survey in the Barents Sea. The top panel is when a maximum of k = 100 fish are selected per subsample for a total of m = 30,403 fish in each run; the middle panel, k = 30, m = 11,123; and the bottom panel, k = 10, m = 3911. The estimate of the population mean based on the entire sample (m=47,286) is 19.96 and its 95% confidence interval is (18.29, 21.63).

was approximately one fish per tow and it seems to be typical that the effective sample size for estimating length distributions is relatively small for trawl surveys. For example, the effective sample size for trawl surveys of haddock on Georges Bank was on average less than 0.5 fish per tow (Pennington and Vølstad, 1994) and for shrimp in a small area off West Greenland, about 3 shrimp per tow (Folmer and Pennington, 2000).

The reason that the effective sample sizes were small, and, therefore, the estimates of the length distributions were rather imprecise, given the number of fish that were measured, is that the lengths of fish in a haul tend to be more similar than those in the entire population. An additional factor is that the density of fish in a survey region is usually quite variable. To see this, consider the equation for the expected value of var$(\hat{R})$. If every fish is measured during a survey, then subject to some assumptions, the expected variance of $\hat{R}$ when n stations are sampled is given approximately by (Pennington and Vølstad, 1994)

$$\operatorname{var}(\hat{R}) = \frac{\sigma_x^2\left\{1+(\overline{M}-1+\sigma_m^2 / \overline{M})\rho\right\}}{M},$$

where $\overline{M}$ = the expected mean catch per tow;
σ_m^2 = the tow-to-tow variance of catch;
$M(= n\overline{M})$ = the expected total number of fish caught;
σ_x^2 = the population variance of length; and
ρ = the coefficient of intrahaul correlation (see Cochran, 1977, p. 209) for length.

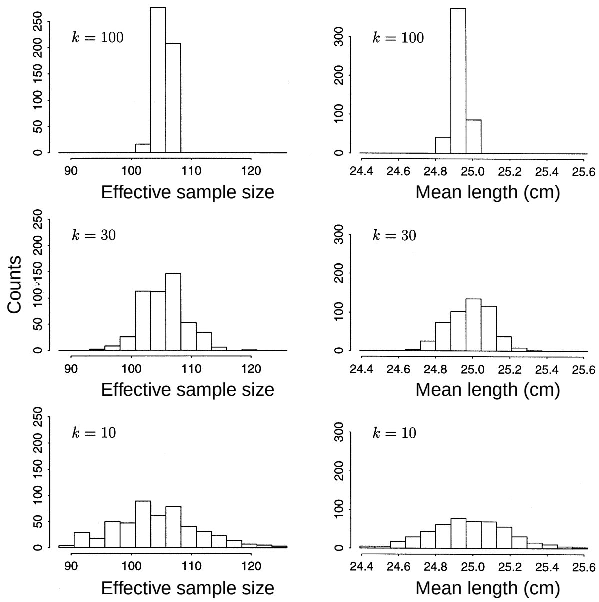

Figure 2

Simulated estimates of the distribution of the effective sample size, $\hat{m}_{eff}$, and of the mean length, $\hat{R}$, when the total number of fish measured is reduced for the 1999 winter survey in the Barents Sea. The top panel is when a maximum of k = 100 fish are selected per subsample for a total of m = 17,615 fish in each run; the middle panel, k = 30, m = 7240; and the bottom panel, k = 10, m = 2597. The estimate of the population mean based on the entire sample (m=21,769) is 24.96 and its 95% confidence interval is (22.26, 27.66).

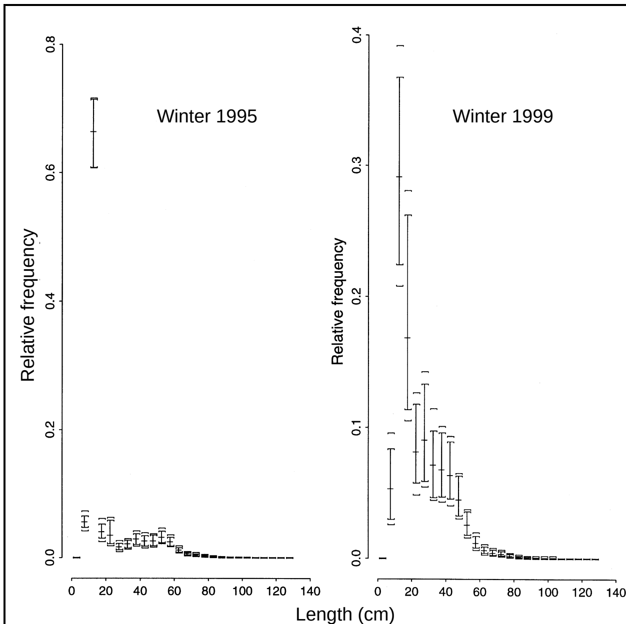

Figure 3

Bootstrapped estimates of the 95% confidence intervals for the proportion of cod in the Barents Sea in each 5-cm length bin, for winter 1995 and for winter 1999. The inner brackets denote the confidence intervals if the estimates are based on all the cod measured during the surveys and the outer brackets denote the confidence intervals if 10 fish are measured for each subsample.

If $\rho = 0$, then $\text{var}(\hat{R}) = \sigma_x^2 / M$ and the effective sample size is equal to M. However if $\rho > 0$ (i.e. fish of similar length tend to be caught together), then the terms in the parentheses can greatly increase the variance and thus drastically reduce the effective size. In particular, the term $\sigma_x^2 / \overline{M}$ is relatively large for trawl surveys. Finally, if $\rho < 0$, which is rarely if ever the case for trawl surveys, then the effective sample size will be larger than M.

The precision of estimates of other population characteristics, such as age distribution, can also be relatively low compared with the number of fish sampled if the particular attribute or measurement is more similar for fish caught together than for those in the general population. For example, the precision of estimates of mean stomach contents (Bogstad et al., 1995) or diet composition (Tirasin and Jørgensen, 1999) can be relatively low because of intrahaul correlation.

An effective sample size of one fish per tow does not mean only one fish should be measured at each station, but it implies that the only way to improve survey precision significantly is to increase the number of stations, i.e. to sample fish from as many locations as possible. The bootstrapped estimates of precision and the sampling simulations showed that reducing or increasing the number of fish measured (or caught and measured) at a station will not significantly affect the precision of length-distribution estimates. In general, if intracluster correlation is positive for an attribute, then it is usually best to take a small sample from as many locations as possible (e.g. Bogstad et al., 1995; McGarvey and Pennington, 2001).

It has been shown that tows of short duration are in general more efficient for estimating stock abundance than long tows (Godø et al., 1990; Pennington and Vølstad, 1991; Gunderson, 1993; Carlsson et al., 2000). Therefore one way to collect samples from more locations and improve overall survey efficiency without increasing survey cost is to reduce tow duration and use the time saved to increase the number of survey stations (Pennington and Vølstad, 1994). For example, if tow duration were reduced from 60 minutes to 15 minutes for a trawl survey of shrimp off West Greenland, then 44% more stations could be surveyed (Carlsson et al., 2000). Likewise, a reduction in tow duration from 30 minutes to 10 minutes for a trawl survey on Georges Bank would increase the number of survey stations by about 30% (Pennington and Vølstad, 1994).

The total number of fish caught would be fewer, on average, if tow duration was reduced, but estimates of fish density would be more precise and the resulting sample of individuals would be more representative of the entire population (Pennington and Vølstad, 1994).

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